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# A framework for adapting urban forests to climate change

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ABSTRACT

Planting urban trees and expanding urban forest canopy cover are often considered key strategies for reducing climate change impacts in urban areas. However, urban trees and forests can also be vulnerable to climate change through shifts in tree habitat suitability, changes in pests and diseases, and changes in extreme weather events. We developed a three-step framework for urban forest vulnerability assessment and adaptation that scales from regional assessment to local on-the-ground action. We piloted this framework in the Chicago region in 10 locations representing an urban-exurban gradient across a range of socioeconomic capacities. The majority of trees across a seven-county region had low to moderate vulnerability, but many of the least vulnerable species were nonnative invasive species. Urban forests in the 10 pilot locations ranged in vulnerability largely due to differences in economic and organizational adaptive capacity. Adaptation actions selected in these locations tended to focus on increased biodiversity and restoration of natural disturbance regimes. However, adaptation actions in more developed sites also included incorporating new species or cultivars. Lessons learned from the pilot area can be used to inform future efforts in other urban areas.



## 1. Introduction

Climate is changing rapidly at a global scale and is projected to change at an even faster rate in the coming decades (IPCC, 2014). Urban areas (areas with populations of 50,000 or more) can be particularly vulnerable to these changes due to urban heat island effects and exacerbated effects of drought and extreme storms due to impervious cover and a high concentration of built structures (Hunt and Watkiss, 2011; Wilby, 2007).

Recognizing the potential for changes in climate to disrupt their social and economic fabric, cities around the world are developing strategies for reducing greenhouse gas emissions and modifying programs to adapt to a warmer future. The urban forest is defined as all publicly and privately owned trees within an urban area—including individual trees along streets and in backyards, as well as stands of remnant forest (Nowak et al., 2001); it is often considered an important component in helping cities adapt to these changes because of its benefit to both people and to nature (Bulkeley and Betsill, 2013). Co-benefits, also termed ecosystem services, that trees in urban regions provide include reducing the urban heat island effect, storing carbon, reducing pollution, mitigating storm water runoff, and providing critical habitat for resident and migratory birds (Cook et al., 2013; Kowarik, 2011; Livesley et al., 2016; Nowak et al., 2013a; Nowak et al., 2014). It is estimated that the urban forest in the Chicago region provides $137 million per year in pollution removal, $14 million per year in carbon sequestration, $44 million/year in energy reduction, and $1.3 million/year in reduced carbon emissions with $51.2 billion in compensatory value (Nowak et al., 2013c).

Despite their important role in helping cities adapt, urban forests may themselves be vulnerable to climate change (Ordóñez and Duinker, 2014). There is increasing empirical evidence documenting the impacts to urban forests both at the global level and local level due to current climate change (Hellmann et al., 2010; Hayhoe and Wuebbles, 2008; IPCC, 2014). Urban sites are often already subject to more extreme heat, temperature fluctuations, and flooding than non-urban sites. Although changes in climate may help reduce some urban stressors (such as a reduction in road salt use with warmer winters), urban trees and forests that are already under stress from the intense urban environment are

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likely to experience added and interactive stress from the effects of global climate change (Gill et al., 2007; Kirshen et al., 2007). Devastating tree losses from large disturbances can lead to economic burdens on cities to remove diseased and dying trees and through the reduction in ecosystem service benefits as trees decline or are lost (Kovacs et al., 2010).

It is important to adapt urban forests to these current and projected climate impacts, yet few attempts have been made to systematically assess urban forest vulnerability and incorporate that information into decision-making. Yang (2009) developed a method for assessing the vulnerability of urban trees in Philadelphia by comparing current and future climate envelopes of tree species and using a scoring system to assess the future impacts of climate change on pests and diseases. However, this study did not include the ecological, organizational, economic, and social adaptive capacity factors that are major contributors to vulnerability in urban forests (Ordóñez and Duinker, 2014). Ordóñez and Duinker (2015) used a qualitative expert elicitation approach for vulnerability assessment in three Canadian cities that focused on many of the social factors of urban forest vulnerability, but did not explicitly incorporate quantitative methods. This approach also asked participants to develop adaptation strategies, but these were not tied to specific projects or planning efforts. Although both these approaches provide important pathways to address aspects of climate impacts to the urban forest, a gap remains for incorporating this information into real-world decisions or actions.

We developed the Urban Forestry Climate Change Response Framework to bridge the gap between assessment and action by combining quantitative and qualitative methods of vulnerability assessment with a structured decision process for adaptation. Beginning in 2014, we piloted this method in municipalities, park districts and forest preserves in the Chicago region that ranged from highly developed areas to natural ecosystems across a range of economic capacities. The objective of this paper is to describe the framework and lessons learned from its application in our pilot effort.

