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Functional Efficiency of the Woody Vegetation Species Composition in Urban Green Spaces

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Abstract—The article discusses the results of a comprehensive analysis of the ecological state and environment-stabilizing functions of woody vegetation species composition in the urban green space. The work is based on a large amount of factual material obtained during the course of a long-term monitoring of Vladivostok's urban vegetation. A methodological substantiation for a comprehensive qualitative-quantitative assessment of species has been developed using the applied qualimetry techniques. An integral indicator, termed the species functional efficiency coefficient (SFEC) has been proposed as the main evaluation unit. It is a relative-quantitative characteristic of plant quality that is based on the vegetation's functional efficiency and significance in urban ecosystems: prevalence in greenery planting, vitality, ability for accumulation of the pollutant metals in the urban environments, their concentration relative to the local environment background, and the capability for accumulating metals from the soil. Comparative analysis of the functional efficiency of 80 species of trees and shrubs of the urban vegetation of Vladivostok has been carried out on the basis of the proposed coefficient. Among the compared sample of plants, the SFEC decreases from 3.70 (*Crataegus pinnatifida*) to 1.13 (*Malus mandshurica* (Maxim.) Kom.). These values correspond to 74 and 23% of the conventional quality standard (QS) of the species. The groups of species with different functional significance in the urban green space structure have been identified. The best efficiency in creating the comfortable environmental conditions in the city has been demonstrated by the widespread species: *Fraxinus mandshurica*, *Ulmus japonica*, *Betula platyphylla*, *Physocarpus opulifolia*, etc. They are of the maximum level of participation in the formation of the urban vegetation structure and a high ability to absorb the main pollutants of the urban environments. The SFEC values for these species are within 3.26–2.61, which corresponds to 65–52% of the QS. Also, some suggestions on a rational use of species for the formation of a comfortable urban environment and the introduction of the results into the practice of managing the urban green fund have been proposed.

Keywords: urban vegetation, urban green spaces, arboriflora, woody vegetation, integrated assessment, ecological functions of plants, functional efficiency of plants, quality of greenery elements, applied qualimetry techniques

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INTRODUCTION

The increasing number of metropolises and urbanized areas, as well as the growth of urban population stimulates scientific and practical interest in rational organization of urban space, including urban housing construction and public landscaping, designed to provide optimal living conditions for the population. This is quite natural, since green spaces in cities are the main environmental stabilizing factor that creates optimal quality conditions for the urban environment, as well as aesthetic and comfortable conditions for people. However, over time, the priorities of such research also change. At the end of the 20th and beginning of the 21st centuries, the maximum attention of urban scientists was paid to the quantitative and qualitative assessment of the biota and soils of urban areas, the ability of biogenic components to transform pollutants, their stability in conditions of environmental distress, as well as the search for adequate indicators of the state of the urban environments. Nowadays, there is an increasing scientific interest in a comprehensive analysis of urban green areas or open green spaces and the search for ways to increase the socio-ecological value of green spaces (Jankevica, 2012; Niemelä, 2014; Aliman et al., 2017). Also a multidimensional green space assessment and interdisciplinary research on the common urban green space issues became demandable (James et al., 2009; Daniels et al., 2018). There has been continuous improvement in methods for economically valuing ecosystem functions and green space services for urban areas, and for planning and managing urban space using an integrated ecological, aesthetic, and social approach (Ridder et al., 2004; Ives et al., 2014; Dennis and James, 2016). At the same time, the available literary sources indicate the current lack of unified methodological approaches to the comprehensive assessment of urban landscaping objects. Both in domestic works (Ufimtseva and Terekhina, 2005; Avdeeva et al., 2008, 2015a, 2015b; Fedorova, 2011; Skachkova and Kopalina, 2018; Shikhova, 2019) and in a number of foreign ones (Jankevica, 2012; Ives et al., 2014; etc.), the authors present a wide range of expert assessments of the quality, comfort, and amenities of urban landscaping objects, as well as the author's methodological support for these studies. Also noteworthy is the fact that in most cases the objects of examination are either integral structural units of urban landscaping (parks, squares, gardens, etc.) (Daniels et al., 2018) or open green spaces (Jankevica, 2012; Ives et al., 2014; Aliman et al., 2017 etc.). Much less often, methods for qualitative assessment of landscaping objects are based on or include indicators of the condition of the main structural units of green spaces and areas, i.e., trees, shrubs, grass, and soil (Ufimtseva and Terekhina, 2005; Fedorova, 2011; Shikhova, 2019).

Our previous studies on the vegetation and soils in Vladivostok revealed the high significance and relevance of rationalizing of the city's urban green economy and construction, as well as improvement of the territorial planning system for more comfortable living conditions for the population. Thus, the environmental zoning of urban green spaces showed that 65% of their area corresponds to satisfactory conditions, 10%, to poor, and only 25%, to good conditions for the growth and development of woody vegetation. In addition, despite a fairly high diversity of woody vegetation (arboriflora) in urban plantings (115 species of trees, shrubs, and woody vines), only 6–7 species are widespread and abundant in urban landscapes. Diagnostics of the vital state of plants revealed various degrees of weakening of vitality in the majority of the listed of species (Shikhova and Polyakova, 2006). In our opinion, this largely resulted from the high susceptibility of urban vegetation to heavy metal pollution (mainly by Pb, Ni, Zn, Cu, and Fe, whose content is from 1.5 (Ni) to 4 (Fe) times higher than background levels (Shikhova, 2015)). Studies of forest ecosystems on the Muravyov-Amursky Peninsula revealed a high environmental, ecological, and geochemical specialization of the Far Eastern arboriflora and differentiated the intensity of accumulation of heavy metals in natural local background conditions in accordance with the species attribution (Shikhova, 2015, 2017).

