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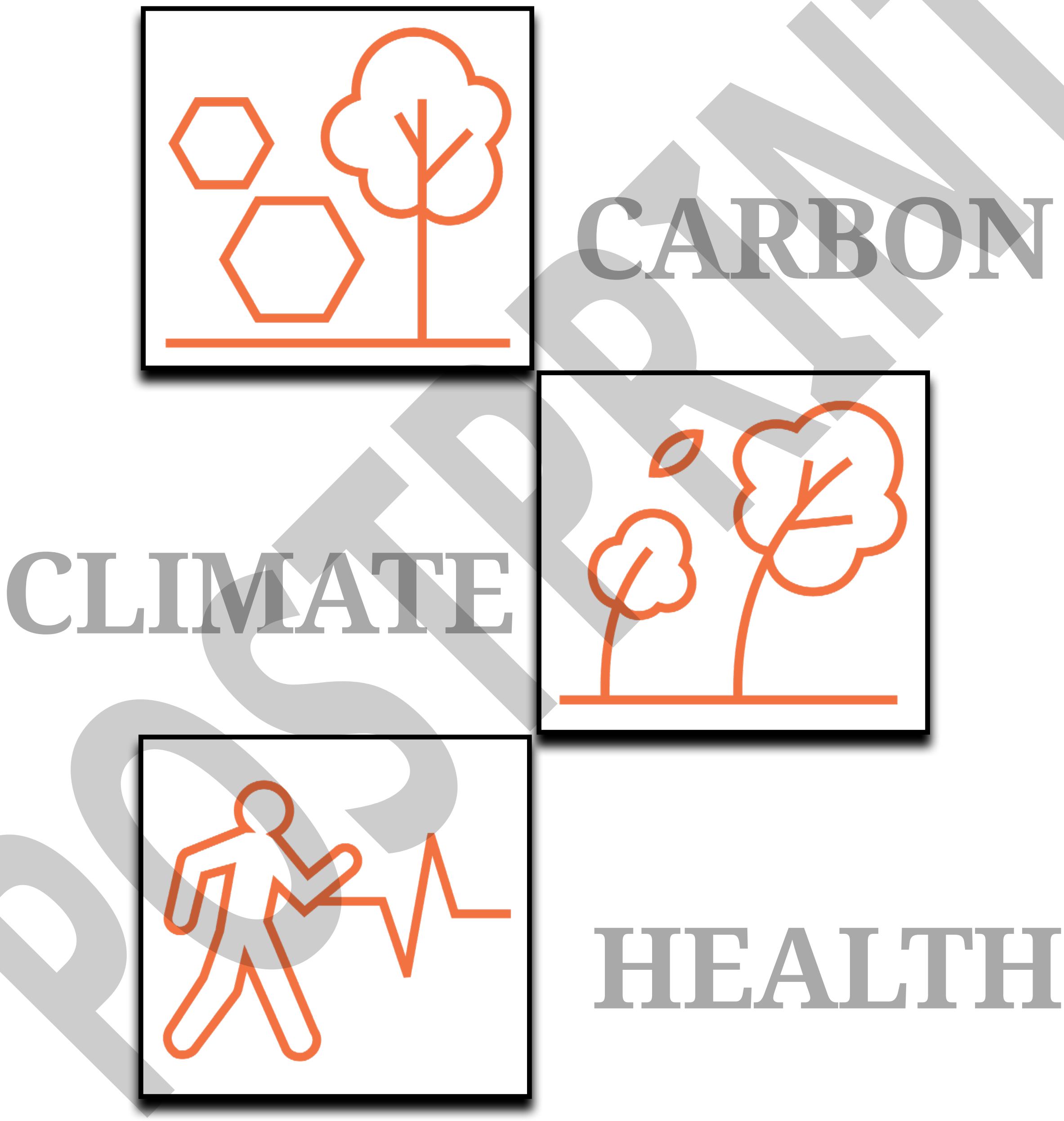
CLIMATE ADAPTATION ACTIONS FOR URBAN FORESTS AND HUMAN HEALTH



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ABSTRACT

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Urban areas can be particularly vulnerable to climate change due to extensive impervious cover, increased pollution, greater human population densities, and a concentration of built structures that intensify impacts from urban heat, drought, and extreme weather. Urban residents are at risk from a variety of climate stressors, which can cause both physical and mental harm. Urban forests and tree cover provide a critical role in helping cities address climate change by supporting greenhouse gas mitigation, reducing the impacts of extreme heat and altered climate that impair human health, and helping communities to adaptively respond through engagement with nature. At the same time, urban forests are vulnerable to changes in climate and in need of robust strategies to adapt to those changes.

As climate change impacts increase, efforts to "green" cities and adapt urban forests to changing conditions take on greater importance to support human health and well-being. Urban forest managers and allied professionals are looking for information to reduce climate risks to urban forests and secure their benefits for people and ecosystems. This report, Climate Adaptation Actions for Urban Forests and Human Health, synthesizes adaptation actions to address climate change in urban forest management and promote human health and well-being through nature-based solutions. It compiles and organizes information from a wide range of peer-reviewed research and evidence-based reports on climate change adaptation, urban forest management, carbon sequestration and storage, and human health response to urban nature.

This report includes the Urban Forest Climate and Health Adaptation Menu, which presents information and ideas for optimizing the climate and human health outcomes of urban forestry projects and provides professionals who are working at the intersection of climate, public health, and urban forestry with resources to support climate adaptation planning and activities. Notably, it *does not* provide specific recommendations or guidance for any particular place; rather, it offers a range of action opportunities at different scales that can be incorporated into either comprehensive or specific climate adaptation initiatives. The Menu can be used with an existing, tested adaptation process to help managers consider climate risks and explore the benefits and drawbacks of potential adaptation actions within the context of a particular situation or project. It also can be useful for generating productive discussions about community needs and values to guide planning, education and outreach, research, or changes in policy or infrastructure within communities.

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INTRODUCTION

Climate change is having a profound impact on cities across the world, and these changes are expected to accelerate in coming decades.[1,2] Urban areas can be particularly vulnerable as extensive impervious cover and concentration of built structures intensify impacts from urban heat, drought, and extreme weather.[3,4] In addition, human population densities in cities increase the risk of human illness and injury from climate influences. Urban forests, defined here as all publicly and privately owned trees within an urban area, provide many ecosystem services. These include helping reduce the impacts of climate change on people and human communities, including reducing the urban heat island effect and moderating stormwater runoff (Table 1). Urban forests are increasingly being recognized for their value in protecting and enhancing human health and safety generally, and particularly in the face of a changing climate.

Table 1—Examples of interactions among climate change, urban forests, and human health and the ways in which urban forests reduce climate impacts on people and communities.

Climate Impact	Potential Impacts on Urban Forests	Potential Impacts on People and Communities	Ways to Reduce Impacts on People and Communities
Warmer temperatures and more days with extreme heat	► Physiological stress on trewes ► Range expansion of pests, disease, and invasive plant species in response to warmer conditions ► Potentially increased production of volatile organic compounds	► Heat stress leading to illness or mortality ► More low air quality days that exacerbate asthma, cardiovascular, and other illnesses ► Increased energy utility demand for cooling and peak use failure	► Reduce extreme heat by providing canopy cover, shade, and moisture ► Reduce energy use for cooling ► Improve air and water quality ► Become thermal refuges for urban dwellers
Fewer days with extreme cold	► Shifts to milder hardiness zones and altered plant habitat suitability ► Reduced mortality of diseases and pests caused by extreme cold	► Reduced demand for energy to heat homes ► Potentially fewer deaths from extreme cold ► Increased survivability in disease-transmitting insects	► Strategically placed trees further reduce wind and improve passive solar, thus reducing energy use ► Improve conditions for physical activity

Climate Impact	Potential Impacts on Urban Forests	Potential Impacts on People and Communities	Ways to Reduce Impacts on People and Communities
Altered precipitation creating wetter conditions in some seasons	▸ Wet conditions may favor some plant pathogens	▸ Increased mold exposure leading to upper respiratory symptoms ▸ Shifts in water quality and quantity	▸ Enhance filtration of pollutants and improved water quality ▸ Canopy interception of precipitation and buffering rain cycles
More frequent heavy precipitation events	▸ Increased stormwater runoff and localized flooding ▸ Mortality of trees in flood-prone areas ▸ Soil saturation and slope failures	▸ Disaster-related injury and death ▸ Reduced water quality ▸ Mold and property damage ▸ Disruption to food systems	▸ Reduce runoff from forest interception and absorption of rain ▸ Root systems prevent erosion and property damage
Elevated risk of drought or aridification	▸ Mortality of drought-susceptible trees ▸ Reduced forest growth and health ▸ Increased stress on forests and shifts to non-forest vegetation	▸ Reducedw water supply ▸ Disruption to food systems ▸ Increased fire risk ▸ Increased dust, smoke, and fine particulates in air	▸ Enhance moisture retention in landscapes helps buffer shifts in precipitation ▸ Improve water quality and storage by healthy soils ▸ Interception and filtering of particulates
Increases in carbon dioxide (CO_2), a greenhouse gas	▸ Increased pollen production	▸ More allergens ▸ Increased respiratory illness and asthma ▸ Human physiology stressor9	▸ Reduce impacts from selection of lower-allergen or female trees ▸ Reduce localized CO2 levels

Urban forests are an integral element of green infrastructure; that is, the "interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations."[5] Urban forests include built and cultural settings such as streetscapes and yards, parks, cemeteries, school grounds, corporate campuses, greenways, and unmanaged green spaces, as well as what are defined here as natural areas, such as patches of native forests, open woodlands, savannahs, and barrens. The vitality and interconnectedness of these urban forest elements are critical in supporting landscape-scale ecological processes (such as carbon sequestration, wildlife migration, and pollination) and long-term ecological functions of urban landscapes.[6] Further, the urban forest contributes to the human habitats of cities, the places and conditions that offer necessary respite from busy lives.[7] Trees and landscapes, if well-planned and designed, can improve human health and quality of life in many ways.

URBAN FOREST BENEFITS FOR CLIMATE, CARBON, AND HUMAN HEALTH

Healthy forests support healthy communities. Urban trees and forests provide many important functions and benefits beyond scenery and aesthetics. These are some of the benefits that urban ecosystems provide:

Climate Adaptation

- Reduced air temperatures from increased tree canopy cover
- Interception and absorption of stormwater, reduced flooding
- Reduced erosion and stable slopes from improved plant cover, which maintain water quality
- Enhanced flood resilience relative to "gray" infrastructure
- Increased biodiversity and wildlife habitat
- Increased refuge for threatened and endangered wildlife species
- Lowered risk of damage from storms or other disturbances
- Reduced wildfire risk

Carbon Mitigation

- Reduced energy use from tree shading and urban forest cooling
- Enhanced carbon storage in trees and ecosystems
- Increased sustainable production through urban wood utilization
- Reduced transportation emissions to create green and walkable communities

Human Health

- Improved air quality and reduced pollutants
- Lowered temperatures and reduced heat-related illness and mortality
- Greater opportunities for physical activity
- Improved mental health, happiness, and wellbeing
- Reduced mental fatigue and enhanced cognitive function
- Relief from mental illness
- Stress reduction/recovery
- Improved social health, cohesion, and resilience
- Contribute to more equitable public health
- Reduced crime and safer communities
- Improved drinking water quality

Figure 1—These are some of the benefits that forested urban ecosystems may provide for climate adaptation, carbon mitigation, and human health.

Urban forests face unique challenges relative to forests outside of cities, such as increased pollution, restricted rooting conditions, and altered soils. These challenges affect the ability of cities to establish, maintain, and improve tree growth and forest canopy cover while simultaneously managing the maintenance costs, infrastructure damage, and nuisance complaints associated with urban trees.[8] Climate change increases many stressors on urban forests and vegetation, with cascading effects on human and community health.

Urban forests and vegetation can be used proactively to address and alleviate many of the effects of climate change on cities and residents (Fig. 1). Urban forests can help reduce the severity of climate change by reducing energy use for heating and cooling and by sequestering carbon. They also can support urban climate adaptation goals, such as heat reduction and improved air quality, which have direct human health implications. Bringing nature closer to people to promote human health is another opportunity of urban forestry and climate response. Urban residents face challenges of crowding, interpersonal stressors, and safety concerns.[10] Interactions with trees—from streetscapes to forested reserves—can counter these experiences and promote mental, social, and physical health benefits.[11]

Urban forest managers and allied professionals, such as urban planners and public health officials, are seeking tools and information to help reduce climate risks to urban forests and promote their beneficial functions. Included in this report is the Urban Forest Climate and Health Adaptation Menu (hereafter referred to as "Menu"), which provides information and ideas for optimizing the climate and human health outcomes of urban forestry projects and gives professionals working at the intersection of climate, health, and urban forestry resources to support climate adaptation planning and activities. Multiple agencies and organizations, along with professionals across multiple disciplines, can collaborate to increase climate and human health benefits. Further, attention to environmental justice and equity is important in these processes. Forestry programs and activities can help address health disparities across underserved populations, as well as inequities in distribution of trees and green spaces across communities. Community engagement that respects local knowledge while incorporating community needs and traditions can support urban forestry projects that promote tree and human health.

What Is The Urban Forest Climate and Health Menu?

One of the major challenges in responding to climate change is translating broad, science-based concepts for climate response into specific, tangible actions that can be implemented within a community or neighborhood. The scientific and technical literature is replete with conceptual frameworks,[12-14] compiled adaptation strategies,[15-17] and tools to support management decisions.[18-20] However, more specific information is needed to help natural resources managers and community leaders identify actions suitable for particular landscapes and projects. The Menu addresses this challenge by providing a synthesis of adaptation actions that are nature-based solutions to address climate change in urban forest management and improve human health and well-being.