## 2. Urban Forestry Climate Change Response Framework

Our approach builds on lessons learned from the Climate Change Response Framework: a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management (Swanston and Janowiak, 2012; Janowiak et al., 2014). This effort has resulted in six published ecoregional vulnerability assessments and over 175 adaptation demonstration projects across the Midwestern and Northeastern United States (Janowiak et al., 2014). We modified our approach from the original Climate Change Response Framework to fill the unique needs of the urban environment, including a greater range in site-level growing conditions including engineered environments, more nonnative species and cultivars, and a mix of social and economic factors that alter communities' adaptive capacity.

The Urban Forestry Climate Change Response Framework has three key components, starting with a broad regional assessment, narrowing to local vulnerability assessment, and ultimately addressing the specific needs of individual on-the-ground projects (Fig. 1).

### 2.1. Pilot area

The Chicago Wilderness region includes parts of four states at the southern end of Lake Michigan and is home to approximately 10 million people (Chicago Wilderness, 2004, 2012). Of the 7 million acres in this region, 500,000 acres are protected green space (i.e., managed for long-term conservation) and about 350,000 are protected natural areas (i.e., protected areas with a composition similar to native ecosystems). The region has already been engaged in several efforts to assess climate change impacts and mitigation potential and develop adaptation strategies (McPherson et al., 1997; Hayhoe and Wuebbles, 2008, Chicago Wilderness, 2012; Nowak et al., 2013c). Additional efforts have been initiated to improve greenspace and tree cover (Chicago Wilderness, 2004; Fahey et al., 2015; Chicago Region Trees Initiative, 2016).

In 2013, tree canopy was estimated to cover 15.5% of the most developed 7-county region within the Illinois section of the Chicago Wilderness region (Nowak et al., 2013c). The Chicago region has lower tree canopy than many other cities, such as Kansas City (18.6%), New York City (20.9%), Washington DC (28.6%), and Minneapolis (26.4%) (Nowak et al., 2010, 2013b). Lower tree canopy in the Chicago region can be partially explained by the presettlement land cover in the region, which was primarily prairie

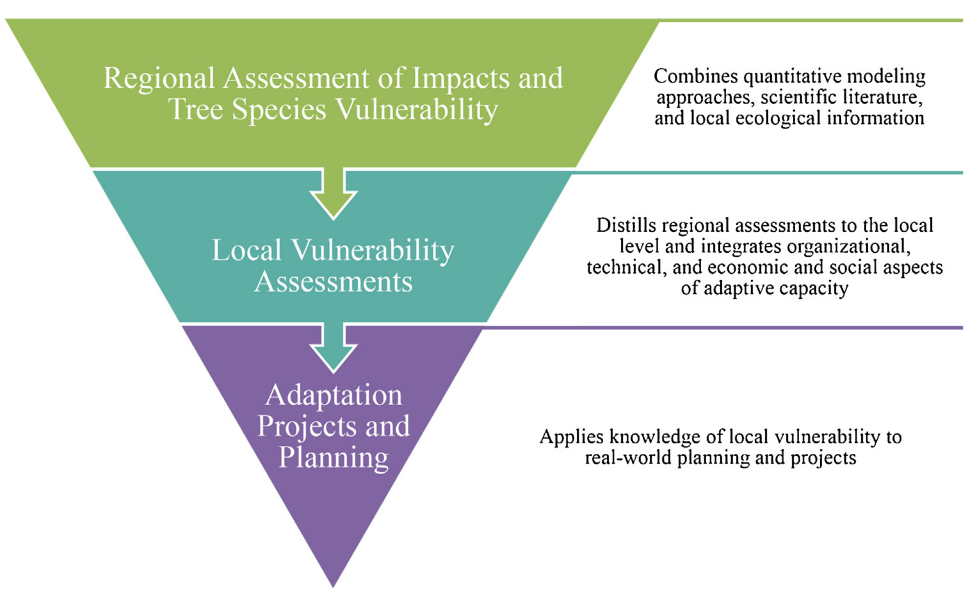


**Fig. 1.** Three-step approach employed by the Urban Forestry Climate Change Response Framework. Spatial scale and focus narrow with each step.

and open woodland and savanna (Nowak et al., 1996; Fahey et al., 2012). The most abundant trees in the region by canopy cover are silver maple (*Acer saccharinum*), boxelder (*Acer negundo*), green ash (*Fraxinus pennsylvanica*), European buckthorn (*Rhamnus cathartica*), and black walnut (*Juglans nigra*) (Nowak et al., 2013c). The regional forest composition is currently transitioning, as emerald ash borer (*Agrilus planipennis*) is killing ash species, which make up nearly 10% of the region's canopy (Nowak et al., 2013c). The third most abundant species in the region (European Buckthorn) is an invasive species that is actively being removed by forest managers and conservationists in much of the region.

### *2.2. Step 1: regional assessment of impacts and tree species vulnerability*

We conducted this step at a regional scale because of greater model uncertainty at finer scales for both habitat suitability models and the climate models that drive them. In addition, much of the information at this step will be similar across a broad geographic area.

