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Management intensity steers the long-term fate of ecological restoration in urban woodlands

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ABSTRACT

To test the impact of management intensity on long-term success of ecological restoration in urban forest patches, we analyzed vegetation structure and community composition in 3 large urban parks in New York City, 15–20 years after restoration was initiated by removal of climbing invasive woody plant species and planting of native trees. Analysis using data from 30 plots, 7626 records of species abundance, and > 6000 records of management reveals significant relationships between differences among plant communities of restored plots and intensity of restoration treatment, measured as number of days on which restoration management activities occurred. Less intense management was also more episodic, suggesting that consistent timing is also important to achieving desired long-term outcomes in plant community composition and structure. These findings indicate the importance of site-specific approaches and consistency in ongoing management to long-term positive outcomes of ecological restoration in urban forest patches.

1. Introduction

Urbanization alters ecological systems, transforming the biophysical landscape, while the structure of cities fails to provide many ecosystem services important to biodiversity and human well-being (United Nations, 2014). Recognizing that many essential ecosystem services must be provided at the local level, municipalities are turning to ecological restoration to provide air and water purification, heat island reduction, and health and other benefits (City of New York, 2017; City of Seattle Parks and Recreation, 2019; Gobster, 2007; Westphal et al., 2010). Efforts to improve environmental quality of human-created environments are inherently experimental. These approaches have great value (Elmqvist et al., 2015), and require innovative approaches to both management and goal-setting.

Research that examines the long-term outcomes of restoration activities is needed to increase our understanding of how ecological interventions affect long-term processes such as ecological succession. This is even more necessary to understand drivers of restoration success in urban environments, where additional factors resulting from urbanization may change the way that ecosystems respond to restoration, reducing the power of models of ecosystem processes developed in more pristine environments to predict long-term outcomes in cities (Ehrenfeld, 2000; Falk et al., 2006; Handel et al., 2013).

Fragments of forest in urban areas are disproportionately important for their small size as both refuges for regional biodiversity and sources of local ecosystem service provision (Barton and Pretty, 2010; Bolund and Hunhammar, 1999; McDonald and Marcotullio, 2011; TEEB, 2011). These islands of habitat are preserved or allowed to revegetate within the urban matrix by a combination of planning, accident, and philanthropic largesse. In this work, we focus on patches of forest in cities of temperate zones, where forests are the dominant native vegetation – or urban woodlands, in contrast with the broader sense of "urban forest" that encompasses all trees in a city.

Cities contain high proportions of non-native and invasive species, and are sites of frequent establishment of new species including both intentionally and unintentionally introduced plants (Aronson et al., 2014; La Sorte Frank et al., 2014; Pyšek, 1998; Sukopp et al., 1990). In urban forest patches, invasive plant species – particularly climbing plants – are an important management concern (e.g. Bounds et al., 2015; City of Seattle Parks and Recreation, 2019). Success of efforts to restore areas dominated by non-native plant species is highly variable, and the factors influencing success rates are in many cases not well understood (Pluess et al., 2012).

Assessment of long-term success of ecological restoration must consider the initial target state toward which the restoration was aimed. Many efforts toward ecological restoration have envisioned targets as pristine reference sites or climax states (SERI, 2004), but a more dynamic, multi-dimensional approach may be needed. In cities, we must

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also take into account spatial heterogeneity, novel disturbance patterns, and the interaction of social and ecological drivers (Alberti and Marzluff, 2004; Alfsen et al., 2011; Grimm et al., 2000; Pickett and Cadenasso, 2009).

Ecological disturbance, defined as any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment (Grimm et al., 2017; White and Pickett, 1985), is a key driver of vegetation change. Landscape management can be considered a "designed disturbance," intentionally applied to alter the trajectory of vegetation change (Luken, 1990). In restoration efforts aimed at reducing the dominance of invasive plant species, this "disturbance" is most often removal of undesired plants and/or addition of desired species, resulting in changes in availability of resources and species propagules along with perturbation of the soil. In restoration, as in other types of disturbance, the frequency, intensity, and type of disturbances a community experiences affect trajectories of change over time. Management activities are not the only type of disturbance influencing community change in urban forest patches under restoration. In these social-ecological systems, legacies of past urban and pre-urban human land uses combine with current uses and fine-scale landscape pattern heterogeneity to shape local site conditions.

Here, we examine long-term outcomes of early approaches to ecological restoration of urban forest patches (assessment and planning initiated in 1984). To test how intensity of management effort impacts the long-term success of ecological restoration in urban forest fragments, we analyzed plant community differences among forests where restoration treatments removed woody invasive plants and planted native trees. We examine relationships between plant community composition and intensity of management effort to uncover factors influencing variability in restoration outcomes.