The Menu compiles and organizes information from a wide range of peer-reviewed research and evidence-based reports on climate change adaptation, urban forest management, and human health response to urban nature. Actions to increase carbon sequestration and storage in urban forests also are included when possible (Box 1), as these activities can reduce the overall impact of climate change on humans and urban ecosystems. This work draws heavily on research and practice from the temperate regions of North America; thus, some adaptation actions may not be appropriate in different climate zones (e.g., semi-desert or desert) or in situations where forest or tree cover is not desirable or feasible.

The Menu builds on previous resources for climate response, in particular, an urban forests menu that was published in "Forest Adaptation Resources: Climate Tools and Approaches for Land Managers."[21] That report and its resources were developed for use in the Upper Midwest and Northeast using information from a comprehensive literature review of adaptation actions at numerous scales and locations. Subsequent testing, review, and feedback from practitioners was used to refine this adaptation Menu, which has been used by urban forestry professionals to develop real-world adaptation projects (www.forestadaptation.org/demos). Our report incorporates new considerations of human health, carbon mitigation, and human dimensions that are integral to urban forest management and expands the scope to temperate regions within North America. The effort was led by the Northern Institute of Applied Climate Science, the USDA Forest Service, American Forests, and the University of Washington.

Box 1: Trees and Climate Mitigation

Forests are increasingly recognized for their potential as "natural climate solutions" for land-based carbon mitigation, given the need to prevent the most severe impacts of climate change in the near-term.[1, 22, 23] Urban forests can support greenhouse gas reductions by reducing energy use,[24, 25] sequestering and storing carbon within trees and soils,[26] and providing material for wood products (Fig. 2). Ecosystems that are adapted to changing and more variable conditions also can provide increasingly important benefits for carbon mitigation.[27] Actions to increase both adaptation and mitigation benefits can have synergistic effects regarding climate change[28] and human health benefits. When possible, the Menu discusses key benefits and tradeoffs for carbon mitigation.

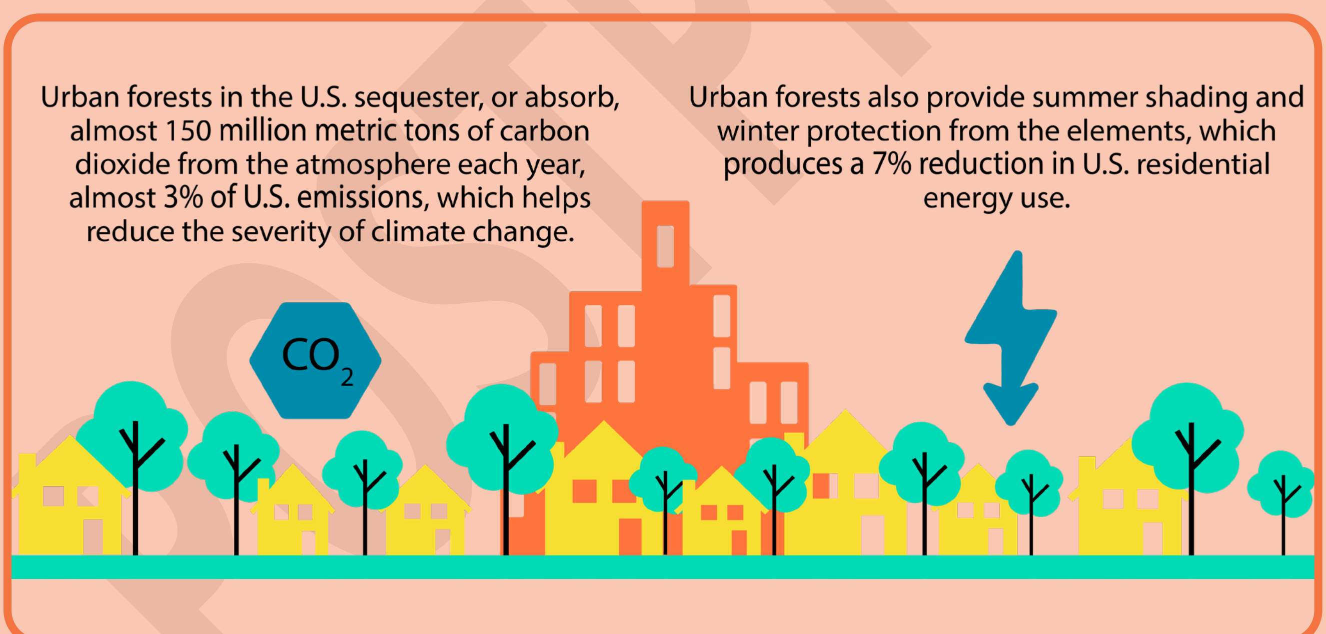

Figure 2—Urban forest carbon mitigation benefits.[24-26]

An Adaptation Planning Process

The Menu is designed to be used in conjunction with the Adaptation Workbook,[21] a tool that provides a structured, adaptive approach for integrating climate change considerations into planning, decision-making, and implementation of urban forest resources (Fig 3). The Adaptation Workbook is a step-by-step process that helps users consider the potential effects of climate change and design land management and conservation actions that can help prepare for changing conditions. It can accommodate a wide variety of geographic locations, ownership types, ecosystems and land uses, management goals, and project sizes.

Together, the Menu and the Adaptation Workbook help managers consider climate risks and explore the benefits and drawbacks of potential adaptation actions within the context of a particular situation or project. While the "Workbook" was developed to be applied in natural resource management, including urban forestry, the process also can be adopted for planning of human health systems. Further, the "Climate & Health Action Guide"[29] [also include hyperlink] is available online as an entry point to the Adaptation Workbook.[21]

The Adaptation Workbook and growing list of resources have been used together in hundreds of real-world natural resources management projects. Other menus address resource areas such as agriculture,[30] forest carbon management,[27] recreation,[31] forested watersheds,[32] open wetlands,[33] and culturally relevant indigenous perspectives.[34] Many of these are presented online as adaptation demonstrations that provide relevant case studies of real-world

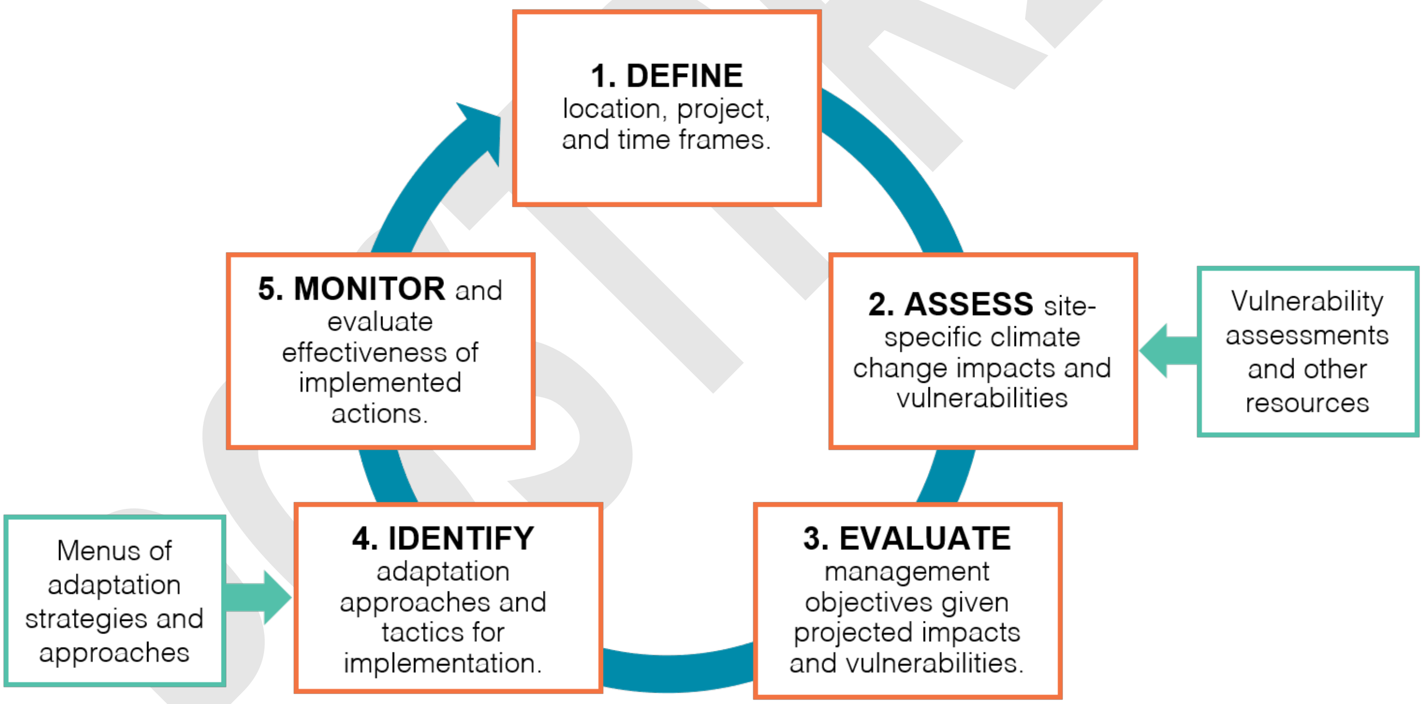

Figure 3—The Adaptation Workbook[21] describes an assessment and decision process that is used in conjunction with vulnerability assessments, local knowledge, and adaptation strategies menus. The results are site-specific actions that address explicit management and conservation objectives under a range of potential future climates. A brief description of the Adaptation Workbook process is presented in appendix 1 and in the "Climate & Health Action Guide".[29]

adaptation projects. To test the relevance of this Menu, community forestry partners from Rhode Island used it and Adaptation Workbook together in the development of an adaptation demonstration for a South Providence neighborhood (Box 2; also, appendix 2).

Box 2: Climate and Health Adaptation on a Neighborhood Scale

A team of urban forestry professionals and community partners in Rhode Island used the Urban Forest Climate and Health Adaptation Menu, the Adaptation Workbook, and other resources to evaluate climate change impacts and outline adaptation efforts for a real-world project. The Providence Parks Department and the Providence Neighborhood Planting Program are working to engage residents and neighborhood stakeholders in developing and implementing community-driven tree-planting and stewardship solutions focused on climate adaptation and human health in Upper and Lower South Providence.

Tree canopy cover in Upper and Lower South Providence is threatened by increased temperatures and precipitation, more frequent extreme weather events, and altered soil moisture. Neighborhoods in this region are disproportionately burdened by the impacts of climate change and environmental injustice.[35] A number of interrelated factors, such as a high coverage of impervious surfaces, low tree canopy cover, and proximity to a major highway and industrial port, result in negative impacts on health and well-being; these include urban heat island effect, flooding, and poor air quality. The local urban forest managers used the Menu to identify adaptation actions, including:

- Increase and improve tree canopy
- Select climate-adapted tree species
- Increase ground cover biodiversity
- Install curbside bioswale tree filter pits
- Assess and maintain existing tree stock

Appendix 2 presents a case study of this adaptation project. Appendix 3 includes a tree species list for Rhode Island that provides information on climate vulnerability, carbon benefits, and health services and disservices for more than 120 tree species.

How to Read this Menu

The Menu offers nature-based solutions that address climate change and promote human health and well-being in urban forest management and conservation. The Menu is organized hierarchically into strategies, approaches, and tactics (Fig 4, Box 3).

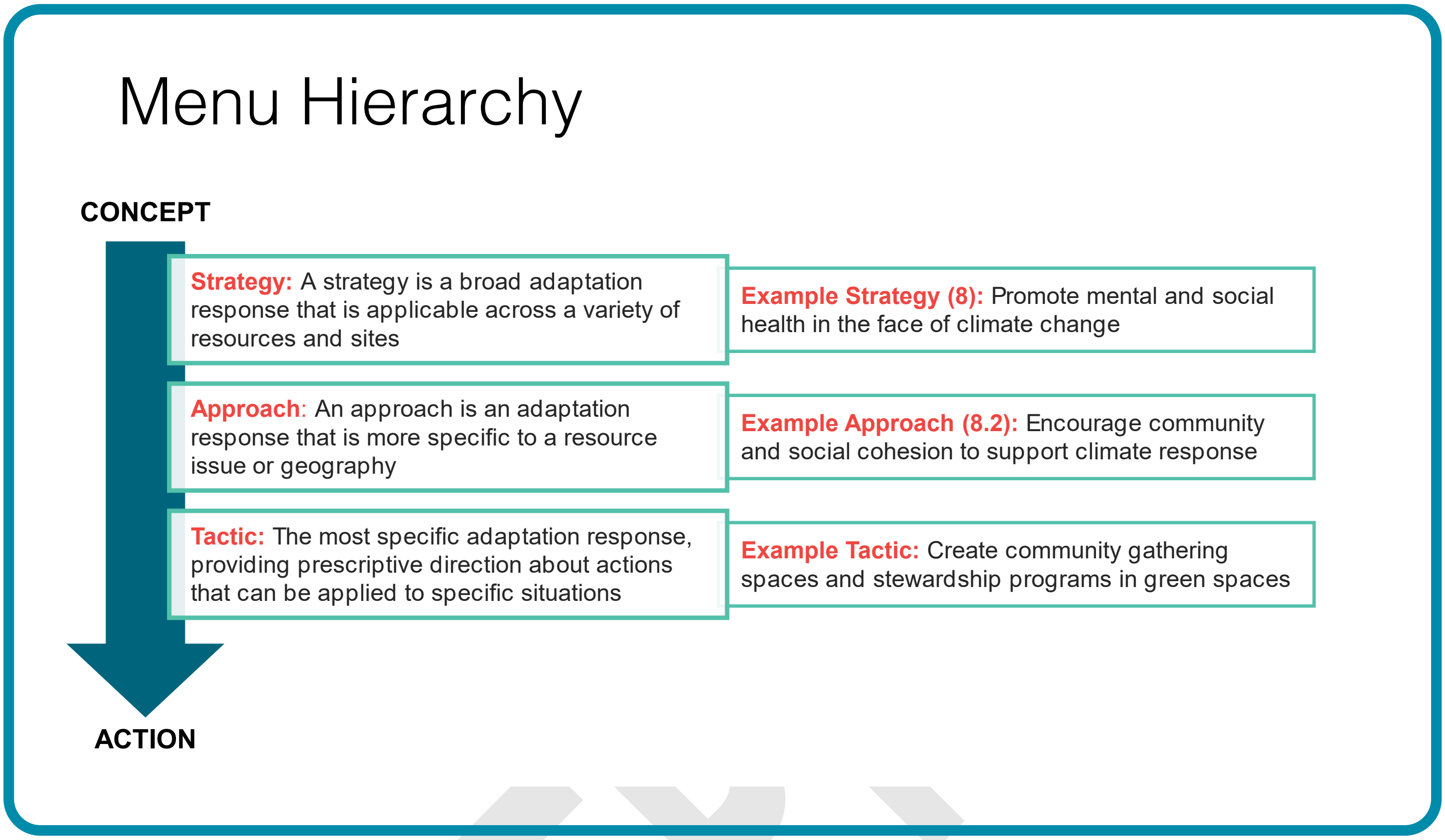

Figure 4—The hierarchical relationship of strategies, approaches, and tactics relevant to urban forestry, with an example of each. These serve as “stepping stones” for moving from broad concepts to actions that can be applied to a project, policy, or planning effort.