We compiled a list of the 120 most common trees in the seven-county region surrounding Chicago as determined by Nowak et al. (2013c). We also evaluated 59 additional species and cultivars on *The Morton Arboretum's Northern Illinois Tree Species List* (The Morton Arboretum, 2015).

We used a suite of quantitative approaches to assess climate change impacts to individual tree species. We used species distribution model projections from the Climate Change Tree Atlas (Iverson et al., 2008; Landscape Change Research Group, 2014) for 70 species native to the United States that are either currently present in the Chicago Wilderness area or likely to have suitable habitat in the area in the future. Changes in suitable habitat were projected through the end of the 21st Century for the region under two model-emission scenario combinations (PCM B1 and GFDL A1FI, Stoner et al., 2013). For the remaining non-native species and cultivars (where species distribution models were unavailable) we compared the known heat and hardiness zone ranges of species to projected shifts in heat and hardiness zones. When heat zone was projected to be at or above the threshold of the species or cultivar over its lifespan, a decrease in habitat suitability was projected. A species was considered to have an increase in habitat suitability if projected hardiness zones were at or above a species minimum threshold.

We evaluated adaptive capacity of each species or cultivar based on modification factors developed by Matthews et al. (2011). This approach evaluates species' life history traits and tolerance to disturbances, and was developed for native trees in natural areas. For species and cultivars in developed sites, we created separate modification factor scores that included considerations specific to urban areas, such as planting site specificity, nursery production potential, and maintenance required (Brandt et al., in press). Thus, a species or cultivar could have an entirely different adaptive capacity based on whether it is naturally-occurring or planted in a highly developed area. Information for adaptive capacity was synthesized from the scientific and gray literature. Individual scores were reviewed by local experts in urban forestry.

We used the information compiled above to develop a vulnerability rating for each species. We defined vulnerability as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes, summarized as a function of the system's impacts (exposure and sensitivity) and adaptive capacity (Glick et al., 2011; IPCC, 2014). We placed all species evaluated into one of five vulnerability categories (low, low-moderate, moderate, moderate-high, or high) based on the sum of the overall impacts projected by species distribution models or heat/hardiness zone and the adaptive capacity score.

We also conducted an extensive literature review to complement the species-level assessment, summarizing past and projected climate change impacts in the region and projected effects on the region's urban forest (Brandt et al., in press). A literature search of both the peer-reviewed and gray literature was


**Fig. 2.** Range of forest cover and development in pilot assessment areas. A. urban forest in Chicago. B. suburban street trees in Riverside. C. Municipal park in Glencoe D. Ryerson Conservation area in Lake County.

compiled using key word searches in ISI Web of Knowledge and Google Scholar with key words including “climate change”; “climate”; “urban forest”; “Chicago”; and “Midwest.”

### 2.3. Step 2: local vulnerability assessments

We applied this step at a finer scale to engage local decision-makers and capture aspects of vulnerability that may not be discernable at a larger regional scale. In November 2014, we piloted this process in a 1-day workshop with municipal foresters, planners, parks managers, and other urban and community forestry professionals. We solicited participants from seven counties in the Chicago region that fall within the Metropolitan Statistical Area, and are thus classified as urban – Lake, McHenry, Kane, Cook, DuPage, Kendall and Will. We included a wide variety of land managers at the community scale, which included municipalities, townships, county, forest preserves and park districts (Fig. 2). Ultimately 10 representatives from 4 municipalities, 3 park districts, and 3 forest preserves participated (Fig. 3). In addition to the participants, three facilitators, three note-takers, and five scientists that contributed to the regional assessment provided workshop assistance.

We designed the workshop based on participatory vulnerability assessment methods (Brandt et al. unpublished; Ordóñez and Duinker, 2015). We developed a self-assessment worksheet for the workshop that bridged regional impacts and adaptive capacity factors to a local scale, using concepts developed by Ordóñez and Duinker (2014) (see Supplementary materials). We asked participants to assess how regional impacts (the sum of exposure and sensitivity; Glick et al., 2011) may differ at the local level when modified by local factors in three dimensions: physical, biological, and human-influenced. Physical factors included the specific soil and geomorphic conditions of the area and its relative closeness to Lake Michigan. Biological factors included the tree species composition and the presence or threat of pests and diseases that could be affected by climate change. Human factors included urban heat island effects, relative ozone pollution, and amount of impervious cover.

We defined adaptive capacity as the general ability of institutions, systems, and individuals to moderate the risks of climate change, or to realize benefits, through changes in their characteristics or behavior. We asked participants to evaluate adaptive capacity in four dimensions: organizational/technical, biological, economic, and social. Organizational/technical factors included staffing, level of planning and preparedness for disasters, and level of planting and maintenance. Biological factors included the diversity of species, genotypes, and age classes in the area. Economic factors included the extent to which funds are available for planting and care. Social factors were the level of public involvement and support for urban forestry activities in the area.

