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FORUM ARTICLE

Challenges and future directions in urban afforestation

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Summary

1. Mature urban trees improve air quality, reduce storm water run-off and sequester carbon. Municipal agencies establish forests of native juvenile trees to enhance these and other ecosystem services to cities. Little data exist, however, regarding whether these trees will form mature, native forests.

2. We review urban forestry research that deals specifically with the growth, survival and recruitment of new native urban forests and use these data to identify knowledge gaps and propose research needed to create and maintain native urban forests.

3. Experimental urban forestry studies are few and most are of durations ≤5 years, shorter than the 10–25 year time frame required to understand forest stand dynamics. Studies capturing initial dynamics of urban afforestation (≤5 years) identify invasive species as the primary threat to native tree establishment. Data exploring longer-term dynamics are needed to evaluate whether early-stage afforestation dynamics can be used to infer the composition and function of mature urban forests.

4. *Synthesis and applications*. Urban afforestation approaches – from natural colonization to large-scale plantings – represent a trade-off in cost vs. efficacy for establishing native forests. A major cost-saving strategy would be to determine whether exotics and natives can co-exist and provide the intended ecosystem services.

Key-words: afforestation, green infrastructure, natural colonization, recruitment, restoration, urban forest, vegetation dynamics

Introduction

City agencies plant native forests to increase green space, reduce air pollutants, reduce storm water run-off, sequester carbon and increase native biodiversity (Pataki *et al.* 2011; Gaffin, Rosenzweig & Kong 2012). The ultimate aim of these afforestation efforts is to improve the environment of an increasingly urban human population. City planners and land managers choose native trees for urban afforestation because locally adapted species use available resources most efficiently and are considered more effective than exotic species at supporting native biodiversity of plants and animals (McKinney 2006; Burghardt, Tallamy & Shriver 2009; Ordonez & Duinker 2012). City agencies spend millions of public and private funds undertaking ambitious projects to re-green large tracts of urban and industrial land (Pincetl 2010; Pataki *et al.* 2011). These projects are being conducted across multiple continents, in cities such as Auckland, London, Los Angeles and New York. Programme objectives across the initiatives focus on the planting of native (as opposed to exotic) species, with the expectation that these plantings will grow into mature, diverse native forests (Sullivan *et al.* 2009; McPhearson *et al.* 2010; Clarkson, Bryan & Clarkson 2012; New York City Department of Parks & Recreation 2013). We ask whether this expectation is grounded in the available science on urban forest dynamics and suggest future research to improve the likelihood of project success.

The scale of native urban afforestation efforts vary widely, from planting as few as 150 native trees and shrubs to as many as 30 000 in a single forest stand (see Clarkson, Bryan & Clarkson 2012; City of London 2012). The MillionTreesNYC initiative, launched in 2007,

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allocated US$400 million over 10 years to the New York City Department of Parks and Recreation to plant 600 000 trees, which includes both street trees and approximately 800 ha of forest restoration (New York City Department of Parks & Recreation 2007). The goal of New York City's forest restoration programme includes the creation of diverse multilayered native forests to preserve wildlife habitat, increase biodiversity, improve air and water quality and mitigate climate change (New York City Department of Parks & Recreation 2013). Hamilton City in New Zealand, a city with a population 2·5% the size of New York City's, is undertaking a 60-ha native urban afforestation project, committing NZ$3.190 million (US$2.537 million) over 10 years (Hamilton City Council 2006). London, UK recently began work on the city's first

'climate change park' to provide increased capacity for flood storage and biodiversity enhancement to the urban landscape. The park's expected budget is £3.8 million (US $5.768 million) and will include river restoration, flood plain improvements and the creation of diversified woodland habitat (Everard, Shuker & Gurnell 2011). Much research documents the ecosystem services provided by urban trees (Brack 2002; Nowak, Crane & Dwyer 2002; McPherson *et al.* 2005; Davies *et al.* 2011), but it focuses on existing mature street and parkland trees. There is almost no data to support the expectation that planted native tree saplings will survive and reproduce to create closed-canopy urban forests that are capable of providing ecosystem services into the future.

