



The potential role of public gardens as sentinels of plant invasion

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Abstract

Public gardens can help prevent detrimental effects of plant invasions by collecting and sharing data on taxa spreading from cultivation early in the invasion process, thereby acting as sentinels of plant invasion. Existing initiatives have called for public gardens to adopt measures preventing plant invasion, but it is unclear what actions individual gardens are implementing, as there is no formal mechanism for communicating their progress. This study used internal lists of escaping taxa from seven public gardens in the Midwestern United States and Canada to demonstrate how public gardens can collectively contribute data that is critical to assessing potential invasiveness. It also reveals methodological differences in how gardens develop their lists of escaping plants, leading to recommendations for standardization. Data pooled across gardens yielded 769 species spreading from cultivation at one or more gardens. Eight woody species were listed by all gardens despite not consistently being recognized as invasive by states and provinces containing the gardens; some species recorded by multiple gardens did not appear on any invasive lists. While it may be premature to call taxa escaping from cultivation at a few public gardens “invasive” or even “potentially invasive”, these plants should be monitored and evaluated with this information shared to facilitate stronger conclusions about risk. Thus, public gardens have a unique expertise in assisting invasive plant efforts as sentinels, particularly if challenges related to methodological inconsistencies and data sharing are suitably addressed, which is herein recommended through the adoption of a set of standardized guidelines.

Keywords Arboreta · Botanical garden · Invasive · Ornamental · Public gardens

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Introduction

Horticulture is one of several pathways by which invasive plant species may be introduced into new areas (Reichard and White 2001; Mack 2005; Hulme et al. 2017; van Kleunen et al. 2018; Beaury et al. 2021). Here, “invasive species” refers to a non-native species that causes or is likely to cause harm to the environment, economy, and/or to human health, as defined in President Clinton’s 1999 Executive Order #13112 and later updated by President Obama’s Executive Order #13751 in 2016. These plants typically exhibit the ability to cross spatial gaps through dispersal of propagules, and persist and spread in natural areas. Many of these plants were originally introduced into new locations with the best of intentions—often for landscaping, as garden novelties, for food production, as livestock fodder, or to control soil erosion. For example, *Celastrus orbiculatus* (Asian bittersweet), *Pueraria montana* var. *lobata* (kudzu), *Ampelopsis brevipedunculata* (porcelain berry) and *Pyrus calleryana* (Callery pear) were all brought into the United States from Asia by plant collectors in the mid to late 1800’s and early 1900’s (e.g., Small 1932; Heywood 2014; Culley 2017; Del Tredici 2017). Horticultural introductions and distribution of non-native species have since continued through botanical gardens and arboreta (e.g., Dosman and Del Tredici 2003), commercial nurseries, the seed industry, and garden club seed exchanges (Reichard and White 2001). We now recognize that some of these introductions, once thought to be innocuous and even beneficial to society, may eventually spread into and damage natural areas. Although only a very small proportion of non-native species may become invasive over time (Williamson and Fitter 1996, but see Jarić and Cvijanović 2012), those that do can have substantial negative impacts on the environment (Pimentel et al. 2000, 2005; Diagne et al. 2021). Reichard (1994) reported that of 235 woody species recognized as invasive in North America, 85% had been introduced primarily for use in the landscape trade. This link between the horticultural pathway and invasiveness reflects an unfortunate reality: gardeners typically desire ornamentals with many of the same traits associated with invasiveness, such as early leaf phenology, prolific flowering, environmental adaptability, pest or disease resistance, easy establishment, rapid growth and fast maturity, fruit production for wildlife, and in certain cases, vegetative spread (Sakai et al. 2001; Cadotte et al. 2006). In addition, commercialization of plant species and their cultivated varieties (hereafter, cultivars) can facilitate multiple introductions, which increase the likelihood of spread outside of cultivation (Dehnen-Schmutz et al. 2007a, b). Consequently, horticultural entities such as commercial nurseries and garden centers, residential and botanical gardens, the seed industry, and garden club seed exchanges, are sometimes blamed for introducing invasive species to natural areas (Reichard and White 2001; Hulme et al. 2017, Beaury et al. 2021).