Each participant completed his or her own assessment in a facilitated group setting and shared their thoughts and responses throughout the process. We provided participants with presentations on local climate change impacts and tree species response, preliminary results from the regional tree vulnerability assessment completed in Step 1, and detailed instructions for completing the worksheet. They were also asked to provide inventories, if available, which we analyzed for tree species vulnerability based on data provided in Step 1.

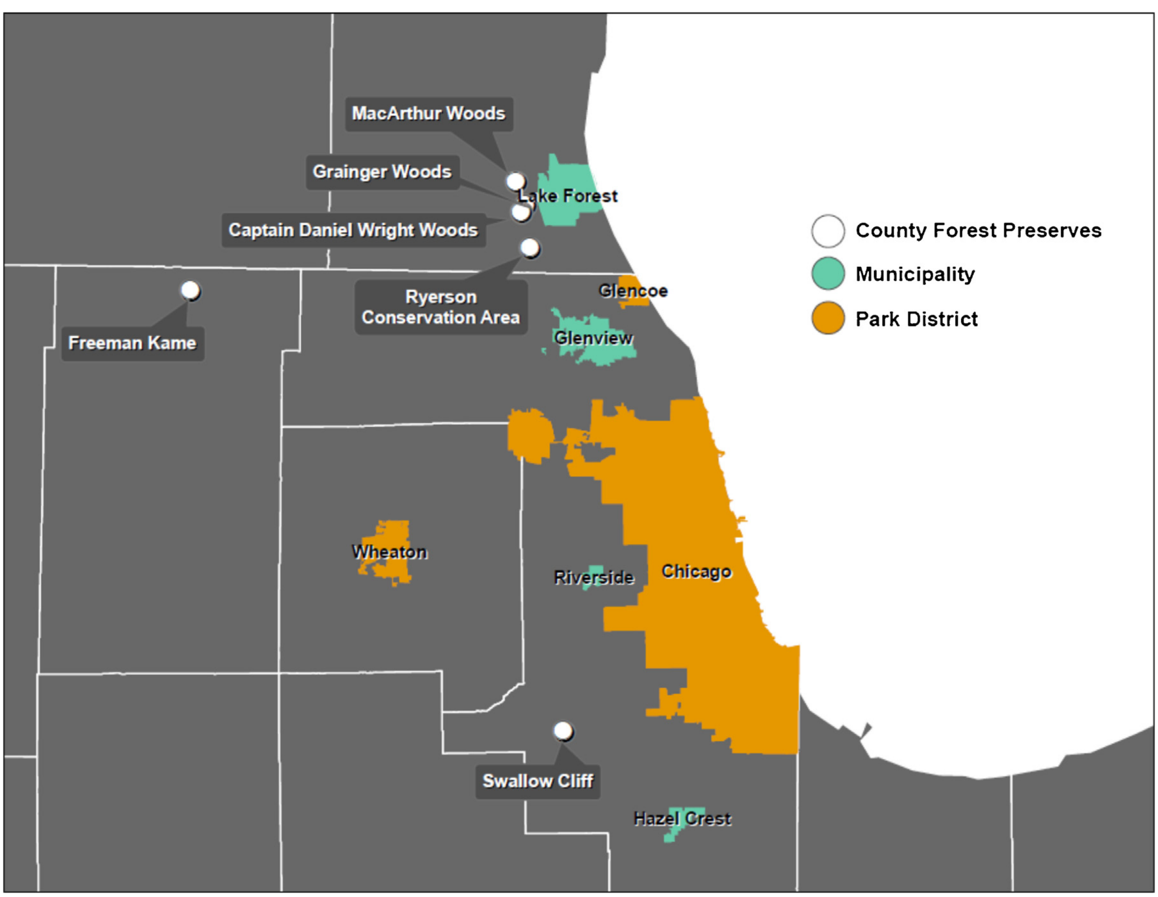


**Fig. 3.** Locations of participants that completed the vulnerability self-assessments. The four forest preserves in Lake County were assessed collectively by one manager as part of one project.

### 2.4. Step 3: adaptation projects and planning

This step takes vulnerability information developed by practitioners and asks them to incorporate it into specific planning efforts or projects. The same 10 participants from the vulnerability workshop participated in a 1-day adaptation planning workshop two months following the vulnerability workshop January 2015). Six others provided facilitation and technical support for the workshop. Each participant was asked to consider a specific on-the-ground project or planning effort in a structured adaptation process.