Ecological restoration of forest patches in cities is a recent phenomenon. Increasing interest in the benefits of nature exposure for urban populations, concern for rapidly disappearing habitat area in an urbanizing region, and a growing understanding of the benefits of ecosystems to people led New York to adopt a city-wide program to promote native forest regeneration in 1984 (Bounds et al., 2015). This early restoration work in New York City was, to our knowledge, the first city-wide program of its kind. Restoration actions focused on invaded canopy gaps lacking native tree regeneration, where trees fell under the weight and shade of exotic woody vines. Species targeted by this program included porcelain berry (*Ampelopsis glandulosa* (Wallich) Momiyama), oriental bittersweet (*Celastrus orbiculatus* Thunberg in J. A. Murray), and multiflora rose (*Rosa multiflora* Thunberg in J. A. Murray). To accomplish these objectives, the city removed invasive plants and planted native trees in the resulting clearings (Fig. 1). Using a gap-succession model for forest regeneration, managers predicted that planted native tree seedlings would eventually change light and other resource availability such that competition would favor native species better adapted to the understory, creating an unsuitable environment for re-establishment of invasive plants less tolerant of shade (NRG, 1991). Native saplings were grown from locally collected seed for initial plantings, and a native plant nursery was subsequently established by the City for restoration plantings. Following initial restoration activities, work crews revisited some areas and additional removal and planting were done, but others received little to no subsequent management due to personnel and budget constraints. This study tests differences among the fates of these forest restoration efforts in locations that received varying levels of restoration maintenance activity over 15–20 years after restoration was initiated.

Our prior work showed that across this city-wide program of urban forest restoration, restored areas where invasive species removal was followed by planting had a more complex vertical forest structure, greater native tree regeneration, and less abundant invasive plants (Johnson and Handel, 2016). These findings indicated that restoration actions had significant and persistent effects on plant community structure, composition, and trajectory of forest development, resulting in divergent successional trajectories consistent with the goals of the project. Drivers of variability among restored sites remained to be explored.

Fig. 1. Invaded and post-planting conditions. A: Canopy gap dominated by *Ampelopsis glandulosa*, Van Cortlandt Park, 2010 (Photo: LR Johnson). B: Planting and irrigation following invasive plant removal, Pelham Bay Park, October 1994 (Photo courtesy of Natural Resources Group archives, New York City Department of Parks and Recreation).

In this study, we tested the hypothesis that intensity of management effort is important to restoration outcomes in urban forest patches. We examined restoration actions as potential sources of differences among plant communities of restored sites after 15–20 years. Using ordination techniques, we explored and visualized the extent of differences in structure among plant communities in relation to records of management activity.

2. Methods

2.1. Site selection

Within New York City, the fraction of city-owned park land where vegetation is allowed to grow wild is managed by the Natural Resources

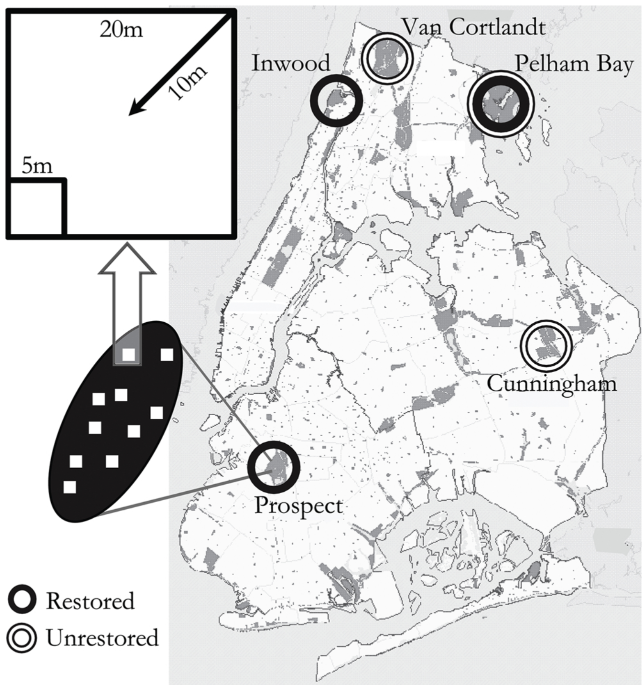

Fig. 2. Sampling design. Plant community composition and structure, soil surface characteristics, and adjacent land use were recorded in urban forest patches dominated by invasive woody plants (n = 30), and in plots where restoration efforts initiated 1988–1992 removed these species and planted native trees (n = 30). Plots were located in large urban parks in New York City (10 per park, except in Pelham Bay, the City's largest park, where sufficient area of both types was available).