Objective—A comprehensive analysis of the functional and ecological efficiency of arboriflora that forms urban green spaces, and development of the methodological support for an integral assessment of the quality of its species composition to improve the comfort of the urban environment.

METHODS AND MATERIALS

The work is based on the available factual material, which we previously obtained during long-term monitoring of vegetation and soils in green areas of the city of Vladivostok (Shikhova and Polyakova, 2006; Shikhova, 2013; etc.). It includes the results of a survey of the vegetation of all city parks and gardens, most public gardens, 44 alleys, boulevards, and ordinary plantings along the main transport routes of the city. Studies with various levels of detail also covered inner-block landscaping objects in all residential neighborhoods of the city and six intra-city recreational forests. During the monitoring, 175 sample plots (500 m^2) and 650 route survey plots for additional strip survey of plantings were laid out, the age and life status of more than 20000 specimens of trees and shrubs were diagnosed, about 650 samples of plants and 300 soil samples were collected and analyzed for the content of heavy metals. Additionally, the results of comprehensive studies (Shikhova, 2015, 2017) of forest ecosystems on the Muravyov-Amursky Peninsula (the local ecological background (LEB) for urban green spaces) were used. The direct object of this work was the species composition of woody vegetation (arboriflora) that forms the urban green area of the city of Vladivostok. The compared sample consists of 80 species of trees and shrubs, including 66 native species and 14 adventitious species. To assess their qualitative condition and functional significance in urban plantings, we introduced the species functional efficiency coefficient (SFEC). It is an integral relatively quantitative indicator of quality, determined by the totality of ecological, biological, sanitary, and hygienic functional properties of plants. The calculation of SFEC was carried out using some techniques and methods of applied qualimetry (Azgaldov et al., 1968; Azgaldov and Raikhman, 1973). According to the available literature data, qualimetry, which develops the theoretical foundations and methodology for a comprehensive assessment of the quality of objects, is gradually being introduced into biological research. Thus, certain techniques and methods of qualimetry have been successfully used by a number of scientists in assessing the condition and quality of urban green spaces (Ufimtseva and Terekhina, 2005; Avdeeva et al., 2008, 2015; Fedorova, 2011; Skachkova and Kopalina, 2018; Shikhova, 2019).

The qualimetry approach assumes that all assessed properties of an object (in our case, a species), measured in absolute values of different scope and dimension, are converted into relative dimensionless indicators (K_i), reflecting the degree of approximation of the absolute indicator of property Q_i to the reference one, in our studies, to the optimal one, highly functionally effective for urban environments, Q_i^{ef}.

$$K_i = \frac{Q_i}{Q_i^{ef}},$$

where Q_i is a qualitative indicator expressed in absolute units of measurement and Q_i^{ef}, is the corresponding indicator of the effective value of the species.

Based on the obtained qualitative properties of the species, their functional efficiency coefficients were calculated using formula:

$$\text{SFEC} = \sum_{i-1}^{n} K_i$$

where K_i represents qualitative indicators ($i = 1, n$; n, the number of considered indicators).

The number of considered indicators (properties) of objects of qualitative assessment may be different. In our studies, the functional efficiency of species in urban plantings was assessed based on a combination of the following five quality indicators: abundance in urban green areas (K_1), life status (K_2), ability to accumulate priority metal pollutants in the urban environments (K_3) and their concentration relative to LEB (K_4), and accumulation of metals from soil (K_5). The weight of the considered indicators in the integral assessment of the quality of species was assumed to be conditionally equivalent. The qualitative and quantitative functional efficiency standard (FES) of each indicator corresponded to 1 conventional unit (100% quality).

The abundance, or the quantitative participation of species in urban vegetation, was assessed by the value of absolute occurrence. It was calculated as the ratio of surveyed areas with the presence of the species to the total number of surveyed areas, expressed as a percentage. According to previous studies, the absolute occurrence of species in urban plantings of Vladivostok varies from 58.6 to 0.3% (Shikhova and Polyakova, 2006). According to the level of the species occurrence in plantings, three groups of species were distinguished: group of widespread (absolute occurrence >25%) species contains 6 species; group of moderately distributed species (absolute occurrence 5–25%) with 33 species; and the group of rare (absolute occurrence <5%), that includes 41 species. The functional efficiency standard for the abundance of species in landscaping (K_1) was taken as the average occurrence in a group of widespread species, 35%.

The assessment of the K_2 quality indicator was carried out on the basis of previously obtained diagnostic data on the vitality status of the urban arboriflora of Vladivostok (Shikhova and Polyakova, 2003, 2006). At the same time, the vital state of species that reflects the response of plants to the complex influence of environmental factors, was determined in accordance with the methodological developments of V.A. Alekseeva (1989), according to which there are five categories of condition (CC) for tree and shrub species: healthy species (CC I, vital state 80–100%), slightly damaged species (CC II, 50–79%), severely damaged species (CC III, 20–49%), drying species (CC IV, <20%), and dead wood (CC V, 0%). The average life status index for each species was calculated using formula:

$$L_n = \frac{100n_1 + 70n_2 + 40n_3 + 10n_4 + 5n_5}{N},$$

where L_n is the relative vital state of the urban population of the species; n_1 is a number of healthy individuals; n_2 is the number of slightly damaged individuals; n_3 is the number of severely damaged individuals; n_4 is the number of dying individuals; n_5 is the number of dead individuals; and N is the total number of individuals of the species.