We walked participants through a structured adaptation process where they defined their goals and objectives, incorporated their vulnerability assessment information, identified challenges and opportunities for their project due to current or projected climate change, selected potential adaptation strategies from a menu of peer-reviewed options, and developed potential on-the-ground tactics. We based our process on the adaptation workbook developed by Swanston and Janowiak (2012). We modified this process from the original in two key ways. First, we provided a list of 31 potential adaptation strategies specific to urban forests (Swanston et al., in press), based on a menu of adaptation strategies developed for natural systems (Swanston and Janowiak 2012). The Chicago Wilderness Trees and Green Infrastructure Task Force reviewed this list and adjusted language, supporting literature, and examples for an urban audience. Second,

**Table 1**
Vulnerability, impacts, and adaptive capacity (with their sub-components) for each location participating in the workshop series.

| | Impacts | | | | Adaptive Capacity | | | | | Overall |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | Physical | Biological | Human | Overall | Biological | Organizational/ Technical | Economic | Social | Overall | Vulnerability |
| Riverside | moderate-negative | moderate | moderate | moderate | high | high | high | high | high | low-moderate |
| Lake Forest | moderate | negative | moderate | moderate-negative | high | moderate | high | high | moderate-high | moderate |
| Hazel Crest | moderate | moderate-negative | moderate-negative | moderate-negative | low | moderate-high | low | moderate | low-moderate | moderate-high |
| Glenview | moderate-negative | moderate-negative | moderate-negative | moderate-negative | moderate | high | high | high | high | moderate |
| Glencoe Parks | moderate | moderate-negative | negative | moderate-negative | moderate | low-moderate | low-moderate | low | low-moderate | moderate-high |
| Wheaton Parks | moderate | negative | negative | moderate-negative | high | high | high | moderate-high | high | moderate |
| Chicago Parks | moderate-negative | moderate-negative | moderate-positive | moderate-negative | moderate | moderate-high | moderate-high | moderate-high | moderate-high | low-moderate |
| Southern Des Plaines River Preserves | negative | moderate-negative | negative | moderate-negative | low-moderate | moderate | moderate-high | moderate-high | high | moderate |
| Freeman Kame Preserve | moderate-negative | moderate-negative | negative | moderate-negative | moderate | moderate | moderate | moderate-high | moderate-high | moderate |
| Swallow Cliff Preserve | moderate | moderate-negative | moderate | moderate-negative | low | moderate | low | low-moderate | low-moderate | moderate-high |

we focused only on the first four steps of the adaptation workbook developed by Swanston and Janowiak (2012), omitting the monitoring component. Although monitoring can be important to informing urban forest management (Roman et al., 2013), we felt monitoring tactics and questions will likely be the same regardless of whether or not climate change was occurring in the area.

## 3. Pilot effort outcomes

### *3.1. Regional assessment of urban trees*

We summarized results of the regional assessment in a report geared toward urban forestry professionals, which includes species-level vulnerability information (Brandt et al. in press). We determined that 15% of the 120 evaluated species currently present have moderate-high or high vulnerability. Many of these species are northern North American species at the southern extent of their range, such as white spruce (*Picea glauca*), white pine (*Pinus strobus*), paper birch (*Betula papyrifera*), and quaking aspen (*Populus tremuloides*). By contrast, 47% were considered to have low or low-moderate vulnerability. Species in this category included many common native species at the center of their range, such as boxelder (*Acer negundo*), bur oak (*Quercus macrocarpa*), and hackberry (*Celtis occidentalis*). However, many species with low vulnerability were nonnative invasive species with life history traits that enhanced their adaptive capacity, such as European buckthorn (*Rhamnus cathartica*), Amur honeysuckle (*Lonicera maackii*), and tree-of-heaven (*Ailanthus altissima*).

Of the species recommended for planting in *The Morton Arboretum's Northern Illinois Tree Species List* (The Morton Arboretum, 2015), 10% of species or cultivars recommended for parks and residential areas were considered to have moderate-high or high vulnerability and 8% of species or cultivars recommended for city parkways (boulevards) were considered to have high or moderate-high vulnerability. As with currently present species, those that had higher vulnerability tended to be species at the southern extent of their range or those with narrow habitat requirements.

### *3.2. Local vulnerability assessments*

We summarized results from local vulnerability assessments into narrative case studies for each community (Brandt et al., in press). Individual assessments of vulnerability ranged from low-moderate to moderate-high, primarily based on differences in adaptive capacity (Table 1). There was a greater range in self-assessment of adaptive capacity as compared to impacts. Generally, more affluent areas had lower vulnerability, most likely due to higher economic adaptive capacity. More affluent areas also tended to be rated more favorably on the other three adaptive capacity dimensions.

We asked participants to identify the factors that they perceived would contribute most strongly to the impacts and adaptive capacity of their respective municipality, park district, or forest preserve. Key impacts of concern were increases in extreme weather events, changes in habitat suitability for current trees, and changes in distribution or abundance of pests and diseases. Key contributors to adaptive capacity identified by participants were funding, staffing, genetic and species diversity, and community support.

Tree inventories were only available for five of the ten locations, which tended to be affluent areas. The proportion of trees that were vulnerable to climate change at these inventoried locations generally appeared lower than for the region as a whole (Fig. 4). This suggests that these areas may not be representative of the broader region, which includes many less affluent areas without inventory data.

