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Invasive Activity of Woody Plants in Tsytsyn Main Botanical Garden, Russian Academy of Sciences

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Abstract—The object of this study is the arboretum of Tsytsyn Main Botanical Garden, Russian Academy of Sciences, which was founded in 1945. The invasive activity is extremely low here: the arboretum collection currently includes 66 taxa of 35 genera belonging to 22 families (5% of the collection fund) of self-seeding or clonal woody plants that have a capacity for further naturalization in the Main Botanical Garden (MBG) of the Russian Academy of Sciences. The highest rates of naturalization were recorded for the species of the families Juglandaceae and Rosaceae, the fruits of which are dispersed by zoochoria. The greatest capacity for naturalization (5.3%) was demonstrated by plants that naturally grow in Europe, while plants growing in Asia (3.4%) and North America (3.0%) have lower naturalization. Only 15 intentionally introduced species (1.1% of the collection fund) were found outside the arboretum in natural cenoses that survived in the Main Botanical Garden of the Russian Academy of Sciences. Some seedlings have intermediate features between collection species and seem to be hybrids. It is concluded that, contrary to the published data, botanical gardens are not a direct vector for the invasion of alien species. Although many invasive species emerged in other regions of the world outside their natural range owing to intentional introduction, their invasion into natural communities should be associated with their further massive cultivation rather than with primary introduction.

Keywords: naturalization, botanical garden, woody plants, invasion

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INTRODUCTION

People have intentionally introduced many plant species as agricultural, orchard, forest, medicinal, or ornamental crops since long ago. A significant role in this process has been played by botanical gardens for the past 500 years. For instance, according to preliminary estimates, 80000 species are cultivated in European botanical gardens (Heywood and Sharrock, 2013).

The introduction of many thousands of plants has unexpectedly led to an "escape" of a significant number of them from private nurseries and botanical gardens into disturbed habitats, followed by their naturalization and penetration into natural plant communities. This process began to be actively observed in the 20th century and invasive alien plants are currently considered the main cause of a decrease in the biological diversity with serious social and economic implications (Heywood and Sharrock, 2013). In the 21st century, the effect of invasive plants on natural ecosystems and native species is one of the most significant factors of a decrease in natural biodiversity and stable development (Fernández-Galiano, 2009; Sharrock et al., 2011).

The introduction of alien plants can also often be unintentional (e.g., introduction with soil or contaminated seeds); however, most of the invasive alien plants were intentionally introduced, in particular, for cultivating them as ornamental plants in public and private gardens (Hulme et al., 2008; Pyšek et al., 2011; Hulme et al., 2018). For instance, 80% of invasive alien species were introduced to Europe as ornamental plants or agricultural crops (Reichard and White, 2001; Dehnen-Schmutz et al., 2007; Drew et al., 2010; Hulme, 2011) and intentional introduction became an invasion vector for 58% of alien species (Pergl et al., 2017).

Plants are selected for their cultivation for a good reason, and their individual features (rapid growth or active reproduction), which are considered as positive in gardening, contribute to invasion and are extremely negative for native flora (van Kleunen et al., 2018).

Analysis of the recently created Global Naturalized Alien Flora (GloNAF) database showed that over 13000 vascular plant species naturalized in other regions of the world (van Kleunen et al., 2015; Pyšek et al., 2017). In addition, for 450 alien plant species (Hulme, 2011), the number of regions in which each of these species is invasive is positively correlated with their presence in the collections of botanical gardens around the world.

Cultivated alien species occur in natural cenoses more frequently than noncultivated species. At the present time, at least 75% of plants that naturalized elsewhere outside their native range are cultivated in private gardens and 93% are grown in botanical gardens (van Kleunen et al., 2018). Therefore, there is strong evidence that ornamental gardening remains the main vector for plant invasion (Mack and Erneberg, 2002; Dehnen-Schmutz et al., 2007; Hanspach et al., 2008; Lambdon et al., 2008; Hulme, 2011; Pyšek et al., 2011; Pergl et al., 2016; Saul et al., 2017; Hulme et al., 2018).

At the same time, the proportion of invasive species is low in the total number of cultivated plants. For instance, in Germany, 50000 taxa were cultivated in 80–90 botanical gardens and only 40 of them became invasive (Heywood and Sharrock, 2013). In the Main Botanical Garden of the Russian Academy of Sciences (MBG RAS), only one species (herbaceous species!)—*Adenocaulon adhaerescens* Maxim—has extended its range beyond the garden over 60 years (Vinogradova, 2015).

The probability of plants introduced in botanical gardens and "escaping" from cultivation can be determined to a certain extent using the methodology of risk assessment analysis (Reichard, 2000; Weber and Gut, 2004; Dawson et al., 2008). If a species demonstrates a high risk of invasive potential, it is most reasonable to avoid its introduction. The use of risk assessment schemes allows gardeners not only to reduce the invasion risk but also to focus their efforts on monitoring the vectors of penetration of those species which have a high invasive potential (Essl et al., 2011; Roberts et al., 2011). Analysis of risks includes three components (NNSS, 2011): (1) determination of the probability of species-induced risks and severity of these risks; (2) practical reduction of risks, and (3) public information and interpretation of the results of analysis.

