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TRUNK DIAMETER GROWTH DYNAMICS OF WOODY PLANTS IN SIBERIAN INDUSTRIAL CITY GREENING

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Abstract

The research undertaken focused on trunk diameter growth dynamics of seven woody species widely used in urban community gardening in Siberian cities: *Picea pungens*, *Betula pendula*, *Ulmus pumila*, *Populus balsamifera*, *Sorbus aucuparia*, *Padus maackii*, *Malus baccata*. Diameter growth rate was used as indirect indicator of the extent to which industrial pollutions may affect woody species in community gardening. Greening of large industrial city Krasnoyarsk was under study. Five sample sites differing in content of industrial pollutions were established within the districts of the city. It was reviled that in the Downtown greenings being under heavy recreation and vehicle-caused pollutions *S. aucuparia,P. maackii, P. pungens, B. pendula* and *P. balsamifera* could be successfully used rather than *U. pumila* and *M. baccata*. Greenings heavily polluted by nonferrous metallurgy enterprises should be composed with tolerant *M. baccata, B. pendula, U. pumila* and *P. maackii,* and; at that time *P. pungens*, *S. aucuparia* and *P. balsamifera* could not be recommended for planting hear. In greenings heavily polluted by heat power plants and chemical (pulp and paper) enterprises should be composed with tolerant *P. pungens, S. aucuparia, P. maackii. B. pendula*, *U. pumila*, *P. balsamifera*, *M. baccata* could not be recommended for planting there. Greenings, if planted in accordance with this recommendations, can be highly effective in fulfilling environmental, protective, sanitary, and esthetic functions in industrial cities. It should be taken into account in the implementation of management programs and development strategies for Siberian urban greenings.

Key words: diameter growth rate, industrial air pollution, urban community gardening, woody species.

Introduction

Continuous urgent problem in the world lies in estimation of the effect of industrial environment on woody plants against the backgrounds of urbanization, fast progressing in the last decades (Kulagin 1974, Avdeyeva and Kuzmichev 1997, McGovern and Pasher 2016). In the frame of this problem, assessments of urban trees provide total picture of urban gardening status in environmental, sanitary, and esthetic meaning in the implementation of management programs for urban resources (Nowak et al. 2014, Lisotova et al. 2018). Assessments of industrial pollutions impact on urban greening are usually carried out by phyto-indication, applying morphometric characteristics of trunks and crowns, architectonics, foliage biometric and biochemical parameters, etc. (Nikolayevsky 1979; Artemiev 2003; Neverova 2009; Skripal'shchikova et al. 2009a, 2009b; Mikhailova et al. 2011; Avdeyeva and Krivonosenko 2013; Belanova et al. 2016). Nevertheless, most part of the characteristics obtained were usually applicable only for current season and unsuitable for revealing time variations or trends. In this context, series of annual growth rings in the trunk could be much more informative and allow fulfilling retrospective and predicting patterns of trunk radial growth process. On one side, growth ring anatomical structure characterized by evolutionary stability, on the other, has a high degree of functional adaptation, especially reflected in water transport function (Gamaley 2011). It has been repeatedly established that tree rings record information on climate (Fritts 1976, Schweingruber 1996, Vaganov et al. 2006) and environment extreme impacts, such as lack of light, draught, severe frost, defoliation by insects, etc. (Schweingruber et al. 2006, He et al. 2007, Gillner et al. 2013, Selikhovkin 2013). The studies of industrial pollution effect on radial growth and wood anatomical structure of trees have a significant place among others. Most of the studies were conducted in native forests and parks developed near big industrial centers (Pasternak et al. 1985, Alexeyev 1990, Arsenyeva and Chavchavadze 2001, Rossinina et al. 2008, Skripal'shchikova et al. 2009b, Kirdyanov et al. 2014, Tyukavina and Lezhneva 2014). Only few studies were concentrated in certain pollutant: nuclear radiation (Musaev 1996), traffic impact (Artemiev and Arsentyeva 2014), heavy metal ions absorbed by roots from the soil (Fedorkov 2006). From this review, it follows that woody species used in city greenings were poorly represented in the studies, predominately by *Caragana* sp., *Quercus* sp.*, Populus balsamifera*.

