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Testing tomorrow's oak management today: Urban silviculture networks advancing regional management

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ABSTRACT

Forests can occur across a continuum of urban-rural land-use contexts. Forests in cities (also referred to as forest patches, urban woodlots, urban forest fragments, or urban forested natural areas) are ecologically akin to wildland forests, but located in dense, urban landscapes. Here, we examine the opportunities and constraints for managing oak forests in cities to demonstrate the value of leveraging urban forests to develop and test adaptive management strategies for oak forests. Oaks dominate eastern United States forest types but face widespread regeneration failure across the urban-rural continuum due to fire suppression, deer browse, and invasive species competition. Urban forest managers routinely employ artificial regeneration methods, primarily direct planting, whereas natural regeneration strategies are more commonplace in non-urban forest management contexts. This reliance positions urban practitioners as experts in pre-planting site preparation, post-planting care, and adaptive strategies under challenging establishment conditions. We highlight case studies from the Urban Silviculture Network, formed in 2020, that demonstrate innovative approaches to oak forest management in cities. Gap-based methods in urban settings include the Haddington Woods Density Experiment in Philadelphia, which tests planting densities and recruitment prescriptions, and the Pennypack Experimental Forest, which leverages naturally occurring gaps to overcome social constraints on cutting. Recruitment treatments in closed-canopy forests, exemplified by work in Hartford's Olmsted-designed Keney Park, enable proactive oak establishment in anticipation of disturbance events like Beech Leaf Disease. The ADAPT-OAK project tests climate adaptation through forestry assisted migration in a reciprocal transplant common garden experiment spanning four northeastern cities, evaluating the provenance performance under elevated urban temperatures that preview future rural conditions. Urban forests serve as controlled, low-risk testing grounds for tree improvement programs and climate adaptation strategies. Knowledge transfer from urban silviculture networks can inform rural management practices, bridging innovative urban approaches with traditional forestry to enhance oak forest resilience across landscapes facing rapid environmental change.

1. Introduction

The northeast U.S. and the Great Lakes regions contain the most densely forested areas in the United States (~70 million ha of forest land cover). However, urbanization and fragmentation also characterize this region. Across the Northeast "megalopolis", which extends from Washington D.C. to Boston, most forests are small, isolated patches embedded within urban and suburban areas (D'Amico unpublished data). The Northeast is the most densely populated region in the U.S. and contains the largest proportion of land area in wildland-urban interface (WUI) (Sonti et al., In press). Seventy-seven percent of forests in the Northeast are privately owned, with most of this forested land held by non-corporate, small landowners (USDA Forest Service, 2020). Given this complex mosaic of land use and social-ecological context,

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researchers and managers can best understand and manage these forests across a continuum of urbanization—from rural and WUI areas to suburban landscapes and forests within cities (Fig. 1).

Forests in cities (also referred to as forest patches, urban woodlots, urban forest fragments or urban forested natural areas) are ecologically akin to wildland forests. These forests are defined as areas dominated by woody vegetation with natural woody plant regeneration and experience limited management (Piana et al., 2021c). Forests in cities are common and abundant, however, researchers, managers, and the public, frequently overlook them. In the US, more than 0.7 million ha of forests exist within urban landscapes, and natural areas comprise more than 84% of city parkland (Harnik et al., 2017). In the northeast U.S., forests in cities are an important part of the urban fabric. For example, in Baltimore, MD, Philadelphia, PA, and New York, NY there are more than 1700 ha, 2200 ha, 3000 ha of forest cover (Sonti et al., 2025). These forests in cities may occur across a mosaic of ownerships and land use histories, with implications for their ecological structure and conservation status (Pregitzer and Bradford, 2023; Sonti et al., 2024, 2025).

Multiple, co-occurring anthropogenic impacts affect forests in cities, including the urban heat island effect, atmospheric nitrogen deposition, and elevated atmospheric CO_2 concentrations (Oke, 1982; Lovett et al., 2000; Idso et al., 2001, 2002). While similar factors occur in other environments, urban areas exacerbate their impacts and may provide a glimpse into future rural forest conditions. Urban forests are often the epicenter of new invasions by plants, pests, and pathogens. These issues highlight the need for adaptive management strategies and long-term planning, giving rise to urban silvicultural practices. Urban silviculture has been increasingly recognized and supported through emergent networks and long-term research (Piana et al., 2021c) with relevance to the management of forests beyond cities.

Forest ecologists and silviculturists typically derive their practices from rural systems. However, as global change factors affect all forests, urban forest management practices can inform rural management practices by implementing novel and adaptive strategies to maintain forest sustainability (Romanelli et al., 2024). This article highlights current science and practices for oak forest management in cities and examines how these forests may provide fertile testing grounds for applied ecological study and adaptive strategies that address multiple current and projected challenges for sustaining oak forests. We review the foundations of sustaining oak in the context of forests in cities and the promise and constraints of current best practices in oak forest management. We also introduce the Urban Silviculture Network (USN), an emergent community of practitioners and scientists, piloting applied research in urban oak forests. Practitioners can combine the research and adaptive practices occurring in cities with emergent applied research in rural oak forests. For example, the DREAM project, led by USDA Forest Service scientists, evaluates oak regeneration methods and climate adaptation in northern forests (Royo et al., 2023). Through urban-based work, we see an opportunity for knowledge sharing between managers and scientists across the urban-rural continuum.