Group (NRG), a division of the New York City Department of Parks and Recreation. NRG oversees more than 4000 ha of forest, woodland, freshwater wetland and salt marsh ecosystems, and conducts ecological restoration of forests, salt marshes, riparian zones, meadows and other habitat types (Bounds et al., 2015). Using NRG and Prospect Park Natural Resources (PPNR) records, 30 sites were selected for sampling in restored New York City Park forest patches in summer 2009, ten in each of three parks where city-wide Park forest restoration was first initiated (1988–1992, Fig. 2). All restoration sites in these parks were treated by removal of woody invasive species and planting with native tree seedlings. This early restoration work focused on large parks containing large forest patches. Plots were located in upland forests in Prospect Park (213 ha) in Brooklyn, Inwood Hill Park (79.5 ha) in Manhattan, and Pelham Bay Park (1122 ha) in the Bronx. All three parks contain forest patches of > 50 ha in size, as well as recreational facilities, mowed areas, and buildings. All parks are adjacent to dense multi-story residential and commercial urban land use. An additional 30 plots were selected for sampling in 2010 (ten per park) in New York City Park forests that were in a similarly invaded condition at the time of the original restoration, but which were not restored. In Pelham Bay, NYC's largest park, both restored and unrestored sites were available to be sampled.

2.2. Vegetation sampling

In each 20 m x 20 m (400 m^2) plot, DBH of all tree stems was measured (Fig. 2). Along four 10 m line transects that extended from each corner of the plot toward center (one shown), linear intercept of all ground-layer vegetation was measured in cm. All woody saplings, vines and shrubs were counted in three randomly located 5 m x 5 m subplots (one shown, see Johnson and Handel, 2016 for additional description of methods and a detailed comparison of restored and unrestored sites). Taxonomy follows *Flora of North America* (2019).

2.3. Management records

We created a relational database (MS Access 2007) by combining an NRG database of georeferenced pre-restoration vegetation descriptions, detailed NRG restoration activity logs, and PPNR restoration activity logs. Field-collected data were added to this database, as were additional data describing initial restoration activities and early monitoring under the Urban Forestry and Education Program gathered from NRG archives. NRG and PPNR records of restoration treatment activities (> 6000 records, 1988–2009) were categorized according to management type, including: a) manual and mechanical removal, where invasive plants were removed by pulling, weeding, mowing, and other machine methods; b) herbicides, where invasive plants were removed using chemical means, such as foliar spray of large vines or cut-and-dab application to individual woody stems; c) erosion control, including cribbing, fabric, matting, coir logs, and mulch; d) access control, where physical barriers such as fencing, bollards, and railings were installed; e) planting, and d) watering. Practices used by managers for recording activities varied over time, and techniques were not always specified beyond the categories above. Intensity of management effort reported here is the total number of days on which a treatment type was recorded in a plot-containing management unit.

2.4. Data analysis

We subjected data to Non-Metric Multidimensional Scaling (NMDS) via the metaMDS function in the R Vegan 2.3–3 package, with Bray-Curtis dissimilarity and three dimensions (R version 3.2.3, 2015-12-10, "Wooden Christmas-Tree," R Foundation for Statistical Computing 2015). Environmental variables were fitted to the NMDS using the R envfit function with 999 permutations; envfit uses Pearson's correlation to derive significance values (Oksanen 2015). Data describing the vegetation of each forest stratum by species and environmental variables were also subjected to canonical correspondence analysis using CANOCO 5 (Ter Braak and Smilauer, 2016). Species and environment data were subjected to direct gradient analysis using environmental data to extract patterns from only the explained variation. Scaling was focused on inter-species differences, using biplot scaling with untransformed data. No samples or species were deleted or made supplementary. Rare species were down-weighted in preparation of figures to increase legibility. We used Monte-Carlo permutation tests to evaluate both the significance of the first ordination axis and the significance of the canonical axes together, with 499 permutations under a reduced model. Permutations were unrestricted. Least squares linear regression was used to examine relationships between treatment intensity and proportional abundance of invasive plants that were not the focus of the initial restoration.

3. Results

After two decades of restoration activity, community differences among restored and unrestored plots were associated with restoration treatment effort in all forest strata (Fig. 3). Unrestored plots were highly similar in composition and dominated by invasive plants, while restored plots exhibited lower abundances of species that were removed and greater variety of species. Unique species and legacies of prior land use, such as persisting cultivated species at a former building sites, contributed to variation among restored sites. (For a detailed description of plant community differences, see Johnson and Handel (2016)).