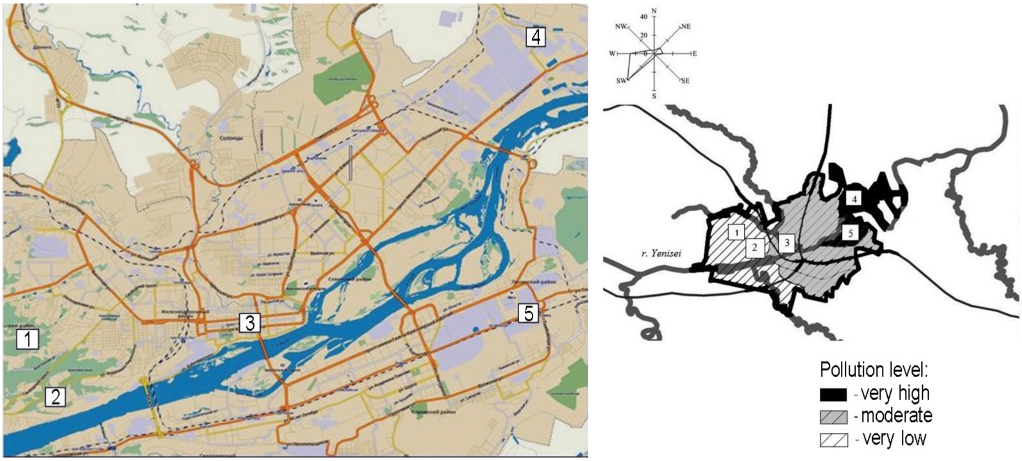
From the review above, it is evident, that the issue remains open in connection with variety of ecological conditions between industrial cities and between districts within the city as well as diversity of the species studied. The purpose of our study was to analyze dynamics of diameter growth of trunks as one of the characteristics of vital state of seven woody species in various ecological zones of a Siberian industrial city.

Materials and Methods

Study area

The research object was the trunk diameter growth dynamics of seven woody species (*Picea pungens* Engelm. (Colorado spruce), *Betula pendula* Roth. (Common birch), *Ulmus pumila* L. (Siberian elm), *Populus balsamifera* L. (Balsam poplar), *Sorbus aucuparia* L. (European mountain ash), *Padus maackii* Rupr. (Maack cherry), *Malus baccata* (L.) Borkh. (Dwarf apple)), most often used in greening of Siberian cities (Vstovskaya and Koropachinskiy 2003). One of the largest Siberian industrial cities, Krasnoyarsk was under study as an example of highly polluted urban area.

Krasnoyarsk is situated at the junction of three geomorphological regions: Yenisei River valley, the plateaus adjoining the valley, and the foothills of Sayan Mountains. Largely, Krasnoyarsk is locat-



a

b

Fig. 1. Sampling plots locations on the territory of Krasnoyarsk: a – Yandex map of Krasnoyarsk with sample plots (1–5); b – ecological zones on the territory of Krasnoyarsk characterized by very low (white), moderate (grey), and very high (black) level of air pollution.

Note: 1 and 2 – very slightly polluted plots, 3 – moderately polluted plot, 4 and 5 – very heavily polluted plots.

ed in Yenisei valley (Fig. 1a). There is a flood plain in the valley and nine terraces discontinuous with the town. The left bank terraces border on the plateaus. On the right bank, Sayan foothills fringe the valley. The left bank of the river is dominated by typical forest-steppe, whereas mountain taiga forest occupies the right bank. The climate is sharply continental, with mean annual, January, and July air temperatures being 0.6 °C, -16.7 °C, and +18.6 °C, respectively. Average precipitation is 372 mm a year, annual relative humidity averages 69 % (Shver and Gerasimova 1982). The soils in the study area had been strongly influenced by the processes of urbanization and long-term aerosol impact by industry, so that, they could not be genetically classified, and as such are related to ‘Technogenic Surface Formations’ (TSF) (Shishov et al. 2004).