2. Oak forest ecology and management

Oaks dominate eastern United States forest types and provide important ecological, social, and economic value. Regionally, more than 76 million ha of oak forest exist, with oaks representing ~45% of growing stock volume and 11% of all living trees (Miles 2017). Oak forests maintain their importance across the urban-rural continuum. In New York City for example, oak forest community types represent more than 25% of the 4266 ha of forested natural areas (Pregitzer et al., 2019). Oak forests in cities and beyond provide vital ecosystem services, especially those related to biodiversity as they function as foundational species and supply food for higher trophic levels (Hansen, 2000; Tallamy and Shropshire, 2009). Thus, conserving and managing oak forests in the eastern U.S. is crucial for maintaining forest resilience and biodiversity across the urban-rural continuum.

Although oaks dominate mature forest canopies, there is also widespread failure of natural oak regeneration in the eastern U.S. and across the urban-rural continuum (Dey, 2002; Götmark et al., 2005; Johnson et al., 2019). These trends intensify in forests within cities, for example, in oak-dominant stands, oak seedlings and advance regeneration are limited (e.g., Pregitzer et al., 2019; Piana et al., 2021a). Advance regeneration metrics are often unavailable to urban forest managers; however, the few existing studies suggest inadequate advance regeneration of all native tree species, let alone oaks (e.g., Piana et al., 2021a). Inventories of forests in cities will benefit from recording height data of seedling and sapling stages to calculate stocking indices and set targets (Piana et al., 2021c). Furthermore, there is a need to calculate stocking

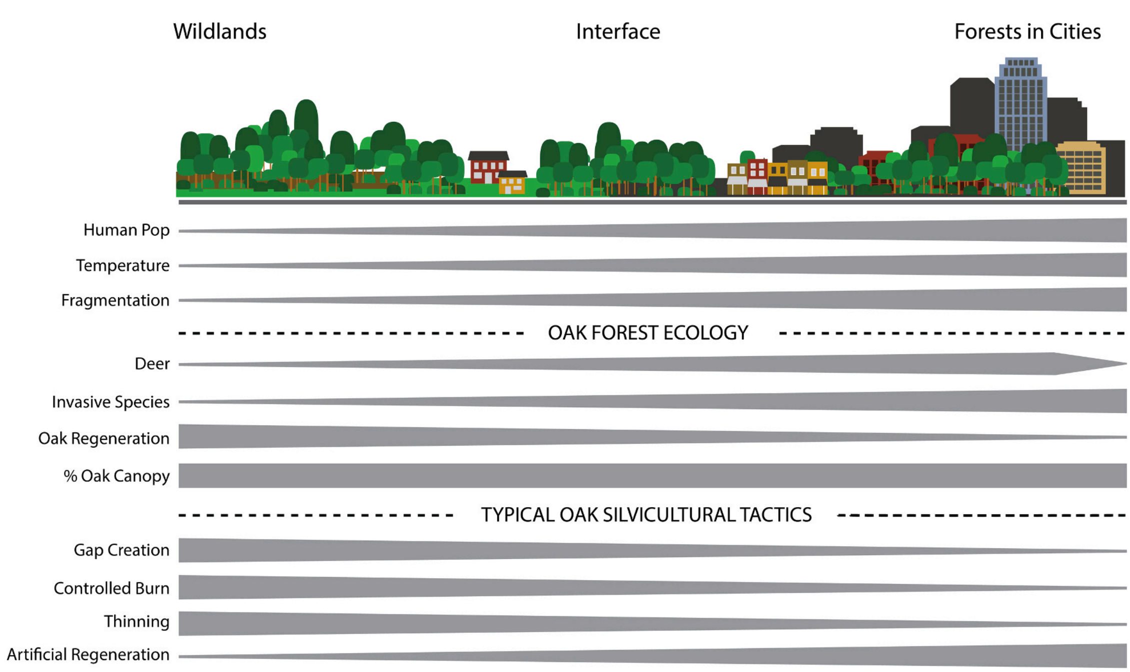

Fig. 1. The social and ecological context, as well as the dominant management of oak forests, varies across the urban-rural forest continuum.

indices by species to select recruitment targets (e.g., Dey et al., 2016).