Plants that are already present in collections and are invasive or exhibit invasive features must be strictly monitored and preferentially eliminated from the garden. If natural vegetation sites have been preserved in a botanical garden, all invasive species revealed in this garden must be monitored or eliminated (Vinogradova, 2015).

To interpret the current trends and predict the probability of future invasions, one should estimate the number and diversity of alien plants cultivated in gardens and trace the history of their introduction. In addition, it is necessary to reveal the species characteristics that contribute to the potential success of invasion. This work has been carried out in the MBG for several decades.

Since February 29, 2016, the territory of Tsytsyn Main Botanical Garden of the Russian Academy of Sciences has had the status of a federal specially protected natural area (SPNA). Over half of the area of the garden is occupied by well-preserved woodland with a protected oak forest in its central part; the oak forest includes old trees with an average age of 150–170 years; at the same time, older specimens (aged up to 200–300 years) also occur here (Vinogradova et al., 2008). The accompanying species of the tree layer include birch trees, linden, spruce, aspen, and maple. The shrub layer is represented by hazel *Corylus avellana* L., mountain ash *Sorbus aucuparia* L., honeysuckle *Lonicera xylosteum* L., alder buckthorn *Frangula alnus* Mill., and spindle tree *Euonymus verrucosus* Scop. Lungwort *Pulmonaria obscura* Dumort., yellow archangel *Lamium galeobdolon* (L.) L., lily-of-the-valley *Convallaria majalis* L., stitchwort *Stellaria holostea* L., and *Carex pilosa* Scop grow in the herbaceous layer. All these plants are typical elements of a natural oak forest. Even today, despite very severe anthropogenic pressure by one of the largest megalopolises, the oak forest of the MBG can be truly considered a pattern of the typical Central Russian broad-leaved forest.

Since 1945, employees of the garden have actively introduced plants of the natural flora of the Soviet Union, ornamental herbaceous plants of Holarctic forest zones, and woody plants of the temperate zone on the planet. The primary introduction test covered over 8000 taxa (*Glavnyi*..., 2005). In addition, the site that was previously located in the outskirts of Moscow turned out to be in the center of the built-up area and transport routes. Both of these factors—intense introduction work and microclimate changes—led to a serious transformation of the composition of the flora of the Main Botanical Garden. Natural vegetation was significantly enriched in plants that "escaped" from collection sites and began to naturalize in the new range, as well as in alien weed species that were accidentally introduced to this area from outside. By 2015, the spontaneous flora in the MBG included 856 species; 60% of them belonged to the native fraction of flora. The alien fraction of flora included 40% of taxa growing in the garden, of which 33% were "refugees" from cultivated areas and 7% were alien weed plants (Vinogradova et al., 2015, 2016).

However, the compilation of the list of spontaneous flora did not take into account species with seed- or vegetation-based self-reproduction in the arboretum of the MBG. Meanwhile, the primary introduction test covered over 2400 taxa in this arboretum collection (*Drevesnye rasteniya*..., 2005), and the currently growing specimens have already adapted to Moscow climate conditions quite successfully. The arboretum of the MBG is currently the largest collection of temperate-climate woody plants in Russia. It includes 137 genera and 972 species (1317 taxa, including cultivars and varieties). Processes that lead to the self-seeding of introduced woody species in the botanical garden have been intensified over the past 15–20 years. This is due to the fact that most plants included in the arboretum collection have already entered the generative phase, as well as to the fact that the reduction of tree management leads to the overgrowing of collection sites, thereby making them more vulnerable to invasion.

The enormous number of introduced species, the long-term period of their cultivation, the mosaic of habitats (from the classical park and zones with high anthropogenic pressure to almost undisturbed natural communities), and the isolation of the area from the woodlands of the Moscow region make the botanical garden an ideal object for studying the invasive potential of plants. The goal of this research was to assess the invasive activity of woody plant species from the arboretum collection of the MBG.

MATERIALS AND METHODS

Fragmentary observations on the presence of self-seeding in the arboretum of the Main Botanical Garden have been carried out since 2010 to assess the level of adaptation of collection trees and shrubs. In 2017, the area of the arboretum was investigated in detail, including the collection of the herbarium of self-seeding specimens. Samples that were collected and identified by the authors are stored in the Herbarium of the MBG (MHA).

The capacity of plants for spontaneous dispersal was estimated according to the four-point scale: (1) does not become naturalized, (2) propagates vegetatively or (occasionally) by self-seeding, (3) sporadically, (4) abundantly (the latter includes species that have already invaded the natural forest in the garden).

We divided all species of woody plants cultivated in the arboretum of the MBG into three main groups for their chorological analysis: plants that natively occur in the flora of (1) Europe, Asia Minor, and the Caucasus, (2) Asia (Siberia, Central Asia, the Far East, and East Asia), and (3) North America. If a species grows naturally both in Europe and in Asia, it was included in both groups, and wide-range species that grow throughout the Holarctic were included in all three groups. Taking into account the relatively small number of naturalizing taxa, as well as the limited number of regions with woody plants that are suitable for introduction to conditions of the Moscow region, we considered it unreasonable to use a more exact classification.

The names of families and species are given in accordance with the database The Plant List (2018).