The quantitative value of the vital status of 80%, corresponding to the lower limit of vitality for the category of healthy plants, was taken as the reference standard for the K_2 quality indicator. It corresponds to 1.00 (100% of quality).

The coefficient of relative intensity of metal accumulation (RIA) was used to calculate quality indicator K_3, which characterizes the abilities of the compared plant species to accumulative metal pollutants from the urban environment. RIA represents the ratio of the metal content in the experimental plant to the standard accepted in the research, in this case, in one form or another to their highly effective content in the general sample of urban arboriflora. It is expressed in relative units (rel. units). The K_3 indicator was determined on the basis of previously obtained analytical data on the content of heavy metals in the leaves of the analyzed sample of plants (Shikhova, 2013, 2015). To calculate it, we first determined the statistically reliable maximum concentrations of metal pollutants in urban vegetation in absolute units. These values were 1430, 204, 25.7, 13.9, and 4.6 mg/kg for Fe, Zn, Pb, Cu, and Ni, respectively. Then, in accordance with these values, the RIA coefficients in the relative units were calculated for metals and their total values for each type of compared arboriflora sample. The total RIA coefficient value for the main metal pollutants of urban vegetation in Vladivostok served as a qualitative assessment of the properties of species to accumulate heavy metals in urban ecosystems. Moreover, if we assume that there is a certain ideal species that is capable of maximally accumulating all five pollutant metals, then its total RIA value should be 5.00 rel. units. This value is taken as the FES of the K_3 indicator and corresponds to 1.00 (100% of quality).

The ability of plants to ecologically optimize the urban environment was also assessed by the concentration coefficient (Kc). It characterizes the excess of the content of pollutants in plants exposed to technogenic pressure above the environmental background level. In the case of this study, in the urban arboriflora of Vladivostok relative to the natural forest vegetation of the Muravyov-Amursky Peninsula. The total accumulation of pollutant metals was calculated using the coefficient of total accumulation of metals (Zt) according to the formula:

$$Zt = \Sigma Kc - (n - 1) \text{ (Saet, 1982)},$$

where Kc is element concentration coefficients >1 and n is the number of accumulated elements.

For calculating Zt we considered only metals with Kc ≥ 1.2. In the study, this condition was met by five main metal pollutants of urban vegetation: Fe, Zn, Pb, Cu, and Ni. However, it should be noted that the ideal condition for the Zt calculation, would be the comparison of populations of the same species in urban and natural habitats. However, of the 66 species of native flora that form the urban plantings of Vladivostok, such a comparison was possible only for 50 species. Moreover, the samples of some of them were very small and statistically unreliable. It should also be taken into account that the urban arboriflora includes 14 non-regional (alien) species. In this regard, the calculation of the concentration coefficient (Kc) of the compared list of species was carried out on the basis of our previously established local background metal contents in tree and shrub vegetation of natural forest ecosystems (Shikhova, 2015, 2017). The reference value of the fourth species quality indicator (K_4) was established as 25.3, based on the statistical processing of the obtained data and after exclusion of artifacts. This value corresponds to 1.00 or 100% FES for this indicator.

The intensity of accumulation of metals from soil by plants (quality indicator K_5) was assessed using the biological accumulation coefficient (BAC), which is the ratio of the content of a chemical element in a plant to its content in the soil. It was calculated based on our previously obtained data on the content of metals in soils and plants of the urban green areas (Shikhova, 2013). In our studies, the sum of the maximum BAC values for the five metals, excluding artifacts, was 2.55. This relative quantitative value was taken as the FES for the K_5 quality indicator and corresponds to 1.00 (100% of quality).

Statistical processing of the analytical data was carried out using Microsoft Excel and Statistica 10 software.

RESULTS AND DISCUSSION

The quantitative participation of the woody species in urban green areas varies from 0.3% (*Picea* sp.) to 58.6% (*Fraxinus mandshurica*) of absolute occurrence. The group of most widespread species was represented by the following species: *F. mandshurica*, *F. rhynchophylla* Hance, *Ulmus japonica* (Rehder) Sarg., *Betula platyphylla*, *Robinia pseudoacacia* L., and *Physocarpus opulifolia* (L.) Maxim. We additionally included one more species in this group, *Padus maackii* (Rupr.) Kom. In terms of occurrence in landscaping, *P. maackii* occupies a borderline position between groups three and two of plant abundance. However, in terms of other qualitative indicators it gravitates more towards the group of species with wide distribution.

Quality index K_1 varies in the compared sample of plants from 0.01 to 1.67, which corresponds to 1 and 167% of the accepted FES, respectively. The average statistical value is 0.23 ± 0.03, the coefficient of variation is the maximum among the quality indicators taken into account, 126%. As the quantitative participation (abundance) of species in landscaping decreases, the K_1 indicator gradually decreases in the group of widespread species from 1.67 in *F. mandshurica* to 0.66 in *P. maackii*. In the group of species with moderate distribution, this indicator decreases from 0.54 in *Populus koreana* Rehd. to 0.14 in *Euonymus maackii* Rupr. In the group of rare species, from 0.10 in *Syringa wolfii* C.K.Schneid. to 0.01 in spruce.