Sampling design

In general, the air in Krasnoyarsk is heavily polluted. Air pollutants distribute within its territory depending on district-specific topography, wind regime, and land-use change. Its local concentration varies frequently from rather slight to very high. Unfortunately, the current Municipal estimates in the frame of the city districts concerning concentration of certain components in air pollution have not been available for us. Nevertheless, taking into account the published data (Skripal’shchikova et al. 2009a, Khlebopros et al. 2012) and basic facts, we could approximately border three contrasting ecological zones (Fig. 1b, white, grey and black coloured) characterized by very low, moderate and very high level of air pollution. Within these zones we chose five greenery objects and used them as 'temporal sampling plots'. Two sample plots, AP and HP, were located in the heavily polluted zone (Fig. 1b, black coloured), near Aluminum and other nonferrous metallurgy enterprises (AP plot) and Heat Power Plants (HP plot) accompanied with chemical enterprises, windward. Another one, DT plot, was positioned in the moderately polluted zone (Fig. 1b, grey coloured, crosshatched), in lowland, heavily populated Downtown. The remainders, AK and VL plots, were located in the favourable, very slightly polluted ecological zone (Fig. 1b, white coloured, crosshatched), at the leeward western outskirts of the town, far from industrial spots, in the city districts 'Akademgorodok' and 'Vetluzhanka'.

On AP plot, the composition of air pollution is typical for Aluminum and other nonferrous metallurgy industry and associated with fluoric, calcium, magnesium, and sulphuric compounds, as well as benzo[a]pyrene, CO, and dust particles. Pollution on HP plot is typical for Heat Power Plants working on brown coals. Emission contains acrylonitrile, aldehydes, butadiene, hydrogen sulphide, formaldehyde, CO, NO, NO_2, SO_2, and ash, abundantly supplied with $CaCO_3$. On DT plot vehicle-caused pollution including CO, NO, NO_2, SO_2, benzo[a]pyrene, and formaldehyde emissions prevailed (Khlebopros et al. 2012). AK and VL plots are very slightly polluted by light local traffic.

The individuals belonging to all these species grow in all studied sample plots; only the trees of *U. pumila* were absent on AK plot. In our study, each species on each sample plot was represented by ten experimental trees. All these ten trees had approximately the same age and well-developed crown that has no signs of pruning. The trees were planted 3–5 m from each other (according to the greenery planting rules in Russia), in rows on AP, HP and DT plots, and in small groups on VL and AK plots. To minimize vehicle-caused pollution effect and concentrate on industrial emission influence, the experimental trees on AP and HP plots were selected approximately 20 m away from the roads. Wood cores taken at 1.3 m from experimental trees by Pressler borer were used in analysis. In total, 370 woody samples (cores) were extracted in 2012–2013 vegetation seasons.

Data analysis

Tree-ring widths (TRW) were measured with an accuracy of 0.01 mm according to standard technics in dendrochronology by means of the semi-automatic device LINTAB (Frank Rinn SA, Heidelberg, Germany). Ring widths were recorded using the original computer program 'Time Series and Presentation Program TSAP V3.5' (Rinn 1998).

Ageing effect in tree radial growth process could emerge from the dependence 'tree-ring width *vs* tree age' (Schweingruber 1996), characterized by high year-to-year variability especially caused by seasonal variation of weather conditions (climate factors) (Fritts 1976, Schweingruber 1996). In this paper, we favoured analyzing the dependence 'trunk diameter at breast height (DBH) *vs* tree age', because in this dependence seasonal variations are smoothing (i.e.) (Simanko 2014, Mashukov et al. 2018). By the latter, we neglected climate impact.