Modern botanical gardens and arboreta (hereafter “public gardens”) historically have had goals related to horticulture such as exhibiting diverse collections of plants for public enjoyment, and sometimes developing economically valuable plants (Del Tredici 2017) by selecting and propagating new plant varieties (Dosman and Del Tredici 2003). These activities are increasingly being integrated with multiple conservation goals such as planting and tending globally rare and endangered plant species (Westwood et al. 2020), demonstrating and interpreting the benefits of native plant gardens, and in some cases, maintaining significant natural areas. The occasional escape from cultivation and proliferation of non-native plants grown by public gardens (e.g., Small 1932; McLean 1935; Glaeser and Kincaid 2005; Mack 2005; Dawson et al. 2008; Morgan 2012; Moesker 2019) can create a perceived tension between gardens’ horticultural and conservation goals. Invasive species

whose spread originated from a public garden include the aquatic *Elodea canadensis* (Canadian pondweed—escaped in Germany), the shrub *Rubus simplex* (bramble—escaped in Canada), the weedy herbs *Senecio squalidus* (Oxford ragwort—escaped in Great Britain), *Oxalis pes-caprae* (Bermuda buttercup—escaped in Malta), and the garden novelty *Heracleum mantegazzianum* (giant hogweed—escaped in Great Britain) (Mack 2005; Heywood 2014). In addition, gardens have promoted plant species to the horticultural trade that have subsequently become invasive, including *Berberis thunbergii* (Japanese barberry), promoted as an alternative to *B. vulgaris* (common barberry) after the latter was identified as a vector for a major crop pest (Silander and Klepeis 1999).

Consequently, public gardens have sometimes been presented as a threat to biodiversity (Hulme 2011, 2015) and some studies have aimed to quantitatively demonstrate that public gardens persistently grow recognized invasive species (e.g., Hulme 2015; van Kleunen et al. 2018). However, the number of gardens growing invasives has likely been overestimated in these cases because gardens were counted even within the native range of the species in question (see also Galera and Sudnĳ-Wójcikowska 2010). In general, the number of species that ultimately invade natural areas after being introduced through public gardens is only a very small proportion of the total number of species they cultivate (Heywood 2014). Nevertheless, there is no arguing that public gardens present a risk if appropriate mitigating measures are not enacted (Dawson et al. 2008; Galera and Sudnĳ-Wójcikowska 2010; Hulme 2011; Hulme 2015; van Kleunen et al. 2018).

The public garden community has taken steps to address this issue. In 1991, Glenn Dreyer argued at the American Association for Botanical Gardens and Arboreta (now the American Public Gardens Association) that public gardens should play a greater role in screening for invasiveness (G. Dreyer, pers. comm.). Similar arguments were made in Australia (Spencer 2006) and Germany (Weber and Burkart 2018) where the *European Code of Conduct for Botanic Gardens on Invasive Alien Species* explicitly called for screening existing collections and any new accessions for invasion risk and then sharing this information with other botanic gardens (Heywood and Sharrock 2013; Heywood 2014). In the United States, the *St. Louis Declaration on Invasive Plant Species* was published in February 2002 (Baskin 2002), and a set of associated recommendations, the *Voluntary Codes of Conduct for Botanic Gardens and Arboreta*, was adopted by the American Public Gardens Association 2 months later (Anonymous 2002). The *European Code* and the *St. Louis Voluntary Codes of Conduct* call for the public garden sector to take significant action to address invasive species, including a call for removing recognized invasive species from plant collections. These codes also ask gardens to establish procedures for assessing plant species' potential for invasiveness and to prohibit the accession of taxa found to pose significant risk, largely by conducting predictive weed risk assessments (e.g., Koop et al. 2012; Conser et al. 2015). These efforts also called for gardens to monitor the escape of plants from cultivation, but no specific guidance was provided on what data should be collected, how it should be managed, and how it might be shared.

Public gardens are in a unique position to form a sentinel network to aid in detecting species that could become invasive. Many public gardens closely monitor non-native taxa (referred to here as species and their cultivars) within their living collections; during regular garden maintenance they may record instances of escape from cultivation, including information on origin, plant vigor, growth, fecundity, and survival. Many larger gardens also have an array of resources and expertise, including horticulturists, curators, naturalists, and herbaria that together can identify plants escaping cultivation. In addition, public gardens often display closely related species and different cultivars of the same species, allowing a comparison of differential reproduction in relation to potential invasiveness, as in *Berberis thunbergii* (Lehrer

et al. 2006; Brand et al. 2012) and *Miscanthus sinensis* (silvergrass; Madeja et al. 2012). Species and their cultivars are often planted in close proximity to one another in living collections, a situation likely to promote spread of certain species through inter- or intra-specific hybridization (e.g., Hardiman and Culley 2010; Culley 2017). Most importantly, some public gardens record the ability of specific accessions to spread seedlings distant from the site of planting, including in monitored natural areas on site (e.g., Schuler and Forrest 2016; Moesker 2019). Gardens often make internal policy decisions based on their observations of how taxa in their collections spread from cultivation. Some gardens remove (hereafter, deaccession) species that spread aggressively from their site of planting. In a survey of staff representing 35 public gardens across North America (Dreisilker et al. 2019), 91% of respondents had observed plants escaping cultivation, 86% believed this to be an issue of concern, and 66% reported that their institutional collections policy contains provisions related to invasive plants. Up to 89% of gardens reported controlling non-native taxa spreading from cultivation, and up to 84% deaccession taxa due to spread on site. Gardens are independently taking actions recommended in the codes of conduct, but without an organized framework until only recently, have been sharing their experiences only informally. If gardens could contribute their data of plant spread to a shared platform, their combined information could form the basis of an early warning system.