STRATEGY is defined as a broad adaptation response that is applicable across a variety of socio-ecological systems, natural resources and sites, hydrologic and ecological conditions, and overarching management goals.

APPROACH is a detailed adaptation method selected in response to a specific issue, site condition, or management objective that further describes how strategies could be employed.

TACTICS are prescriptive actions designed to be useful for local community or site conditions and management objectives. Tactics are the most specific adaptation response, being practical actions that can be tailored to unique situations and fit the needs of particular species, ecosystem type, site conditions, management objectives, and other factors. For communities and health, tactics span choices to engage in planning, reduce risk, protect vulnerable populations, and design for optimal vegetation placement. Examples of tactics are provided for each approach.

The strategies, approaches, and tactics are derived from a wide variety of peer-reviewed research and evidence-based reports. The Menu helps to translate these sources and their concepts into targeted and prescriptive tactics for responding to climate change in communities and offers opportunities at different scales that can be incorporated into either comprehensive or specific climate adaptation initiatives. Notably, it does not provide specific recommendations or guidance for any particular place or situation, and not all strategies and approaches will work together (Table 2). Like any menu, the Urban Forest Climate and Health Adaptation Menu presents options to the user; however, some options will appear more suitable and appropriate than others. Actions that work well in one setting or community type may not work in another.

Table 2. Considerations for using the menu of adaptation strategies and approaches.

menu provides:	menu does not:
► A broad spectrum of climate adaptation actions that can help sustain healthy ecosystems and resilient green infrastructure.	► Make recommendations or set guidelines for management decisions. It is up to the manager and stakeholders to decide how this information is used.
► A platform for discussing climate change-related challenges and adaptation methods for projects from site to citywide scale.	► Express preference for any strategies or approaches within a particular community or place, as these will depend on site-specific factors, local knowledge, and management goals.
► An actions framework offering managers choices for new programs and actions that align with their specific management goals and objectives.	► Provide an exhaustive set of tactics. Managers and stakeholders are encouraged to consider additional actionable tactics appropriate for their projects.
► Approaches to address climate-related human health threats and additional nature-based solutions for wellness, especially for disadvantaged communities.	► Apply equally to all regions. The Menu will be most applicable to temperate regions and areas capable of supporting trees.
► A framework that promotes collaborative discussions and partnerships among urban forestry, planning, public health, and other allied professionals.	► Cover all topics that pertain to urban forestry and human health. Additional menus related to recreation, wildlife management, and watershed management, among others, can be found at www.forestadaptation.org/strategies. A recent review[11] provides additional urban forestry and human health information.
► Examples of tactics that can be used to implement a strategy or approach, yet are flexible and adaptable to local conditions and programs.	

The Menu items can be applied in various combinations to achieve desired outcomes and can build upon any current management actions that support long-term urban forest sustainability and resilience, as well as more livable human communities. In addition to actionable choices, the Menu can be useful for brainstorming adaptation actions and generating productive discussions about community needs and values. Menu choices can be used to guide planning, education and outreach, and research, as well as changes in policy or infrastructure within communities.

BOX 3: URBAN FOREST CLIMATE AND HEALTH ADAPTATION MENU

Strategy 1: Activate social systems for equitable climate adaptation, urban forest, and human health outcomes

Approach 1.1: Address socio-ecological systems in early, comprehensive response

Approach 1.2: Integrate urban forestry in climate planning and policy

Approach 1.3: Address climate and health challenges of disadvantaged communities and vulnerable populations

Strategy 2: Reduce the impact of human health threats and stressors using urban trees and forests

Approach 2.1: Reduce extreme temperatures and heat exposure

Approach 2.2: Improve urban air quality conditions

Approach 2.3: Anticipate and reduce human health impacts of hazardous weather and disturbance events

Strategy 3: Maintain or increase extent of urban forests and vegetative cover

Approach 3.1: Minimize forest loss and degradation

Approach 3.2: Maintain existing trees through proper care and maintenance

Approach 3.3: Restore and increase tree, forest, and vegetative cover

Approach 3.4: Sustain sites and ecosystems that provide high value across the landscape

Strategy 4: Sustain or restore fundamental ecological functions of urban ecosystems

Approach 4.1: Maintain or restore soils and nutrient cycling in urban areas

Approach 4.2: Maintain or restore hydrologic processes in urban forests

Approach 4.3: Restore or maintain fire in fire-adapted ecosystems

Strategy 5: Reduce the impact of physical and biological stressors on urban forests

Approach 5.1: Reduce impacts from extreme rainfall and enhance water infiltration and storage

Approach 5.2: Reduce risk of damage from extreme storms and wind.

Approach 5.3: Reduce risk of damage from wildfire.

Approach 5.4: Maintain or improve the ability of forests to resist pests and pathogens

Approach 5.5: Prevent invasive plant establishment and remove existing invasive species

Approach 5.6: Manage herbivory to promote regeneration, growth, and form of desired species

Strategy 6: Enhance taxonomic, functional, and structural diversity

Approach 6.1: Enhance age class and structural diversity in forests

Approach 6.2: Maintain or enhance diversity of native species

Approach 6.3: Optimize and diversify tree species selection for multiple long-term benefits

Approach 6.4: Maintain or enhance genetic diversity

Strategy 7. Alter urban ecosystems toward new and expected conditions

Approach 7.1: Favor or restore non-invasive species that are expected to be adapted to future conditions.

Approach 7.2: Establish or encourage new species mixes

Approach 7.3: Introduce species, genotypes, and cultivars that are expected to be adapted to future conditions

Approach 7.4: Disfavor species that are distinctly maladapted

Approach 7.5: Move at-risk species to more suitable locations

Approach 7.6: Promptly revegetate and remediate sites after disturbance

Approach 7.7: Realign severely altered systems toward future conditions

Strategy 8: Promote mental and social health in response to climate change

Approach 8.1: Provide nature experiences to ease stress and support mental function

Approach 8.2: Encourage community and social cohesion to support climate response

Strategy 9: Promote human health co-benefits in nature-based climate adaptation

Approach 9.1: Co-design large-scale green infrastructure and built systems to promote health

Approach 9.2: Provide micro-scale nature experiences to promote health and healing

DESCRIPTION OF MENU ITEMS

Strategy 1: Activate social systems for equitable climate adaptation, urban forest, and human health outcomes

This strategy addresses how the goals and programs for urban forest ecological adaptation can fit into the broader policy- and decision-making processes of local governments and organizations. It encourages action and engagement at the broadest scale of governance and policy within jurisdictions and by agencies. Effectively addressing climate change is complex, from identifying causes to understanding effects. Although urban forests are not the dominant land use or land cover in most cities, urban trees can deliver practical solutions for climate mitigation and adaptation, while delivering important co-benefits—including human health.[36] This is especially important as most Americans now live in urbanized areas, a term that encompasses cities and towns of all sizes. The success of climate strategies depends on the dedicated activity of stakeholders, passionate champions, and innovations within social systems from the local to regional level. An action model has been used to promote sustainable urban forests and includes three general activities: understand the vegetation resource, engage urban forest stakeholder communities, and enact quality resource management.[37] A focus on the urban forest resource and its management is important, alongside equal commitment to community involvement and public outreach. Effectively engaging urban residents and leadership can help sustain urban forest, climate, and environmental justice goals for the health of both trees and humans.

Approach 1.1: Address socio-ecological systems in early, comprehensive response

Addressing both climate and health implications at the earliest stages of planning can be helpful in ensuring a cohesive and comprehensive response.[38, 39] Urban forest projects may range from a site-scale memorial tree planting to a tree-planting campaign across an entire city. Combined analysis using big data (such as remote sensing), on-the-ground measures, civic science inputs, and social media records can inform better understanding of urban situations and climate patterns from local to regional scales.[40] Planning and working effectively at all scales involves partnership and collaboration, engaging professional expertise, local knowledge, and civic leadership and pride embedded within communities.[41] Organizations and institutions that once regarded trees as beyond their scope are now becoming more attuned to nature-based solutions.[42] While complex and sometimes time-consuming, a commitment to incorporating a socio-ecological outlook in urban forestry planning and management can lead to more trees planted and stewarded, broader cross-sectoral support, and dedicated resources.[43]

EXAMPLE ADAPTATION TACTICS

- Engage the public, decision-makers, and thought leaders in discussions of shared visions about urban forest planning and management, particularly on topics of climate and human health.[44]
- For all tree and forest projects, evaluate potential to address multiple climate-based human health impacts[45] using a co-benefits outlook.[46]

- ▶ Collaborate with public health and other agencies that work on climate planning to promote the urban forest as an upstream public health solution that addresses root causes of health problems rather than symptoms.[47, 48]

- ▶ Synchronize urban forest planning and management across jurisdictions and departments to address emergent climate-based community health risks and threats.[49]

- ▶ Identify, assess, and acknowledge disparities in canopy, parks, and green space distribution[50] as part of tree canopy analysis.[51]

- ▶ Co-develop community-driven projects that increase nearby nature, including experiences of trees and forests, an evidence-supported social determinant of health, and a path to tree equity.[52, 53]

- ▶ Involve and engage communities in development of tree projects that reflect community and cultural values, while addressing local climate impacts and associated health effects.[54, 55]

Approach 1.2: Integrate urban forestry in climate planning and policy

Many government agencies promote green infrastructure strategies and nature-based solutions in climate planning and policy.[56, 57] Including urban forestry in planning and policy development helps ensure that trees are integrated into long-term climate response and that urban forestry professionals are included in these decisions. Connecting trees to climate change mitigation can also lead to more sustained and consistent urban forestry support.[58] There are multiple dimensions of planning that can include urban forestry and address climate and health. Comprehensive and strategic plans that serve as blueprints for most city initiatives and governance can include climate goals. Additionally, explicit climate mitigation and adaptation plans can be developed at the level of local government, ideally also addressing disaster preparedness. Further, municipalities may incorporate provisions for climate and health into urban forest management plans, as they provide guidance for sustainable urban forests and promote best practices. Planning entails processes of developing, drafting, and stakeholder vetting of initiatives, with reliance on public education, outreach, and engagement.[49] The resulting public dialog about planning and policy fosters improved awareness of emergent concerns and solutions by the public and local leaders, which can extend to urban forestry.[59] Incorporating trees and urban forests in all plans that reference climate can help promote climate-resilient communities, protect all people from the health impacts of climate change, and optimize health and health equity outcomes.

EXAMPLE ADAPTATION TACTICS

- ▶ Within and across local jurisdictions, assess tree canopy and other green spaces to analyze and ascertain tree distribution as a baseline for planning.[60]

- ▶ Analyze disparities of green infrastructure distribution, especially in relationship to patterns of health morbidity (meaning rates of diseases) and mortality.[61-63]

- Include climate and health interactions, with attention to environmental justice and equity, within municipal or county urban forest management plans.[64-66]

- Conduct a Health Impact Assessment of any urban forestry program or management plan on the community to local jurisdiction scale.[67]

- Prepare Urban Forest Emergency Management Plans or Storm Mitigation Plans at the local government level to anticipate and respond to extreme weather and potential hazards from trees.[68]

- Collaborate across city departments and agencies—including parks, transportation, public works, utilities, and school districts—to include trees, open space, or other components of green infrastructure in comprehensive climate action planning.[69, 70]

- Facilitate the inclusion of trees and urban forests in all foundational urban planning (such as comprehensive plans and strategic plans) and associated departmental or sector-specific plans (such as tree retention in development, permitting policy, and transportation).[54]

- Incorporate trees, natural areas, parks, and the urban forest in local government capital planning and budgeting that is dedicated to climate response and resilience.[71]

- Include urban forest, climate, and health interactions in more localized planning, such as Tribal or community plans,[72] and also in implementation, such as code and ordinances.