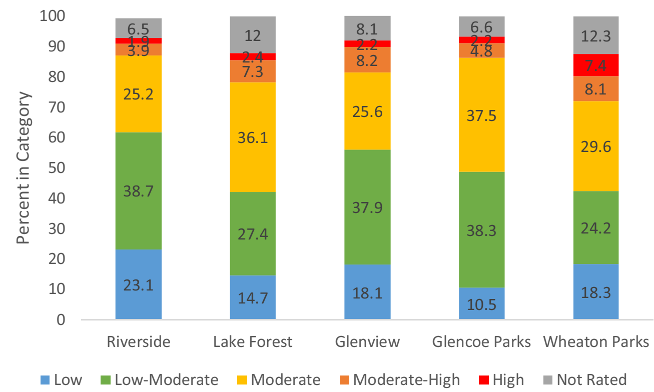


**Fig. 4.** Percent of trees in each vulnerability category for the five communities with available inventories. Inventoried trees that were only identified to genus or extremely rare were not rated. Inventories for Riverside and Lake Forest had both park and street trees. Glenview's inventory was just street trees, and Glencoe and Wheaton parks were just park trees.

### *3.3. Structured adaptation process*

Project types selected for the adaptation workshop varied from community-wide to site-specific and for both natural and developed sites. Projects included a flood control project in open lands, selection of nursery stock, planting parkways to replace trees lost by emerald ash borer, and restoration of upland and bottomland natural areas. Many communities shared similar management goals of enhanced diversity, greater resilience to storm events, and increases in canopy cover. Goals for the natural areas also included restoring native ecosystem structure and function, and reducing nonnative invasive species.

Participants identified a wide range of challenges and opportunities posed by climate change that may affect achieving their objectives. Several common challenges and opportunities arose as being of greatest interest across communities (Table 2). Many of these challenges relate to key impacts and adaptive capacity factors identified in Step 1, but were specific to achieving the goals and objectives of their particular project. Challenges and opportunities included a range of physical, biological, organizational, and social factors.

Participants chose to further evaluate and develop on-the-ground tactics for 19 of the 31 adaptatation strategies provided in the menu. Several strategies were chosen by more than one location (Table 3). The most common strategy selected across all locations was to reduce the spread of invasive species, something that many natural areas had already listed as a management goal. Strategies for natural areas tended to focus on increasing resilience to disturbances by restoring flood and fire-adapted species and ecosystems, and enhancing species, genetic, and age class diversity. Strategies selected for developed sites also emphasized diversity, but had a greater focus on transitioning toward likely future climates by evaluating species native to far southern Illinois for planting, and planting pest or disease-resistant cultivars.

Strategies not selected from the menu tended to focus on expanding green space, reducing fragmentation, and establishing reserves. These strategies tend to be more appropriate for long-term regional planning, so they may not have been appropriate for the smaller-scale projects selected for this workshop.

**Table 2**
Top management challenges and opportunities from climate change as identified by participants.

| Management Challenges | Management Opportunities |
|---|---|
| • Increases in precipitation, runoff and flooding will increase stress and mortality | • Climate change may stimulate interest in planting native species that are adapted to extreme events |
| • Decreases in habitat suitability for existing trees will increase susceptibility to disease and mortality | • There may be more support for planting new species and cultivars in the area |
| • Increases in insect pests, diseases, and invasive species | • Climate change may decrease the viability of some invasive plants and pests, thus facilitating their control |
| • Social and political barriers to addressing climate change impacts | • Impacts and threats from climate change may increase public interest and involvement |
| • Increased workload for staff | • The existing diversity of trees within individual communities may facilitate adaptation |
| • Uncertainty in climate projections for species | • New canopy gaps from disturbances can crease regeneration opportunities for future climate-adapted species |

## 4. Lessons learned from the Chicago region pilot

This Urban Forestry Climate Change Response Framework pilot project adapted years of collaborative learning and tool development in rural systems to an urban environment, generating new lessons and perspectives on improvement. The regional assessment provided quantitative, science-based information to aid urban foresters in assessing which trees are most vulnerable to climate change. This approach combined species distribution modeling, projections of heat and hardiness zones, and assessments of species-level adaptive capacity to give a comprehensive summary of vulnerability for each species (Glick et al., 2011). We provided this information to workshop participants early in the process hoping to receive feedback and further refine our results. However, practitioners generally did not have the interest or expertise to provide feedback on model results, and the preliminary nature of the results generated uncertainty and even distrust in the information. This differed from the rural Climate Change Response Framework in which practitioners have provided modelers with valuable feedback based on management experience, sometimes leading to improvements in the models. In the future, having results fully vetted by a smaller group of experts, while still acknowledging uncertainty, before providing to a larger group of urban forestry practitioners may be more effective.