We examine published, peer-reviewed literature that focuses on native urban afforestation methods ranging from natural colonization to large-scale tree plantings (we did not assess singular street tree planting methods). We review how these methods affect important stages in native tree demography: growth, survival and recruitment–the critical stage when seeds germinate and grow into seedlings (Grubb 1977; Eriksson & Ehrlen 1992; Clark, Macklin & Wood 1998; Myers & Harms 2009; Warren, Bahn & Bradford 2012). Using Thomson Reuters Web of Science and Google Scholar, we used combinations of keywords such as afforestation, dispersal, forest, invasive, native, natural colonization, restoration, species richness, succession, urban and woody species. We found only five controlled experimental studies exploring native urban afforestation (Table 1). These studies were focused on the establishment of woody species through either natural colonization (from seed bank and dispersal) or the planting of juvenile trees. There are a number of studies that explored vegetation establishment on urban sites through natural colonization (Prach & Pyšek 1994; Hodge & Harmer 1996; Millard 2000; Prach & Pysek 2001; Prach 2003), and studies that explored native woody recruitment in established urban forest patches or along urban to rural gradients (Burton, Samuelson & Pan 2005; Vidra, Shear & Wentworth 2006; Vidra, Shear & Stucky 2007; Pennington, Hansel & Gorchov 2010; Michalak 2011; Trammell & Carreiro 2011; Overdyck *et al.* 2013). These papers provide important insights into natural colonization in urban landscapes, and we cite them accordingly. We do not, however, include them in Table 1 as the focus of this paper is on establishment and recruitment of native trees in newly afforested sites, that is, the objective of urban afforestation initiatives.

Below, we show that current research reveals patterns for the initial years (1–5) of afforestation, but there is a paucity of data exploring longer-term dynamics that will help guide expectations about the ability of native trees to persist in urban forests. In the light of this absence of data on longer-term dynamics in establishing urban forests, we identify three key areas for research to address before we can evaluate if early-stage afforestation dynamics can be used to infer the composition and function of mature urban forests. We divide our review into three sections: succession, invasive species and local site conditions and follow each with the recommendations for future research.

Urban forest succession

CURRENT RESEARCH

Succession is regularly cited as the conceptual framework informing the dynamics of forest growth and regeneration (Pickett, Cadenasso & Meiners 2009). The study of succession identifies critical life stages of forest dynamics and the underlying mechanisms that shape these stages and hence forest composition (Bazzaz 1996; Walker & del Moral 2009). Current experimental research on urban afforestation covers short time frames (generally <5 years) in the context of forest development (Table 1). Following a simple model of succession, short-lived woody species with high growth rates and herbaceous perennials should dominate initially with slower growing woody species colonizing and establishing during later successional stages (Crawley 1997). In old-field succession, woody species richness and biomass increases with time, surpassing that for herbaceous species 20 years after agricultural abandonment (Myster 1993). Woody species may appear during early succession (years 1–10) but it may take several years of repeated colonization before they establish–usually about 20–25 years following abandonment (Pickett, Cadenasso & Bartha 2001). Similar patterns are observed on naturally colonized urban sites (Prach & Pyšek 1994; Millard 2000; Prach, Pysek & Bastl 2001; Overdyck & Clarkson 2012). For example, in one of the only long-term controlled afforestation experiments (>35 years), herbs dominated the early years on initially bare plots and woody species dominated from year 10 onwards. Some urban plots did not achieve woody dominance until year 25 (Bornkamm 2007). This delay in woody dominance is due to a number of interacting factors including soil conditions, climatic extremes

Table 1. Research studies specifically exploring native, urban afforestation through natural colonization and tree and shrub plantings. Natural colonization studies are either targeted experimental sites (Natural colonization plus intervention) or studies of land recolonized after abandonment (Natural colonization, no intervention). The type of study is either a natural experiment exploring native establishment and recruitment on afforested land or a controlled experiment with specific treatments related to site preparation, planting techniques and/or management activities. The location of the study, age of the afforested site(s), main findings for native establishment and recruitment, and any management interventions and results are also included