According to previous diagnostics of the vital state of plants (Shikhova and Polyakova, 2003, 2006), the vital status of the absolute majority of the compared sample of species corresponded to the categories of slightly (27 species) and severely (51 species) damaged plants and decreased from 65% in the *Euonymus macroptera* Rupr. to 23% in spruce. *F. pennsylvanica* Marsh., *F. rhinchophylla*, *F. mandshurica*, *Robinia pseudoacacia*, *Syringa oblate* Lindl., *Physocarpus opulifolia*, and *Swida alba* (L.) Opiz are more resistant to urban anthropogenic-technogenic load. The vitality indices of the dominant urban tree and shrub species, *F. mandshurica* and *Ph. opulifolia*, respectively, were 49 and 61%, respectively. Only two species rarely found in the urban green plantings, *Sambucus racemosa* L. and *Euonymus pauciflora* Maxim., were characterized by good vital condition (80%) and were attributed to the category of healthy plants.

Quality index K_2, according to the calculations, varies in the compared sample of species from 0.29 to 1.00, which is equivalent to 29 and 100% quality. Its average statistical value is 0.58 ± 0.01, the coefficient of variation is 20%. In the group of species that correspond to the category of healthy plants, K_2 corresponds to 1.00. In species with average life status, it gradually decreases from 0.81 in *E. macroptera* to 0.63 in *Tilia mandshurica* Rupr. In the group of species with a strong weakening of vitality, it varies from 0.60 in *F. mandshurica* to 0.29 in spruce.

The K_3 indicator, on the one hand, characterizes the effective importance of species in the environmental optimization of the urban environment, and on the other hand, it determines species specialization in the ability to accumulate metal pollutants. Among the compared sample of species, K_3 varies from 0.23 *Acer tegmentosum* Maxim. to 1.20 in *C. pinnatifida*. The average content of the indicator is 0.49 ± 0.02, the coefficient of variation is 31%. The maximum value of the K_3 index was recorded in *C. pinnatifida* results from its hyperaccumulation of Fe (RIA = 2.08) and Cu (RIA = 1.29) and high accumulation of Pb (RIA = 1.00). Good accumulative abilities to priority pollutants of the urban environment were also noted in *P. nigra* L. ($K_3 = 0.85$), *P. maximowiczii* A. Henry ($K_3 = 0.73$), *Cor-*

ylus heterophylla Fisch. et Trautv. (K_3 = 0.74), and *Euonymus maackii* (K_3 = 0.71). Noteworthy is the hyperactive accumulation of Zn by all *Populus* L. species (RIA = 0.97–2.15). More than that, *P. nigra* also accumulates Ni (RIA = 1.00). *Cor. heterophylla* was characterized by a high content of Pb and Fe (RIA = 0.95) and little bit lesser, although high content of Cu (RIA = 0.79). *E. maakii* was characterized by high content of Cu, Ni, and Pb (RIA = 0.81–0.91). A weak accumulation of metals, 1.5–2.0 times lower than the average for the total sample of species, along with the maple *A. tegmentosum*, was also determined in *Micromeles alnifolia* (Siebold et Zucc.) Koehne, *Spiraea salicifolia* L., *F. pennsylvanica*, *Aesculus hyppocastanum* L., and *Carpinus cordata* Blume. Their K_3 indicator does not exceed 0.33.

Qualitative indicator K_4, which characterizes the ability of plants to concentrate metals in an urban environment relative to background levels, very clearly illustrates the sanitary and hygienic functions of plants in creating comfortable urban living conditions for the population. Its average content in the compared sample of species is 0.34 ± 0.02 and varies from 0.10 in Pennsylvania ash to 1.47 in *C. pinnatifida*. The coefficient of variation is 61%. The low functional efficiency of Pennsylvania ash in accumulation of priority pollutants of urban vegetation is explained by its weak accumulation of most metals. The Zn content in ash leaves is close to, while those of Pb and Ni are even slightly lower than the background levels. The hawthorn, unlike ash, is significantly enriched (relative to forest vegetation) in all the metals under consideration: in Fe for 22 times, in Zn and Pb, for up to 4.5 times, Ni and Cu, for 2–3 times. It is challenging that according to the degree of decrease in the K_4 indicator, the dominant of urban planting species, Manchurian ash, occupies almost the median 43rd place, and the dominant of the background forest phytocenoses, Mongolian oak (*Quercus mongolica* Fisch. ex Ledeb.), the 53rd place out of a total sample of 80 species. The K_4 indicator for the Manchurian ash is 0.26 and for the oak, 0.23. The comparison of the contents of metals in urban and natural populations of these species shows that in urban environments, the ash concentrates the association of the main polluting metals 1.6 times more intensely than oak. The leaves of Manchurian ash in urban habitats are enriched (in comparison to the natural background conditions) by almost 5 times in Pb and Fe, 3 times in Zn, and 2 times in Ni. The Mongolian oak plants in urban populations, relative to natural ones, accumulate 3 times more Fe, 1.7 times more Pb, and approximately 1.3 times more Zn and Ni. The increased content of metals in the leaves of the Manchurian ash is explained by the characteristics of its urban habitats. This species forms 2/3 of the hedgerows along central transport routes, as well as roadside alleys that are subjected to intense anthropogenic and/or technogenic pressure. Oak is a dominant species in city parks and old gardens, which vegetation is in many ways close to natural phytocenoses and is less susceptible to the negative load of urbanization.