The vulnerability self-assessment helped practitioners step down broad, regional information to their local level. It also enabled them to examine which factors were the largest contributor to vulnerability and how their assessments compared with other communities in the area. We incorporated physical, biological, and social aspects that could contribute to the vulnerability of the urban forest in an effort to capture a full picture of urban forest vulnerability (Ordóñez and Duinker, 2014).

**Table 3**
Adaptation strategies selected from a menu of 31 peer-reviewed options for more than one project. Examples tactics are a sample of those developed by individual projects.

| Option | Adaptation Strategies Selected | Number of Projects Selecting | Developed or Natural Area? | Example Tactics |
|---|---|---|---|---|
| Resist Change | Prevent the introductions and establishment of invasive plant species and remove existing invasives | 4 | natural | • Manage and monitor natural area buffers to limit invasive spread into high quality areas<br>• Herbicide treatment of existing invasive plants |
| | Promptly remove major hazards | 4 | both | • Remove hazard trees and broken limbs near trails and roadways<br>• Remove large logs and other debris that could impact plantings during flood events (natural areas) |
| | Retain biological legacies | 2 | both | • Retain snags and downed trees for habitat (natural areas)<br>• Protect some healthy ash trees from emerald ash borer to retain them on the landscape (developed sites) |
| Enhance Resilience | Maintain, restore, enhance native species diversity | 3 | both | • Restore conditions that allow for successful regeneration of native canopy trees in the understory (natural areas)<br>• Design planting projects with high species diversity (developed areas) |
| | Manage and restore hydrology | 3 | both | • Install french drains to reduce local flooding<br>• Evaluate potential for modifications to increase on-site flood absorption |
| | Promote diverse age structure | 2 | both | • Create conditions that allow for development of an advance regeneration layer (natural areas)<br>• Develop staggered planting cycles for new trees (developed areas) |
| Facilitate Transitions | Select tree species to match current and future site conditions | 2 | both | • Plant flood-adapted trees in areas subjected to flooding<br>• Plant drought-adapted trees in extremely well-drained soils |
| | Introduce species that are expected to be adapted to future conditions | 2 | developed | • Plant species from areas south of the region that model projections suggest will do well |
| | Maintain or improve the ability of forests to resist pests & pathogens | 2 | both | • Incorporate disease and insect-resistant varieties of trees (developed areas) |

Based on workshop feedback, participants reported an increased understanding of which tree species may be most vulnerable to climate change over the next century and an enhanced ability to identify impacts and adaptive capacity factors that contribute to their local vulnerability. They also reported that working in a collaborative setting with other professionals and experts on climate change and urban forests helped provide new perspectives and insights to which they would not otherwise be exposed.

Lessons from previous climate adaptation efforts for urban ecosystems in the Chicago region revealed the importance of targeting a wide range of decision-makers in order to fully integrate climate considerations into an organization's structure and prioritized efforts (Derby Lewis et al., 2014). To meet this need, we modified a structured adaptation process that has been successfully used to develop real-world adaptation projects in forested plantations and natural areas (Janowiak et al., 2014), and also considered other adaptation processes in natural resources (Stein et al., 2014). Many of the projects in the workshop focused on natural ecosystems, and those participants selected adaptation strategies similar to those often chosen in our workshops in rural areas. However, projects that focused more on developed sites were more likely to suggest strategies and tactics involving novel species or cultivars, indicating that developed urban areas may require different tools and approaches to adaptation than natural areas.

We attempted to obtain a representative sample of workshop participants from across the region. However, purely due to self-selection, participants in the workshop series tended to be early adopters with a high level of technical expertise. The villages of Riverside, Lake Forest, Hazel Crest, Glenview, Glencoe Park District, Wheaton Park District and the Chicago Park District have full-time certified arborists on staff. Many participants had considerable knowledge of local climate change impacts and had been involved in previous efforts related to climate change and urban forestry. Because of this, the organizational and technical adaptive capacity of participants may be greater than the Chicago region as a whole. Low –income areas across the region are likely more vulnerable to climate impacts because they have no professional forestry staff, no inventory, and are not able to plant or care for trees.

The project relied on a highly developed network linking science and other resources with decision-makers. Two unique efforts in the Chicago region helped facilitate this: Chicago Wilderness and the Chicago Region Trees Initiative (CRTI). The Chicago Wilderness alliance was launched in 1996 and has grown to include over 250 member organizations and corporations working toward common goals to restore nature and improve the quality of life for native biodiversity and human communities (Moskovits et al., 2004; Miller, 2005 and Derby Lewis et al., 2014). The CRTI is a collaboration of more than 150 organizations across the seven-county Chicago metropolitan area with the focus to preserve, protect and enhance the urban forest. Training of urban forestry landowners and managers to understand and manage for existing and potential impacts to the urban forest is a central focus of CRTI. Other metropolitan areas may lack such organized networks, but may still be successful at projects such as these if a few key organizations are able to convene other groups engaged on the topics of urban forestry and climate change.