Study	Location of study	Afforestation strategy	Type of study	Age of afforested site(s)	Main findings for native tree establishment and recruitment	Management interventions and results
Overdyck & Clarkson (2012)	Urban forest site, Hamilton City, New Zealand; rural forested zones in Hakarimata Range Scenic Reserve, New Zealand	Plantings and natural colonization	Natural experiment	Up to 36 years	Urban planted sites had higher exotic species richness in both soil seed banks (*c.* 65% of all species) and seed rain (*c.* 60% of all species) than rural forested zones	No intervention
Bornkamm (2007)	Experimental garden, Berlin, Germany	Natural colonization Intervention	Controlled experiment	>35 years	Invasive *Solidago canadensis* occupied plots early on in succession (years 1–20) but declined as native woody tree species took over (after year 20)	Treatments: Tracked natural colonization on different soil mixes (texture and nutrient status) Results: Vegetation developed on all plots with sandier and lower nutrient soils developing woody cover faster than higher nutrient soils
Rebele & Lehmann (2002)	Landfill site, Berlin, Germany	Natural colonization Intervention	Controlled experiment	5 years	Invasives gained 45% of total cover on unmowed plots affecting habitat and species diversity; mowing suppressed invasives and allowed greater species richness to develop	Treatments: Mowed plots vs. unmowed plots Results: Mowing suppressed invasives
Robinson & Handel (1993)	Landfill site, New Jersey, USA	Plantings	Natural experiment	1 year	Planted native trees contributed 4% to overall recruitment to the site with the rest coming from adjacent seed sources; 18% of incoming vegetation was exotic	No intervention
Rawlinson *et al.* (2004)	Landfill sites, North West England	Plantings	Natural experiment	3 years	Tracked survival and growth of 21 pioneer and later successional tree species (14 native and seven exotic) on different landfill sites; native pioneers had the highest growth rates while native nonpioneer species had lowest mortality; overall, natives had less risk of mortality than exotics	No intervention
Sullivan *et al.* (2009)	Urban forest site, Auckland, New Zealand	Plantings	Controlled experiment	4 years	Exotics overwhelmed the afforestation plots with 3000 new recruits (21 species) vs. only *c.* 200 new native recruits (10 species)	Plot treatments: Species mix (bird dispersed vs. wind dispersed) and planting methods (high density + ripped soil vs. low density + mulch)
MacKay, Wehi & Clarkson 2011;	Urban forest site, Hamilton City, New Zealand	Plantings and natural colonization	Controlled experiment	Up to 30 years	Across all plots, there were 141 recorded live native taxa vs. 112 live exotic taxa; the ten most common species across all plots were native	Treatments: Age (0–10, 10–20, 20–30), maintenance (low vs. high), initial planting (diverse vs. depauperate), enrichment planting (yes or no) vs. revegetated reference sites Results: Enrichment plantings and high maintenance (i.e. evidence of pruning, thinning,

Table 1. (continued)

Study	Location of study	Afforestation strategy	Type of study	Age of afforested site(s)	Main findings for native tree establishment and recruitment	Management interventions and results
						spraying) had higher levels of native species across all age groups
Robinson & Handel (2000)	Landfill site, New Jersey, USA	Plantings	Controlled experiment	5 years	Planted trees and shrubs contributed minimally to recruitment, and the majority came from external native seed sources with five species (three of them native) representing 93% of overall recruitment	Plot treatments: Plant size (larger or smaller) and Nitrogen-fixers (with or without) vs. empty plots Results: Planted plots saw more recruits than empty plots, though plant size had minimal effect and authors concluded larger plants not worth the money; N-fixer treatments ineffective
Zipperer (2002)	Urban forest sites, Syracuse, NY, USA	Natural colonization No intervention	Natural experiment	30–60 years	Non-native trees compromised 48% of the total stem density for naturally colonized urban forest patches	No intervention
Robinson, Handel & Schmalhofer (1992)	Landfill site, New Jersey, USA	Plantings	Natural experiment	14 years	Greater than 95% of overall recruitment from 18 species from outside the planted site, with natives representing 74% of all recruiting species	No intervention
Ruiz-Jaen & Aide (2006)	Urban forest site, San Juan, Puerto Rico	Plantings	Natural experiment	4 years	The afforested site exhibited both native and exotic recruitment through animal and wind dispersal; of 20 species recruiting into afforested site, eight were exotic species	No intervention

and the available species pool. Bornkamm (2007) noted that the presence of a canopy of perennial herbaceous vegetation had the largest inhibitory effect on woody establishment.