RESULTS

During the investigation of the arboretum, the authors revealed 66 taxa that have a capacity for further naturalization and penetration into SPNA vegetation. Some of these species had already been included in the list (Vinogradova et al., 2015, 2016), since other geographical samples of the same 66 taxa had “escaped” from the exposition sites of other divisions of the MBG. For example, *Juglans mandshurica* Maxim. actively “escapes” from the exposition of the Far East flora; numerous young trees and seedlings of *Acer pseudoplatanus* L. were recorded near the exposition of the Caucasus flora. *Rubus caucasicus* Focke expands in abundance in the same exposition of the Caucasus flora and annual seedlings of *Robinia pseudoacacia* L. are annually observed in the production area of the MBG. In addition to these species, *Amelanchier spicata* (Lam.) K. Koch, *Acer campestre* L., *Acer negundo* L., *Cornus alba* L., *Euonymus europaeus* L. *Euonymus maackii* Rupr., *Prunus avium* (L.) L., *Quercus rubra* L., *Symphoricarpos albus* (L.) S.F. Blake, and *Syringa josikaea* Jacq. f. ex Rchb were already recorded in the spontaneous flora of the MBG.

Below, we present the list of all woody plant species that naturalized in the arboretum of the MBG. The names of species that were recorded for the alien fraction of the flora of the botanical garden for the first time are in bold and marked by an asterisk.

(1) *Acer campestre* L. It has been cultivated in the MBG since 1938; the collection currently (2017) includes 29 specimens.

Abundant self-seeding of field maple is recorded in the arboretum in the immediate vicinity of collection plants; some of these specimens have already reached the generative phase.

(2) *Acer negundo* L. It has been cultivated in the MBG since 1937; the collection included 12 specimens in 2017.

Ash-leaved maple specimens, including flowering and fruiting ones, occur throughout the MBG. The greater number of young plants of this species in the arboretum plot around the collection site of the genus *Acer* compared to the average number for the botanical garden suggests that some of them originated from collection trees rather than trees that grow in areas adjacent to the garden.

(3)–(4) *Acer pseudoplatanus* L. It has been cultivated in the MBG since 1941; the collection currently includes 60 specimens.

The abundant self-seeding of sycamore is recorded in the maple collection site; many plants are of a significant size (up to 7 m high); however, generative self-seeding individuals have not yet been recorded. Some of self-seeding specimens represent a form of *f. *purpureum* (Loudon) Rehder.

(5) ***Acer rubrum* L.** It has been cultivated in the MBG since 1939; the arboretum collection currently includes 25 specimens (including cultivars).

Seedlings annually emerge on root tori of collection specimens; they rarely reach a size of over several centimeters, since this site of the arboretum is regularly mowed.

(6) ***Acer spicatum* Lam.** It has been cultivated in the MBG since 1939; the arboretum collection currently includes 36 specimens.

Single young (4- to 5-year-old) self-seeding specimens were recorded at a small distance from collection specimens.

(7) ***Acer tegmentosum* Maxim.** It has been cultivated in the MBG since 1937; the arboretum collection currently includes 29 specimens.

A great amount of self-seeding emerges in the immediate vicinity of collection specimens; it dies on the second to third year as a result of mowing.

(8) *Aesculus hippocastanum* L. It has been cultivated in the MBG since 1941; the collection currently includes 22 specimens.

Young self-seeding plants occur both in the immediate vicinity of the collection of the genus *Aesculus* and at a significant distance from it.

(9)–(11) ***Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem.** It has been cultivated in the MBG since 1938; the collection currently includes 18 specimens. ***Amelanchier arborea* (F. Michx.) Fernald.** It has been cultivated in the MBG since 1938; the arboretum collection currently includes 14 specimens. *Amelanchier spicata* (Lam.) K. Koch. It has been cultivated in the MBG since 1937; the collection currently includes 39 specimens.

The above-mentioned Juneberry species sporadically provide uneven-aged self-seeding throughout the botanical garden; many of the specimens enter the generative phase.

(12) ***Carpinus betulus* L.** It has been cultivated in the MBG since 1937; the collection currently includes 62 specimens (including cultivars).

There are two large (15- to 20-year-old) self-seeding trees at some distance from the collection site; they flower and bear fruit.

(13) ***Carpinus cordata* Blume.** It has been cultivated in the MBG since 1946; the collection currently includes six specimens.

It is propagated by numerous layerings of drooping branches.

(14) *Cornus alba* L. It has been cultivated in the MBG since 1938; the collection currently includes 43 specimens.

Single specimens were recorded in several habitats in the MBG arboretum; some of them reach a significant size, enter the generative phase, and are actively propagated by layerings, thereby forming colonies and thickets.

(15) ***Corylus sieboldiana* var. *mandshurica* (Maxim.) C.K. Schneid**. It has been cultivated in the MBG since 1939; the collection currently includes 27 specimens.

A few young self-seeding specimens were revealed in the collection site of the genus *Corylus*.

(16) *Cotoneaster* aff. *lucidus* Schltdl. It has been cultivated in the MBG since 1939; the collection currently includes 19 specimens.

Cotoneaster seedlings sporadically occur in the MBG arboretum; they flower and bear fruit. They were not identified to the species level owing to the taxonomic complex structure of the genus, as well as to the fact that cotoneasters that develop under significantly shaded arboretum conditions do not exhibit species-typical features.

(17) *Crataegus submollis* Sarg. It has been cultivated in the MBG since 1939; the collection currently includes 19 specimens.