Using measured data on TRW, annual diameter growth values for each experimental tree were reconstructed, from the year of planting in greenery through the year we took a core, by summing ring widths multiplied by 2 sequentially, year by year, along one radius of the trunk (along the core). By averaging, we obtained mean annual trunk diameter of each tree and then, mean annual data of trunk diameter (accompanied with standard deviation) for each species on each experimental plot. The dependences of mean trunk DBH *vs* an age for 7 species studied growing on 5 sample plots are shown in figures 2 A–G. We split each curve into one to three linear sections. By each linear portion, we obtained the value of mean diameter growth rate in corresponding period of ageing (in X-axis) and then, we analyzed dynamics of trunk DBH growth of the species growing on each sample plot.

Results

Picea pungens **(Fig. 2A)**

Comparatively high diameter growth intensity was on the ecologically safe VL and AK plots. It took the value 7.5±0.5 mm·year^{-1} (curve 1) and 8.3±0.7 mm·year^{-1} (curve 2) in average (the difference between them are not significant at F-test, $P \geq 0.95$). These characteristics stayed approximately invariable for 19 years, from the start of tree growth to the age of taking cores.

On DT plot (curve 3), affected by heavy recreation impact and traffic pollutants, diameter growth rate averaged 4.0±0.6 mm·year^{-1} for the first four years after planting and then it increased to 7.0±0.6 mm·year^{-1}.

On very heavily polluted AP plot, diameter growth rate averaged 3.4±1.0 mm·year^{-1} from the year of planting to the year of taking cores (curve 4). Growth process suppressed obviously by constant negative impact of atmospheric emissions represented chemical compounds of nonferrous metallurgy.

On very heavily polluted HP plot (curve 5), the trees grew slowly during the first seven post-planting years with DBH growth rate being 3.1±1.0 mm·year^{-1}, then it follows a phase of rather intensive growth (9.4±1.0 mm·year^{-1}).

Betula pendula **(Fig. 2B)**

On the quite clear VL and AK plots (curves 1 and 2), the birch trees showed relatively high average DBH growth rate in comparison to the others. From planting to 14 years in age these values were 9.4±1.0 mm·year^{-1} on AK plot and 8.0±1.0 mm·year^{-1} on VL plot. Then, these values continuously dropped down: on AK plot to 5.9±1.0 mm·year^{-1} and on VL plot to 7.4 (to 37 years) and then, to 3.6 mm·year^{-1} from 37 to 42 years in age.

On the moderate- and high-polluted DT and AP plots (curves 3 and 4) the individuals grew in diameter by approximately the same average rate of 6.5±0.4 and 6.5±1.1 mm·year^{-1} up to 18 years of age. Then, the rates dropped down to 3.0±0.3 mm·year^{-1}on AP plot and 4.3±0.1 mm·year^{-1}on DT plot.

On the very dirty HP plot the DBH growth rate averaged 5.6±1.1 mm·year^{-1} for the first eight years after planting (curve 5), then it dropped down to 3.0±1.0 mm·year^{-1}.

Ulmus pumila **(Fig. 2C)**

The experimental trees on VL plot (curve 1) grew in diameter with even average rate of 8.3±1.1 mm·year^{-1} from planting through the age 18 (the age when we took the cores).