The ability of plants to absorb metals from the soil (K_5) is also an important qualitative indicator for the assessment of the functional effectiveness of species in urban landscaping. This process helps to optimize the environmental condition and remediate urban soils and lands. The effectiveness of implementation of this ability in different plant species was assessed using the BAC for metals. According to the previously obtained data, in the soils of urban green areas of Vladivostok the concentration of Pb exceeds the local environmental background by 4 times, Cu, by 3 times, Zn, by 2 times, and Fe, by 1.3 times (Shikhova, 2013). At the same time, the average statistical values of BAC for urban vegetation of Vladivostok indicate a natural decrease in the intensity of metal absorption in the soil-plant system in the series Zn (BAC = 0.35) → Cu (BAC = 0.32) → Pb (BAC = 0.15) → Ni (BAC = 0.07) → Fe (BAC = 0.02). According to the series of biological uptake of elements, created by a famous geochemist A.I. Perelman (1979), Zn and Cu in the study region correspond to the group of elements of strong biological uptake, while Pb, Ni, and Fe, to that of medium biological uptake. Depending on the plant species, the K_5 index varies from 0.15 in *Malus mandshurica* to 1.00 in *Salix schwerinii* E. Wolf, with an average statistical value of 0.37 ± 0.02. The coefficient of variation is 33%. The range of species ranked according to this indicator shows its high values (0.56–0.96) in most native species of the family Salicaceae Mirb. (willows), many representatives of the family Betulaceae S.F. Gray (birches), and certain species of the family Rosaceae Juss. All these plants are similar in their active absorption of Zn, Cu, and Pb from the soil. The species that significantly accumulate Zn are *Pop. maximowiczii* (BAC = 2.2), *Salix schwerinii* (BAC = 1.6), *S. caprea* L. (BAC = 1.3), *B. platyphylla* and *Pop. koreana* (BAC = 1.2). High accumulation of Cu in soil is typical for *Syr. oblate* and *A. tegmentosum* (BAC = 0.7), *Cor. mandshurica* Maxim., *Eleutherococcus senticosus* (Rupr. et Maxim.), *Maackia amurensis* Rupr. et Maxim., and *S. caprea* (BAC = 0.6). The absorption of soil Pb by plants is less than the accumulation of the biogenic elements (Zn and Cu). The highest Pb BAC values were recorded for *E. pauciflora* Maxim. (BAC = 0.5) and *S. schwerinii* (BAC = 0.4). More than that, the typical dominants of the urban green spaces of Vladivostok (*F. mandshurica* and *Ph. opulifolia*) are characterized by very weak absorption of metals from the soil. This pattern is typical not only for the dominant species, but also for all species of ash trees found in urban landscaping. The K_5 index for these species does not exceed the values of 0.25–0.28, which indicates that an ecological function of these plants for sanitizing urban soils from technogenic metal pollution is only a quarter of the accepted qualitative maximum. For 14 species the values of this indicator are even lower. And only 20 species, i.e., 1/4 of their total sample, perform this ecological function at 50% or higher relative to FES. These species are listed above; they actively absorb Zn, Cu, and Pb from the soil. Increased accumulation of Ni, Cu, and Fe from the soil was also observed in *Cor. mandshurica* and *Cor. heterophylla*, while Fe and Pb, in Microcerasus tomentosa.

The correlation analysis showed a high positive relationship ($r = 0.96$) between indicators K_3 and K_4, which characterize the interspecific differentiation of plants according to the ability to accumulate heavy metals under urban loads (relative to the environmental background). Less significant relationships were established between indicators that somehow reflect the entering pathways of metals into the plants: K_5 and K_3 ($r = 0.37$), as well as K_5 and K_4 ($r = 0.35$). According to the basics of qualimetry, dependent properties should be avoided when assessing quality. So, the final calculation of SFEC, was based on indicator K_3 (from two indicators with a high correlation dependence, K_3 and K_4), as it more objectively reflects the intraspecific differentiation of the compared list of woody vegetation in the heavy metal accumulation.

Following the methodological principles adopted in the work, a certain "ideal species" can serve as a quality standard for the effective implementation of the biological, ecological, sanitary, and hygienic functions of plants in the urban environment. It meets functionally effective reference values for all considered quality indicators. The functional efficiency coefficient of this species should be 4.00 rel. units (according to the number of quality indicators), and the "quality standard" (QS) is 100%.

Based on the results of the analysis and determined SFEC, a ranked series was constructed for 80 species according to the decrease of their functional significance in the structure of urban landscaping in Vladivostok. It is headed by the dominant of the urban green space in Vladivostok, *F. mandshurica* (SFEC = 2.99), and is finished by a rare species in the plantings, *M. mandshurica* (SFEC = 0.97). Compared to the ideal species, the ash tree performs ecological functions in the urban environment by 75%, while the apple tree, by 24%. Manchurian ash is a leader in functional significance, mainly due to its wide distribution in landscaping and a fairly high vitality status (indicators K_1 and K_2). The *M. mandshurica*, on the contrary, is characterized by minimal levels of accumulation of metals from the soil (K_5), weakened vitality (K_2), and completely insufficient quantitative representation in landscaping (K_1). In general, a comparative analysis of the species composition of urban plantings indicates a significant diversity of functional abilities and potential capabilities of the woody vegetation to stabilize urban ecosystems and optimize the urban environment for people. According to the data, the functional activity of some species is largely determined by their distribution area, i.e., quantitative participation in the structure of urban plantings, while of others, by their high decorativeness and good abilities to transform priority pollutants of the urban environment, i.e., environmental opportunities for its optimization. However, most of the species compared are mostly characterized by average rates of occurrence, life status, and accumulation of environmental pollutants.