Uneven-aged specimens sporadically occur in the MBG arboretum; some of them flower and bear fruit.

(18) ***Crataegus* spp**. Eighty hawthorn species and varieties are cultivated in the MBG arboretum.

Uneven-aged hawthorns with a wide range of morphological features occur throughout the MBG arboretum. The species identification is difficult not only owing to the complex structure of the genus *Crataegus* as a taxonomic group but also because of the fact that the identification of hawthorn by its vegetative features proves to be impossible: under the shady conditions of the arboretum, many specimens do not exhibit their typical structural features. In addition, we assume that many seedlings are of hybrid origin, since the hawthorn collection is not the only source of seeds in the MBG: birds also transport seeds from hawthorns that are used in yard gardening in surrounding areas.

(19) ***Eleutherococcus sessiliflorus* (Rupr. et Maxim.) S.Y. Hu.** It has been cultivated in the MBG since 1947; the collection currently includes 34 specimens.

Only one young self-seeding specimen was found at a small distance from the collection site of the genus. Although having a rather small size, it has already entered the generative phase.

(20) *Euonymus europaeus* L. It has been cultivated in the MBG since 1940; the collection currently includes 48 specimens.

European spindle tree specimens sporadically occur throughout the arboretum; they often reach the species-typical size, flower, and bear fruit. The abundant self-seeding of young plants is recorded in the collection site of the genus *Euonymus*.

(21) *Euonymus maackii* Rupr. It has been cultivated in the MBG since 1938; the collection currently includes 21 specimens.

Numerous seedlings and young plants occur under collection plants; self-seeding can be rarely found at a small distance from the collection specimens. Only individual young plants were able to enter the generative phase.

(22) ***Euonymus macropterus* Rupr.** It has been cultivated in the MBG since 1937; the collection currently includes seven specimens.

Numerous young plants and seedlings are revealed under the collection specimens.

(23) ***Fraxinus excelsior* "Diversifolia"** (=*Fraxinus monophylla* Dum. Cours.). It has been cultivated in the

MBG since 1952; it is absent in the collection because of its death caused by emerald ash borer.

Young uneven-aged specimens with the features of this cultivar are found in the place of the borer-damaged collection of the genus *Fraxinus*.

(24) ***Fraxinus sogdiana* Bunge.** It has been cultivated in the MBG since 1938; it is currently (in 2017) absent in the collection because of its death caused by emerald ash borer.

A few self-seeding plants were revealed in the former location of the collection of the genus *Fraxinus*. However, the studied specimens did not exhibit sufficiently clear species-typical features, which is due to the adaptation to the shady conditions of the arboretum or due to the hybrid origin of seedlings.

(25) ***Hypericum androsaemum* L.** It has been cultivated in the MBG since 1962.

It demonstrates vegetative reproduction by underground stolons, thereby gradually extending from collection groups.

(26)–(30) ***Juglans ailantifolia* Carrière** and its variation **var. *cordiformis* (Makino) Rehder** have been cultivated in the MBG since 1950; the collection currently includes 22 specimens. ***Juglans cinerea* L.** It has been cultivated in the MBG since 1937; the collection currently includes six specimens. *Juglans mandshurica* Maxim. It has been cultivated in the MBG since 1937; the collection currently includes 30 specimens.

Different walnut species are independently dispersed in the MBG. Their fruits are dispersed by squirrels, jays, and ravens; therefore, seedlings are often significantly far from maternal plants. As a rule, it is difficult to identify species on the basis of their vegetative features; however, it can be stated that mass distribution is inherent in Manchurian walnut, while bitternut walnut and ailanthus-leaved walnut form self-seeding less frequently. Some walnut seedlings may be of hybrid origin; thus, the leaf structure of some of the revealed plants had features that are characteristic of Circassian walnut (*Juglans regia* L.).

(31) ***Kerria japonica* (L.) DC.** It has been cultivated in the MBG since 1949.

Both the species *Kerria* and cultivar ***"Pleniflora"** are spread from collection groups on the basis of underground stolons and rooted runners.

(32) *Ligustrum vulgare* L. It has been cultivated in the MBG since 1941.

A few self-seeding specimens were recorded in the propagating nursery (production area). Plants demonstrate good growth rates; however, they do not enter the generative phase.

(33) *Malus domestica* Borkh. It has been cultivated in the MBG since 1939; the collection currently includes four specimens.

Domesticated apple specimens available in the arboretum are apparently of different origin: they were brought by visitors (self-seeding specimens are often found in the immediate vicinity of roads and paths) or birds (specimens under the crowns of large trees). Apple plantings along Botanicheskaya Street, as well as the collections of cultivars of the Department of Cultural Plants, could have served as sources for specimens brought by birds. The latter is confirmed by the fact that some specimens demonstrate unusual features, e.g., the columnar growth habit.

(34) ***Menispermum canadense* L.** It has been cultivated in the MBG since 1948; it is currently absent in the collection.

There are two clonal common moonseed colonies in the MBG arboretum; the colonies themselves are most likely of self-seeding origin.

(35) ***Mespilus germanica* L.** It has been cultivated in the MBG since 1949; the collection currently includes 19 specimens.

One large self-seeding medlar specimen is known at a small distance from collection plants; it flowers and bears fruit.

(36) *Prunus avium* (L.) L. It has been cultivated in the MBG since 1938; the collection currently includes seven specimens.