On the very high-polluted AP plot (curve 4) the saplings grew quite rapidly for 4–5 years after planting with mean growth rate of 11.0±0.5 mm·year^{-1}; then,

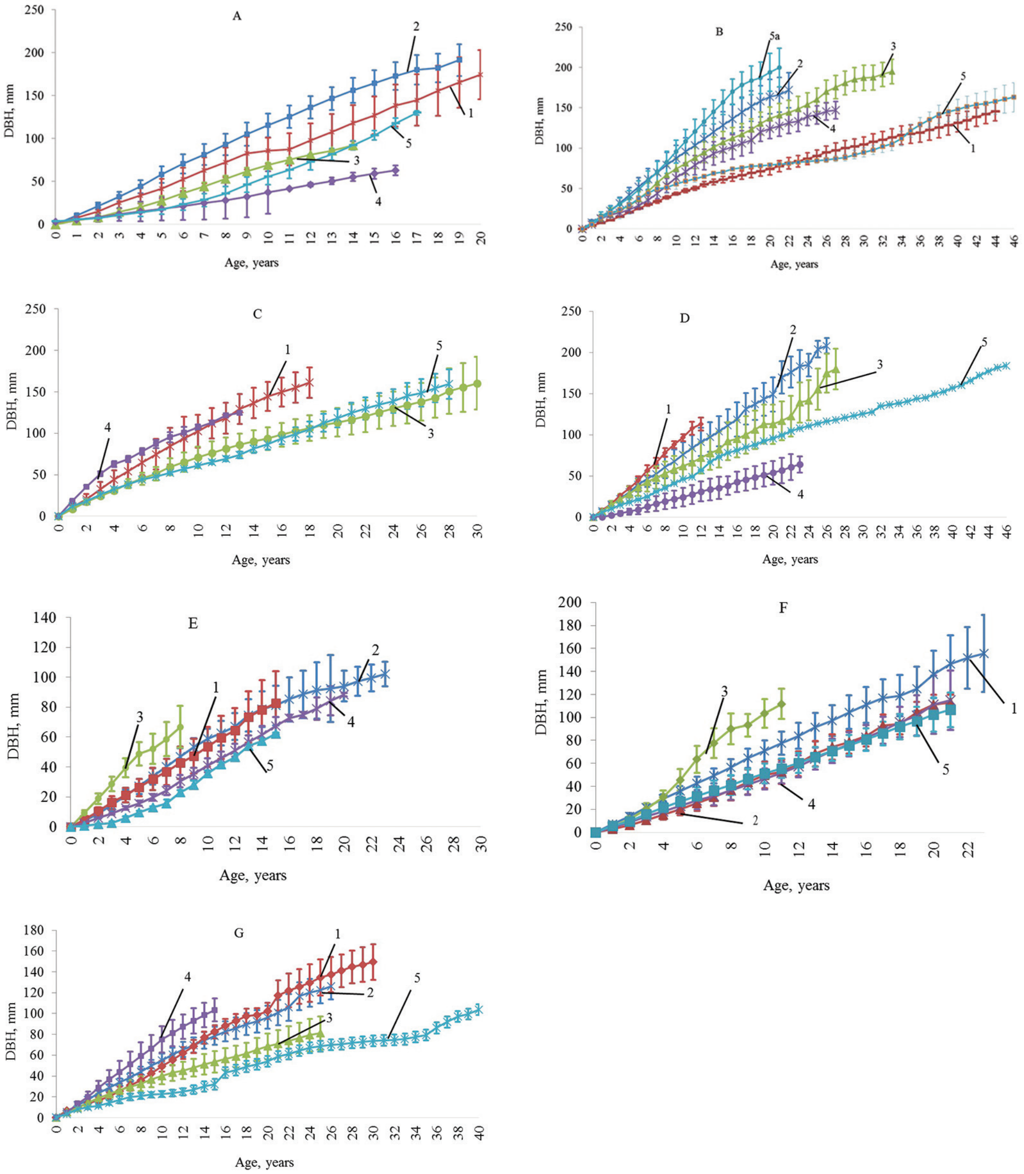


Fig. 2. Mean DBH diameter *vs* an age for *P. pungens* (A), *B. pendula* (B), *U. pumila* (C), *P. balsamifera* (D), *S. aucuparia* (E), *P. maackii* (F), and *M. baccata* (G).