Natural succession dynamics are often manipulated to achieve a desired species composition or structure in restoration projects (del Moral, Walker & Bakker 2007; Hobbs, Walker & Walker 2007). Rebele & Lehmann (2002) studied succession on a capped landfill in Berlin, Germany. They investigated whether vegetation establishment occurred without any management on unmowed plots (via spontaneous succession) and if targeted management through plot mowing created higher structural and species diversity (through directed succession). Unmowed plots had 80% vegetation cover in the fifth (and final) year of the study, but two invasive species comprised 45% of the cover. These two species, *Calamagrostis epigejos* and *Solidago canadensis*, are rhizomatous species that reproduce quickly and capture available sunlight to shade out short herbaceous species. Mowed plots had less overall cover (45%), but herbaceous species richness was higher (25 vs. 20 species), probably due to suppression of *C. epigejos* and *S. canadensis* through mowing. The seedlings of two tree species from adjacent habitats, *Salix rubens* and *Populus nigra*, together had 22·5% cover in unmowed plots at year 5 and were expected to dominate by year 10. Where nearby tree seed sources exist, vegetation establishment is possible without intervention. Management through mowing, however, may help promote on site diversity by keeping competitive exotics from out-competing native herbaceous species (Rebele & Lehmann 2002).

FUTURE DIRECTIONS

We found only five native afforestation experiments studying afforested sites older than 5 years (Table 1), and only one continuously monitored vegetation over the course of afforestation (years 1–35) to provide details about urban forest succession (Bornkamm 2007). Longer-term (10–25 years) studies are necessary to understand vegetation dynamics in urban forests, as work on old-field succession and in urban sites (Myster 1993; Prach & Pyšek 1994; Millard 2000; Pickett, Cadenasso & Bartha 2001; Prach, Pysek & Bastl 2001; Bornkamm 2007; Overdyck & Clarkson 2012) suggest that species composition and structure is likely to change after the initial (1–10) years of afforestation. We recognize that results from long-term studies, although critical for understanding urban forest dynamics, present difficulties for land managers who need to make management decisions now. In the shorter-term, studies on newly afforested sites that incorporate management techniques such as mowing or targeted invasive removal can provide information on whether these strategies initially promote desired species compositions and structures (for more on management interventions, see below). However, whether the desired species compositions will be maintained through forest maturation is an open question. Furthermore, studies incorporating management techniques such as mowing tend to operate at small plot level scales (e.g. 2 m × 2 m) (see Rebele & Lehmann 2002), which are difficult to extrapolate to a scale relevant to land managers who are often maintaining several hectares of urban forest. Research incorporating management strategies at relevant scales will help clarify the best strategies for accomplishing the goal of creating diverse, native, multilayered, urban forests.

Invasive species

CURRENT RESEARCH

Urban areas are especially susceptible to invasion by exotic species (Ehrenfeld 1997; Hobbs *et al.* 2006; McKinney 2006; Duguay, Eigenbrod & Fahrig 2007; Williams *et al.* 2009; Overdyck & Clarkson 2012). Invading exotic species may put enormous pressure on urban forests and eventually replace the intended native species composition (Vidra, Shear & Wentworth 2006; Vidra, Shear & Stucky 2007). Planting juvenile trees may bypass earlier stages of succession in order to achieve a desired species composition (Robinson & Handel 1993; Rawlinson *et al.* 2004; Sullivan *et al.* 2009). Researchers in Auckland, New Zealand (see Sullivan *et al.* 2009) tested how various planting and site preparation methods affected planted native tree growth and exotic recruitment. Treatments included dense plantings into ripped soil and sparse plantings in mulched soils. All plots were planted with native pioneer species mixtures. Recruitment into the plots was tracked for 4 years. The sparse plots had the fastest per capita growth of planted trees, but they also had a threefold increase in non-native woody recruitment. All plots, no matter the strategy used, saw a huge influx of non-native species. Twenty-one non-native woody species dispersed into the plots from adjacent seed sources resulting in more than 3000 > 50-cm tall recruits at the end of the experiment. By contrast, there were only about 200 native woody seedlings (10 species) of any height that recruited into the site. Sullivan *et al.* (2009) advocate removing any exotic seed sources within 100 m of planned native afforestation areas, and ensuring there is an abundance of nearby native seed sources through the creation of native buffer areas surrounding urban afforestation sites. The trade-off is the cost of effective removal and extraction of potential exotic seed sources.