Sharing information recorded by gardens about plants escaping from cultivation across a large region is imperative to fill gaps for accurate assessment of ornamental plant species recently introduced to North America, especially through predictive weed risk assessment. By compiling and sharing their data, public gardens can facilitate timely identification of taxa just beginning to spread. These taxa tend to be under-represented in existing invasive species distribution databases, such as the Early Detection and Distribution Mapping System (EDD-MapS: <https://www.eddmaps.org>). Pooled public garden data can also influence internal garden policies about how to handle potentially invasive species (such as pre-emptively removing them from collections), especially as growing zones shift poleward with a warming climate (Dullinger et al. 2017). For example, gardens in the northern United States could receive advance warning about specific plant species to monitor, based on invasive behavior reported in southern gardens. Garden data can also inform councils and government agencies responsible for assessing, listing, and/or regulating invasive species, and be used to apprise commercial plant propagators, landscape architects, and the horticultural industry of taxa showing a high risk of invasiveness. Such knowledge, if acted upon early enough, could potentially stop invasive plants from being widely introduced, and reduce economic impacts on the nursery industry resulting from post-hoc regulation.

Here we present the results of an initial effort to demonstrate the value of compiling garden data on plants escaping from cultivation by using lists of plant species and hybrids considered problematic or invasive that were independently developed by seven public gardens. We first characterized the compiled information and analyzed the extent to which the listed plants appear in common among gardens and on relevant state invasive species lists. Finally, we compared the different methodologies by which gardens developed their individual lists and subsequently propose guidelines to standardize how gardens should collect these data to enable a streamlined comparison going forward.

Methods

Compilation of garden lists

Seven public gardens voluntarily contributed their lists of plant species and cultivars (i.e., taxa) escaping cultivation. Participating gardens were located within the Midwestern and Northeastern United States and Canada: Chicago Botanic Garden (IL—USDA Hardiness Zone 5b), Dawes Arboretum (OH—Zone 6a), Holden Arboretum (OH—Zone 6b), Missouri Botanic Garden (MO—Zone 6b), The Morton Arboretum (IL—Zone 5b), New York Botanical Garden—Thain Family Forest (NY—Zone 7a), and Royal Botanical Gardens—Ontario (Zone 6b). The gardens ranged in size from 20 hectares to 1457 hectares, with an average of 586 hectares (including both the living collections and natural areas in most cases). Most gardens were founded in the late 19th and early 20th centuries, although one originated in 1965. At the request of some participating gardens, individual garden's association with particular data are kept confidential here; more information may be provided from the authors upon request.

These lists consisted of taxa that were flagged as reaching a threshold for concern of spread established independently by each garden. Some gardens only produced a single, undifferentiated list while others sorted taxa on their lists into categories. Terms used to describe and categorize these taxa varied by garden and included “problematic”, “species of concern”, “invasive”, “potentially invasive”, and “watch list”. Five gardens provided lists that consisted of species and their cultivars observed escaping from cultivation on the gardens' grounds; these lists were developed over time as an outgrowth of the gardens' normal maintenance of their collections. In some instances, garden staff from research, natural areas, and horticulture departments met every 1–3 years to discuss any new species escaping from cultivation and to make adjustments to their list (as opposed to a systematic inventory of the entire collection). The remaining two gardens listed taxa based on results of predictive weed risk assessments.

The seven gardens' lists were compiled into a single combined list, with the nomenclature (i.e., taxonomic synonymies) standardized by The Morton Arboretum's Manager of Plant Records, based on the *Flora of North America* (Flora of North America Editorial Committee 1993), *Flora of China* (Zhengyi et al. 2013), USDA GRIN, and USDA Plants. Taxa on the combined list were then grouped into three categories based on information supplied by each garden. Category A consisted of species or cultivars in a garden's collection that were deaccessioned or targeted for deaccession due to spread from cultivation or identified as invasive through risk assessment. Category B plants also originated from gardens' collections and were being actively monitored and managed (sometimes termed a “watch list”), but were not targeted for immediate deaccession. Category C consisted of species that had never been accessioned at the garden but likely had arrived through natural dispersal from elsewhere. Throughout the rest of the paper, the generalized term “problematic species or taxa” and “species of concern” refer to species or cultivars in all three categories.