Multiple factors contribute to the observed decline in oak regeneration and recruitment in eastern US forests (Dey, 2014). Fire suppression has limited regeneration and release events in oak forests by controlling natural disturbance regimes (Alexander et al., 2021). Additionally, increasing white tailed deer populations have increased browse pressure on native trees, including oak (McWilliams et al., 2018; Kelly, 2019). Consequently, oaks remain limited in the understory while more shade tolerant species, such as maple, dominate advanced recruitment stages and begin to enter the forest canopy. These conditions collectively represent what scientists call the mesophication of eastern forests and transition of oak forests to alternate community states (Nowacki and Abrams, 2008). Arrested oak succession and transitions to alternative forest types require novel management approaches to maintain oak dominant stands across the urban-rural continuum (Fig. 2).

To sustain and recover oak forests, managers can implement proactive forest management approaches (Dey, 2014). Ecological forest management builds on a fundamental understanding of species recruitment and regeneration, the two processes that direct stand development (Oliver and Larson, 1996). Regeneration is the establishment of new seedlings in the understory. Recruitment advances seedlings and saplings to more mature forest development stages. Sustaining oak forests involves managing across these stages and processes. Oaks are relatively shade-intolerant, typically demonstrate slow early aboveground growth, and commonly occur on upland sites ranging from mesic to xeric conditions (Lorimer, 1993; Abrams, 1996; Dey, 2014). Generally, oak species depend on disturbance events, such as wind and fire, that increase light availability (McEwan et al., 2011, 2014). Oaks demonstrate strong ability to respond to release as saplings, through stump sprouting, and via mass seed production (Dey, 2014).

Fundamental management strategies that support oak forest communities mimic natural disturbances to create favorable conditions (see Dey, 2014 and Johnson et al., 2019 for review). Regeneration treatments employ gap-based methods, such as shelterwood, group selection, and clearcuts with group retention, to mimic natural disturbances and facilitate seedling regeneration (e.g., Iverson et al., 2008; Hackworth et al., 2020). Recruitment, or intermediate, treatments facilitate advancement of oak seedling and saplings into the canopy and include prescribed burns, thinning, browse protection, and occasionally artificial regeneration (e.g., Albrecht and McCarthy, 2006; Ward, 2009; Iverson et al., 2017). These tactics may be more necessary on richer sites, where competition from faster growing and shade-tolerant tree species can inhibit oak recruitment (Dey, 2014).

In addition to these ecological constraints for oak regeneration and recruitment, there are multiple emergent issues that threaten oak forest systems and management, as well as gap-based silviculture more broadly (Kern et al., 2017; Dey, 2014). Invasive species, including diseases, pathogens, insects, pests, and plants, will likely exacerbate the oak regeneration problem. Indeed, gap-based silviculture practices may need to adapt to global change factors. For example, Kern et al. (2017) emphasize the potential need for greater focus on direct planting to supplement natural regeneration, as well as proactive management of invasive plants during seedling and sapling advancement stages. Social factors may further complicate the advancement of sustainable oak forest management strategies. These management strategies require long-term commitment to management practices and may not survive land transfers in private forests. In the eastern U.S., private owners hold 31% percent of the forest land in parcels smaller than 20 ha (Butler and Leatherberry, 2004). Coordination and sustained forest management practices present significant barriers to managing oak, especially where ownership changes occur across private forests.

In cities, forest managers have been addressing many of these emergent impacts, from invasive species to limited natural regeneration to complex stakeholder groups for decades (Wienke et al., 2022). With a greater abundance of invasive plants and frequent introduction of new invasive species, urban forest managers possess decades of experience directly managing these stressors in oak systems. Conversely, urban forest managers often face constraints in their silvicultural practices, especially those involving gap creation or thinning, due to limited formal training in traditional management practices and to social pressure and policies that restrict tree removal and prescribed burning. Furthermore, cities lack systematic research and management frameworks through which practitioners can track and share best practices between urban areas or across the urban-rural continuum (Piana et al., 2021c). By applying models established in rural silviculture and our national forest system, our pilot studies may begin to support best practices and advance long-term forest management studies in cities, with relevance beyond urban boundaries.