The structure of qualitative indicators of the functional efficiency of dominant species of the urban green spaces (group 3 according to the distribution in landscaping) is illustrated in Fig. 1. These species predominantly form the structure of urban greening and are provided with representative samples of factual data. The SFEC values of the main dominants of the urban plantings (*F. mandshurica*, *F. rhynchophylla*, *U. japonica*, and *Ph. opulifolia*) are formed mainly due to the high participation in urban plantings (K_1), which is quite natural, and good abilities to accumulate the main environmental pollutants (K_3). Moreover, for the majority of the species of the group, the proportion of the K_1 indicator reaches 1/3 and even 1/2 of the SFEC value (Fig. 1). The increased accumulation of metals by these species is mainly associated with the characteristics of their habitats: hedgerows along highways, as well as squares and alleys that are subjected to high anthropogenic and technogenic loads. As the absolute dominant species of shrub plantations, *Ph. opulifolia*, is also characterized by the best life state in the group ($K_2 = 0.76$). *P. maackii* is less abundant in landscaping and is characterized by lower vitality rates than other abovementioned species; however, this species significantly exceeds them in the absorption of metal pollutants in the urban environment ($K_3 = 0.68$). The birch *B. platyphylla* very actively controls heavy metal pollution in urban soils (K_5 = 0.66). In general, the SFEC in plants of group 3 varies from 1.99 (*F. rhinchophylla*) to 2.99 (*F. mandshurica*), i.e., this group of species fulfills their environment-stabilizing "responsibilities" in the urban environment up to 50–75% of the accepted quality standard that meets the requirements of the ideal species.

The less common landscaping tree and shrub species are characterized by slightly different patterns. Indicators of the functional efficiency for 48 species, moderately (group 2) and rarely (group 1) represented in the urban green spaces, are provided in Table 1. They indicate that species of the group 2 are characterized, as a rule, by a good life status (K_2), close to average for urban area indicators of the accumulation of metals by assimilative organs of plants (K_3), and a weak accumulation of metal pollutants from the soil (K_5). This group includes such highly decorative species of Far Eastern woody vegetation as *Carpinus cordata*, *Phellodendron amurense* Rupr., *Sorbus alnifolia*, *Juglans mandshurica* Maxim., *Acer pseudosieboldianum* (Pax) Kom., the dominant of suburban forests,

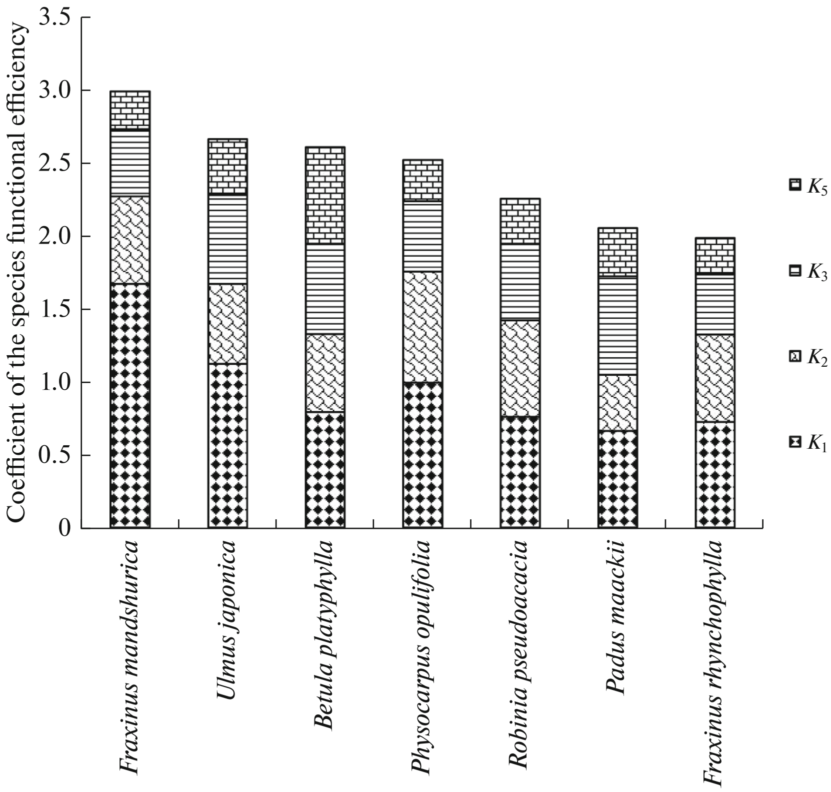

Fig. 1. Functional efficiency of widespread species in urban green space in Vladivostok. K_1–K_5, indicators of the functional quality of species in landscaping.

Mongolian oak, as well as beautifully blooming Manchurian apricot (*Armeniaca mandshurica* (Maxim.) B. Skvortz.), Manchurian pear (*Pyrus ussuriensis* Maxim.), *Ligustrina amurensis*, *Philadelphus tenuifolius* Ropr. et Maxim., and *Weigela praecox* (Lemoine) Bailey. In urban plantings they form tree stands and shrub layers of vegetation in parks, intra-city recreational forests, old city gardens, i.e., in urban habitats with more favorable environmental conditions, less susceptible to anthropogenic and technogenic pressure. The SFEC values for representatives of this group vary from 1.27 (*Alnus hirsuta* (Spach) Fisch. ex Rupr) to 2.44 (*S. schwerinii*), which corresponds to 32% and 61% QS. It should be noted that both species are characterized by poor representation in landscaping (K_1 = 0.17), but differ significantly (up to 4–5 times) in other quality indicators, especially in K_5. The leaders in the group (according to the functional significance) are the species of the family Salicaceae (*S. schwerinii*, *Pop. koreana*, and *Pop. nigra*), for which the SFEC is quite high, 2.02–2.44.