A key difference occurred in terms of how gardens treated cultivars: five gardens listed only species (no cultivars), one included cultivars which were listed individually by name, and one garden grouped all cultivars of a given species together (i.e., noted as “all cultivars”). Consequently, the combined list was examined in two ways. First, all data were examined together without any modification (see Supplemental Information); therefore, a species and any named cultivars appeared as separate entries, such as “*Pyrus calleryana*”

and “*Pyrus calleryana* ‘Bradford’”. In contrast, if a garden only listed “all cultivars”, it was subsumed into the species epithet (“*Pyrus calleryana*—all cultivars”). We then created a reduced dataset of species in which all cultivars were collapsed into their corresponding species, such that each species was only represented once (Table 1 in Online Resource 3). Nearly all garden lists contained some entries that only went to the genus level, such as “*Callicarpa* spp.” and these entries were kept separate from named species already included in the genus. Identical analyses were conducted on both the original and reduced datasets, but are primarily reported below for the reduced dataset for simplicity.

Analysis of garden data

We explored the distribution and prevalence of individual plant species and their cultivars by counting how many times each was listed across participating gardens. We also determined whether taxa in the reduced species dataset disproportionately exhibited specific growth habits such as a trees, shrubs, vines, or herbs. We classified each species by habit, using the USDA PLANTS database (USDA 2020) or the EDDMapS website (EDDMapS 2020). Species were only included in the growth habit analysis if they were consistently in the same category (A, B or C) across the participating gardens that listed them ($n=589$ species). This information was then used to test whether plants within the three categories (A, B, and C) differed in growth habit, using a χ^2 Test of Independence.

To determine if any of the species on the reduced list were already broadly recognized as invasive, we compared the identified species against state and provincial lists of invasive species within the geographic region occupied by the gardens. We used the invasive list of the Midwest Invasive Plant Network (MIPN; see <https://www.mipn.org/plantlist/>), a compilation of plant species regulated or listed in eight states (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin). We also used the New York list of prohibited and regulated species (<https://www.dec.ny.gov/animals/99141.html>) and the list of regulated species for Ontario, Canada (<https://www.invasivespeciescentre.ca/invasive-species/meet-the-species/invasive-plants/>). All of these lists are developed by invasive plant councils or governmental entities (see Buerger et al. 2016). We then counted the number of states or the province that listed or regulated each species as invasive. To determine if the same plant species has been consistently identified as problematic by public gardens and state entities alike, we used a paired t-test to compare observed garden values with expected values if all the ten states and the province had listed each species as invasive.

Comparison of how gardens constructed lists & development of guidelines

Given that gardens often developed their lists differently, meaningful comparisons and categorization were challenging. Consequently, after we identified differences in how gardens constructed their lists, we developed guidelines for a standardized methodology based in part on conversations with each participating garden. Discussions focused on the purpose of each list, how and why taxa were included, when lists were updated, how taxa were verified, the degree of staff involvement, and horticultural management of listed taxa within the garden. Guidelines were then developed through a consensus-based model and application of the professional judgement of participants and their first-hand knowledge of the operational and budgetary capacity of public gardens. The document was then reviewed by public garden sector peers outside of the group of authors and refined further.

Results

Analysis of garden data

The number of taxa listed by each of the seven contributing gardens varied greatly, ranging from 32 to 529 taxa per garden when listed cultivars were counted separately. When the seven lists were combined across gardens, 881 species and cultivars were recorded by at least one of the seven gardens (Online Resource 1). Of these, seven species were listed as escaping cultivation by all seven gardens: *Acer platanoides* (Norway maple), *Celastrus orbiculatus* (Asian bittersweet), *Euonymus alatus* (winged burning bush), *Lonicera japonica* (Japanese honeysuckle), *L. maackii* (Amur honeysuckle), *Phellodendron amurense* (Amur corktree), and *Rhamnus cathartica* (common buckthorn). The original dataset included 100 cultivars listed by one or more gardens (Table 2 in Online Resource 3). The most frequently listed cultivar was *Euonymus europaeus* ‘Aldenhamensis’, listed by four gardens. Three cultivars (*Euonymus alatus* ‘Compactus’, *Phellodendron amurense* ‘His Majesty’, and *Pyrus calleryana* ‘Chanticleer’) were listed by two gardens. The most cultivars listed for a single species were 16 cultivars of *Acer platanoides* (Norway maple), 14 cultivars of *Miscanthus sinensis* (Chinese silvergrass), 13 cultivars of *Viburnum plicatum* (Japanese snowball), and 10 cultivars of *Pyrus calleryana* (Callery pear).

After individual cultivars were subsumed into their parental species in the reduced dataset, 769 problematic species were listed by one or more of the seven gardens (Table 1 in Online Resource 3). In this case, eight plant species (1%) were listed by all seven gardens; these include all of the aforementioned species, plus *Frangula alnus* (*syn. Rhamnus frangula*, glossy buckthorn). The addition of *F. alnus* in the reduced dataset reflects the fact that two gardens had listed either the ‘Columnaris’ or ‘Ron Williams’ Fine Line® cultivars, in contrast to five other gardens that listed the species.