3. Co-producing evidence based urban-adapted oak silviculture

The Urban Silviculture Network (USN) was formed in 2020 following

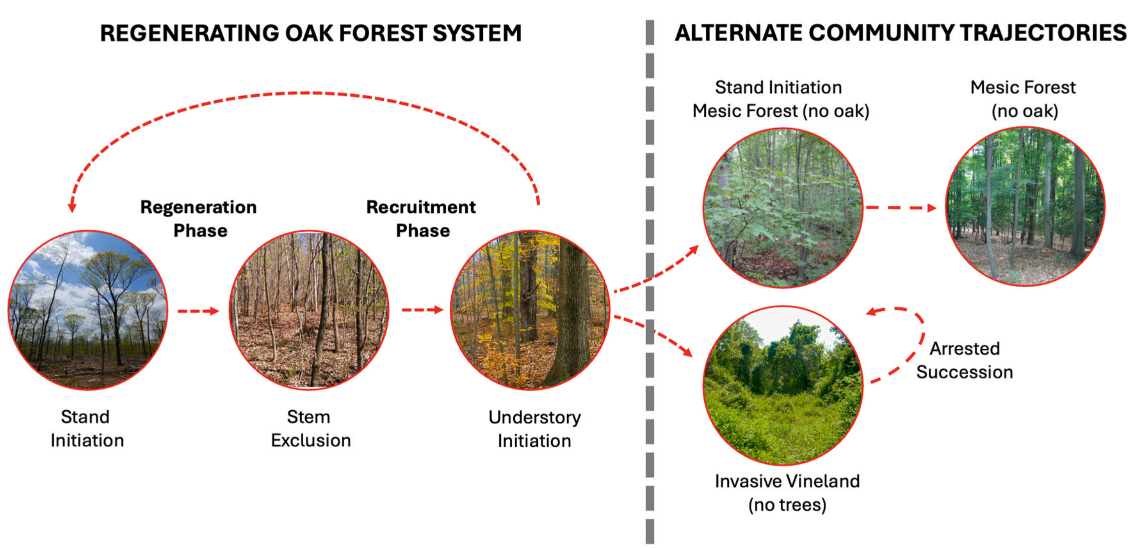

Fig. 2. The regeneration and recruitment phases of oak forests are critical for forest management. In the eastern U.S., oak forests are transitioning to alternate communities due to limitations in both advanced recruitment and constraints on natural disturbance regimes that facilitate oak regeneration. Whereas much of historic oak forest undergoes mesophication and a transition to shade tolerant forest, such as maple-beech, invasive plants may arrest succession and limit the establishment of tree species. This is especially true in forests in cities.

a workshop focused on urban climate vulnerability and adaptation for forests in the northeast U.S. The workshop built upon forest vulnerability and adaptation assessment methods that the Northern Institute of Applied Climate Science carried out in the Adaptive Silviculture for Climate Change (ASCC) program established for non-urban forests. Organizers modified these methods to include urban impacts on forest ecology and management. During the workshop, practitioners and scientists convened to share current research on climate impacts and vulnerability for forests in the region, best management practices for sustaining native tree species, and current practices in urban forest management. The USN workshop created comprehensive vulnerability and adaptation assessments for 8 cities in the region and produced a conceptual outline of management priorities and questions to test in urban forests (Piana et al., 2021b).

Since 2020, the Network has expanded across the U.S. and is working to expand internationally to Europe. Network members have worked together to establish local and regionally replicated studies on oak forest ecology and management strategies, developing an urban silviculture toolbox for oak forest management. The USN has focused on oak forests given their prevalence in the urban northeast US and relevance to one of the most densely urban areas in the country. In the following subsections, we introduce case studies from this network and its member organizations that highlight how traditional and adaptive processes have been integrated and deployed in these collaborative research projects to advance oak silvicultural practices.

3.1. Gap based methods in cities

Gap-based methods form a pillar of oak silviculture and support the regeneration phase of oak forests (Dey, 2014). However, artificial regeneration (i.e., planting) may be necessary when stocking indices and advanced regeneration are low or when site conditions limit oak seedling establishment (Vickers et al., 2023, Dey, 2014). In cities, oak regeneration may fall below rural forest levels, due to greater abundance of and competition with invasive plants, as well as increased seed predation and browse pressure from deer and small mammals. For example, urban-rural comparisons of oak forests have shown that although seed production remains comparable, site-limiting factors hinder early oak establishment in urban areas (Piana et al., 2021a; Pregitzer et al., 2019; McDonnell and Pickett 1990).

As a result of these conditions, direct planting often becomes the preferred operation in urban forests, and pre- and post-planting strategies to support these plantings or natural regeneration frequently prove necessary. The Haddington Woods Density Experiment (Fig. 3) is located in a 24-haupland oak-tulip and oak-hickory forest in Philadelphia, PA. In 2014, managers clear cut a 1.5 ha area of standing dead trees that had succumbed to Emerald Ash Borer (EAB). The site had dense invasive plant cover, and the goal was to establish an oak-hickory community. The city installed a deer exclosure around the forest and prescribed an artificial regeneration strategy due to the threat of rapid invasion by vines (e.g., mile a minute, bittersweet) and undesirable tree species (e.g., Ailanthus altissima, Robinia pseudoacacia) and minimal advanced regeneration. The site design included four planting densities: high density (2 m spacing), medium density (3 m spacing), low density (4.5 m spacing), and a natural regeneration control where no planting occurred. Each treatment plot is 0.4 ha (1/10 acre), replicated four times and planted with the standard upland forest restoration palette used by Philadelphia Parks and Recreation, including *Quercus rubra*, *Q. alba*, *Carya tomentosa*, *C. glabra*, *Cercis occidentalis*, *Diospyros virginiana*, *Tilia cordata*, and *Nyssa sylvatica*. Planting stock was 1–2-gallon potted seedlings (n = total seedlings planted). After 10 years, managers developed and implemented a recruitment prescription in the high-density plots based on established stocking indices and canopy closure. Stocking indices and basal area matched expectations from rural systems; however, invasion intensity was higher and tree health was more vulnerable.