Self-seeding wild cherry plants occur throughout the arboretum and botanical garden; most of them originated from arboretum collection plants; however, some of them originated from cultivar plants that are grown at the Natural Flora Department and Department of Cultural Plants. Many self-seeding wild cherries abundantly flower; however, regular and abundant fruiting is recorded only in the two largest self-seeding specimens with a height of over 18 m.

(37) *Prunus cerasifera* Ehrh. It has been cultivated in the MBG since 1938; the collection currently includes 11 specimens.

Self-seeding specimens sporadically occur throughout the MBG arboretum; some of the specimens enter the generative phase and demonstrate diversity in fruit size and color.

(38)–(39) ***Prunus incisa* Thunb.** It has been cultivated in the MBG since 1966; the collection currently includes six specimens. ***Prunus sachalinensis* (F. Schmidt) Koidz.** It has been cultivated in the MBG since 1953; the collection currently includes six specimens.

The self-seeding of several Japanese cherry tree species sporadically occurs in the MBG arboretum (sometimes, a few hundred meters from the collection plants); some of the specimens have entered the generative phase.

(40) ***Prunus maackii* Rupr.** It has been cultivated in the MBG since 1937; the collection currently includes 13 specimens.

The arboretum has several specimens of self-seeding origin; some of them have reached a large size; it annually flowers and bears fruit.

(41) ****Prunus maximowiczii* Rupr.** It has been cultivated in the MBG since 1953; the collection currently includes 21 specimens.

Uneven-aged specimens of this bird cherry species occur almost throughout the arboretum; many of them have entered the generative phase.

(42) ****Prunus ssiori* F. Schmidt.** It has been cultivated in the MBG since 1965; the collection currently includes two specimens.

A few self-seeding specimens have been recorded in the immediate vicinity of collection specimens; the largest of them are beginning to flower and bear fruit.

(43)–(44) ****Pterocarya fraxinifolia* (Lam.) Spach.** It has been cultivated in the MBG since 1950; the collection currently includes two specimens. ****Pterocarya rhoifolia* Siebold & Zucc.** It has been cultivated in the MBG since 1947; the collection currently includes four specimens.

The abundant young self-seeding of *Pterocarya fraxinifolia* is recorded on lawns that are adjacent to the collection of the genus *Pterocarya*. The absence of older specimens is due to the fact that these lawns were not previously cleared of the undergrowth of forest plants. In addition to self-seeding, both *Pterocarya* species present in the collection reproduce by coppice shoots.

(45) ****Quercus bicolor* Willd.** It has been cultivated in the MBG since 1978; the collection currently includes one specimen.

The arboretum has only one 4-year-old seedling directly under the collection specimen.

(46) *Quercus rubra* L. It has been cultivated in the MBG since 1951; the collection currently includes 133 specimens and a few dozen specimens that were planted in the arboretum as ornamental groups.

Abundant self-seeding is recorded directly under the crowns of collection plants of the arboretum and ornamental groups. There are extremely few specimens at a significant distance from maternal plants; at the same time, their size significantly exceeds that of self-seeding under the collection.

(47) ****Rhamnus cathartica* L.** It has been cultivated in the MBG since 1948; the collection currently includes 12 specimens.

Uneven-aged specimens of common buckthorn sporadically occur not only throughout the botanical garden but also in the adjacent Ostankino park.

(48) *Robinia pseudoacacia* L. It has been cultivated in the MBG since 1935; the collection currently includes 28 specimens.

Collection specimens reproduce by coppice shoots; some of the daughter specimens are over 10 m high and have already entered the generative phase.

(49) *Rubus caucasicus* Focke. It has been cultivated in the MBG since 1976.

Clonal specimens occur in the area that was previously occupied by the collection of the genus *Rubus*.

(50) *Sambucus nigra* L. It has been cultivated in the MBG since 1938; the collection currently includes ten specimens.

Self-seeding specimens occur in the MBG; they often reach the maximum size typical of the species; they flower and bear fruit.

(51) ****Sorbus alnifolia* (Siebold & Zucc.) K. Koch.** It has been cultivated in the MBG since 1946; the collection currently includes nine specimens.

Several uneven-aged (in some cases, very large) specimens are recorded in the arboretum. Many of them flower and bear fruit.

(52)–(53) ****Sorbus intermedia* (Ehrh.) Pers.** It has been cultivated in the MBG since 1938; the collection currently includes 12 specimens.

It occurs throughout the arboretum; however, it is most often recorded in the immediate vicinity of the collection site of the genus *Sorbus*. Some self-seeding specimens are 5–7 m high; they flower and bear fruit. Self-seeding whitebeam specimens (*Sorbus* sp.), which have not been identified to the species level, are also periodically found in the MBG. The arboretum collection contains 23 *Sorbus* L. subg. *Aria* species.

(54) ****Spiraea japonica* L. f.** It has been cultivated in the MBG since 1938.

Self-seeding specimens with frequently observed cultivar features occur in the propagating nursery (production area). They flower and bear fruit.

(55) ****Staphylea pinnata* L.** It has been cultivated in the MBG since 1949; the collection currently includes two specimens.

Some specimens sporadically occur at a small distance from the collection site of the genus *Staphylea*. Occasionally, some specimens pass to the generative phase; however, their flowering and fruiting are extremely poor.