Plant taxa listed by all seven surveyed gardens were more likely to be in Category A, meaning the garden had already deaccessioned them or had scheduled them for deaccession, or that the garden had determined the taxon to be invasive via a predictive weed risk assessment (Table 1 in Online Resource 3). The severity of categorization (from Category A to C) declined as taxa were listed across fewer gardens (Fig. 1; Table 1 in Online Resource 3). Among the eight taxa listed by all seven gardens, 91.1% of listings were in Category A, 5.4% were in Category B and 3.6% were in Category C. Similarly, of the 11 taxa listed by six gardens 90.9% of the listing incidences were in Category A, 9.1% were in Category B and 0% were in Category C. Among taxa listed by few gardens, the number of listings in each category approached parity. For example, of the 149 species listed by two gardens, 39.3% were in Category A, 30.5% were in Category B, and 30.2% were in Category C. There was a significant difference in growth habit among the three categories, with more trees and shrubs represented in Categories A and B, and more herbs present in Category C (Fig. 2; $\chi^2 = 117.3$, $df = 4$, $P < 0.0001$).

Species listed by the public gardens were sometimes, but not always, recognized as invasive on state or provincial lists (Table 1 in Online Resource 3). Of the eight species in Category A listed by all gardens, only *R. cathartica* was listed or regulated as invasive in all ten jurisdictions (nine states and one province, hereafter collectively referred to as states). *Lonicera maackii* was listed in nine states, *Celastrus orbiculatus*, *F. alnus*, and *L. japonica* were listed in seven states, *A. platanoides* in six states, *E. alatus* in five states, and *P. amurense* was included on invasive or regulatory lists in four of the ten states. All species listed by six or seven gardens were on at least one state list. Many other species

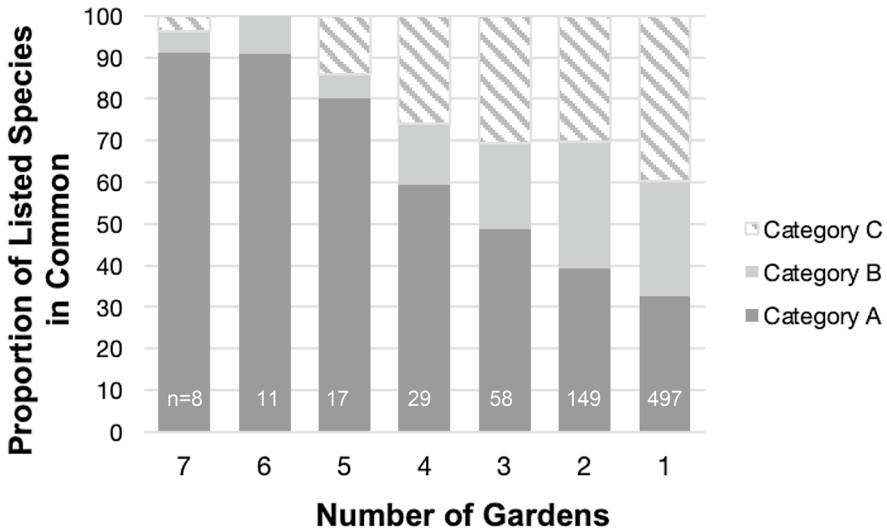
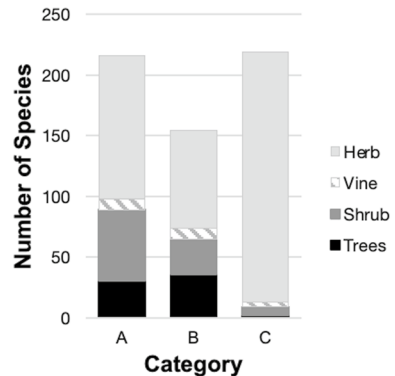


Fig. 1 Proportion of species escaping cultivation commonly listed across different numbers of public gardens, categorized as being removed or scheduled for removal (Category A), being actively monitored (Category B), or a weedy species originating from outside the garden (Category C). Cultivars have been collapsed within their parental species. Shown within each bar is the total number of species identified as being common across the indicated number of gardens

were listed by multiple gardens but appeared on very few or no state lists. In fact, 77% of all species on the reduced list did not appear on any state invasive plant lists; this included 6% of species listed by five gardens, 14% of species listed by four gardens, 24% of species listed by three gardens, 63% of species listed by two gardens, and 92% of species listed by a single garden. The number of public gardens that identified a species as problematic was significantly higher than the number of states that recognized that species as already invasive; this was true, even of species listed in common by all seven gardens (paired t-test, $t=4.511$, $df=7$, $P=0.0014$), six gardens ($t=5.418$, $df=10$, $P=0.0001$), and five gardens ($t=7.466$, $df=16$, $P<0.0001$).