Legal constraints and public perceptions associated with cutting are fundamental barriers to gap-based methods in cities. Forests in cities often involve multiple stakeholders and exist in the public realm. Consequently, social perceptions of forest management, especially cutting and gap creation, may not gain ready acceptance. Indeed, Fredrick Law Olmsted, the famous landscape architect, noted this conflict between forest management needs and public perception in an essay describing public perceptions to the use of the axe in "public plantations". Olmsted laments the inability to enact prescribed thinning and management post-planting in large forest parks (including Central Park in NYC) due to public opposition (Olmsted and Harrison, 1889). Social constraints on forest management strategies may extend beyond perceptions and face legal restrictions through policy, such as ordinances on tree removal.

Without changing these societal constraints, one strategy may involve leveraging naturally occurring gaps. Following this logic, park managers in Philadelphia have established the Pennypack Experimental Forest (Fig. 4). The project operates within a 10-ha oak-tulip forest located in a 650-ha park consisting of forest, wetlands, and meadows. Managers targeted the site as an example of "good woods", featuring a native dominant overstory and midstory, and fenced it in 2014 to exclude deer. The site contained minimal advanced regeneration and a dense spice bush thicket in the understory that limited development of oak and other tree species. Pre-planting treatments included using a forestry mower to remove all vegetation from naturally occurring gaps throughout the stand. These gaps varied in size, from single tree to small tree groups (0.016 – 0.214 ha). Following mowing, the sites underwent one of three pre-planting treatments: synthetic herbicide, organic

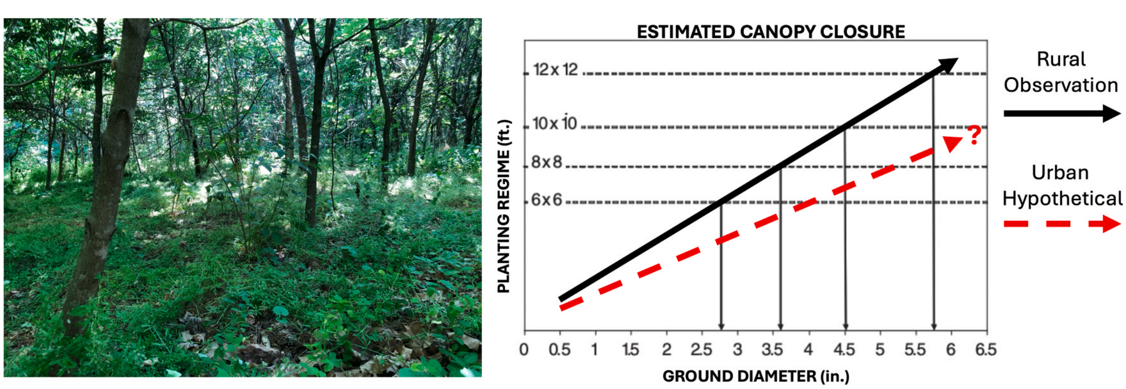

Fig. 3. How thick should we plant, how quick should we thin oak forests? A density experiment in Philadelphia, PA compares initial planting densities (2 ×2 m, 3 ×3 m, 4.5 ×4.5 m) in 0.04 ha plots to determine rates of canopy closure and optimal thinning regimes (left). Such stocking indices are common in rural forestry, but not in urban forests. Oak forests in cities may need to be planted thicker than non-urban oak forests to minimize invasive plant establishment.

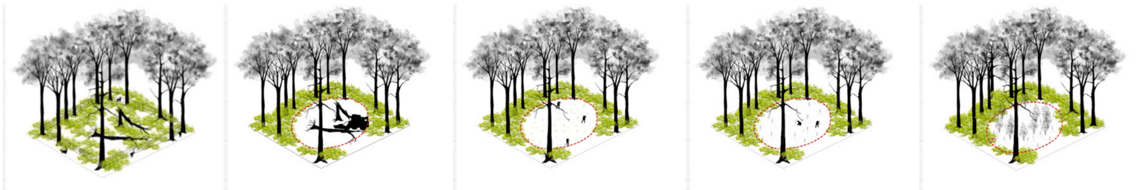

Fig. 4. How can we improve artificial regeneration practices for oak forests? Pre- and post-planting treatments may be applied to naturally forming canopy gaps in mature forests to establish the regeneration phase of oak forest. In Philadelphia, the USN project team is testing the viability of forestry mowing and invasive species control using mechanical removal, synthetic and organic herbicide, and nurse tree plantings to facilitate oak establishment in 36 canopy gap plots spanning 0.016–0.214 ha. Pre-planting treatment occurs once each growing season, and invasive plant cover is monitored in early and late summer. Tree plantings are monitored for survival, caliper, height, and tree health (defoliation, leaf discoloration, fine-twig dieback, and herbivory) Image credit (Z. Kikon).