- Include green infrastructure and urban forest parameters when developing metrics and benchmarking performance of climate policies or programs and addressing health outcomes.[49, 73]

- Expand planning and policy from single communities to multi-jurisdictional regional collaborations, supporting expansion of climate adaptation functions and services to the ecosystem scale.[74, 75]

Approach 1.3: Address climate and health challenges of disadvantaged communities and vulnerable populations

Certain communities and populations are disproportionately at risk of impacts from climate change. Such risks are due to both historic legacies of discrimination (such as redlining[76, 77]) and ongoing social, economic, and health challenges. Health concerns touch both place and person. Disadvantaged communities are often situated physically and economically such that they may experience "first and worst" climate change consequences. Native and Tribal communities are disproportionately affected by these consequences, as are residents living in lower-income or marginalized neighborhoods. Insufficient economic funding and infrastructure to respond to these threats can jeopardize these vulnerable communities.[78] In addition, there are population groups of specific demographics (such as elder or young age, or those with pre-existing health conditions) that are generally more vulnerable to changing conditions and environmental health threats.[79] Some climate conditions affect both disadvantaged communities and vulnerable populations disproportionately,[80] so attention to both human and tree health impacts is important. Equity is becoming a guiding principle in urban forestry, as there are disparities in the distribution of tree canopy in many cities.[62, 81] Lower-income communities often have less tree canopy cover than nearby communities of greater affluence.[82, 83] Successfully addressing these inequities is more complex than simply planting trees, however; careful consideration of potential positive and negative consequences for residents across the project location, including people having particular health sensitivities, may lead to more nuanced planning and implementation of tree planting.[84] A carefully planned urban forest project can generate a wide range of health benefits; however, urban greening, such as tree planting, also can be associated with dynamics of gentrification that can result in displacement of long-established residents.[85-87] Careful, responsible urban forestry and urban greening planning includes important goals of community engagement, as well as involvement and collaboration with those who know their communities best.

EXAMPLE ADAPTATION TACTICS

Work to understand local climate-based human health vulnerabilities, possibly including a formal vulnerability analysis to define, identify, classify, and prioritize response to risk.[61, 88]

- Apply the principles and practices of Community Based Climate Adaptation,[89, 90] an inclusive approach that engages residents of disadvantaged communities early in projects and integrates local knowledge in the design and implementation of climate actions.
- Identify and prioritize sites for urban forest projects where vulnerable populations are concentrated, such as schools, elder care facilities, or health treatment centers.[91, 92]
- Plan and select tree projects that can initiate and anchor the creation of public and civic nature spaces, and in so doing, address known disparities of parks and green space distribution and access.[65, 93]
- Conduct outreach to residents of disadvantaged communities to understand their experience with urban forestry programs, determine needs, and initiate collaborations on improvements.[53, 94]
- Engage residents and community organizations in planning and stewardship of tree projects so that benefits are sustained.[95]
- Collaborate with community members and organizations to evaluate and implement culturally significant, relevant, and symbolic choices for green space vegetation, including trees and other vegetation.[96-99]
- Address potential gentrification or displacement consequences of urban forest enhancements within marginalized communities.[85, 100-104]
- Involve local businesses and hire community residents to develop green infrastructure jobs and career pathways that are place-based and support beneficial climate and health outcomes.[105-110]

Strategy 2: Reduce the impact of human health threats and stressors using urban trees and forests.

This strategy describes how the urban forest can address multiple direct climate-related impacts in communities. Climate change is altering fundamental processes and conditions that sustain the lives and health of local trees and people. Communities are feeling the resulting consequences; there also are multiple public health implications for people within most cities.[111] Rising temperatures lead to more frequent heatwaves, with impacts amplified in urban settings, leading to heat-related illness and mortality.[112] Heat and other climate influences combine to impact air quality, while increased levels of particulates and allergens contribute to cardiovascular and respiratory illnesses.[113] Extreme weather sets up conditions for increased flooding and storm events, along with more frequent and intense wildfires. Sea level rise introduces risks for coastal properties and residents. These disruptive events and changes can directly impact basic life support, such as drinking water contamination or loss of homes, and can introduce indirect health effects, such as psychological trauma and grieving.[114] Nature-based adaptation strategies can be used to both prevent and respond to these interrelated human and ecosystem health threats. Strategically planned and implemented urban tree, forest, and greening projects present important opportunities to mitigate and accelerate recovery from extreme weather and disturbance events.[115]

Approach 2.1: Reduce extreme temperatures and heat exposure

One of the primary public health concerns regarding climate change is the increased intensity and frequency of heat waves. For instance, the number of days hotter than 100 °F in cities may increase nearly threefold in the United States by 2050, and the duration of the longest extreme heat events in an average year will double.[112] Extreme heat events cause more deaths in the United States annually than all other weather-related causes combined (including hurricanes, lightning, tornadoes, and floods), and the effects of these events are most pronounced in urban areas.[116] Increased heat is associated with higher rates of both heat stroke and hyperthermia; mortality rates may be even greater than reported because heat events trigger serious complications from pre-existing health conditions.[117] Some people are at higher risk of heat-related illness, including those who are elderly, very young, disabled, poor, or live alone; those with existing cardiovascular medical conditions; and those living in urban areas having high air pollution or in buildings without air conditioning. Urban greening, particularly tree cover, is a heat-mitigation approach.[117] Thermal comfort is improved when people spend time in tree-covered spaces.[118] Trees have been found to reduce the risk for heatstroke and heat-related ambulance calls during extreme heat events.[119, 120] Groups of trees cool the immediate, and sometimes extended adjacent, area by way of evapotranspiration and shading, and also by affecting air movements and heat exchange.[121] In warmer climates, shaded surfaces can range from 25 °F to 35 °F cooler than the peak temperatures of exposed surfaces.[122, 123] Planning for placement of specific vegetation types can help control actual and localized effects, potentially creating a more amenable environment for communities.[124, 125]

EXAMPLE ADAPTATION TACTICS

- Plan tree projects to reduce ambient summer temperatures in and around higher density residential areas and civic spaces serving more frequent visitors and users (such as transit centers, playgrounds, and plazas).[126, 127]
- Plan projects to increase tree canopy cover and shading of heat-absorbing impervious surfaces, such as roads, sidewalks, large parking areas, and roof areas.[123, 128-130]
- Plan tree planting or conservation to create patches, as tree clusters provide greater shading and transpiration benefits, though analysis of microclimate conditions is important (such as solar aspect, topography, and wind).[127, 131]
- Promote and conserve large trees using local government policy or code and best management practices, as larger trees provide greater area and density of shade for cooling effects and human comfort.[132]
- Create thermal refuges in frequently used public spaces (e.g., residential courtyards and neighborhood parks) through careful tree selection and arrangement, and incorporate built elements (e.g., shade structures, pools or fountains, and spray or mist systems) to provide additional respite during high heat events.[133-136]
- Design and locate tree projects to reduce extreme heat in under-resourced neighborhoods and near facilities that serve vulnerable populations, such as schools, hospitals, or elder care facilities.[135, 137-140]
- Incorporate native grasses and other understory plants in spaces too small for trees to reduce urban heat island effects and use organic mulch instead of rock mulch to prevent the heat load of parkway strips, parking lot aprons, and other commercial planting spaces.
- Work closely with local or state health departments on efforts to monitor and report heat-related illness and other climate-related human health impacts to facilitate forest and public health data integration and planning.

Approach 2.2: Improve urban air quality conditions

Climate change is contributing to reduced air quality in many places by modifying weather patterns that increase and focus pollutants, enhance storm and disturbance events that raise particulate levels, and elevate the release of pollen and volatile organic compounds.[141, 142] Poor air quality, most notably from fine particulates, compromises human respiratory and cardiovascular systems.[143] Ground-level ozone (generated by volatile organic compounds) and particle pollution can have a range of adverse effects on human health and are responsible for extensive human respiratory illness and mortality each year.[144] Higher pollen concentrations and longer pollen seasons, combined with other aeroallergens, can increase the prevalence and severity of allergic disease.[145] Pollen allergenicity is a seasonal health concern that interacts with broader environmental conditions, such as temperature, humidity, and other air pollutants, to negatively influence human health.[146] Although tree pollen may contribute to illness, some household allergens[147, 148] and other plants (such as ragweed, which produces the most allergenic pollen[149]) pose equal or greater risk. All of these conditions can disproportionately harm older people and children.[150] Awareness and consideration of these complexities are critical when planning health benefit pathways using the urban forest. Reduced asthma has been associated with exposure to natural areas and biodiversity,[151] including in children.[152] In some case, trees can intercept particles on leaf and limb surfaces, reducing the amount of respiratory irritants in the air.[153] They can also absorb and remove polluting gases, such as ozone and nitrous oxide.[154, 155] Careful planning of plant selection, planting density and location, and management can increase health benefits while reducing risks.[156]

EXAMPLE ADAPTATION TACTICS

- Use tree projects at local and citywide scales to mitigate sources of air pollutant compounds and particulates to help protect people from negative health effects.[157-160]
- Select tree species having specific traits when planting to improve air quality, as different leaf structures and surfaces enable better capture at different times of the year,[161-165] with coniferous trees being more effective for overall particulate capture.[166]
- Plant trees near major emissions sources, such as industrial or manufacturing sites, to reduce air pollution. Consider species selection, tree size, and leaf area, as well as the position of plantings relative to nearby buildings and other features that can influence wind direction and speed.[167]
- Plan tree projects in alignment with transportation plans to provide "green screens" for high-speed, high-volume transportation corridors, as these are concentrated sources of particulates and emissions that can drift into adjacent residential areas and facilities that serve vulnerable populations (such as schools).[160, 168, 169]
- Plan for the interactions of microclimate conditions of wind speed and direction, ventilation patterns, and adjacent structures (especially in urban canyons) to avoid elevating concentrations of aerial particulates due to tree plantings.[170, 171]
- Plan tree projects to reduce locally recognized sources of plant-based allergens, such as using fewer male trees to reduce pollen or avoiding species that cause increased allergenic response.[172-174]
- Select and manage trees to reduce biogenic volatile organic compound emissions to limit contributions to air pollution.[175-177]

Approach 2.3: Anticipate and reduce human health impacts of hazardous weather and disturbance events

Climate change is exacerbating the incidence of episodic events and disturbances, such as coastal storms, hurricanes, tornadoes, flooding, and wildfires. These events can take a devastating toll on health within a community,[178] ranging from loss of shelter to reduced potable water, limited food access, and increased infectious disease transmission.[179, 180] People in urban areas can be at greater risk given extensive transportation and utility infrastructures that are vulnerable to damage, along with higher density residential housing that may be hard-hit by property damage and personal injury. Additionally, increased incidence and severity of wildfire amplifies risk of tragic personal and property loss, especially in the wildland-urban interface, and severely compromises air quality over large areas. Urbanized areas are more prone to certain disturbance events (such as tornadoes or floods[181]) than rural or wildland areas because of changing weather cycles. Managed landscapes and forests can be incorporated into emergency planning to prepare for these large, infrequent disturbances.[182] Analysis and preparation before a storm event will help communities minimize harm to trees, property, and people. While trees can become hazards during high-wind events such as hurricanes and tornadoes, proper preparations can make trees more wind-resistant and storm recovery more effective.[183] Planning and management can also reduce tree and property damage during ice storms.[184] In addition, green infrastructure and natural resources are increasingly valued as buffers that protect human populations against weather-related acute shocks. For instance, maritime forests and forested swamps can be part of hybrid nature and infrastructure systems for coastal defense from storms.[185, 186] This approach complements, and can be used in conjunction with, approaches 5.2 and 5.3, which describe actions for reducing extreme weather and wildfire impacts on trees and forests.

EXAMPLE ADAPTATION TACTICS

- Assess and prioritize areas that are vulnerable to extreme events, such neighborhoods located in storm- or flood-prone areas.[178]
- Conduct hazard and resilience assessments in ways that acknowledge and respond to historic socio-cultural inequities.[187]
- Create, test, and implement urban forestry best practices for tree management prior to a disturbance event, an immediate response system after disturbance, and a mid-term recovery process.[188, 189]
- Participate in local emergency preparedness initiatives to engage residents in developing community-based planning and response processes for their neighborhood urban forest.[187, 190]
- Engage and educate community residents in tree management best practices and ongoing stewardship on both private properties (such as homeowners' yards) and public lands (e.g., municipal parks and community gardens) to minimize damages and loss during disturbance events.[191]
- In areas prone to high winds, implement best practices to manage trees (such as species selection and pruning) to minimize property damage and human injury during storm events.[192]

- Educate property owners and community members to promote adoption of Stormwise practices of forest and management in urban and suburban areas that are at risk for extreme storms.[193, 194]
- Educate property owners and community members to promote adoption of Firewise USA® practices of tree planting and management in urban and wildland urban interface areas that are at risk for wildfires.[195]

Strategy 3: Maintain or increase extent of urban forests and vegetative cover

This strategy addresses the foundational role of healthy tree and vegetative cover in urban areas to reduce climate impacts to human health and ecosystem function, while maintaining carbon sequestration and other ecosystem services. Urban forests and other forms of vegetative cover can ameliorate many climate-related threats and help mitigate climate change through reduced energy demands and carbon sequestration. Increasing the extent of urban forests not only allows for enhanced climate adaptation and carbon mitigation benefits for all communities, it is also a primary opportunity for addressing the environmental inequities in our cities. For example, urban trees and greenspace can help reduce the urban heat effect that is exacerbated by climate change.[123, 196] Green infrastructure, when properly planned and sited, can help minimize urban heat islands through increased shading and evaporative cooling.[57, 197] Further, carbon mitigation in urban areas reaches its highest levels where tree canopy densities are highest, while simultaneously reducing energy usage in buildings.[25, 198] Actions that retain or increase tree canopy cover, while preserving the integrity of these ecosystems in the face of climate change, can have some of the most significant benefits for maintaining human health, climate mitigation, and other environmental benefits into the future. Activities within this strategy seek to sustain or enhance the long-term benefits of urban forests on human well-being and ecosystem function by minimizing loss and fragmentation of historically forested areas, maintaining current tree and forest cover, and increasing tree canopy.