FUTURE DIRECTIONS

Potential threats from exotic species must be examined before initiating an urban afforestation programme to assess their threat and the cost of eradication. Rather than fight or ignore invasive species, a third option is to investigate whether native and non-native species can provide ecosystem services side by side (Carroll 2011; Davis *et al.* 2011). As novel assemblages of natives and exotics increase within urban landscapes (Hobbs, Higgs & Harris 2009; Kowarik 2011), ecologists increasingly recognize that mixed communities are not necessarily a threat to native flora persistence (Norton 2009). We must test whether a forest composed wholly of natives is necessary to accomplish the multiple objectives (e.g. flood prevention, native biodiversity and carbon capture) of urban afforestation.

We need more studies comparing land management with exotic species removed vs. those allowing exotic species invasion. Such studies can identify species that inhibit or facilitate native species growth and recruitment. Experiments can then be used to test such observations to evaluate whether intensive management of all invasives is required to achieve the desired forest composition of natives or if less-intensive management of specific invasives is equally effective for establishing native woody species. We found only two studies that explored different maintenance regimes and their impacts on native biodiversity and recruitment (Rebele & Lehmann 2002; MacKay, Wehi & Clarkson 2011). More of these studies will help elucidate the cost-effectiveness of different management techniques. Exploring these strategies over the long-term may reveal an initial dominance by invasives (years 1–10) that levels off with canopy closure as shade-intolerant exotics are over-topped (Bornkamm 2007; Norton 2009; Overdyck & Clarkson 2012).

Local site conditions

CURRENT RESEARCH

Recruitment is a key process in succession, and a species' ability to successfully recruit depends on a host of factors that arise from local site conditions. These factors include competition from exotics and other natives, abiotic environmental filters such as soil moisture and pH, and management activities, all of which have large effects on plant community structure (Eriksson & Ehrlen 1992; Myers & Harms 2009; Williams *et al.* 2009). Robinson & Handel (2000) worked on a capped landfill in New Jersey, USA. They planted clusters of native, bird-dispersed tree species with high reproductive output and clonal growth, including black locust *Robinia pseudoacacia* and black cherry *Prunus serotina*. They expected these traits to accelerate woodland establishment through reproduction from planted species and by attracting more bird dispersers into the plots. Treatments included planting 21 native woody species (six trees and 15 shrubs) and unplanted plots. The plantings were established in a factorial design, which included plant size (larger and smaller) and nitrogen fixation (with our without N-fixers). Plots planted with trees did attract more woody recruits (empty plots had three to four times less woody recruitment than planted plots), but the majority of recruits were from external sources. After 5 years of study, reproduction and recruitment from planted species were minimal with only six of the twenty-one planted species contributing recruits. Diversity was also low: five species (only one of them planted) represented 93% of nonclonal recruitment (clonal recruitment accounted for 11% of overall recruitment). Three of these species were from nearby native seed sources. These results demonstrate the difficulty of achieving a diverse native forest if planted natives do not contribute to recruitment, and local seed source diversity is low. Robinson & Handel (2000) concluded that the cost associated with planting larger nursery trees was not worth the minimal benefit they provided to recruitment, as new recruits came from adjacent habitats. The failure of planted species to recruit and spread throughout the site points to the issue that although native species are likely to be locally adapted to a region, they are often not matched to local site conditions (Robinson & Handel 2000). Adult growth is not necessarily indicative of seedling niche requirements. For example, many urban soils have neutral to weakly basic soil pH due to concrete rubble chemistry, but many native species populations in temperate systems are associated with acidic soils (e.g. black cherry, red oak).