herbicide, and mechanical removal of invasive plants. These treatments were applied across 36 plots for one growing season prior to planting in fall 2023. Understory plant species abundance was evaluated twice each growing season before, during, and after the treatments were applied to test the effectiveness of the treatments on invasive plants (Fuentes-Gigliotti et al., 2025). The planting design tested two strategies: 1) tree and shrub plantings, and 2) tree, shrub, and nurse tree plantings. The nurse tree planting used early-successional species to quickly establish canopy closure and limit the establishment of invasive plants. Planting density for trees was 12 ft on center (~120 trees ha), following standard contracted restoration practices. The early-successional trees were interplanted in nurse tree plots, increasing tree densities to 6 ft on center. Managers can then thin these trees following oak establishment. In each planting treatment, three post-planting treatments were applied: synthetic and organic herbicide, mechanical plant removal, and control. Invasive plant removal occurred once during each growing season following standard restoration practices in the city. Tree survival, caliper, height, and a tree health index, which includes metrics of defoliation, leaf discoloration, fine twig dieback, and herbivory (see Pontius and Hallett 2014), are measured at the end of each growing season.

Perspectives on urban oak regeneration methods:

- *Direct planting and intensive management represent standard practices in cities. Formal study of these practices will equip managers outside of cities with proven best management practices developed under challenging conditions.*
- *Urban forests provide opportunities to test diverse artificial regeneration strategies and methods, including broadcast seeding, tree stock size variations, and planting densities, as well as comprehensive pre- and post-planting management protocols.*
- *Cities offer unique settings to integrate naturally occurring gaps with gap creation methods. For example, an urban femelschlag approach could focus gap expansion around areas of natural canopy tree loss, providing socially acceptable alternatives to traditional cutting practices.*
- *Urban settings enable testing of rural stocking indices under different environmental pressures and management constraints, validating their applicability across the urban-rural continuum.*
- *Cities provide laboratories for assessing differential vulnerabilities to invasive species and developing targeted management responses that may inform rural practices.*
- *Urban forests allow evaluation of natural regeneration capacity under multiple stressors, helping identify threshold conditions where artificial regeneration becomes necessary.*
- *Urban environments offer opportunities to introduce and refine thinning regimes in settings where cutting traditionally faces social constraints, developing communication and implementation strategies transferable to sensitive rural contexts.*
- *Urban forests can provide a platform for engaging and educating the public in ecological forest management integrating the skills of other urban disciplines, including planning, design, and community development.*

3.2. Recruitment treatments in closed canopy forests in cities

Research demonstrates that oak recruitment is higher when oak is present as advanced reproduction prior to disturbance and that limited advanced recruitment of oak poses the dominant threat to oak forest health and sustainability. Consequently, advanced recruitment of oak may prove just as important and can be approached as a “co-morbidity” when considering the risk and management potential for upland oak forests in the eastern U.S. (Vickers et al., 2023). In areas with limited oak advance regeneration, planting may be required to supplement the recruitment phase before stand initiating disturbances occur (Dey, 2008, 2012). This may be especially true in cities where prolonged browse history and constrained natural disturbance regimes (i.e., fire) exist as well as greater immediate competition following natural or artificial canopy gap creation events.

Proactively planting or supporting oak recruitment in anticipation of gap events is one silvicultural strategy to address the recruitment limitation of oak forests in cities, as well as the social and political barriers, to gap-based prescriptions. Managers can assess mature canopy for health and threat to different disturbances, including natural senescence, windthrow, or susceptibility to emerging pests and pathogens. One example of this work occurs in Keney Park in Hartford, CT, a 280-ha forest park designed by Fredrick Law Olmsted, which includes a 53-ha beech-maple stand that risks losing canopy-dominant beech trees due to the emergent Beech Leaf Disease (BLD). Several oak species are present in the canopy and the imminent disturbance to canopy trees from BLD presents an opportunity to re-establish oak species in the forest. In 2025, researchers installed a study that includes two regeneration treatments (direct planting and natural regeneration) with one of two initial treatments (thinning of understory plants and no thinning). Trees planted were 2-y white oak seedlings, planted 8 ft on center (n = 72 per plot). Additionally, plots were located in existing gaps and imminent gaps, where beech dominates the canopy. Finally, all planted plots and half of the unplanted plots had a temporary 8-ft tall heavy duty poly deer exclosure installed. The study design allowed for a comparison of increasingly intensive management options for establishing oak in a declining oak-beech forest to inform passive vs. increasingly proactive management strategies.

Perspectives on Urban Oak Recruitment Treatments:

- Urban forests, with their predictable disturbance patterns from emerging pests and diseases, offer managers opportunities to test proactive recruitment strategies that rural managers can adapt for anticipated threats.
- Urban settings enable testing additive management strategies that help managers identify optimal intervention levels—from simple natural regeneration monitoring to increasingly complex

combinations of planting, thinning, and protection treatments. This gradient approach allows practitioners to determine the minimum effective management intensity needed for successful oak recruitment under different site conditions and disturbance scenarios.