Approach 3.1: Minimize forest loss and degradation

Conversion of historically forested areas to other land uses, fragmentation, and degradation threaten the climate adaptation, carbon mitigation, human health, and other benefits these forests provide. Development pressures are a major threat to urban forests; from 2009 to 2014, forest loss due to urbanization was estimated at 175,000 acres per year in the United States.[199] Over the same time period, pavement and other impervious surfaces increased by 167,000 acres annually. Actions to minimize forest loss, landscape fragmentation, and ecosystem degradation can be fundamental to protecting ecosystem services, or the benefits people receive from nature. In some states, such as New Jersey and Maryland, municipalities have created policies or ordinances to reduce forest loss from development and reforest affected areas.[200, 201] Additionally, planning for new urban infrastructure and site development that takes advantage of existing green infrastructure, including desirable trees, shrubs, and grass cover, will reduce the time and resources needed for vegetation establishment. Making efficient use of existing tree canopy allows for immediate benefits for climate and health for communities.

EXAMPLE ADAPTATION TACTICS

- Develop urban forest regulations, policies, or plans that reduce land-use change and land disturbance and identify requirements for remediation of disturbed sites.[202]
- Minimize the amount of land disturbed by urban site development and locate hardscaped areas, such as roads, sidewalks, and parking spaces, to minimize negative impacts to existing vegetation.[203]
- Retain and protect existing trees during development of urban green spaces.[204, 205]
- Restrict development in priority areas by acquiring property for preserves or using conservation easements on private land holdings to protect natural land cover or maintain corridors between existing natural areas.
- Implement protective guidelines, such as best management practices and tree heritage and protection ordinances, to avoid unintentional loss of trees during development.[204, 206, 207]

Approach 3.2: Maintain existing trees through proper care and maintenance

Urban forests will continue to face increasing pressure from climate change. More active management and investment to promote tree health, survivability, and longevity may be necessary to reduce hazards to human health and safety, and to ensure long-term health and continued provisioning of environmental benefits such as carbon sequestration. In developed urban sites, sustained maintenance of urban trees includes pruning, watering, mulching, and other soil improvements, along with pest and disease monitoring and management, and protection from extreme weather. Although these activities are costly, accounting for roughly a third of urban forest budgets, research has shown the costs of not maintaining trees can be even greater.[208] For example, insecticide treatments, especially for large, long-lived trees that can store up to 1,000 times more carbon relative to smaller trees in some locations,[209] can be more a cost-effective method for maintaining a tree versus the cost of removing and replacing a tree killed by emerald ash borer.[210, 211] Street trees, in particular, face challenging growing conditions, with annual mortality rates at 3 to 5 percent, causing the average lifespan of a street tree to be 15 years or less.[212] Some maintenance activities, such as watering, may become even more necessary as droughts become more frequent or severe.[213] In urban natural areas or forest patches, certain activities, such as hazardous tree removal, prescribed burning, and non-native invasive species removal, can be used to maintain or improve forest condition. In addition, some localities are beginning to incorporate traditionally rural silvicultural practices in their urban natural areas management as an integrated forest health and climate change strategy.[214]

EXAMPLE ADAPTATION TACTICS

- Water individual trees in susceptible locations during extreme droughts and heat waves to reduce mortality.[215]
- Prune street trees to establish strong branching structure with a central leader to reduce the center of gravity. Remove structural defects in mature canopy trees.

- Ensure that trees are planted properly, such as at an appropriate depth and with no root girdling, to optimize growth rates and make trees less susceptible to drought and other stressors.[215]

- Remove mowed turf from the rooting zone of trees and replace it with organic mulch or other plants that require less water and nutrients, also protecting the tree from mower damage.

- Implement silvicultural practices in urban natural areas to improve the health of the entire forest community, such as thinning forest stands to increase growing space for the remaining trees.

- Manage stand density and age in forested areas to reduce risks of property damage and hazards from severe weather events, using Stormwise[193, 194] or other forest management practices.

- Ensure that newly planted trees have sufficient soil volume to support the tree at maturity and enough space to grow without interfering with underground or overhead utilities.

- Utilize stormwater to supplement irrigation of street trees and urban forest vegetation.

Approach 3.3: Restore and increase tree, forest, and vegetative cover

Efforts to increase urban tree cover and forest canopy are growing across many parts of the United States and globally in recognition of the benefits to human health, climate adaptation, carbon sequestration, and environmental quality. A growing body of research points to the potential of increasing forest cover as a natural climate solution across all ecosystem types[22] and in urban areas, in particular.[23, 216, 217] Urban forestry is highlighted as an important mechanism for increasing stored carbon, as trees in urban areas can have significant biomass and carbon sequestration.[198] Carbon sequestration rates in individual trees within urban areas can exceed those in natural forests due to greater foliar biomass and reduced competition from lower tree densities, as well as irrigation and fertilization[218]—and a changing climate may be further accelerating these growth rates in some urban areas if there is also sufficient moisture.[219, 220] Trees can have an additional important influence on carbon mitigation in urban zones by reducing the energy requirements for building heating in winter (due to wind protection) and summer cooling (from tree shading).[155] Increasing tree and forest cover in urban areas takes advantage of opportunities to increase canopy in places where trees are not currently present or abundant and will not interfere with other uses of the sites, which may include increasing tree density in green spaces where trees already exist, such as in urban riparian zones,[221] as well as afforestation on abandoned industrial or previously developed sites.

EXAMPLE ADAPTATION TACTICS

- Create parks and green spaces on abandoned or underutilized spaces, such as brownfields and vacant lots.[222, 223]

- Plant trees on abandoned land that was cleared for agriculture, mining, or other reversible uses.

- Add street trees or other vegetation to help "green" areas that currently have low canopy, recognizing many of these areas have been historically disenfranchised.[224]

- Plant trees in strategic locations, such as upwind of areas most prone to extreme heat or in positions to provide maximum building shading or cooling benefits.[57, 197]

- Integrate trees as part of low-impact development or stormwater runoff projects.[225]

- Replant forests following disturbances in urban parks.

- Allow passive reforestation on land that had been cleared for agriculture or other uses and retain tree species that grow quickly and provide cover and shade on sites where passive reforestation is occurring.

- Use fast-growing native tree species to rapidly create a privacy screen or shade for outdoor spaces or buildings, ensuring proper species selection for long-term sustainability on the site.

- Establish trees adjacent to urban streams[221, 226] to create or expand riparian areas and help reduce impacts from extreme heat and floods.

- Ensure planting stock used for projects has been grown using techniques that provide healthy, vigorous root systems, such as in gravel beds,[227] and provide planted trees with adequate soil volume for root growth and anchoring.

- Use urban tree canopy inventories and remotely sensed data to identify new and existing areas that can serve as wildlife corridors or greenways and inform reforestation efforts.

- Construct wildlife corridors between natural areas to mimic habitat and ecosystem structure of the natural habitat (e.g., by maintaining or promoting oak (*Quercus spp*.) canopy cover in a residential development between two oak woodland natural areas) while avoiding the creation of ecological traps in these areas.[228]

- Plant native shrubs, grasses, or herbaceous plants in places where there is insufficient space for mature trees, such as parkway strips, medians, or other narrow or restricted planting zones.

- Create pollinator habitat with native shrubs and herbaceous plants along roadways or transportation corridors that are inappropriate tree-planting areas or are adjacent to forest edges.

Approach 3.4: Sustain sites and ecosystems that provide high value across the landscape

Urban forests provide numerous ecosystem services and benefits, and some sites or ecosystems may provide disproportionately high benefits for biodiversity, carbon storage, or other services. Some urban sites currently support high levels of biodiversity and contain geophysical characteristics that are likely to sustain and promote diversity even as the climate continues to change. Urban areas have the potential to host a significant percentage of locally occurring native species, including endangered species and other species of concern. These sites may be quite rare, however, because many pre-urban forest ecosystems have been fragmented, degraded by human use and invasive species, or developed into other land uses.[229] Remnant forest ecosystems can provide a suitable habitat for relict populations of species that were previously more widespread[12, 230] and act as refugia by providing habitat for species lost from surrounding areas due to human-caused disturbance. Sites with several topographically related microclimates and local permeability may provide the best chance for species responding to climate change.[231] Where forest carbon is valued, remnant forests may provide the greatest carbon densities and sequestration rates in developed areas,[232] while riparian areas may provide good opportunities for maintaining carbon mitigation both in biomass and in soils.[233] Restoration or reclamation projects may be needed to increase the representation of these habitats on the landscape or maintain the values associated with these systems. This approach places additional emphasis on targeted efforts to maintain and restore ecosystems that have been identified as high value, which extends efforts under Approach 3.1: Minimize forest loss and degradation.

EXAMPLE ADAPTATION TACTICS

- ▶ Identify areas with high diversity (species, topography, soils, or other factors) or other desirable attributes that can be set aside as natural areas or reserves, perhaps with the support of conservation easements, public tax funds used for municipal acquisition, or similar tools.
- ▶ Protect existing habitat remnants from loss, conversion, or invasion from nonnative plants, particularly if they are in areas that may provide future climate refugia.[234]
- ▶ Restore unique habitats that may be less susceptible to climate change or use reclamation efforts to create new patches of such habitats on suitable sites.
- ▶ Identify and protect areas of high geophysical or topographic diversity with the expectation that these areas may provide a range of climatic options to species with diverse requirements.[234]
- ▶ Identify urban plantings within developed landscapes that could serve as climate refugia.
- ▶ Establish and support development and management ordinances and regulations that protect and reduce impacts to high-quality forest remnants and ecological features.
- ▶ Use urban tree canopy inventories and remotely sensed data to identify new and existing areas that can serve as wildlife corridors or greenways.

- Manage natural areas that serve as wildlife corridors to promote their maximum habitat value (e.g., by removing invasive species) and prioritizing management in those locations.[235]

- Manage riparian corridors within otherwise highly developed landscapes to provide habitat value and ecosystem services.[236, 237]

Strategy 4: Sustain or restore fundamental ecological functions of urban ecosystems

This strategy emphasizes ecological processes and functions to preserve the capacity of systems to cope with changing and more variable climate conditions. Complex interactions among shifting climate, vegetation, and landforms may result in changes in ecosystem hydrology, soil quality, and nutrient cycling.[238] Ecosystems in urban environments are shaped not only by these changes, but also by the people who have shaped the landscape in the past, along with those who currently live, work, and recreate in them. Challenges to maintaining natural ecosystem functions in urban areas include impermeable surfaces, air and water pollution, frequent human disturbance, and altered soil characteristics. Climate change impacts can exacerbate these issues via extreme events and disturbances on ecosystems that may already be under stress or otherwise disrupted.[239] For example, urban forests in coastal areas are increasingly susceptible to the impacts from sea-level rise, coastal flooding, salinization, and storm damage. Climate change impacts, either alone or interacting with other stressors, can impair the health and productivity of urban trees, thereby reducing human health benefits for communities and the carbon mitigation capacity of urban forests. This strategy seeks to sustain or enhance ecological functions to reduce the potential negative impacts of a changing climate on urban forests.

Approach 4.1: Maintain or restore soils and nutrient cycling in urban areas

Urban soils provide a critical foundation for the health and productivity of urban forests. Poor soils and growing conditions cause most urban tree problems,[240] and these less favorable conditions will be exacerbated by climate change.[241] Urban soils vary across a continuum from undisturbed to highly engineered;[241, 242] soils in disturbed sites can lack essential nutrients and commonly include detrimental elements, such as chemicals, concrete, asphalt, and other foreign matter, that limit the long-term viability of a tree.[242, 243] Rising temperatures can increase drought conditions and alter nutrient cycling in all forests; the urban heat effect can intensify these impacts. Extreme rain events increase the potential for greater stormwater runoff and erosion.[239] Minimizing impacts to soils and restoring natural function can increase the benefits of urban soils. For example, although soil characteristics such as carbon content can vary widely in urban landscapes, urban soils store large amounts of carbon in organic matter[244] and have a substantial capacity to sequester carbon, especially in residential areas or other locations with lower levels of disturbance and other significant management inputs.[245] This approach focuses on preserving and restoring natural soil processes as a way to sustain urban trees and forests; it complements other approaches focused on maintaining urban ecosystems and reducing the impacts from extreme weather.[246]

EXAMPLE ADAPTATION TACTICS

- Analyze soil conditions prior to tree-planting activities to determine whether conditions are sufficient for healthy tree growth and identify deficiencies that need to be addressed.
- Improve growing conditions for revegetation or restoration efforts by adding organic matter amendments, such as mulch or biochar,[247-249] which can help improve drainage, pH, soil carbon storage, and rooting conditions.
- Identify areas that have had minimal soil disturbance and include high-quality soil conditions as a consideration when creating reserves or undeveloped areas.
- Prevent or reduce soil erosion in areas prone to soil loss during heavy rainfall events, particularly when soils are exposed following disturbance.
- Urban natural areas
- Remove invasive species that negatively affect soil processes or alter nutrient levels, such as European buckthorn (Rhamnus cathartica).[250]
- Add organic soil amendments (e.g., mulch, biochar) to urban sites undergoing restoration or revegetation.[247, 248]
- Inoculate soil with mycorrhizal fungi to increase organic matter and improve nutrient cycling and moisture retention.[251]
- Developed urban sites
- Provide adequate root volume in tree planters while ensuring soil conditions (texture, pH, nutrient levels) match tree requirements.[252, 253]
- Provide and develop adequate soil volume, texture, structure, and organic matter to support healthy tree growth.[253-255]
- Remove and replace the soil if toxicity or chemical levels are too high.
- Install a layer of mulch over the root zone of the tree to help retain moisture and mimic a natural growing environment.[253, 256]
- Rebuild the soil profile following development.[257, 258]

Approach 4.2: Maintain or restore hydrologic processes in urban forests

Climate change is altering precipitation patterns and increasing the frequency and intensity of rainfall and storms in many areas.[239] Urban forests and vegetation help to maintain urban hydrologic processes by intercepting, absorbing, and filtering rainfall and stormwater, which can reduce runoff and improve the quality of water reaching streams and lakes.[259] Likewise, vegetation can help retain soil moisture, which helps support urban forests and tree canopy and the associated benefits for human health and climate mitigation.[260] Many cities are recognizing the value of this green infrastructure and increasing tree planting and other efforts to improve vegetative cover, especially in riparian areas. Riparian forests, wetlands, and floodplain forests serve important ecosystem functions, such as decreasing soil erosion, filtering water, and storing and recycling organic matter and nutrients,[261-263] along with elevated carbon benefits.[23, 233] Trees in riparian areas also provide shade, which helps to buffer stream temperatures. Forested riparian areas can serve as corridors for wildlife and plant species migrating across otherwise fragmented landscapes[16] and provide substantial co-benefits for biodiversity and carbon storage.[233] Urban wetlands, whether remnant, intentionally restored, or "accidental," can also play an important role in hydrological functioning and other ecosystem services.[263, 264] This approach focuses on maintaining or restoring natural ecosystems and features as elements of the urbanized landscape to protect water quality and cycling.