(56) *Symphoricarpos albus* (L.) S.F. Blake. It has been cultivated in the MBG since 1939; the collection currently includes four specimens.

A few self-seeding plants are recorded in the MBG arboretum. It is unclear whether they originated from collection specimens or from the plants of the species that are used in urban landscaping.

(57) *Syringa josikaea* Jacq. f. ex Rchb. It has been cultivated in the MBG since 1937; the collection currently includes 13 specimens.

Only one self-seeding specimen was found in the MBG arboretum. Despite a relatively small size, it flowers and bears fruit.

(58) ****Taxus baccata* L.** It has been cultivated in the MBG since 1938; the collection currently includes ten specimens.

A few two-year-old seedlings were found in the collection site of the genus *Taxus* and in its immediate vicinity.

(59) ****Tilia americana* L.** It has been cultivated in the MBG since 1940; the collection currently includes seven specimens.

A few self-seeding individuals were revealed not far from basswood collection specimens.

(60)–(61) ****Tilia begoniifolia* Steven.** It has been cultivated in the MBG since 1940; the collection currently includes four specimens.

Bushy plants were revealed under the crowns of this linden species; most likely, they are of root-sucker origin and have been damaged many times during grass mowing. In addition to the above-described species, numerous seedlings of ****Tilia* sp.** were also found in the collection site of the genus *Tilia*; their exact species affiliation is not identified, which is most likely due to their hybrid origin. The total number of basswood species cultivated in the MBG arboretum is 12.

(62) ****Toxicodendron radicans* (L.) Kuntze.** It has been cultivated in the MBG since 1953.

Only one specimen of this species in the collection is actively dispersed by vegetation in the collection site; it has a bushy habit. Its shoots, which often pass to the lianoid growth, are damaged by winter frosts.

(63) ****Ulmus davidiana* var. *japonica* (Rehder) Nakai.** It has been cultivated in the MBG since 1953; the collection currently includes three specimens.

A few self-seeding specimens were recorded in the collection site of the genus *Ulmus*.

(64) ****Ulmus laciniata* (Trautv.) Mayr.** It has been cultivated in the MBG since 1953; the collection currently includes two specimens.

A few self-seeding specimens that were found in the immediate vicinity of collection plants have features that are characteristic of Manchurian elm; however, they are insufficiently pronounced. This may be due to the juvenility of plants, specific arboretum conditions, or the hybrid origin of seedlings (possibly, hybridization with native *Ulmus laevis* Pall.).

(65) ****Viburnum burejaeticum* Regel & Herd.** It has been cultivated in the MBG since 1954; the collection currently includes ten specimens.

Numerous young shoots are formed directly under collection specimens.

(66) *Viburnum lantana* L. It has been cultivated in the MBG since 1948; the collection currently includes 40 specimens.

Self-seeding specimens rarely occur in the arboretum; some of them flower and bear fruit.

DISCUSSION

A taxonomic analysis of species that naturalized in the exposition sites of the MBG RAS arboretum was carried out. Spontaneous dispersal was recorded for representatives of 66 species and varieties of 35 genera belonging to 23 families (Table 1). The number of naturalized species is only 5.0% of the species and varieties that are cultivated in the arboretum; however, they constitute over a quarter (26%) of all genera and almost a half (45%) of all families. Representatives of 102 plant genera and over 1200 plant species that are cultivated in the MBG arboretum did not have naturalization features. None of the species cultivated in the arboretum extended beyond the boundary of the MBG.

The maximum number of species passing to spontaneous reproduction is recorded for the genera of *Prunus* s.l. (seven taxa), *Acer* (six taxa), and *Juglans* (five taxa). Three taxa are recorded in each of the three following genera: *Euonymus*, *Amelanchier*, *Sorbus*, and *Tilia*. Each of the other genera includes one or two species passing to spontaneous reproduction. Among families, Rosaceae differs significantly in the number of naturalized representatives; it includes 22 naturalized taxa, which is due to a frequent occurrence of this family in the arboretum collection (436 taxa). Therefore, the Rosaceae family is dominant with respect to the absolute index; however, the percent of naturalized Rosaceae taxa is the same as that for the whole arboretum (5.0%). Of greater interest is the family Juglandaceae; among its representatives, only one species did not have features of naturalization, while the other seven taxa in the arboretum collection are subject to a certain degree of naturalization in the MBG. It should be noted that species the fruits of which are dispersed by birds or squirrels, i.e., on the basis of zoochoria, have good naturalization. The rates of naturalization of plants the fruits of which are dispersed by wind are significantly lower.

Self-seeding is almost completely absent in plants that belong to large and well-represented families in the MBG arboretum, such as Cupressaceae and Pinaceae. This is apparently due to the absence of suitable conditions for seed germination, in particular, to the fact that moss groups are not formed under the oak canopy (while it is moss groups that determine the germination of many conifers in natural conditions).