Among restored plots, intensity and timing of management over two decades were important to differences in plant community composition, and to relative abundances of native and nonnative species.

Total management effort applied, measured in days, was significantly correlated with differences in plant community composition across all restored plots and in all forest strata (Table 1), and with reduced abundance of targeted invasive plants (Fig. 4).

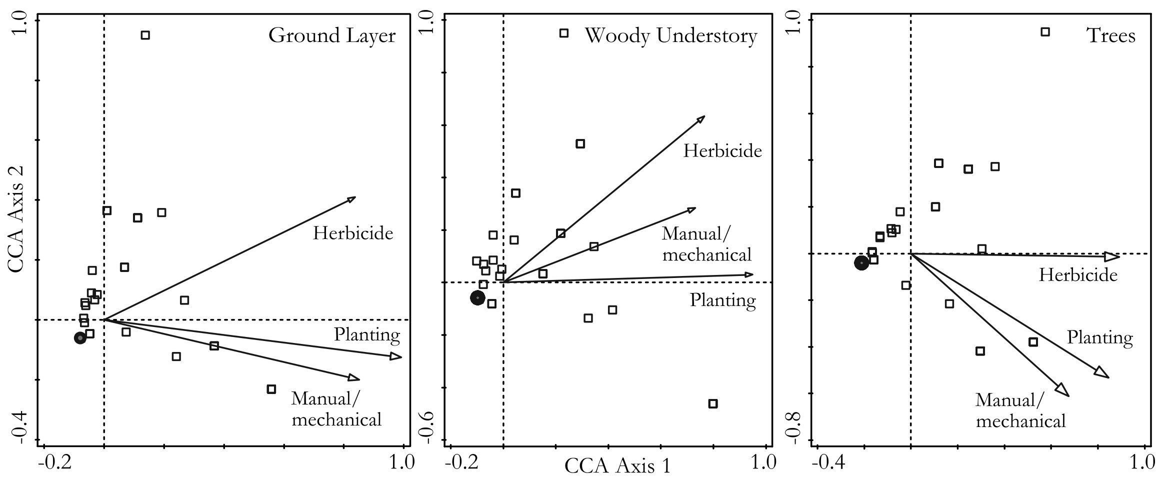

Fig. 3. Similarity of plant communities in relation to management effort in three forest layers. Unrestored plots (●) were highly similar in composition and dominated by invasive plants, while restored plots (□) exhibited lower abundances of species that were removed and greater variety of species (CCA; n = 60 plots, 30 restored and 30 unrestored; 157 ground layer, 90 woody understory, and 68 tree species). Distance between plot symbols indicates similarity of species composition and abundance. The first two canonical axes explain 86%, 78%, and 81% of fitted variation in plant community composition of the ground (pseudo-F = 3.4 (2.1) P = 0.002 (0.002) for first (all) axes), woody understory (pseudo-F = 3.0 (2.0), P = 0.014 (0.006)), and tree strata (pseudo-F = 4.0 (2.3), P = 0.002 (0.002)).

Table 1
Effects of differences in total treatment effort on community composition of forest strata in restored urban forest patches.

	Ground	Understory	Trees
Total Management Effort			
All Treatments	.507***	.383***	.341**
Herbicide Removal	.111	.209*	.314**
Manual/Mechanical Removal	.385***	.368***	.242*
All Removal Types	.357**	.364***	.256*
Planting	.554***	.294**	.368***

Management effort, measured as number of days of action taken in a plot-containing unit, had significant effects on community composition of all forest layers. (N = 30, NMDS with envfit, R Vegan 2.3–3, Bray-Curtis dissimilarity; R^2 values shown; asterisks indicate significance at α = *** 0.001; ** 0.01; * 0.05; '.' 0.1).

Each type of removal and planting action had significant effects on all three forest strata when considered separately, except differences in ground layer vegetation related to number of herbicide applications (Table 1). Differences between plots in pre-planting invasive plant removal (the most evenly-applied treatment across plots) did not have significant effects. Differences in post-planting follow-up removal of invasive woody plant re-sprouting had significant effects on tree and woody understory composition (Table 2). Erosion control and access control prior to planting were also correlated with differences in the woody understory.

In addition to effects on invasive woody plant species that were the city-wide primary targets for removal, greater management was also correlated with decreased relative abundance of invasive plants that were not the primary focus of the initial restoration, but which were subsequently targeted for removal (Fig. 5). Lower proportional abundance of these "secondary target" species was correlated with total treatment (p = 0.0003, R^2 0.206) as well as total effort in the three major types of restoration effort employed in all parks: planting ($p < 0.001$, R^2 0.236); manual and mechanical removal of invasive plants (p = 0.0004, R^2 0.180); and removal using herbicide (p = 0.0002, R^2 0.234).