Note: plots: 1 – VL, 2 – AK, 3 – DT, 4 – AP, 5 – HP.

from the age of 6 to 13 (being the coring age), averaged diameter growth rate halved to 6.2±0.6 mm·year^{-1}.

On moderate polluted DT plot (curve 3) the individuals exhibited DBH growth rate equaled by 6.3±1.1 mm·year^{-1} during the first 7–9 years. With time, from the age of 10 to 30 (being the coring age), this value dropped to 4.8±1.0 mm·year^{-1}. Approximately the same dynamics of DBH growth was established on very-high-polluted HP plot (curve 5): from the age of 10 to the coring age, this value was equaled to 5.2±1.2 mm·year^{-1}.

Populus balsamifera **(Fig. 2D)**

Averaged diameter growth rate on all sample plots did not significantly varied ($P \geq 0.95$) from planting to taking cores. Poplar trees grew in diameter rather intensively on quite clear VL and AK plots (10.1±0.5 and 7.7±1.1 mm·year^{-1} respectively, curves 1 and 2), but slower on very-high-polluted AP and HP plots (3.9±0.8 and 3.4±0.1 mm·year^{-1}, curves 4 and 5). On moderate-polluted DT plot (curve 3), this value was 5.3±1.0 mm·year^{-1}.

Sorbus aucuparia **(Fig. 2E)**

On moderate polluted DT plot (curve 3), DBH growth rate was highest, 9.0±1.1 mm·year^{-1} in average, after planting up to the age of 4. At the age of 5 to 8 (being the age of taking cores), this parameter decreased to 7.0±1.1 mm·year^{-1}.

On low-polluted VL and AK plots (curves 1 and 2), the averaged diameter growth rates were 4.9±1.5 and 5.4±0.8 mm·year^{-1}, which did not vary to the age of 15 (being the age of taking cores on VL plot). On AK plot, from 15 to 23 years of age, this value dropped to 2.3±1.6 mm·year^{-1}.

On high-polluted AP and HP plots (curves 4 and 5), averaged diameter growth rate was very low during six post-planting years – 2.9±0.3 and 2.0±0.2 mm·year^{-1} respectively. Then, until the year of taking cores, these values increased gradually on both sites to reach 4.6±0.4 and 5.4±0.2 mm·year^{-1} respectively.

Padus maackii **(Fig. 2F)**

On clear VL and AK plots, as well as on very dirty AP and HP plots (curves 1, 2, 4 and 5, respectively) DBH growth rates did not vary significantly from the year of planting to the year of taking cores. The average value was about 5.1±0.6 mm·year^{-1} on AK, AP and HP plots (curves 2, 4 and 5), but on VL plot (curve 1) it was higher, 6.5±0.6 mm·year^{-1}.

On DT plot (curve 3), diameter growth rate of saplings was quite high, averaged by 6.1 mm·year^{-1} to the age of 4. Between 5 and 9 years in age, this parameter increased markedly to 11.0±0.8 mm·year^{-1}. From 8 to 11 years of age (being the age of taking cores), the growth rate dropped again to 5.5±0.8 mm·year^{-1}. Commonly, dynamics of DBH growth for *P. maackii* and *S. aucuparia* growing on DT plot are similar to each other (figs 2E and 2F, curve 3).

Malus baccata **(Fig. 2G)**

On clear VL and AK plots (curves 1 and 2) growth rates did not vary significantly, exhibited averaged meanings 5.7±0.3 and 4.8±0.6 mm·year^{-1} until 17 years of age, since then these parameters decreased to become almost equal ($P \geq 0.95$) (4.0±1.2 and 4.0±0.4 mm·year^{-1} to the age of taking cores.