Interesting data were also obtained even when the chorological analysis was simplified. The ratio of naturalized woody plants with respect to their distribution in different parts of the world proved to be as follows: 34% of European species, 45% of Asian species, and 21% of North American species. At the same, the ratio of the total number of cultivated taxa in the collection differs somewhat from the above ratio: 24.5% for Europe, 49.4% for Asia, and 26.1% for North America. The greatest capacity for naturalization (5.3%) is demonstrated by plants that naturally grow in Europe; plants from Asia (3.4%) and North America (3.0%) naturalize less actively (Fig. 1). In addition, the number of naturalized plants with the European range are actually higher, since some European species, the collection specimens of which provide self-seeding in the

Table 1. Taxonomic analysis of the MBG arboretum collection with respect to the capacity of plants for spontaneous dispersal

Family	Genus	Number of taxa with vegetative or self-seeding dispersal				Not naturalized
		abundantly	sporadically	occasionally	total	
Aceraceae	*Acer*	3	2	1	6	42
Araliaceae	*Eleutherococcus*			1	1	3
Anacardiaceae	*Toxicodendron*			1	1	0
Betulaceae	*Carpinus*			2	2	3
	Corylus			1	1	6
Caprifoliaceae	*Symphoricarpos*	1			1	5
Celastraceae	*Euonymus*	1	2		3	14
Clusiaceae	*Hypericum*			1	1	0
Cornaceae	*Cornus*	1			1	21
Fabaceae	*Robinia*		1		1	0
Fagaceae	*Quercus*	1		1	2	11
Hippocastanaceae	*Aesculus*		1		1	5
Juglandaceae	*Juglans*	1	3	1	5	1
	Pterocarya		2		2	0
Menispermaceae	*Menispermum*			1	1	0
Oleaceae	*Fraxinus*		1	1	2	23
	Ligustrum			1	1	11
	Syringa	1			1	13
Rosaceae	*Amelanchier*	1	2		3	8
	Cotoneaster		1		1	19
	Crataegus		2		2	70
	Kerria			2	2	0
	Malus	1			1	30
	Rubus	1			1	3
	Mespilus			1	1	0
	Prunus	1	6		7	28
	Sorbus		3		3	62
	Spiraea		1		1	65
Rhamnaceae	*Rhamnus*	1			1	12
Sambucaceae	*Sambucus*	1			1	3
Staphyleaceae	*Staphylea*		1		1	6
Taxaceae	*Taxus*			1	1	5
Tiliaceae	*Tilia*		1	2	3	20
Ulmaceae	*Ulmus*			2	2	7
Viburnaceae	*Viburnum*		1	1	2	17
TOTAL		15	30	21	66	513

arboretum, were not taken into account because of the fact that these species also natively occur in the MBG. The great number of naturalized European species can be explained both by their more frequent occurrence in the arboretum and by their higher adaptation to the ecological conditions of the cultigenic range.

During the research, we faced the problem of species identification of many of the revealed self-seeding plants, which was caused by several factors. First, the greater part of the revealed self-seeding plants had not yet entered the generative phase and the use of vegetative organ features alone proves to be insufficient for the species identification of self-seeding plants. Second, the greater part of the arboretum area is currently highly shaded, since it is located under the crowns of collection plants or preserved forest trees. Young self-seeding plants that develop in shaded and partially shaded areas often significantly differ from the "typical appearance" that is described in identification guides and inherent in adult specimens growing under full light conditions. Third, there are very insufficient published data on the structure of juvenile woody plants. The available studies describe the structure of young plants that grew up under full-light nursery conditions; however, they are not suitable for identifying self-seeding plants in the arboretum. Fourth is hybridization. The construction of the arboretum according to the systematic principle (i.e., when species that belong to the same family, genus, or even smaller taxonomic units were planted together in the arboretum) led to the formation of a significant number of hybrid seeds. The average number of hybrid and wrongly identified seeds that are distributed among botanical gardens according to the Index Seminum system is estimated to be 20% and reaches 50% for complex taxonomic groups (Skvortsov; 1996). Since hybridization is one of the extremely important factors both for the acclimatization of plants and for their naturalization and transition to invasive behavior (Huxel, 1999; Zalapa et al., 2009; Tokhtar et al., 2011; Ainouche et al., 2016), it is logical to assume that many self-seeding plants are of hybrid origin in the arboretum. However, it is very difficult to determine the hybrid origin both owing to the above-described causes and owing to a huge number of species cultivated in the arboretum.

On the basis of the aforementioned causes, we assume that the list of species naturalizing in the MBG RAS arboretum will significantly increase in the future. The involvement of experts will make it possible to find new species belonging to complex taxonomic groups, such as hawthorns and whitebeams. The growing up of self-seeding specimens that are already present in the arboretum and their transition to the generative phase will make it possible to determine the species affiliation of those plants which we fail to identify to the species level at the juvenile or immature development stage. Works on clearing and thinning out of collection sites that are carried out in the arboretum may also

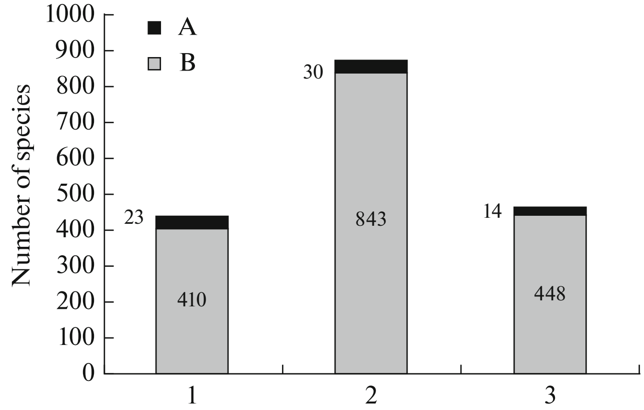

Fig. 1. The ratio of naturalized and nonnaturalized woody species of different geographical origin in the MBG. (A) Naturalized species; (B) cultivated species. Naturally growing species: (1) in Europe; (2) in Asia; (3) in North America.

help clarify the species composition of introduced self-seeding woody species. The role of hybridization in the emergence of woody plant self-seeding in the arboretum can be determined using laboratory methods of analysis: chromosomal, biochemical, molecular, and other analyses. It will be possible to obtain more accurate data of analysis of the taxonomic composition of naturalizing woody plants after determining the species composition of self-seeding in complex groups.