Extant records from this early phase of management did not consistently include detailed information regarding number of personnel or specifics regarding equipment or supplies, but in Prospect Park where staff and volunteer effort were recorded during this period, there was a pattern of consistent action by a small staff and occasional large events with volunteers. An average of 2.7 staff (median staff: 2, range: 1–33, SD 1.64) contributed an average of 8.1 total person-hours/day (median staff hours: 5, range 1–118, SD 8.96). When volunteers were present, an average of 5.1 volunteers (median: 2, range: 1–98, SD 5.94) contributed an average of 15.6 h/day (median hours: 7, range: 1–156 total, SD 20.71). Sixty-three percent of volunteer hours devoted to restoration activities were focused on planting, followed by removal of invasive plants (20%). Staff hours followed a similar pattern, with 50% of restoration treatment hours focused on planting, and 23% on vegetation control, followed by 15% access control.

Parks varied in the timing pattern of treatments in relation to the date of first planting (Table 3, Fig. 6). Total post-restoration treatment occurred in fewer, more sporadic episodes where least management was applied (Fig. 6 A, Pelham Bay Park). In the most-managed park (C, Prospect Park), management units containing restoration plots were treated more frequently and consistently over ca. 20 years following initial planting, and a greater number of unique treatment interventions were applied. Intermediate total management and timing were observed in Inwood Park (B).

4. Discussion

These analyses reveal that among restored urban forest patches, intensity of management effort applied over time significantly improves long-term community composition change. Our findings support the hypothesis that investment of materials and labor over time affects the positive long-term outcomes of urban ecological restoration, and that consistency of effort over time is important for success.

4.1. Shaping change over time in urban woodlands

The restoration actions studied here sought to effect a shift in community trajectories toward native-dominated, regenerating, multi-

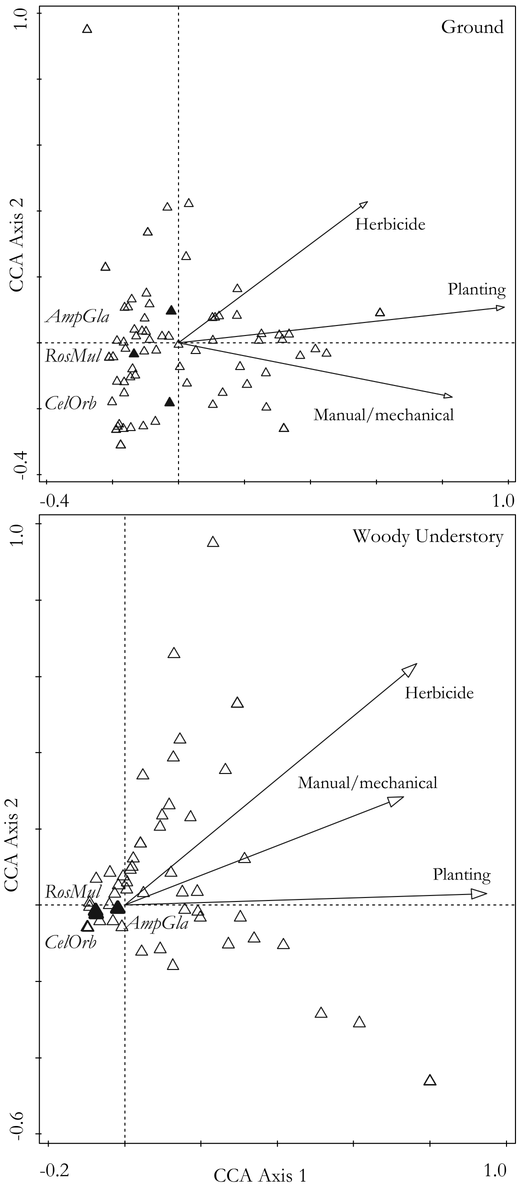

Fig. 4. Abundance of invasive woody plants in restored plots in relation to total management effort. Invasive climbing woody plants targeted for removal (▲) were negatively associated with increasing management effort (CCA, N = 30 restored plots, 102 ground layer and 65 woody understory species). *Celastrus orbiculatus* (oriental bittersweet), *Rosa multiflora* (multiflora rose), and *Ampelopsis glandulosa* (porcelain berry), and all other species (Δ) are shown. The first two canonical axes explained 86% and 78% of explained fitted variation in species abundance in the ground (pseudo-F = 3.4 (2.1) P = 0.002 (0.002) for first (all) axes) and woody understory (pseudo-F = 3.0 (2.0), P = 0.014 (0.006)) forest layers.