Fig. 2 Relative numbers of species of different habit types (tree, shrub, vine, and herb) within the three categories of concern: **A** removed or scheduled for removal, **B** actively monitored on a watchlist, or **C** a weedy species originating from outside the garden. Cultivars have been collapsed within their parental species. The three categories significantly differed in the relative proportion of growth habit types ($\chi^2=117.3$, $df=4$, $P<0.0001$)



Comparison of garden processes to create lists

Public gardens did not develop their lists in the same way. First, gardens did not consistently include taxa within the same categories, which could be an indicator of differing spread behavior across gardens. Second, gardens with fewer listed taxa focused only on plants in Categories A and B, while gardens with more listed taxa included plants in all three categories. The frequent inclusion of taxa within Category C by some gardens was associated with the development and use of their list as an onsite natural areas management tool. In addition, most gardens developed their lists based on observations of plant behavior on site. However, two participating gardens listed species that failed predictive weed risk assessment, including species that were never grown onsite (either intentionally or incidentally). Examples of other differences among the seven gardens included the following:

- Among gardens that based their lists on observations, some placed all species observed escaping from cultivation into a single, undifferentiated list while others sorted their list into categories.
- If lists included multiple categories, those categories were defined according to different, sometimes incongruent criteria among gardens. For example, at some gardens, “watch list” might refer to species that had been accessioned and were being closely monitored for spread, while at others, it referred to species recognized as invasive within the region but not yet present in the garden.
- Some gardens only considered species and cultivars that originated from their collections for inclusion on their lists (i.e., the progeny of accessioned plants), while others also included widely recognized invasive species that originated from outside the garden (taxa that were never accessioned). Some lists only included taxa belonging to specific growth habits, especially among gardens whose collections only consisted largely of woody species.
- The completeness of some gardens’ lists was determined in part by the number of staff or volunteers available to document plant spread, and this differed among institutions.
- Different taxonomic systems and nomenclature were used, resulting in issues with synonymy once lists were compiled.
- Some gardens always listed species individually, while others sometimes lumped multiple species under a genus, especially in genera where complex hybridization occurs.
- Cultivars were not addressed the same way across gardens. Some gardens listed individual cultivars, while others grouped all cultivars together, and others did not list cultivars at all.
- Some gardens included policy implications in their lists. For example, certain gardens chose to maintain putatively invasive taxa in their collections for monitoring purposes while others aimed to deaccession and remove all listed species and cultivars.
- Some gardens listed taxa as problematic only in specific environments, recognizing that their potential to spread depends on the characteristics of the landscape in which they are planted. For example, one garden listed *Vinca minor*, a species that spreads primarily vegetatively, in Category A but noted it was only a problem if planted next to a forest; plantings surrounded by pavement did not pose a threat of spread. The same garden was also concerned with *Syringa reticulata*, an important urban and ornamental tree, noting that it can invade forests if planted near woodlands through wind dispersal of seeds.

- The type of data being collected and integrated into lists varied among gardens, as well as how these records were maintained (paper, spreadsheets, or digital databases).

Development of guidelines

Despite their clear value, public garden data on escape from cultivation are not being collected according to any standardized methodology, which limits their usefulness. The data are also seldom shared with other gardens or with other stakeholders, which is essential to serving in a sentinel function. To overcome this hurdle, we have developed guidelines containing a standard methodology whereby public gardens may collect and share data about plant escapes that can be readily synthesized and compared among gardens (See Online Resource 2; also available at <https://www.mipn.org/edrr/early-detection-of-new-invaders-at-public-gardens/>). These guidelines are intended to be iterative, with clarifications and updates implemented as more gardens adopt them and provide feedback. A summary of the main recommendations include:

- (1) All public gardens should develop and maintain a sentinel list of their collected plant taxa observed escaping from cultivation both within and beyond their property bounds.
- (2) Gardens should assign staff and volunteers with sufficient expertise on plant collections and their horticultural care to make accurate observations of plant spread behavior.
- (3) Gardens should tier their lists using standardized categories with defined parameters. We recommend *invasive*, *potentially invasive*, *watchlist*, and *assessed as invasive*, defined by parameters that can be rapidly assessed through observation and include escaped population size, distribution distance, and maintenance context of where escaped plants are growing (e.g., other garden beds, compost or maintenance areas, or managed natural areas). (Refer to the Supplemental Material for full definitions of these categories.)
- (4) Policy and management recommendations are associated with each category. For example, we recommend that gardens prioritize deaccessioning any species in their collections that they rank invasive. Decisions about retaining potentially invasive species may be balanced with other goals, but these species should be monitored closely, managed in a way that prevents spread, and not promoted to the public via education programs or plant sales. Watchlist species should also be monitored for further spread, as the name implies, but without other limitations on use.
- (5) Gardens should share their sentinel lists by means of a shared restricted-access database (<http://pgsip.mortonarb.org/Bol/pgsip>).
- (6) Species and their cultivars should be periodically reassessed and updated in lists as spread could gradually increase over time.