Representatives of the group 1, which is the most numerous, are characterized not only by low occurrence, but also by a low share of participation in plantings, i.e., small quantitative participation in the structure of tree and shrub layers of urban vegetation. This group includes the majority of ornamental introduced plants and varietal plants, fruit and berry crops, as well as conifers. These species predominate in the landscaping of residential areas, administrative territories, school areas, as well as in the plantings of streets and sidewalks, and less often in public gardens. The ecological functionality of representatives of the group is changing quite significantly depending on growing conditions. The group differs from the more common species of the urban green areas in the high variability of all quality indicators, but especially in the accumulation of metals (K_4) and occurrence in landscaping (K_1): coefficients of variation are 36 and 56%, respectively. Representatives of the group are characterized by a good living state (K_2) and increased accumulation of metals from the soil (K_5). The maximum SFEC values were recorded for *M. mandshurica* (0.97) and *Pop. maximowiczii* A. Henry (2.36). They correspond to 24 and 59% of the QS, respectively. It also should be noted that, despite the small participation in landscaping, some species (C. pinnatifida, *C. maximowiczii*, *Pop. maximowiczii*, *Pop. tremula*, *B. ermanii*, *Cor. heterophylala*, *Syringa wolfii*, *Salix alba* L., .*Cerasus sargentii*, *Deutzia amurensis*, *P. padus*, *Forsythia suspensa* Vahl., etc.), showed high ecological plasticity and efficiency in the transformation of heavy metals in urban ecosystems and, ultimately, in optimizing the urban environment for people. At the same time, some

Table 1. Functional efficiency of species moderately and rarely distributed in urban green spaces of Vladivostok

Plant species	Indicators of functional quality of species				SFEC	QS(%)
	K_1	K_2	K_3	K_5		
Moderately distributed species (group no. 2)						
Populus koreana	0.54	0.50	0.59	0.69	2.33	58
Microcerasus tomentosa	0.49	0.44	0.70	0.48	2.11	53
Betula davurica	0.37	0.53	0.60	0.57	2.06	52
Philadelphus tenuifolius	0.38	0.59	0.61	0.37	1.96	49
Weigela praecox	0.40	0.58	0.57	0.33	1.88	47
Lonicera maackii	0.33	0.58	0.55	0.41	1.87	47
Swida alba	0.45	0.68	0.41	0.27	1.81	45
Euonymus maackii	0.14	0.66	0.71	0.29	1.80	45
Pyrus ussuriensis	0.47	0.59	0.42	0.28	1.77	44
Acer negundo	0.46	0.58	0.48	0.24	1.76	44
Ulmus pumila	0.28	0.55	0.58	0.29	1.71	43
Fraxinus pennsylvanica	0.36	0.75	0.31	0.28	1.69	42
Tilia amurensis	0.39	0.58	0.42	0.30	1.69	42
Juglans mandshurica	0.35	0.51	0.46	0.34	1.67	42
Quercus mongolica	0.33	0.59	0.43	0.32	1.67	42
Larix sp.	0.27	0.54	0.51	0.30	1.62	40
Ligustrina amurensis	0.30	0.50	0.40	0.39	1.59	40
Carpinus cordata	0.18	0.74	0.33	0.34	1.58	40
Acer mono	0.34	0.50	0.43	0.30	1.57	39
Fraxinus rhynchophylla × F. mandshurica	0.15	0.61	0.55	0.23	1.55	39
Amorpha fruticose	0.26	0.56	0.37	0.35	1.54	39
Armeniaca mandshurica	0.37	0.46	0.43	0.24	1.51	38
Acer pseudosieboldianum	0.33	0.55	0.33	0.28	1.49	37
Acer ginnala	0.28	0.49	0.41	0.30	1.47	37
Lespedeza bicolor	0.17	0.71	0.34	0.19	1.41	35
Micromeles alnifolia	0.19	0.71	0.27	0.23	1.39	35
Pinus sylvestris	0.15	0.49	0.41	0.30	1.36	34
Phellodendron amurense	0.18	0.49	0.43	0.25	1.34	34
Rare species (group 1)						
Crataegus pinnatifida	0.06	0.69	1.20	0.28	2.24	56
Corylus heterophylla	0.02	0.63	0.74	0.46	1.85	46
Populus tremula	0.05	0.54	0.57	0.56	1.71	43
Syringa wolfii	0.10	0.41	0.68	0.49	1.68	42
Deutzia amurensis	0.05	0.53	0.57	0.49	1.63	41
Pinus koraiensis	0.04	0.60	0.59	0.36	1.59	40
Sorbaria sorbifolia	0.08	0.69	0.48	0.33	1.58	39
Padus avium	0.10	0.53	0.53	0.42	1.58	39
Crataegus maximowiczii	0.07	0.44	0.63	0.41	1.55	39
Euonymus macroptera	0.02	0.81	0.32	0.33	1.49	37
Viburnum sargentii	0.06	0.63	0.46	0.34	1.48	37
Morus alba	0.08	0.55	0.43	0.39	1.44	36
Corylus mandshurica	0.04	0.44	0.33	0.61	1.42	36
Maackia amurensis	0.08	0.58	0.36	0.39	1.40	35
Lonicera praeflorens	0.04	0.63	0.36	0.36	1.38	35
Tilia mandshurica	0.05	0.63	0.44	0.23	1.33	33
Kalopanax septemlobus	0.06	0,70	0.34	0.23	1.33	33
Prunus salicina	0.07	0.49	0.47	0.21	1.25	31
Abies holophylla	0.02	0.46	0.45	0.22	1.15	29
Malus mandshurica	0.06	0.39	0.37	0.15	0.97	24

K_1–K_5, quality indicators for species; SFEC, coefficient of the species functional efficiency; QS, quality standard.