layered forest conditions (Bounds et al., 2015; NRG, 1996, 1986; Toth and Sauer, 1994). The physical structure and community composition of vegetation are shaped over time by: 1) site conditions that make them available - or unavailable - for species to establish and grow; 2) seeds, root fragments, and other propagules of species present and arriving; and 3) by interactions that determine species' performance in relation to one another (Meiners et al., 2015; Pickett and White, 1985). Urban environments act as dynamic filters on local species pools (Aronson et al., 2016) and on the interactions between species. Though beyond the scope of this study, shifts in abundance of other taxa – pollinators, seed dispersers, herbivores, predators, decomposers – can alter key interactions that influence plant species performance. The type, frequency, and intensity of ecological disturbances – including the intentional disturbances of ecological restoration – set the stage and the scene in which these dynamics play out. Each of these drivers of vegetation dynamics is important to long-term outcomes of restoration, and each is affected by restoration treatments.

The initial phase of the restoration efforts studied here – like many others where invasive species are a focal problem – entailed wholesale removal of dense woody vegetation. This is an intentional ecological disturbance, designed to disrupt a relatively homogenous community structure dominated by invasive plants and to make the biophysical environment more favorable to regeneration of diverse desired species. Removal and planting directly alter relative abundance and identity of individuals, changing the physical and competitive conditions for germination, establishment, and growth, resulting in a shifting composition toward desired species. This is particularly important in urban woodlands where plant species typical of older regional forests have been locally extirpated or face barriers to regeneration.

We have previously observed multiple indicators that restoration actions have altered species pools of forest vegetation: unrestored plots contained homogeneous communities dominated by invasive species, while restored plots had less invasive plants, greater plant species variability, and more regenerating native trees (Johnson and Handel, 2016). In this study, we find that consistent application of designed disturbances enhances the degree to which invasive-dominated urban woodland communities are disrupted.

4.2. Consistent versus episodic intervention

These findings underscore the importance of planting following invasive plant removal illustrated by the findings of Simmons et al. (2016), and indicate that in invaded urban forest patches, consistent management increases survival of desired species. Ongoing addition and subtraction of individuals places weight on the balance of species composition. Our finding that mean abundance of secondarily targeted invasive plants decreased with management supports this view. Managers returning to a site more frequently are able to address new challenges as they arise, and removal of invasive plants is most effective when target populations are small. “Early detection, rapid response” is a mantra in many eradication programs (Westbrooks, 2004). Our findings give foundational data to support that approach.

Plots in all parks varied independently in management intensity. However, there were general differences in management intensity among the three parks examined during this study period in relative proportions of the treatments applied and timing of restoration activity. In the most-managed park, interventions occurred a minimum of once per year in management units containing plots, and a greater number of unique management approaches were employed. In contrast, efforts in the least-managed park occurred in discrete, concentrated episodes with gaps of up to five years between interventions, and employed fewer unique techniques. In the most-managed park, site preparation by removal of invasive species was initiated longer before the first planting date. Where less management was applied, the majority of effort was focused on the immediate post-planting period.

Reasons for the variation in consistency and total effort we observed are beyond the scope of this study, but may be related to socio-economic context influencing stewardship patterns. The city-wide ecological restoration program was implemented in all restored parks, but the park with the most consistent and varied management approaches

Table 2
Effects of treatment timing in relation to first planting date on community composition of forest layers in restored plots.

	Ground	Understory	Trees
Prior to First Planting			
Access Control	.053	.282*	.032
Erosion Control	.108	.303*	.081
Herbicide	.001	.100	.088
Manual/Mechanical	.102	.069	.08
After First Planting			
Access Control	.508***	.398**	.319**
Erosion Control	.423**	.327**	.249*
Herbicide	.163.	.286*	.310*
Manual/Mechanical	.395**	.363**	.237*
Planting	.551***	.286**	.343**
Watering	.518***	.230*	.344**

Effects of treatment effort (number of days on which action was taken in a plot-containing management unit) in relation to the first day of planting were observed in all forest strata. All restoration activities were associated with time effects except pre-planting removal, which was more evenly applied across parks and made up the bulk of effort in the least-managed parks (see Fig. 6). (N = 30, NMDS with envfit; R^2 values shown; asterisks indicate significance at α = *** 0.001; ** 0.01; * 0.05; '.' 0.1).