EXAMPLE ADAPTATION TACTICS

- Restore natural hydrology where appropriate by removing drain tiles or other remnant hydrological modifications.[265]
- Restore or reforest native communities and ecosystem components (e.g., natural groundcover, litter layer, coarse woody debris) in riparian areas, particularly those adjacent to developed areas, in order to reduce erosion and nutrient loading into adjacent water bodies.[226, 265, 266]
- Adjust the location and design of trails in natural areas to minimize erosion under more intense surface runoff.[267, 268]
- Restore or promote a diversity of riparian tree and plant species in order to increase stream shading, provide a source of woody debris, stabilize the soil, and provide habitat and connectivity for wildlife.[265]
- Manage water levels to supply proper soil moisture to vegetation adjacent to the stream during critical time periods, either by manipulation of existing dams and water control structures or restoration of natural dynamic water fluctuations.
- Locate new natural areas or green space in areas prone to ponding or flooding to add additional water storage capacity during extreme events.
- Direct water into natural features with herbaceous and woody plant cover to reduce runoff and nonpoint source pollution, while still providing outflow for excess water.
- Reforest floodplain forests with high degrees of mortality from emerald ash borer with a climate-adapted mix of trees.[214]
- Take advantage of "accidental" wetland areas that arise in urban areas, using management to augment desired services and minimize disservices.[264]

- Connect elements of green infrastructure, such as planting beds, bioswales, rain gardens, and sequential stormwater treatments to natural systems.

Approach 4.3: Restore or maintain fire in fire-adapted ecosystems

Restoring natural fire regimes can help reduce ecosystem vulnerability to a changing climate, especially in areas that are susceptible to increases in wildfire under hotter, drier conditions.[269] Using fire as a management tool can be difficult in urban settings due to potential or perceived impacts to the built environment and public health.[270] However, residents are generally supportive of prescribed fire if it can reduce risks of wildfire or increase native plant diversity in suburban and wildland-urban interface areas.[271-273] Where possible, fire can be an important management strategy in supporting ecosystem function and resilience. For example, even small prescribed fires in suburban forest patches can lead to increases in species richness and diversity.[274] Prescribed fire can reduce wildfire risk and severity, improve tree survival, and prevent loss of forest conditions.[275] Prescribed fire also can have long-term carbon mitigation benefits through reductions in risk of large-scale carbon losses from wildfires, although carbon may be reduced in parts of the forest (such as the forest floor). For example, conditions during implementation of prescribed fire typically result in low overstory tree mortality rates, preserving both carbon in live trees and the potential to sequester future carbon through tree growth.[276] Additional care can also be taken to reduce potential impacts on public health through timing of prescribed fire to minimize air quality effects and providing advanced communication to community residents.[277, 278] Where ecological or social constraints limit the application of prescribed fire, alternative management strategies (i.e., fire surrogates) can provide some benefits, but do not fully mimic the effects of prescribed fire.[279, 280] This approach complements, and can be used in conjunction with, approach 5.3, which describes actions for reducing the risk of wildfire in ecosystems.

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- Use prescribed fire to maintain fire-adapted ecosystems and reduce risk of fire spread into the wildland-urban interface.[281-283]

- Use prescribed fire during suitable conditions (periods of low air pollution, low winds, low temperatures) to avoid negative impacts and potential for unwanted spread.

- Provide advance warning to community residents about prescribed fire activities and efforts to minimize adverse impacts from smoke.[278]

- Incorporate understory thinning, mowing, or other fire surrogate strategies to support native ecosystems in addition to prescribed fire or where fire management is not possible.[284]

Developed urban sites

- Manage fire-adapted urban trees and ecosystems using fire-surrogate treatments, such as understory thinning, mowing, hand-weeding, and appropriate herbicide application.

Strategy 5: Reduce the impact of physical and biological stressors on urban forests

Urban forests are experiencing increasing threats as a result of altered climate conditions and interactions with other environmental stressors.[239] The stressors that affect urban forests vary widely based on the impacts of climate change in a particular region or area, as well as local factors that influence exposure and sensitivity to climate change.[239, 285] For example, cities in the western United States may be at greater risk of wildfire conditions given development in the wildland-urban interface,[239, 286] while coastal cities are likely to be at greater risk of sea-level rise, coastal storms, and hurricanes.[239, 287] Although the nature and severity of climate risks will vary for individual cities, there are many threats in common across urban areas. For example, climate change is expected to increase the impact of biological stressors, such as insect pests, pathogens, and invasive plant species;[288-292] urban areas may be especially prone to these stressors as a result of urban warming, human disturbance, and proximity to points of introductions.[293]

Approach 5.1: Reduce impacts from extreme rainfall and enhance water infiltration and storage

Urban forests can be used in combination with gray and green stormwater infrastructure to reduce harm from extreme rainfall to people, the built environment, and vulnerable soils. Natural and low-impact development techniques help to reduce stormwater conveyance, enhance groundwater recharge, and improve water quality by decentralizing flows and using soil and plants to capture and filter pollutants.[294-297] Increasingly severe rainfall events interact with impervious surfaces to concentrate stormwater flows, often exceeding the capacity of urban gray infrastructure (e.g., pipes and sewers) to direct water to desired locations. Concentrated stormwater runoff can cause adjacent areas to erode, flood, destabilize stream channels, and impair water quality.[295, 296, 298] Further, stormwater that is directed into water bodies through storm sewers bypasses vegetation and other natural features and can discharge untreated sewage and stormwater directly into surface waters, reducing water quality and creating human health risks. Trees and other green infrastructure can help manage excess stormwater volume at its source, reducing the burden on stormwater collection systems through canopy interception, evapotranspiration, and improved soil infiltration.[225] Vegetation and soils can also reduce nutrient loading in stormwater, as runoff often contains nutrients, such as nitrogen and phosphorus, that are detrimental to surface water quality, yet important for plant growth.[225, 299] Prioritizing the use of native plants and trees for this approach, when feasible, can help increase wildlife habitat for a wide range of species. Implementing green infrastructure approaches may be more effective in managing excess stormwater flows and far less expensive than upgrading gray infrastructure systems.[225] While the primary benefits are hydrological regulation and water quality improvement, green infrastructure also provides notable carbon sequestration and storage benefits.[300]

EXAMPLE ADAPTATION TACTICS

- Incorporate a mixture of plant functional types to provide year-round interception and evapotranspiration benefits (e.g., deciduous and coniferous trees, turfgrass).[225, 299]

- Manage the urban forest to increase leaf surface area; when planting, select species with greater leaf surface area and/or rough-surfaced leaves and bark.[299, 301]
- Use ground covers and consider underplanting with smaller trees or shrubs to increase surface area for interception.[299]
- Retain as much tree canopy as possible to intercept rainfall; encourage canopy growth over impervious surfaces.[299]
- Provide appropriate care and maintenance for trees to ensure health and continued function.[299]
- Maximize belowground soil volume and use biological mulches below tree canopy to improve water infiltration and storage.[299]
- Select species based upon their intended use and transpiration capabilities; for example, species that transpire water in greater volumes (such as tulip tree *[Liriodendron tulipifera]*, black gum [*Nyssa sylvatica*], birch [*Betula* spp.], dogwood [*Cornus* spp.], red maple [*Acer rubrum*], sycamore [*Platanus* spp.]) can be planted in areas that that receive stormwater.[299]
- Plan ahead to manage stormwater in the event of widespread tree loss due to storm damage or pest outbreaks.[225]
- Strategically grade soil where needed and avoid unnecessary soil disturbance to preserve soil porosity and natural drainages.

Developed urban sites

- Integrate trees into other types of green infrastructure, such as rain gardens, to enhance their capacity and improve the regulation of soil moisture content.[302]
- Select water-tolerant tree species to plant in shallow, concave settings to collect runoff.[225]
- Improve soil quality and minimize compaction to increase rooting volume and infiltration capacity.
- Make use of structural soils systems (mix of mineral soil and coarse stone), such as Silva Cells™ or StormTree™, or suspended pavement over noncompacted soils.[225, 303]
- Use permeable paving, suspended surfaces, or Silva Cells[304] to enable runoff to collect and water trees.
- Incorporate permeable surfaces into designs, such as block pavers, porous asphalt, and concrete, to reduce hardening of surfaces and increase infiltration of storm flows.
- Attenuate and treat stormflows in depressional areas using bioretention systems to capture runoff, recharge groundwater, and reduce pollutant loads.[296]

- Divert and disperse stormwater off of impervious surfaces (such as walkways, roofs, roads, trails) to forests, densely vegetated areas, swales, and filter strips to increase water retention on site and enhance filtering of water.[296]

- Use vegetated shoulders and embankments of compacted soils to resist storm surge water flowing across a roadway.

Approach 5.2: Reduce risk of damage from extreme storms and wind

Climate change has increased the likelihood and severity of storms,[305] which damage urban trees. Urban tree failures can cause severe property damage, electric outages,[306] and human injuries or fatalities.[307] Damage can also reduce the carbon mitigation capacity of urban forests and impair other ecosystem services.[189] In developed urban sites, these potential impacts make it essential for risk to be managed at the individual tree level.[308] Factors such as tree form, size, condition, species, wind speed, pruning, and wood material properties affect tree resistance to storm damage.[309-312] Urban foresters may need to balance the risk of tree failure, including the danger to people and property, with the loss of benefits when shade trees are removed. This is especially important for large trees, which provide greater benefits and take a long time to replace.[313] Although intensive hazard management is common in developed areas, it may also take place in urban natural areas where individual tree management is necessary or possible, such as in high-use areas or near infrastructure where damaged trees present hazards. Elsewhere, management approaches in natural areas are more likely to be focused on minimizing the impact of disturbances on tree communities. Public involvement and education are critical factors in wide and effective implementation of this approach.

EXAMPLE ADAPTATION TACTICS

- Develop disaster management plans and risk assessments to prepare for more frequent extreme storms.[189]

- Create education and outreach programs for arborists, utilities, and the public to ensure tree removals are necessary.

- Monitor for hazard trees near potential targets (e.g., playgrounds, walking paths, or roads), and repair or replace these trees as quickly as possible.[314]

- "Soften" the edges of forests and natural areas (i.e., reduce the edge influence at regenerating edges and minimize abrupt transitions) to reduce susceptibility to wind damage.[315]

- Manage stand density and age in forested areas to reduce risks of property damage and hazards from severe weather events using Stormwise or other forest management practices.[193, 194]

- Implement a predisturbance structural pruning program to improve tree health and ability to withstand extreme weather events.[192]

- The main determinant of a tree's ability to withstand extreme winds is a strong root system; when planting, provide ample area for future root growth and maintain adequate distance from restrictive pavement. If soil space is limited, select smaller-maturing species.[316]
- Select species that are more tolerant of high winds to improve wind-resistance, plant trees in groups rather than as solitary individuals.[192, 316]
- Use structural pruning to reduce safety and infrastructure issues by fostering mechanically strong branch structure.[317, 318]
- Avoid planting trees susceptible to breakage in areas with high wind exposure or species susceptible to damage from ice loading.[189]
- Develop programs for waste wood utilization to facilitate tree maintenance and forest management.[319]
- Ensure nursery stock is properly pruned and has no circling roots.

Approach 5.3: Reduce risk of damage from wildfire

The increases in the frequency, size, and severity of wildfires in the United States. have included greater incidence and risk of wildfires in the wildland-urban interface, especially in the western part of the country.[320-324] This corresponds with an expansion of development in fire-prone areas in the last several decades.[325] Methods for reducing risk to urban natural areas and surrounding communities may be similar, though on a smaller scale, than those employed in rural areas. However, due to their proximity to human communities and infrastructure, urban natural areas are of especially high priority in risk reduction.[283, 320] Developed landscapes in the wildland-urban interface may incorporate somewhat different principles of risk reduction to both property and vegetation through altering forest structure and composition,[283] such as the Firewise USA® methods of creating defensible space around structures and using less-combustible landscaping.[195] In some situations, this approach can be used in conjunction with approach 4.3, which describes actions for using fire as a management tool in fire-adapted systems. Public involvement and education are critical factors in wide and effective implementation of this approach.

EXAMPLE ADAPTATION TACTICS

- Create, update, and implement a community wildfire protection plan: a plan that communities create in collaboration with emergency management and land management agencies to reduce wildfire risk.[326]
- Engage the public, decision-makers, and thought leaders in discussions about land use planning and regulations to reduce wildfire risk.[327]
- Use prescribed fire where possible or fire-surrogate treatments to manage the woody understory and other potential fuels to reduce the risk of wildfire.[284]

- Cooperate withappropriate authorities to train municipal fire fighters to respond quickly and appropriately to fires in natural areas.

- Promote treatments on private lands that reduce the risk of wildfire by creating defensible space around homes and other structures and by removing fuels,[322] including Firewise USA® practices.[195]

- Avoid using highly flammable species in plantings near natural areas, such those containing pine or eucalyptus trees or chaparral shrubs.

- Avoid using highly flammable landscape materials (e.g., pine straw, shredded bark mulch) near buildings located near natural areas.