We found that a major challenge in assessing the vulnerability of urban forests was the large number of nonnative species and cultivars. Analysis of 59 municipal and park district inventories identified over 330 species in the Chicago region (Morton Arboretum, unpublished data), over 7 times higher than the 45 native tree species that were identified in pre-settlement surveys (Bowles and Mcbride, 2001). There is typically very little information on the ability of many of these species and cultivars to withstand the variety of stressors and large-scale disturbances posed by climate change. Habitat suitability modeling can also be difficult due to the lack of a native range or rarity of species. In addition, the highly altered environments on developed sites add further complexity to habitat suitability modeling for all urban trees, including natives, because the soils, microclimate, and topography may not match those of surrounding natural areas. Cultivars may also perform very differently in reaction to a disturbance or have a very different range of temperature or moisture tolerances than the species from which they are derived. Different habitat suitability models may be needed for each individual cultivar, which may not be scientifically or logistically feasible.

Through our pilot effort, we discovered that a major barrier to vulnerability assessment and adaptation is the lack of complete tree inventory data for many communities. Inventories allow managers to monitor and improve species diversity within their forest, identify trees that may have issues (like structural problems, diseases or interactions with powerlines) and proactively manage them. Despite the fact that the participating communities in this effort tended to be well staffed with highly-trained technical experts, only half of them had inventories. The quality of these inventories is also often an issue. The best inventories are geo-referenced, which allows managers to relocate individual trees and monitor them over time. Many municipalities do not have the time or resources to conduct a complete inventory, and instead conduct sample inventories and extrapolate the findings to estimate tree counts and species. Although these inventories can give broad information about the condition of their trees, they do not allow for the deliberate management of individual trees. Even amongst the best inventories, there are frequently errors and many are out of date and thus not representative of the current species composition and condition.

It is unclear whether the adaptation strategies selected will be sufficient to address the biggest climate change vulnerabilities and management challenges identified by workshop participants. Efforts to restore hydrology, enhance biodiversity, and incorporate future-adapted species will help address many of the physical and biological issues at play. However, many factors contributing to vulnerability and creating management challenges identified are social and economic. If there isn't sufficient financial support or buy-in by local communities, the extent to which these strategies are implemented will be limited. In addition, uncertainty about future projections means that even if these strategies are implemented, there is the risk that they will be inadequate in magnitude or fail to address unanticipated impacts.

## 5. Concluding remarks

The Urban Forestry Climate Change Response Framework has resulted in several outcomes for the Chicago region and beyond. The results of the regional assessment are being used to inform strategies for a regional master plan as part of the Chicago Region Trees Initiative (CRTI). The list of vulnerable and adaptable trees will be used to inform a regional planting list of recommended trees also being developed as part of the CRTI. Several projects identified in the workshop have already been implemented and project coordinators have worked with communities to apply for additional funding. As these projects are implemented, they will be used in local trainings. Other communities outside of the Chicago region have also expressed interest in implementing the framework, and work is underway to expand to at least four other large metropolitan areas in the Midwest and Northeast.

The core data and resources to undertake the Urban Forestry Climate Change Response Framework are already available to communities of a range of sizes. Many communities have undertaken inventories that can provide information on species composition. Information on changes in habitat suitability for native trees is accessible on the World Wide Web (Landscape Change Research Group, 2014). Projections for heat and hardiness are also becoming available (Matthews et al., 2016). The adaptive capacity scores developed for this pilot effort can easily be modified for other areas (Brandt et al., *in press*). Both the vulnerability worksheets and adaptation workbook are also available to practitioners at no cost (Brandt et al., *in press* and Swanston et al., *in press*). Ultimately, however, our experience suggests that one of the most important resources needed is an engaged network of scientists and practitioners who possess the desire, ability, and financial means to apply these concepts to real-world actions.

The current state of research on understanding climate change impacts on urban trees limits the ability to adapt urban ecosystems. Our work has illuminated a need for improved understanding of how to parameterize species distribution models for species in cultivated settings. More observational and empirical research is also needed to better understand tolerance of extreme events such as wind storms, heavy rain events, and drought, though some work in this area is beginning to emerge (Fahey et al., 2013). In addition, our understanding of how insect pests and diseases may impact urban trees in a changing climate is still relatively rudimentary, though some methods for assessment are beginning to emerge (Laćan and McBride, 2008; Yang, 2009).

The Urban Forestry Climate Change Response Framework is a comprehensive approach to adapting urban trees and forests that we have piloted in real-world communities and shows promise for expansion to other urban areas. This approach can be used to estimate the number of trees and species that are vulnerable to climate change at multiple scales. Using this approach, regional quantitative information can be merged with qualitative assessments at a local scale. The tools developed through this process can aid individual municipalities and other ownerships in adapting their urban forest management decisions to a changing climate. The exact nature of climate change impacts to urban forests remains uncertain, and managers will build on their own skills and experience to adapt.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2016.06.005.

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