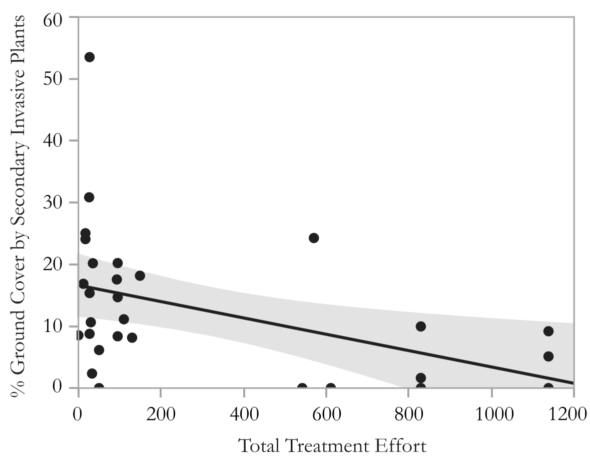

Fig. 5. Proportional abundance of secondarily targeted invasive plants in relation to management intensity. These species were not the central focus at the outset of restoration, but were removed on at least 100 unique occasions during the 20 year period. (ANOVA Prob. > F = 0.01, 95% confidence interval shown).

had additional year-round staff supported by a non-profit foundation. Differences in management have been shown to support older forest structure and greater tree diversity in U.S. National Parks compared to forests in surrounding landscapes (Miller et al., 2018, 2016). The importance of civic stewardship and governance to urban forest health is a subject deserving additional study.

In Fig. 7, we extrapolate from the observed continuum between episodic and consistent management of urban forest patches following ecological restoration. Following any removal and planting event, some invasive plants re-establish from the remaining seed bank, plant fragments, and dispersal from nearby areas. With a longer return interval between management interventions, similar effort may therefore be expended in sporadically managed plots as in regularly managed ones. This is due to the greater effort required to effect removal of large, established plants that contribute to the local seed bank.

Urban forest patches tend to be small. Limited funding, diverse property ownership, and jurisdictional control often limit the physical extent of restoration areas. Outside these boundaries, invasive plants often remain, and their seeds will travel. We hypothesize that with episodic intervention, abundance of invasive plants at a given time may be high despite similar effort expended. With longer time lags between periods of management, increasing effort is required as plants grow from remaining seeds or fragments, spread into the area, and reproduce over time. More consistent intervention minimizes this re-establishment – particularly by limiting the addition of new reproductive individuals – and populations are reduced (though not eliminated) over time as other species are able to fill available niches. Note that this scenario holds other factors equal.

4.3. Conclusion

Our findings show the importance of sustained, coordinated management effort to long-term outcomes of ecological restoration in urban forests. This effort is shown to move the levers of plant community composition by changing sites, species, and interactions that were set in motion by land uses past.

However, cities continue to be subject to frequent, intense, and long-lasting human-caused changes, at multiple scales, while forest recovery is slow in comparison. Ongoing management will be required where urban impacts exceed the pace of ecosystem recovery. The most straightforward and simple form of ecological restoration removes a single disturbance and allows time for ecosystem processes to restore function, but urban areas offer few such simple pathways. Instead, they offer opportunities to optimize potential for local species and communities to recover and continue to reassemble, adapt, and evolve (McDonald et al., 2016). Urban ecological restoration requires site-specific assessment of social and ecological context to select the most pragmatic approaches. This approach is consistent with current thinking in ecological restoration, which considers that a restored ecosystem may not necessarily recover its former state, since contemporary constraints and conditions, which in cities include both local and global climate change, may cause it to develop along an altered trajectory. Ecological restoration requires long-term commitment and effort (McDonald et al., 2016).

It is unrealistic to expect an urban habitat fragment to acquire in a few years ecological properties that accumulate over centuries of complex interactions. Decades are required for structural and reproductive maturation of canopy trees, while new species are continually introduced to urban areas (Kowarik, 2008) and invasive vines may disperse and grow many meters in length and height in a single season. Managers of urban forests should expect the arrival of new plants, animals and pests in the future. Adjacent parcels may contribute propagules of desired or undesired species, and these areas may not be under the jurisdiction of a given land management agency. Enhancing forest regeneration requires patience and institutional memory, both essential to learning from past management effort.

Despite these challenges, the material and personnel effort expended in the most frequently managed restored forests is less than in comparable-sized manicured park areas, often dominated by turf (Elmqvist et al., 2015). This should encourage forest restoration action in temperate-zone cities where forest is the dominant native vegetation. By anticipating patterns of future disturbance, more effective goals and strategies can be developed.

Forest patches in cities are shaped by legacies of past land use and current desires of nearby residents. Social-ecological systems research provides another lens helpful to management and planning for ecological restoration in urban forests. Analyses of environmental

Table 3
Treatment Type and Relative Frequency by Park.