Approach 5.4: Maintain or improve the ability of forests to resist pests and pathogens

Forest pests and pathogens create substantial challenges to urban trees and forests and their ability to provide many ecosystem services.[328] These challenges are expected to be amplified by climate interactions with pest and pathogen ranges and life cycles.[329] Insect pests, such as the mountain pine beetle in the western United States and the southern pine beetle and hemlock woolly adelgid in the eastern states, have expanded their ranges northward, at least partly in response to warmer climate conditions.[289, 290, 329] The urban heat effect can further increase the risk in cities, particularly when urban heat also contributes to drought stress.[293] Urban forests may also have higher levels of plant stress due to suboptimal growing conditions,[330] sometimes combined with lower tree species diversity and associated reduction of ecosystem resistance to pests.[293] Avoiding the introduction of pests and pathogens is often not possible. Reducing or eliminating stressors that might make a tree more susceptible to new or existing pests or pathogens will be important to maintaining forests in urban areas.[330] While interventions to prevent tree mortality from pests and disease can be expensive, the cost is often less than tree removal and replacement.[210, 211]

EXAMPLE ADAPTATION TACTICS

All urban sites

- Increase age diversity to help avoid large concentrations of declining trees that may be more susceptible to certain pests or pathogens.

- Monitor for new invaders so action can be taken before the pest or pathogen becomes established.

- Participate in a rapid response system for pest and pathogen detection, including training volunteers and local organizations to assist with identifying pests and pathogens.

- Use new remote sensing to detect pest and disease outbreaks.[331, 332]

- Plant pest- and disease-resistant genotypes of native species when undertaking forest restoration projects.

- Developed urban sites
- Select species and cultivars that are less susceptible to pests and pathogens.[333]
- Treat susceptible trees with pesticides and fungicides prior to infestation or use behavioral manipulation techniques to disrupt insects.
- Ensure adequate watering to avoid drought stress in susceptible trees.[293]
- Use new technology and data analysis techniques to monitor tree health at extremely fine scales, including for individual trees.[334, 335]
- Apply sanitation practices, including removal of infected trees or use of pesticides, to limit spread.[333]
- Promote diversity across taxonomic levels by reducing the concentration of any one genus, species, or cultivar in order to reduce the risk from a selective pest or pathogen.[333]
- Encourage the use of best management practices that limit the spread or level of damage caused by pests or pathogens.

Approach 5.5: Prevent invasive plant establishment and remove existing invasive species

Invasive plant species—that is, species that are not native to an area and whose introduction causes harm—already pose significant problems in many urban forests, and climate change is likely to increase the rate of spread of invasive plant species in several ways.[291, 292, 336] Urban areas are especially susceptible to introduction and spread of invasive plants due to the proximity of urban areas to the global transport linkages that are often points of introduction. Further, the conditions commonly found in urban areas give invasive plants a competitive advantage; this includes high levels of disturbance, nutrient loading, and warm or moderated microclimates. Warmer temperatures and altered climate conditions may remove existing climatic restraints and allow species to move into new areas, while increases in climate-related disturbances and changing ecosystem dynamics may create conditions that allow new species to invade more easily.[291] Early detection and rapid response will be very important as opportunities for new invaders increase.

EXAMPLE ADAPTATION TACTICS

- Manage and monitor natural area buffers to limit the spread of invasive plants to high quality or unaffected areas.
- Limit the spread of invasive species introduced through recreational activities (e.g., boot brushes at trailheads).
- Use stewardship groups and volunteers as part of a rapid response program to limit the spread of and remove invasive species.

- ▶ Avoid the use of known invaders in horticultural plantings (especially in and around natural areas) through partnerships with homeowners, municipalities, and park districts.
- ▶ Train local land managers, landowners, volunteers, and organizations to recognize possible threats and report them to appropriate local and state agencies.
- ▶ Plant a dense layer of larger native trees to shade out invasive plants in the understory.
- ▶ Remove existing invasive species using nonchemical treatments, such as directed flame or hot foam.[337, 338]

Approach 5.6: Manage herbivory to promote regeneration, growth, and form of desired species

Changes in habitat quality and extent associated with climate change and increasing urbanization and fragmentation of natural areas are likely to alter the interaction of mammalian herbivores with managed systems, potentially resulting in ecosystem degradation.[339-341] Herbivory can cause substantial damage to desired plant species; for example, herbivory from white-tailed deer (*Odocoileus virginianus)* has been linked to reduced understory and native plant diversity, a lack of natural regeneration, increased drought stress, and enhanced susceptibility from invasive plant species in forest ecosystems.[342] It is difficult to predict how individual wildlife species will respond to climate change given complex interactions with the local environment and management.[343-345] White-tailed deer populations are generally expected to remain high or increase as a result of more favorable climate conditions and also high behavioral plasticity.[346, 347] Protecting desired species from herbivory can effectively reduce browse damage and prevent associated impacts of reduced growth and carbon sequestration. Managing herbivory also can be important in fostering resilience to other stressors that are exacerbated by climate change. This approach may be combined with tree-planting efforts or forest management activities that release advance regeneration or stimulate new regeneration.

EXAMPLE ADAPTATION TACTICS

- ▶ Use community-based management techniques to develop deer management plans based on management goals and community capacity.[339, 348]
- ▶ Manage populations of deer or other herbivores using control methods.[339, 349, 350]
- ▶ Apply repellant, tree tubes, bud caps, and other physical barriers to protect individual plants, especially during planting projects.
- ▶ Use fences to protect sensitive plant communities or restoration areas.
- ▶ Promote abundant regeneration of multiple species to supply more browse than herbivores are expected to consume.

Strategy 6: Enhance taxonomic, functional, and structural diversity

This strategy addresses the value of diverse ecosystems in supporting the adaptive capacity of urban areas under changing conditions. Uncertainty about the continued pattern and effects of climate change is a hallmark challenge of adaptation planning, and encouraging diversity in a range of ecosystem components is often considered a "no regrets" investment in ecosystem resilience.[351, 352] Promoting species and structural diversity is as important in urban forests as in non-urbanized forest landscapes, if not more so. Urban areas are highly susceptible to introduction of nonnative pests and pathogens and often exhibit high occurrence of invasive plant species.[203, 353] Examples of urban tree mortality demonstrate the role that species diversity can play in the face of pest introductions.[354, 355] Widespread awareness has led to guidelines focused on diversification of the urban forest.[355] However, urban areas contain sites with challenging growing conditions, and only a limited set of tree species may be able to tolerate such conditions.[356] Species and structural diversity are especially important as both a climate adaptation and mitigation strategy because urban habitats (both natural areas and developed land uses) are likely to be stressed in the future in many ways, some of which will be unforeseeable.[56, 357] A diverse set of species, carefully selected to match the urban environment, will be more likely to maintain adequate forest cover, carbon mitigation, and other ecosystem services under a changing and increasingly variable climate.

Approach 6.1: Enhance age class and structural diversity in forests

Diverse age structures can be beneficial in both developed and natural areas because trees are most vulnerable to specific stressors at different ages, an especially important consideration as climate exacerbates many forest stressors. For example, while both droughts and wind events are increasing in the changing climate, droughts typically are more damaging to seedlings than to mature trees, whereas older trees may be more susceptible to damage from wind events. Increasing age—and, perhaps correspondingly, size—diversity can increase the habitat value of the urban forest and spread out tree losses from natural mortality.[12, 37] Further, greater diversity in tree ages can benefit forest carbon sequestration capacity.[358, 359] Some urban forests are dominated by trees that established before the urbanized landscape; these legacy trees are now reaching the end of their lifespan.[360] In natural areas, active forest management may be necessary to promote the development of multiple age classes, while maintaining greater amounts of dead wood, including snags, downed logs, and coarse woody debris, may increase carbon storage and enhance wildlife habitat.[361, 362] In contrast, managers often focus on individual trees in developed urban areas, which are removed upon death or damage and replanted as soon as resources permit. In developed sites, some planting and tree removal practices could help develop a more diverse tree age structure both within and among management units. In addition, pre-urban legacy trees often provide much of the carbon mitigation value, along with other ecosystem services and functional value (e.g., shading and habitat) of the urban forest,[360] emphasizing the importance of preserving older and larger legacy trees. Preservation of these features will be essential to adapting the urban forest to future climates, as old trees may have superior genetics and may play a valuable role in helping species persist on the landscape.[363]

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- Implement silvicultural practices in urban natural areas to promote multi-aged forests, such as single-tree or group selection methods.[364]
- Restore or create conditions that allow tree seedlings to thrive by removing nonnative species in the shrub layer and canopy trees while controlling herbivory.[365, 366]
- Implement silvicultural practices to reduce competition around large, long-lived trees to maintain tree health, such as thinning dense stands from below or using prescribed fire in fire-adapted ecosystems.
- Retain and protect large, old, or long-lived tree species during forest management activities, such as invasive species treatment, removal of hazardous trees, and development of recreational trails.
- Retaining snags and downed trees when possible (i.e., those that pose no threat to people or infrastructure).

Developed urban sites

- Retain legacy trees from the pre-urban landscape during development or redesign of urban areas.
- Plant replacement trees in anticipation of mortality from pests and disease and before actual loss of canopy trees to diversify age structures.
- Rotate planting schedules so that removal and replanting is dispersed geographically, thereby avoiding complete tree removal or replanting within a single area (e.g., street or park) during a single year.
- Plant species of different average lifespans on the same block.
- Provide adequate clearance from structures, driveways, sidewalks, and other established trees when planting long-lived trees to avoid resource competition or future obstructions to growth.
- Improve growing conditions for large, old trees, such as improving soil infiltration or drainage conditions, installing irrigation and protective barriers during construction, enhancing soil fertility, or limiting soil compaction from pedestrian or automobile traffic.
- Enact tree preservation ordinances to protect older age classes of trees.

Approach 6.2: Maintain or enhance diversity of native species

Climate change threatens many native tree species and communities and is expected to reduce the ability of these systems to ameliorate climate impacts and sequester carbon over the long term.[367-369] Although urban forests serve important ecological and social functions through a wide variety of native and nonnative plants, native species and ecosystems can provide elevated benefits in regard to some ecosystem services, such as pollination, relative to nonnative plants.[370] Native plants that are adapted to both current urban conditions (which are often extreme) and anticipated future conditions can be used to restore and enhance species diversity in urban systems.[37, 352, 371] Increasing the abundance of native species that are expected to persist into the future can have multiple important positive effects on the adaptation potential of the urban ecosystem.[37] For example, native species planted in urban locations can provide important habitat value for wildlife species; some areas, such as parks, may be able to emulate a functioning ecosystem to some degree and support functioning food webs.[372, 373] Native plant ecosystems also may be able to provide migration corridors through intensely fragmented urban landscapes.[374] It is important to recognize that it may be more difficult to promote native species diversity in urban systems due to more extensive planting and promotion of nonnative species, including invasive species.[203] This approach may be used in conjunction with approach 7.3, which identifies the potential for novel species introductions.

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- Restore or create conditions that allow for successful regeneration of a diverse mix of native species, which may require removing some existing trees to open the canopy.[375]
- Supplement natural regeneration by planting desired native species to add diversity.
- Identify and expand the size of urban natural areas to support a larger array of native species.[229]
- Developed urban sites
- Identify native tree species for urban tree planting lists that provide important co-benefits, such as high value for wildlife[37] or adaptability to environmental or climate stressors.[369]
- Use native plant species as ground cover or horticultural plantings in the root zone of urban trees.

Approach 6.3: Optimize and diversify tree species selection for multiple long-term benefits

Warmer temperatures, altered precipitation patterns, and other changes in the climate are expected to affect the growth, productivity, and distribution of tree and plant species.[368, 369] Individual plants will respond differently based on the combination of functional traits (e.g., broadleaf versus conifer), species characteristics, and site-level characteristics, which increases the need to ensure that species are matched to both current and anticipated future conditions. The "right plant, right place" consideration that is already used in urban forestry can be extended to consider emerging hazards that may affect plant success during its entire lifespan.[352, 355] Species selection for tree plantings in public spaces, such as streetscapes and parks, and also on private properties, can be used to enhance functional and taxonomic diversity and reduce the risk from any one species failing under future conditions. Current species selection criteria often include site tolerance, aesthetics, community input, maintenance required, and mature size. Climate adaptability can be added as an additional criterion through which to evaluate planting lists, as well as for desired co-benefits such as carbon storage, health benefits, or wildlife value (appendix 3). Species or functional traits, such as soil requirements, susceptibility to breakage, or phenology, can help identify trees that are less susceptible to extreme weather or other disturbances.[189] By altering lists of recommended species for planting or adjusting which species are planted at a given site, urban foresters can influence the taxonomic diversity of their urban forest and increase the adaptability of urban forests to a range of plausible future climates. Some cities are beginning to develop and use tools to optimize species selection at the site scale based on tree species characteristics (e.g., Baltimore, Maryland).[376] This approach complements, and can be used in conjunction with, approaches 6.2 and 7.3, which employ native and introduced species, respectively.

EXAMPLE ADAPTATION TACTICS

- Include species that are less prone to ice and wind damage in forest restoration projects. Avoid planting trees susceptible to breakage in areas with high wind exposure.
- Select short-statured trees for planting under power lines to reduce susceptibility to infrastructure damage.
- Select species that are well-adapted to the soils in the area for restoration projects.[377]
- Select species that can provide multiple ecosystem services, such as carbon sequestration, stormwater mitigation, or pollinator habitat.
- Develop species selection decision-support tools to ensure “right tree, right place” planting.
- Add information to recommended plant lists to identify species that may provide human health, carbon mitigation, or adaptation benefits (appendix 3).
- Plant or retain fast-growing species to provide carbon sequestration, cover, shade, and food sources for wildlife during forest restoration efforts.
- Establish or promote species with higher carbon sequestration capacity near buildings and homes as part of plantings designed to reduce building energy use.
- Plant species with diverse timing of phenological events (e.g., flowering, fruiting, leaf out, and leaf drop) to provide necessary resources over a longer timeframe to forest-dependent wildlife species.[378]
- Work with nurseries, the local community, or conservation organizations to ensure the future availability of desired planting stock.