Discussion

This compilation and analysis demonstrates that at least some North American public gardens have been collecting data on plant taxa escaping cultivation to generate their own internal lists, based on onsite observations at their sites and/or on predictive weed risk assessment. In doing so, these gardens are implementing the recommendation of the *Voluntary Codes of Conduct* to responsibly monitor their sites for invasive species, and some

have been doing so for many years. However, public gardens are doing this work independently, and are not following any standardized protocols, and have not been consistently sharing information on aggressively spreading taxa with other gardens or outside audiences. The findings here demonstrate that when these observations are compiled, categorized, and compared within a geographical region, valuable patterns emerge, adding to the body of regional knowledge on plants at risk of becoming invasive. In some cases, species identified as most invasive by multiple gardens are already broadly recognized as invasive by non-garden entities, but in other instances, they do not appear on state lists and are not otherwise acknowledged outside of the garden community as problematic. This illustrates the potential role of public gardens as sentinels.

By adopting standardized methods and creating a data sharing network of other gardens, public gardens can help bring attention to species in the earliest stages of spread when such plants are not yet considered problematic within a growing zone or geographical area. Without this work, these plants may escape notice until it is too late and populations are too large and widespread to effectively eradicate them. Such species may also be sold and disseminated further by the broader horticultural industry (Beaury et al. 2021), often as ornamental cultivars, exacerbating their potential for spreading. Examples from the presented data include *Clematis terniflora* (sweet autumn clematis), *Hedera helix* (English ivy), *Viburnum opulus var. opulus* (Guelder-rose), *Wisteria sinensis* (Chinese wisteria), *Koelreuteria paniculata* (golden rain tree), *Spiraea japonica* (Japanese meadowsweet), and *Phyllostachys aureosulcata* (yellow groove bamboo), which were all strongly represented in the compiled garden data but occur on few Midwestern state invasive plant lists. Although it is tempting to view the occurrence of species listed by one or two gardens (e.g., *Cornus kousa* [Kousa dogwood], *Eleutherococcus sieboldianus* [five-leaved aralia], and *Zelkova serrata* [Japanese zelkova]) as early indicators of invasiveness, caution is warranted as differential microclimates, propagule pressure, and the availability of cross-compatible species or cultivars may lead to differences in a plant's ability to spread at different sites. While it may be too early to call these species even "potentially invasive", continued monitoring by public gardens in the region is critical. This is an additional potential sentinel function of public gardens. We are now determining suitable thresholds for alert (e.g., determining how many gardens listing the plant in the same region warrants notification of non-garden entities).

Taxa listed by multiple gardens included both commercially available popular ornamentals and long-recognized invasive species no longer in trade. Examples of commercially available ornamental species were *Pyrus calleryana* (Callery pear, n=6 gardens); *Euonymus fortunei* (wintercreeper, n=5); *Miscanthus sinensis* (maiden silvergrass), *Spiraea japonica* (Japanese spiraea), and *Vinca minor* (common periwinkle), all listed by 4 gardens; *Buddleja davidii* (butterfly bush), *Rhodotypos scandens* (jetbead), and *Viburnum spp.* (*V. dilatatum*, *V. plicatum*, *V. sieboldii*) listed by 3 gardens; *Magnolia kobus*, *Prunus mahaleb* (Mahaleb cherry), *Zelkova serrata* (Japanese elm) by 2 gardens; and *Malus spp.* (crabapples) by a single garden. In fact, of the eight species flagged as problematic in all gardens, at least half are still actively sold by many nurseries and garden centers in the Midwest region (see also Beaury et al. 2021). Some gardens deaccessioned an entire genus, such as *Ligustrum*, *Malus*, *Miscanthus*, *Prunus*, or *Rubus*. Well-known invasive species identified as problematic in public gardens but not currently in regulated trade (although seeds or live plants may be available through online marketplaces) include *Ailanthus altissima* (tree-of-heaven, n=6 gardens); *Alliaria petiolata* (garlic mustard, n=4), *Cirsium arvense* (Canada thistle, n=4); and *Dipsacus laciniatus* (common teasel, n=2) and *Typha x glauca* (hybrid cattail, n=2). Aquatic species included *Butomus umbellatus* (flowering rush) listed

by five gardens, and *Najas minor* (brittle naiad) and *Eichhornia crassipes* (common water hyacinth) listed by three gardens. In many cases, these species were not intentionally introduced into the public gardens, but emerged incidentally (as they also appear as invasive in many natural areas in the Midwestern region).