	Access Control	Erosion Control	Herbicide	Manual/ Mechanical Removal	Planting	Watering	Total Treatment
Days % of Total Column % park %			105	58	84	21	272
			1.1	0.6	0.9	0.2	2.8
			12.9	2.2	4.1	7.6	
			39.2	21.6	31.3	7.8	
Days % of Total Column % park %	16	37	277	167	343	25	866
	0.2	0.4	2.9	1.7	3.6	0.3	9.0
	0.5	6.6	34.0	6.4	16.7	9.1	
	1.8	4.3	32.0	19.3	39.6	2.9	
Days % of Total Column % park %	3121	523	432	2370	1624	230	8463
	32.5	5.4	4.5	24.7	16.9	2.4	88.2
	99.5	93.4	53.1	91.3	79.2	83.3	
		36.9	6.2	5.1	28.0	19.2	2.7
Days % of Total		3137	560	814	2595	2051	276
		32.7	5.8	8.5	27.0	21.4	2.9

Frequency and relative proportions of treatment efforts, measured as number of days when restoration activity was recorded in a plot-containing management unit, over a 20-year period after restoration activities were initiated.

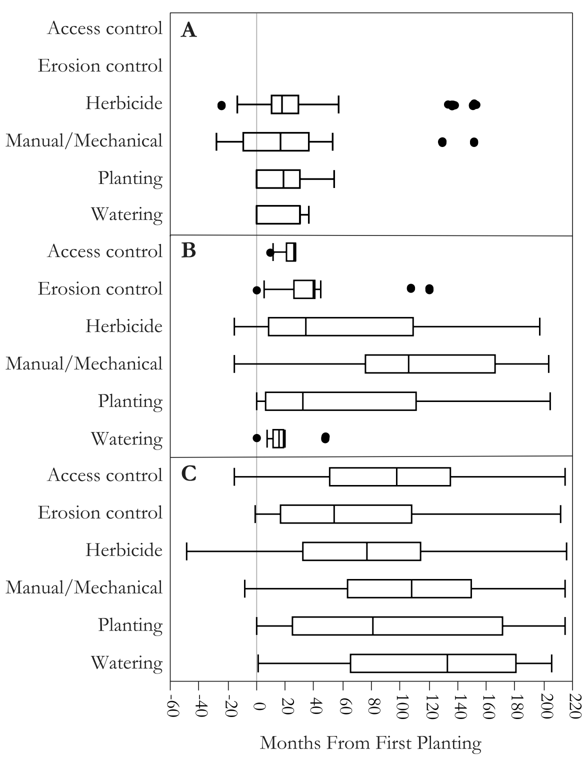

Fig. 6. Patterns of Treatment in Relation to First Planting Date. Urban parks under long-term ecological restoration differed in treatment timing. Total post-restoration treatment occurred in fewer, more sporadic episodes where least management was applied (A, Pelham Bay Park). In the most-managed park (C, Prospect Park), management units containing restoration plots were treated more frequently and consistently over ca. 20 y following initial planting, and a greater number of unique treatment interventions were applied. Intermediate total management and timing were observed in Inwood Park (B). (Boxes display median value and 25th to 75th quantiles; whiskers 1.5 x interquartile range.).

stewardship in U.S. cities indicate that networks of civic stewards who can play a role in the future of these forests are already present (Svendsen and Campbell, 2008), and an increasingly large body of work documents the benefits of nearby nature to urban communities. In addition to the ecological management procedures studied here, increasing engagement across communities and jurisdictional boundaries will improve the success of urban ecological restoration.

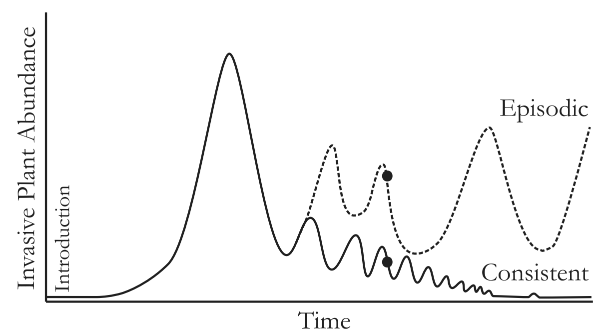

Fig. 7. Hypothetical response of invasive plant abundance to consistent versus episodic management intervention schemes. With episodic intervention, abundance of invasive plants at a given point in time (●) may be high despite similar effort expended due to increasing effort required to effect removal with plant establishment and reproduction over time. With consistent intervention, reinvasion is minimized, and populations are reduced over time. Note that this scenario holds other factors equal.

CRediT authorship contribution statement

Lea R. Johnson: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing - original draft, Writing - review & editing. **Steven N. Handel:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing - review & editing.

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