Our data do not support the hypothesis known as the "Rule of Ten"; according to this hypothesis, only 10% of taxa that have overcome one of the barriers on their way from an alien to an invasive species overcome the next barrier (Kühn et al., 2004). Thus, about 2400 taxa have overcome the geographical barrier on the basis of intentional introduction for over 70 years of the existence of the MBG (Fig. 2); 1317 (55%!) of them have overcome the ecological barrier (because employees of botanical gardens intentionally prepare the collection and pay much attention to the selection of sustainable species); 66 taxa (5%) have overcome the reproductive barrier, which is explained by a long-term entry of woody species into the generative development phase. Only 12 species (8%) really "escaped" from the arboretum collection and intruded into the natural phytocenoses of the botanical garden, while three species in this group (*Acer negundo*, *Cotoneaster lucidus*, and *Malus domestica*), on the contrary, externally penetrated into the botanical garden, generally from landscape plantings. Presumably, the Rule of Ten covers only unintentionally introduced (=randomly introduced) plants and is not applicable to introduction institutions.

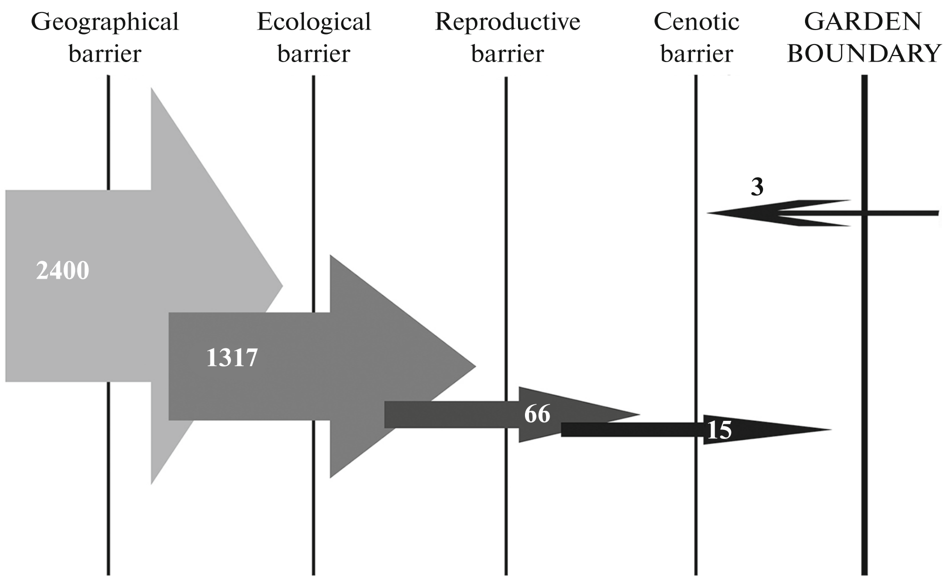

Fig. 2. Diagram of stages of alien plant naturalization and the distribution of species of the MBG arboretum collection with respect to the degree of invasiveness.

CONCLUSIONS

The invasive activity of woody plants is rather low in the collection funds of botanical gardens: for over 70 years, self-reproduction has been recorded only for 5% of species in the MBG and only 1.1% of intentionally introduced species have extended beyond the arboretum to natural forests preserved in the MBG. None of the species cultivated in the arboretum has extended beyond the boundary of the MBG. We believe that the risk of invasion of new alien species of woody plants through the vector of intentional introduction has low probability.

The invasive activity is higher for species that are cultivated in several exposition sites and represented by samples of different geographical origin in the MBG. These taxa have an initially higher genetic variability, which contributes to a more rapid adaptation to new soil and climate conditions.

The invasive activity of plants with European range is at least 1.7 times higher than that of Asian and North American species.

The highest invasive activity was recorded for species of the families Juglandaceae (seven of the available eight taxa in the collection) and Rosaceae (22 of the available 436 taxa in the collection), the fruits of which are dispersed by zoochoria.

The combined cultivation of closely related woody species of different geographical origin in botanical gardens involves active processes of hybridization and it is difficult to identify numerous seedlings because of the fact that they have intermediate features between parental species.

Contrary to the published data, botanical gardens are not a direct vector for the invasion of alien species. Although many invasive species emerged in other regions of the world owing to intentional introduction, their invasion into natural communities should be associated with their further mass cultivation rather than with introduction institutions, under the assumption that mass cultivation contributes to an increase in the genetic variability in initial introduction populations.

The Rule of Ten is not applicable when intentional introduction is used at introduction institutions; presumably, it can be applied only in the case of other invasion vectors.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interest.

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

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