- Cities provide unique laboratories for developing recruitment treatments that work within social and ecological constraints. Management strategies developed to establish oak recruitment while maintaining public acceptance can inform rural practitioners working in sensitive areas or with concerned stakeholders, creating transferable approaches for politically challenging forestry situations.

3.3. *Climate adapted oaks and tree improvement programs*

The propensity for forest managers in cities to plant trees in natural areas provides opportunities to support tree improvement programs and climate adaptation methods. The White Oak Genetics and Tree Improvement Program (DeWald and Williams 2024) is one such program that aims to identify and select for adaptive traits in *Quercus alba* through a series of provenance trials located through the native range of this species. Tree improvement programs have a long history in forestry and in the case of oaks may be used to select for traits that facilitate resilience to invasive species and favorable growth characteristics (e.g., shade tolerance, apical dominance).

Forestry assisted migration (FAM) represents another emergent strategy, with a suite of climate adaptation practices that many forest managers are considering (Fontaine and Larson, 2016; Bower et al., 2024; Schattman et al., 2024). Although multiple factors threaten the resilience of oak forest systems in the eastern U.S., climate change may favor oaks moving forward. Throughout the region, scientists expect fire-prone systems to increase, and intermittent periods of drought may favor oak species. Indeed, many climate models project oak forest types to be favorable and expanding throughout the region and northward (e.g., USDA Forest Service Tree Atlas, Janowiak et al., 2018). Forestry assisted migration includes three approaches: 1) assisted population migration, moving provenances within their range, 2) assisted range expansion, moving species just outside their range, and 3) assisted species migration, moving a species outside its range (Pedlar et al., 2012). The ADAPT-OAK project (Fig. 5) is a reciprocal transplant common garden experiment located in Baltimore, MD, Philadelphia, PA, New Haven, CT, and Springfield, MA that tests climate adaptation of two oak species (*Q. alba* and *Q. montana*). The ADAPT-OAK study tests assisted population migration, operating within, but near the edge of, the ranges of *Q. alba* and *Q. montana*. The study involves 6000 seedlings planted across 40 gaps (½ Q. *alba*, ½ *Q. montana*). Seeds were collected in 2020 from 7 parent trees located in different forest parks in Springfield, MA (42.078° N, 72.569° W, elev. ~30–50 m), New Haven, CT (41.327°N, 72.904°W, elev. 25–100 m), Philadelphia, PA (40.054° N, 75.016° W, 20–60 m), and Baltimore, MD (39.352° N, 76.652° W, elev. 25–75 m). Additionally, seeds were collected from forest sites near Louisville, KY (38.241° N, 85.697° W, elev. 75–150 m) and Memphis, TN (35.334° N, 90.068° W, elev. 50–100 m). Seedlings were grown in the Kentucky State Division of Forestry nursery and transplanted in spring 2021 as 1 y bareroot stock. In each plot, 150 seedlings were planted randomly at 4-ft centers. Seedlings evenly represented each of the six seed zones and five seedlings (half-siblings) from five of the seven mother trees.

FAM is a proactive approach that addresses future ecosystem sustainability, but questions remain about how to achieve successful establishment of provenances that may be better adapted to future climates (Bower et al., 2024). An important question involves how to identify candidate populations for moving and how far to move them. Seed zone maps, which integrate plant hardiness zones and ecoregions, have traditionally provided guidelines for seed transfer distances (Pike et al., 2020). In a changing climate, projection models that consider expected shifts in temperature and precipitation can now identify present day analogs to source material (e.g., Royo et al., 2023). Still, maladaptation to current climatic conditions could take the form of greater sensitivity to late spring frosts by southern provenances. The ADAPT-OAK project used a climate analog approach that uses temperature and total precipitation data for urban areas (Fitzpatrick and Dunn, 2019) to inform our study design, while also considering Pedlar's (2021) critical seed transfer distance theory. Urban climate analog models account for urban ecosystem conditions which include altered temperature regimes (urban heat island) and precipitation patterns (e.g., Carton et al., 2024).