FUTURE DIRECTIONS

Research exists on native recruitment in existing and establishing native forests, but the mechanisms underlying these recruitment patterns have received little attention (Lehvavirta & Rita 2002; Zipperer 2002). Most plant mortality occurs during early life stages (Grubb 1977; Clark, Macklin & Wood 1998; Warren & Bradford 2011) and native seedling abundance in urban forests is lower when compared to rural forests (Burton, Samuelson & Pan 2005; Pennington, Hansel & Gorchov 2010; Michalak 2011; Trammell & Carreiro 2011; Overdyck & Clarkson 2012). Determining the causes underlying this difference within the urban landscape is necessary for developing models of urban afforestation (Hauru, Niemi & Lehvavirta 2012). For example, we should ask whether dispersal limitation, establishment limitation, seed predation or competition (with native and exotic herb and tree species) might be the overwhelming driver of recruitment dynamics of natives in urban forests. Concomitantly, we must determine the environmental requirements–such as light, temperature and soil pH–that favour or inhibit native recruitment. Studies examining these mechanisms can help shape management interventions. For instance, an invasive removal experiment helped target especially aggressive invasives threatening native regeneration in existing urban forest patches in North Carolina, USA (Vidra, Shear & Stucky 2007). Furthering our understanding of urban forest recruitment, especially the conditions that determine successful seed germination and survival, is essential for developing effective strategies for maintaining native urban forests.

CONCLUSION

A city forest may shift from planted to unintended tree species for two reasons: (1) incoming vegetation is better adapted to the location than planted individuals; and/or (2) planted trees fail to recruit. The research presented above points out key ecological issues to consider when attempting native afforestation in urban areas. Local seed sources play a critical role in urban forests, and the results summarized above show that local recruitment impacts the ultimate forest species composition and diversity. Natural colonization of native species is possible with nearby native seed sources and if the site is suitable for native establishment (Robinson, Handel & Schmalhofer 1992; Robinson & Handel 1993; Prach 2003; Ruiz-Jaen & Aide 2006; Vidra, Shear & Stucky 2007). Creating suitable habitat for desired local native trees may require site management in the form of weed suppression, thinning or supplementary plantings (Robinson & Handel 2000; Overdyck & Clarkson 2012; Overdyck *et al.* 2013). Planting trees bypasses the high-mortality seedling recruitment stage to achieve a desired species composition. A species' adult niche, however, can be completely different from its recruitment niche (Pulliam 2000; Bradford & Warren 2012). A planted species may survive through sapling and adult stages, but its seedlings may not survive at the same site. Without successful recruitment, planted native forests will be limited to a single generation.

Researchers, city agencies and land managers involved in urban afforestation should consider the following four points:

1. Planners and managers are planting native trees to create urban forests. Five controlled experimental studies test different management interventions and/or planting strategies for native urban afforestation (Table 1) and find that no managements meet all the project objectives. More experimental studies are needed that not only test the ability of different management strategies to achieve the various and sometimes competing objectives of urban afforestation projects but also the cost-effectiveness of these strategies.

2. Studies of durations >10 years and up to 25 years are needed to ascertain whether plantings and initial successional dynamics (years 1–10) can be used to infer the structure and composition of a mature urban forest. Only five published studies examine afforested sites older than 5 years (Table 1). Woody establishment and dominance in old-field succession can take up to 20 years.

3. Natural colonization of natives and/or exotics will happen as long as there are adjacent seed sources to supply propagules. Published studies (Table 1) suggest that the desired species composition of urban forests established via natural colonization will only be achieved with interventions such as strategic plantings of locally adapted species, knowledge and control of local seed sources and suppression of exotics through removal, herbicides or mowing.

4. A key objective of tree planting initiatives is to maintain or increase native biodiversity. This objective needs to be tempered by the knowledge that exotics are likely to be co-dominant in the mix of urban forest species. Research is required to determine if exotics and natives can co-exist and, if so, still promote native biodiversity and meet the other objectives of urban afforestation initiatives.

Urban populations continue to grow, increasing the need for and pressures on green space. These spaces are expected to serve as multifunctional landscapes that improve air quality, mitigate storm water run-off, capture carbon, enhance native biodiversity and promote recreation. Cities have limited land available for urban forests so afforestation initiatives are under intense pressure to succeed. To increase the likelihood they will succeed, applied urban afforestation research is required to advance our understanding of the ecological dynamics controlling urban forest establishment and long-term resilience.

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