Until the age of 10, the trees growing on heavy polluted AP plot (curve 4), had the highest average growth rate equaled by 6.6±1.1 mm·year^{-1}. Over the past years to the year of taking cores, it dropped to 4.4±0.3 mm·year^{-1}. Meanwhile, on heavy polluted HP plot (curve 5), the trees exhibited the lowest average diameter growth rate – 2.5±0.3 mm·year^{-1} in average from the year of planting to the year of taking cores.

On DT plot (curve 3), DBH growth rate, equaled by 2.7±0.7 mm·year^{-1} in average, has remained stable in time.

Discussion

Our study aimed at practical demands, implied in developing and implementation successful management programs for urban greening taking into account specific tolerance to particular air pollutants. Because of that, we made some preliminary simplifications before interpretation of the results.

Highlighting the importance of air pollution impact on DBH growth dynamics, we made the effort to eliminate some other factors could hardly be considered. As it follows from Fig. 2, for several years after planting some saplings grew slowly, but the others grew fast (as an example, *S. aucuparia* in Fig. 2E, curve 5 and *U. pumila* in Fig. 2C, curve 4). Such opposite particularities are possibly caused by low or high quality of planting material, bad or good looking after planting or different specific adaptive strategy to new conditions just after planting, etc. Then, after this initial period, diameter growth rate of the trees became more or less stable for some time (second period of growth) and then, it could gradually diminish (third period) caused by lots of reasons (ageing effect, insect attacks, pruning and other harmful impacts). For further analysis we took into account the stable period of growth, avoiding the other two. We believed by this approach pollution impacts got highlighted. Then, we changed over from the numerical values of obtained DBH growth rate, statistically distinguished at F-test ($P \geq 0,95$), to three qualitative characteristics which indicated comparatively high, moderate and slow DBH growth intensity of the certain species growing on various sample plots. We represented comparatively high, moderate and slow DBH growth intensity for every species studied by green, yellow and red. This simplification may be of advantage in greenery management practices.

From Table 1, it follows that the dependence ‘the heavier the industrial pollution – the lower DBH growth rate’ does not universally true. Out of the seven species studied only *P. balsamifera* obeyed the dependence mentioned. It characterized by low DBH growth intensity near highly polluted Aluminum Plant (AP plot) and Heat Power Plants accompanied with chemical enterprises (HP plot), medium growth intensity on moderately polluted plots and high intensity on clear VL and AK plots. We also fixed crown density decline and chemical burns on lives accompanied slow diameter growth of poplar trees on AP and HP plots. Based on those features, *P. balsamifera* should be used as indicator in assessment of industrial air pollution extent.

Our attention focused on *P. pungens* on heavily polluted HP and *M. baccata* on heavily polluted AP plot, characterized by comparatively high DBH growth rates (Table 1). It served to suggest that technogenic substances could influence positively in some cases.

To take well-known illustration, air polluted ash, resulting from brown coal burning in heat power plants, contains $CaCO_3$ which, landing on soil, continuously deoxidizes it. The latter takes place on HP plot. The positive effect of deoxidizing was especially obvious in *P. pungens*; this effect was slightly lowered by pathogen damages in *S. aucuparia* and *P. maackii* (we found them when expertise their crowns). The other four species studied demonstrated negative reaction on technogenic substances polluted HP plot.

Table 1. Qualitative representation of mean DBH growth rates of the species.

Species	Sample plots				
	VL	**AK**	**DT**	**AP**	**HP**
P. pungens	🟨 7.0-8.0	🟩 7.5-9.0	🟨 6.4-7.6	🟥 1.9-4.9	🟩 8.4-9.4
B. pendula	🟩 6.4-8.4	🟩 7.0-9.0	🟨 6.1-6.9	🟨 5.4-7.6	🟥 2.0-4.0
U. pumila	🟩 7.2-9.4	-	🟥 3.8-5.8	🟨 5.6-6.8	🟥 4.0-6.4
P. balsamifera	🟩 10.6-11.6	🟩 6.6-8.8	🟨 4.3-6.3	🟥 3.1-4.7	🟥 3.3-3.5
S. aucuparia	🟨 3.4-6.4	🟨 4.6-6.2	🟩 5.9-8.1	🟥 4.2-5.0	🟨 5.2-5.6
P. maackii	🟩 5.9-7.1	🟨 4.5-5.7	🟩 10.2-11.8	🟨 4.5-5.7	🟨 4.5-5.7
M. baccata	🟩 5.4-6.0	🟩 4.2-5.4	🟥 2.0-3.4	🟩 5.5-7.7	🟥 2.2-2.8