Elevated temperatures in urban environments offer dynamic settings for studying implications for future rural forest populations. Urban forests may serve as harbingers of future climate conditions (Lahr et al., 2018) or perhaps even steppingstones for tree migration (Han et al., 2021). Urban climate analog models provide a means for selecting seed sources based on projected temperature and precipitation for cities (Royo et al., 2023; Fitzpatrick and Dunn, 2019). In the northernmost regions of the ADAPT-OAK study area, temperatures are projected to rise

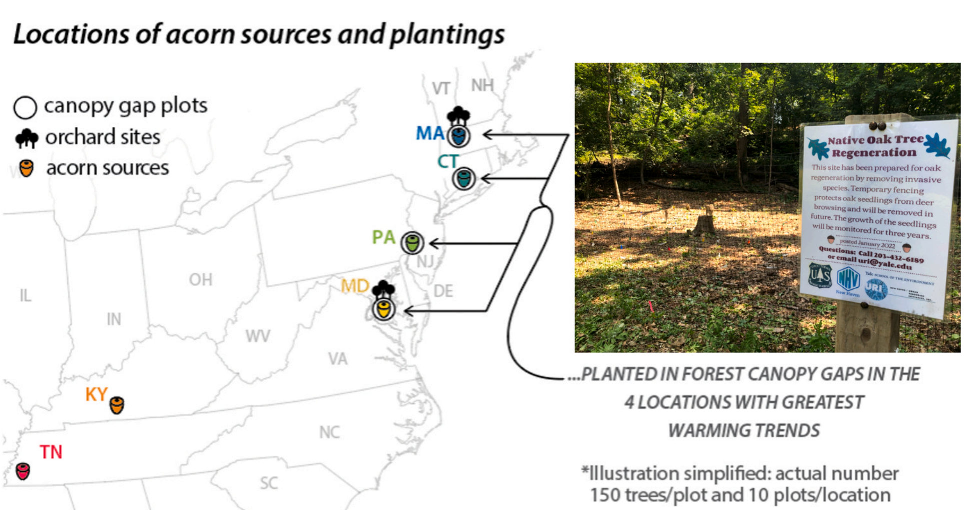

Fig. 5. Can cities serve as future climate analogs and allow scientists and managers to test forestry assisted migration strategies? The ADAPT OAK project is a reciprocal transplant common garden study that evaluates the response of *Q. alba* and *Q. montana* across a latitudinal gradient in Baltimore, MD; Philadelphia, PA; New Haven, CT; and Springfield, MA. Experimental plots are located in three forest parks in each metro region, with 10 replicate plots planted with 150 oak seedlings representing 30 mother trees from six provenances (the four metro regions as well as Louisville, KY and Memphis, TN).

by approximately 4–5°C (Fan et al., 2014). For cities in the northeast U.S., growing season temperatures have already increased by 1.7–2.6°C, whereas in cities like Memphis, TN, and Louisville, KY, temperatures have remained relatively constant over the last 80 years, providing valuable testbeds for responses to shifting climates and assisted migration studies (NOAA, 2023). Consequently, these sites represent logical locations to pilot assisted migration and tree improvement studies. Given these projected climate impacts, proactive ecological interventions may prove necessary to sustain forested ecosystems.

Perspectives on Climate Adapted Oaks and Tree Improvement in Cities:

- Forests in cities can pilot tree improvement and forestry assisted migration studies in controlled, low-risk environments. Urban forest managers routinely practice direct planting as standard management, making them natural early adopters of novel strategies like assisted migration that rural foresters may hesitate to implement due to time commitments and unfamiliarity with artificial regeneration methods.
- Cities provide unique opportunities to evaluate climate adaptation strategies under accelerated warming conditions that preview future rural environments. Urban heat islands allow managers to test provenance performance under climate conditions that rural forests may not experience for decades, enabling proactive development of climate-adapted management strategies.

4. Integrating urban-rural research, practice, and knowledge transfer

Artificial regeneration methods, primarily direct planting, represent standard practice for forest managers in cities, and a reliance on these practices distinguishes urban from rural forestry approaches. Consequently, urban forest managers have developed expertise in pre-planting site preparation, post-planting care, and adaptive strategies for challenging establishment conditions. Cities serve as testing grounds for emerging approaches such as forest assisted migration and tree improvement programs, where managers can evaluate novel techniques under controlled conditions before broader implementation. Urban practitioners routinely navigate complex social constraints, invasive species pressures, and intensive management scenarios that rural foresters may encounter only occasionally, making urban forests valuable laboratories for developing resilient oak management strategies. The innovation in silvicultural practices emerging from urban contexts—including creative design solutions, adaptive planning frameworks, and diverse stakeholder engagement strategies—offers transferable knowledge for rural practitioners facing similar challenges (Piana et al., 2023; Schattman et al., 2024; Wienke et al., 2022). Co-production of silvicultural treatments in urban settings can provide a model for scientists, land managers, landscape designers, policymakers, and local communities to define goals and realize creative solutions through long-term partnerships (Wienke et al., 2022). Urban forest managers are beginning to operate within systematic research and monitoring frameworks reminiscent of the tradition established in the USDA Forest Service's National Forest System, creating opportunities for rigorous data collection and long-term study. By adapting models from rural silviculture to urban realities, these pilot studies support best practices and advance forest management knowledge relevant across the urban-rural continuum. The collaborative networks and evidence-based approaches developed in cities can inform adaptive management strategies needed to sustain oak forests throughout their range, bridging the gap between innovative urban practices and traditional rural forestry to enhance oak forest resilience amid rapid environmental change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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