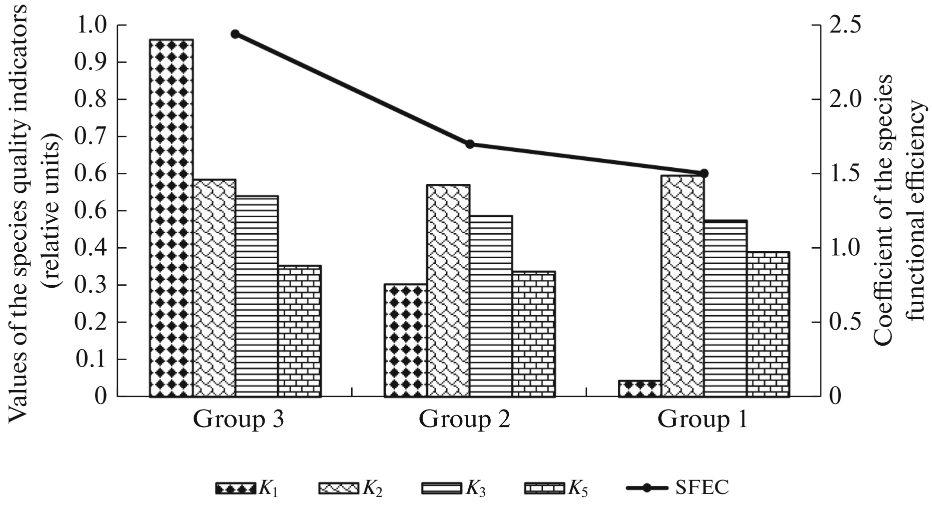

Fig. 2. Functional efficiency of species in accordance with their occurrence in landscaping. K_1–K_5, indicators of the functional quality of species in landscaping; SFEC, coefficient of the species functional efficiency in landscaping.

of the representatives of the group, despite the active absorption of environmental pollutants, remain in good vital conditions, which allow them to maintain high decorative properties. This fact arouses further scientific and practical attention for these species, since it is of particular interest to assess the limits of their tolerance and resistance to man-made environmental pollutants, as well as the prospects for wider use in landscaping.

The average values of qualitative indicators of functionality for the groups of species that differ in their prevalence in landscaping are presented in Fig 2. They indicate a gradual decrease in the efficiency of environmental and biological functions performed by plants (approximately 1.7 times) as the quantitative participation (abundance) of these species in green spaces decreases. SFEC decreases from 2.44 (widespread species) to 1.47 (rare species), i.e., from 61 to 37% QS. Differences between the groups were noted not only in the quantitative composition, but also in the intensity of their metal accumulation. Thus, dominant species (group 3) were characterized by a 1.2–1.3-fold enrichment in metals (K_3) in comparison to the other species; rare species (group 1) have a slight advantage (up to 1.2 times) in soil uptake of metals (K_5), and higher life status (K_2). The established patterns for the compared groups of plants can be clearly traced by the priority quality indicators in the general structure of the SFEC (Fig. 3). In groups of species with rare and moderate distribution in landscaping, 60–70% of SFEC is formed by high indicators of vitality (K_2) and accumulation of heavy metals (K_3), in the widespread group, almost 40% of SFEC results from the very high occurrence rates (K_1), and another 46%, from the total value of vitality indicators (K_2) and accumulation of heavy metals (K_3).

CONCLUSIONS

The proposed method for the integral assessment of the functional efficiency of the species of urban green spaces was developed on an example of the structure of urban green areas in Vladivostok. The method can serve as a basic model for the qualitative and quantitative assessment of the existing urban green fund, monitoring its condition, and quality management using modern information technologies. We used four indicators to assess the functional quality of the research objects. Any number of the most informative indicators can be used, depending on the future goals and tasks. The method makes it possible to provide an information base to authorities and organizations related to environmental and urban planning activities.

The results of a qualitative assessment of the species composition and its effectiveness in the structure of urban landscaping also serve as a scientific basis for the creation of new and reconstruction of existing urban green spaces as well as differentiated measures for their care. In general, it will contribute to the organization of a rational and sustainable system of urban landscaping.

The methodological techniques used in the work and the data obtained may also be useful for development of methods for the economic assessment of green space services, planning, and management of urban areas based on integrated approaches, which is currently very relevant in the world practice of modern urban planning.

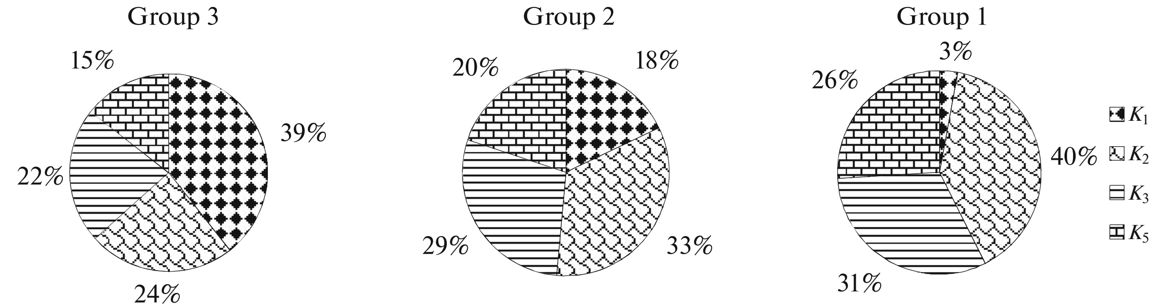

Fig. 3. The structure of the integral indicator of the quality of species in groups of plants with different of distribution in urban plantings. K_1–K_5, indicators of the functional quality of species in landscaping.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This article does not contain any studies involving animals performed by any of the authors.

CONFLICT OF INTEREST

The author declares that she has no conflicts of interest.

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