Comparison of garden lists indicated that growth habit was important, with significantly more woody trees and shrubs represented in Categories A and B and more herbs in Category C (Table 1 in Online Resource 3; Fig. 2). Furthermore, the eight species identified as problematic across all surveyed gardens were woody and included trees, vines, and shrubs (Table 1 in Online Resource 3). The 11 species listed by six gardens were also woody or semi-woody, but species listed across fewer gardens were comprised of both woody and herbaceous taxa. Strong representation of woody species was not surprising, given that three of the gardens providing data were arboreta with a focus on woody collections. Furthermore, two gardens only included woody taxa on their lists, as they had not yet considered herbaceous species. In contrast, one garden alone listed 300 species (Table 1 in Online Resource 3), many of which were widely recognized herbaceous weeds or invasive species originating from outside the garden (in Category C), which led to a preponderance of single herbs reported by a single garden on the combined list. Regardless, the strong representation of problematic trees, shrubs, and woody vine taxa in public gardens is consistent with estimates that 82–86% of known invasive woody species have a horticultural origin (Reichard 1994; Culley and Feldman, in review), compared to only 29% of herbs (Culley and Feldman, in review).

Cultivars were addressed differently by the public gardens, which is consistent with ongoing debate among those involved in invasive plant assessment and regulation, centering on whether cultivars should be considered individually or grouped under their parental species. Some gardens specifically listed individual cultivars as escaping cultivation, often removing them, while allowing other cultivars of the same species to remain in their collections. Other gardens were much more conservative and listed all cultivars of a species as problematic (Table 2 in Online Resource 3), placing them on a watch list or deaccessioning them. This was usually done out of an abundance of caution, as even low-fertility cultivars of long-lived invasive plants can contribute to escaped populations if not completely sterile (Knight et al. 2011). Gardens reported occasionally retaining putatively sterile cultivars, such as *Miscanthus sinensis* ‘Bandwidth’ and ‘Scout’, for further study. The importance of cultivars in plant invasions may depend in part on species-specific situations in which hybridization among genotypes drives the formation of wild populations (Ammon et al. 2007; Hardiman and Culley 2010). Thus it is key for individual cultivars to be screened for cross-compatibility and putative sterility, an activity for which public gardens are uniquely positioned, especially when cultivars are planted together within the living collection or in trial gardens.

The identity of plants showing early escape from cultivation in public gardens must be shared broadly to effectively reduce plant invasions. Compiled garden information could potentially be used to develop alerts for the horticulture industry, governmental regulators, and land managers about plants to monitor or to evaluate further. For example, governmental regulators could use information about the sterility of individual cultivars, which is often not well-documented, in their deliberations about regulating plants in the trade. Additionally, focusing on the earliest signs of escape would provide a longer timeframe for plant propagators to develop sterile cultivars and nurseries to plan inventory accordingly and reduce the adverse economic impacts associated with regulation. The potential

effectiveness of the sentinel role of gardens is exemplified by *Phellodendron amurense* (Amur corktree), a large shade tree often planted at golf courses, parks, and cemeteries. Although this species had been noted earlier to have a tendency to spread (Glaser and Kincaid 2005; Morgan 2012; Morgan and Borysiewicz 2012), it has largely been overlooked by authorities, being regulated by only three states in our analysis (IN, NY, and WI). However, every participating garden had noted its ability to escape cultivation, with staff at one garden observing reported male trees of this dioecious species occasionally producing fruits along one or more branches, indicating that sex lability may facilitate spread (K. Dreisilker, pers. obs). This behavior had not been reported in the scientific literature. Had this information from gardens had been shared and acted upon much earlier, the ever-increasing numbers of wild populations now being reported in the Midwest (T. Culley, pers. obs.) may have been avoided.

The potential role of public gardens as sentinels of these plant invasions will be enhanced by the wide adoption of the guidelines proposed here, which will: (1) allow more rigorous trend analysis of compiled data on a regional scale, potentially across dozens of gardens per region, enabling the generation of data-supported alerts to other sectors about sentinel taxa that are being observed spreading at public gardens but are not yet “on the radar” as invasive species; (2) provide additional insight across regions about which plant species may become problematic as plant ranges change in response to climate change; (3) allow garden staff insight into how peers at other sites are addressing taxa escaping from cultivation; and (4) facilitate a culture of data sharing among gardens so that they feel empowered to channel their botanical expertise toward a common goal of preventing future invasions. Furthermore, we continue to encourage gardens to participate in the PGSIP program to contribute their data and further expand the list of problematic taxa. This effort also allows gardens in the same region to work together to coordinate their activities. Beyond these immediate goals, there are other potential future applications of garden data, including the development of a “green list” of non-native ornamental species with low or no risk of escaping cultivation (Dehnen-Schmutz 2011). While we recognize and respect that some gardens may be reluctant to broadly share information on plants escaping from cultivation on their property, the gardens participating in this project see great potential in working together to prevent future invasions. We fully anticipate that public gardens will continue to apply professional judgment and weigh their different objectives when making policy decisions informed by their sentinel lists. Gardens should continue to monitor those species and cultivars that escape from cultivation and share that information to contribute to our understanding of their potential to spread—in other words, maintain their role as sentinels to ultimately reduce the impact of invasive species.

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Declarations

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