Note: comparatively low, moderate and high growth rates marked by red, yellow and green are significantly different according to F-test at *P*≥0.95.

As to our assessment (Table 1), on AP plot, situated near nonferrous metallurgy enterprises, the trees of *B. pendula, U. pumila, P. maackii* and especially *M. baccata* grew in diameter quite well in spite of toxic air pollution impact. We believe that ‘positive’ effect of the latter concerned suppression of vital activity of harmful insect species. Indeed, the effect of their suppression by toxic pollution from Aluminum and pulp and paper enterprises was reviled in earlier entomologic studies (Selikhovkin 2013). When expertise crowns of the species growing on AP plot, we did not fix any insects, only its slight markings on *P. balsamifera* leaves (at the same time, in quite clear sites poplar leaves were hitting markedly). This ‘indirect’ positive effect slightly lowered in *B. pendula, U. pumil* and *P. maackii* trees by appearance of chemical burns we fixed in their crowns (Klad’ko and Skripal’shchikova 2019), caused by toxic pollutants. In *P. pungens, P. balsamifera* and *S. aucuparia* comparatively slow DBH growth accompanied of crown density decline and hard chemical burns on needles and leaves (Klad’ko and Skripal’shchikova 2019).

The Downtown gardenings (DT plot, Table 1) are characterized by heavy recreation and moderate vehicle-caused impacts which affected quite adversely on diameter growth rate of *U. pumila* and *M. baccata* trees; we also fixed their crown density decline, harmful insects and chemical burns on the surface of needles and leaves. Meanwhile, *S. aucuparia* and *P. maackii* trees exhibited comparatively high DBH growth rates accompanied of healthy crowns.

Conclusion

The current state of greenings and parks in the large industrial city of Krasnoyarsk requires urgent measures to improve their quality (Lisotova et al. 2018). Unfortunately they have been hardly updated; the woody plants have been regularly partly eliminated without equivalent planting. In greening, specific resistance to toxic pollution impacts has not been taken into account. Information resided in reconstructed dynamics of tree diameter growth in some cases could substitute regular visual monitoring, as it reflects resulting impact of many factors on urban tree health. In this paper, we tried to highlight technogenic impact as the major one analyzing specific adaptation of woody trees in greening to air industrial pollution of various composition. In the next studies, we are going to revile climate influence on urban greening.

In accordance with specific response of woody species studied to pollution impacts in Krasnoyarsk we could conclude the following.

In the greenings being under heavy recreation and vehicle-caused pollutions we could not recommend planting *Ulmus pumila* and *Malus baccata*; *Sorbus aucuparia* and *Padus maackii* have high advantages over them and other species studied, nevertheless, *Picea pungens Betula pendula* and *Populus balsamifera* could be successfully used also.

In greenings heavily polluted by nonferrous metallurgy enterprises we could not recommend planting *Picea pungens*, *Sorbus aucuparia* and *Populus balsamifera*. Greening should be composed with tolerant *Betula pendula*, *Ulmus pumila,* and *Padus maackii* but *Malus baccata* should be prevailed.

In greenings heavily polluted by heat power plants and chemical (pulp and paper) enterprises should be composed with tolerant *Picea pungens*, *Sorbus aucuparia*, *Padus maackii*.

These recommendations could serve for better efficiency of greening in polluted districts of Krasnoyarsk and other industrial Siberian cities.

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