Approach 6.4: Maintain or enhance genetic diversity

Enhancing genetic diversity of urban trees can help reduce risks to a variety of stressors, including pests and pathogens. Street and park trees are often cultivars or grown from seeds that are sourced from a small number of parents to ensure that trees have predictable growth, survivorship, and tolerances. However, this can result in a lack of genetic diversity and may prove to be deleterious to long-term survivorship during changing conditions.[333] For example, if all of the maple trees in an area are a single cultivar, they will probably react to climate change in a nearly identical manner. Increasing genetic diversity in the urban forest will ensure that some individuals are better equipped to withstand climate-induced stressors. Also, urban natural areas are heavily fragmented, which can cause reduced gene flow and lead to a decline in genetic diversity.[379] This reduction can lead to increased vulnerability if the variants prove susceptible to prevalent climate change impacts.

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- Select seeds and planting stock that originate from a variety of sites or a broader geographic area to increase genetic diversity in restoration and reclamation projects when local provenance is not a priority.
- Collect and plant seeds from individuals or populations that have survived pest outbreaks, dieback events, or extreme weather events as these plants may have resistant genotypes or have a greater tolerance to stressors.

Developed urban sites

- Plant a variety of both cultivars and wild genotypes for a given species. Use a greater number of plant varieties and sources to increase overall genetic diversity.
- Use cultivars of species that will be better suited for hotter and drier climates.
- Plant disease-resistant cultivars that had been previously lost due to pests or disease to re-establish a form of this species on the landscape, such as disease-resistant elm (*Ulmus* spp.) or chestnut (*Castanea* spp.).
- Work with growers to create new genotypes and cultivars of currently planted species that will be best adapted to anticipated climate changes.
- Use contract growing nurseries—or establish municipal nurseries—to increase supply of promising new cultivars.

Strategy 7. Alter urban ecosystems toward new and expected conditions

Urban areas often contain a mixture of planted species that come from diverse regions. Planted trees may be non-native taxa or species that are regionally native; that is, those from the same region but not currently growing at the particular location. Because these species evolved in locations with different climates or site conditions, they may have very different tolerances to future climates and local conditions. Continuing to plant novel species can facilitate climate adaptation when species are carefully selected. Intentional consideration of the tolerances and traits of species will ideally help increase the capacity of the urban landscape to cope with change. Additionally, urban forests could help facilitate the migration of species that will be favored under future climate to new habitats at or beyond the edges of their current range.[380]

Approach 7.1: Favor or restore non-invasive species that are expected to be adapted to future conditions

Selecting native and non-invasive species already present in an urban area that are likely to do well under a range of future climate conditions can be a low-risk approach for transitioning to future climate conditions while ensuring continued or enhanced provisioning of health and mitigation benefits. Native species can provide important ecosystem services such as habitat for vertebrate and invertebrate species, and do not carry a risk of becoming invasive or lead to genetic mixing.[370] However, there may be a limited set of native species that will be able to withstand future climate conditions and also thrive in urban environments.[381, 382] Therefore, the use of "near-native" (e.g., from within 100 miles of the site) and non-native species that have been proven to tolerate urban -conditions and lack invasive characteristics may be warranted in highly disturbed or developed areas.[383] This approach complements efforts to remove problematic nonnative invasive plant species (Approach 5.5).

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- Plant native seedlings in restoration projects that are likely to do well, based on climate model projections and information about climatic tolerances.
- Plant "near-native" seedlings that do not have invasive properties.

Developed urban sites

- Promote native species that are near their northern range limit and future-adapted native species in tree planting lists and projects.
- Incorporate species and cultivars that are proven urban tolerant and not invasive when native species are insufficient in achieving biodiversity goals.[377]
- Select trees that are hardier to extreme storm and wind events and less likely to break up when pruned correctly, especially in wind-prone areas.

- Plant tree species that are less sensitive to flooding in low-lying areas that are expected to become wetter.
- Select species based on their physiological tolerance to drought.[384]

Approach 7.2: Establish or encourage new species mixes

Future conditions in urban areas are likely to become extreme, with higher peaks in temperature and moisture than might be seen in non-urban landscapes.[385] However, considerable uncertainty exists in what future conditions will be, especially at the site level. Thus, encouraging new species mixtures when planting in urban forest communities could help these systems adapt, reducing tree mortality while maintaining ecological function[12] and carbon mitigation value[386]. This approach could also discourage invasion by exotic invasive species that reduce valued ecological function.[387] Managers may need to prioritize diversity—in terms of species, as well as functional groups[388-390] and genetic lineages—over historical species combinations to increase community resilience.[391, 392]

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- Plant a mixture of locally and regionally native species during ecosystem restoration to diversify beyond species that are adapted to current site conditions or that represent the historical plant community.
- Create heterogeneous conditions in canopy structure, ground layer, and hydrology that will allow a variety of species to become established.
- Developed urban sites
- Include a diverse mix of locally and regionally native species in plantings, especially in plantings that are near natural areas.
- Intentionally design ecosystems to meet human-centered needs, such as green stormwater infrastructure or agro-ecosystems.[393]
- Establish mixes of tree functional groups (e.g., conifer, deciduous, and evergreen broadleaf) that can provide important ecosystem services across different seasons.[388, 390]

Approach 7.3: Introduce species, genotypes, and cultivars that are expected to be adapted to future conditions

Urban foresters have moved species across states, continents, and even oceans for centuries, although only in recent decades has their intent included climate adaptation. This adaptation approach can include relatively low-risk actions, such as moving a species to slightly north of its current range. It also could include riskier actions, such as introducing a nonnative species from another continent. Although seeds and nursery stock from local sources may be the best adapted for an area currently, they may be maladapted to the changing climate in coming decades.[394] Likewise, the unique climate in an urban center may already necessitate a different set of genetic material than for more pristine natural areas. Alternatively, seeds and nursery stock that are native to areas with a climate similar to the projected climate and conditions of the targeted urban landscape may have higher survivorship than local seeds if other habitat factors (e.g., soils) are also suitable.[395] Risks associated with introducing trees from distant sources include the potential for also introducing foreign pests and diseases, or the possibility that the introduced species may become invasive or hybridize with other local species.[394, 396] These risks are reduced, but not eliminated, when a species is moved within its native range.[395] Trials can help ensure that seedlings from distant areas will thrive in a new environment, but not harm ecosystem values, before large-scale plantings are undertaken.

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- Incorporate regionally native species as well as non-native species into reclamation projects in degraded habitats to assess their viability and aggressiveness.
- Encourage southern species that become established in natural areas.
- Use mapping programs to track the origin of seed stocks and monitor their success to inform seed sourcing decisions in the future.
- Source seeds from a variety of areas to increase overall genetic diversity.
- Developed urban sites:
- Introduce or increase regionally native or likely future native species in urban plant projects; for example, Kentucky coffeetree (*Gymnocladus dioicus*) or tulip tree in upper midwestern cities.
- Plant non-native species from analogous climates.
- Use climate change projections to determine what region currently has a climate that is similar to the expected future climate in the target area, then source seeds from this area.
- Create a dialogue with nurseries and growers to ensure that seeds are being selected from healthy trees in areas that have a climate similar to the target area's expected climate.
- Plant and produce individuals collected or propagated from a variety of sites (including drought- and flood-prone areas) in consideration of the uncertainty of future conditions.
- Use cultivars of species that will be better suited for hotter and drier climates.
- Work with growers to create new genotypes and cultivars of currently planted species that will be best adapted to climate changes.
- Plant disease-resistant cultivars that had been previously lost due to pests or disease to re-

establish a form of this species on the landscape, such as disease-resistant elm or chestnut.

Approach 7.4: Disfavor species that are distinctly maladapted

Urban areas are already experiencing especially rapid changes in climatic extremes, and some species at the edges of their natural ranges may more quickly become maladapted to these conditions.[378] With some urban environments already experiencing extreme climatic events, it is possible that an increasing number of species eventually may become more poorly adapted there.[397] For example, species with a climate envelope that encompasses an urban area in large-scale future climate projections may not be able to tolerate conditions in more extreme urban microclimates.[398] In some cases, species that are no longer adapted to an area may be removed from—or be considered for removal from—recommended planting lists.

EXAMPLE ADAPTATION TACTICS

- Use information from especially extreme urban sites, or areas with similar climatic extremes and fluctuations, to determine which native species are likely to decline.
- Do not replace, trees of selected species that are not drought-, heat-, or flood-tolerant. Instead, promote more tolerant native or near-native species.
- Protect healthy legacy trees that fail to regenerate, while de-emphasizing their importance in the mix of species being planted or regenerated.
- Remove species from recommended planting lists that are no longer able to tolerate current conditions.

Approach 7.5: Move at-risk species to more suitable locations

Climate may be changing more rapidly than some species can migrate, and the movement of plant and animal species may be restricted by land use or other impediments between areas of suitable habitat.[399, 400] Fragmentation of natural ecosystems and physical barriers in urban areas may make this even more challenging, especially for rare or threatened species.[401-403] At-risk species, such as rare or sensitive species that are constrained to a specific set of environmental conditions, are often incorporated into urban reserves (e.g., botanical gardens, arboretums, and municipal parks) and urban plantings (e.g., street trees and backyard gardens), and could, in some cases, be included in restoration or reclamation projects, such as urban river ways. Additional at-risk species—or species that provide habitat for at-risk species—could be added to urban planting lists where suitable habitat exists to increase their representation in the landscape. Assisted migration for species rescue, which focuses on avoiding extinction by physically relocating climate-threatened species, may be an option to consider in some cases. This approach is best implemented with great caution, incorporating due consideration of the uncertainties inherent in climate change, the sparse record of previous examples, and continued uncertainties of forest response.[396] Providing new artificial habitat for at-risk species could help sustain them through increasing alterations in climate.

EXAMPLE ADAPTATION TACTICS

- ▶ Plant or seed a rare or threatened species that is at risk for extinction into a newly suitable habitat outside its current range.
- ▶ Assist the migration of wildlife around barriers by trapping and releasing into newly suitable locations.
- ▶ Plant heat-sensitive species on north slopes or in cold-air drainages.
- ▶ Collect seeds and other genetic material of at-risk species to contribute to a genetic repository.
- ▶ Plant individuals in a protected location that is expected to provide suitable habitat into the future.
- ▶ Use local conservatories, arboreta, botanical gardens, and parks to cultivate species once climate change challenges natural regeneration.
- ▶ Include at-risk species (or species that provide habitat for at-risk wildlife) in urban park, street, or campus plantings and in restoration or reclamation projects whenever possible or feasible (e.g., planting endangered southern species in parks).

Approach 7.6: Promptly revegetate and remediate sites after disturbance

Changes in climate will increase some large-scale disturbances, such as floods and windstorms. These disturbances can lead to catastrophic losses of trees and other vegetation in some areas. Proper management prior to disturbance events is critical, as an estimated 80 percent of tree damage during natural disasters can be attributed to pre-existing defects.[404] The risk of damage can be minimized through proper selection of planting site and species, and appropriate maintenance, such as pruning.[316, 405] Following a disturbance, swiftly remediating and re-establishing vegetation on disturbed sites can help maintain the carbon sequestration capacity of urban forests. Additionally, planting vegetation may be needed to stabilize soils to prevent erosion and could help reduce the impacts of invasive species. In highly developed areas, replanting may be the only way to ensure the presence of species that provide desired ecosystem services, such as shade, aesthetics, or stormwater control. In natural areas, where a native seedbank may remain, replanting or managing natural regeneration may be beneficial to ensure the area has a species composition and structure that is aligned with management goals. In most cases, disturbances will not lead to complete loss of vegetation, but the remaining trees may have some degree of damage. After urgent severe hazards are handled, damage assessments and restoration planning are important to site recovery, including attention to amenity and legacy trees for their carbon and ecosystem benefits. The retention of these trees can help provide ecosystem services while new trees and other vegetation are becoming established.[360] Revegetation may require appropriate site preparation. Some disturbances will leave behind woody debris or sedimentation that may need to be remediated prior to planting. Areas that are at risk to debris flows may require some amount of stabilization before restoration work can begin. In other cases, the soil organic layer may have been removed; therefore, mulch or other soil amendments will be needed. Disturbance events also provide an opportunity to strengthen public-private partnerships, as well as engaging and educating citizens and volunteers in regreening efforts.[189]

EXAMPLE ADAPTATION TACTICS

Urban natural areas

- ▶ Promptly mitigate and prepare the site for restoration to avoid further damage to soils, vegetation, and property.
- ▶ Amend the soil to restore organic matter when topsoil is lost from previous disturbance.
- ▶ Manage for natural regeneration of native species after disturbance through such practices as protecting seedlings and saplings from herbivory.
- ▶ Use the disturbance as an opportunity to eradicate or reduce the impact of invasive or undesirable species.
- ▶ Allow non-invasive species migrants that are not native to the site to remain as part of a novel mix of species, rather than eradicating these species.
- ▶ Prioritize planting of trees into recently disturbed areas.
- ▶ Include early-successional species in forest restoration projects to provide initial canopy cover.
- ▶ Retain nonhazardous dead and damaged trees for wildlife habitat and other ecosystem services.

Developed urban sites

- ▶ Replace damaged trees with those that increase taxonomic and functional diversity.
- ▶ Plant over several years to create a diverse age and size class structure in the urban canopy.
- ▶ Establish fast-growing or future-adapted tree species in locations heavily impacted by disturbance or human use.[406]
- ▶ Remove the remaining severely damaged trees that were not immediately removed during emergency response if they pose a hazard to people or property.
- ▶ Implement appropriate tree crown restoration pruning strategies for less severely damaged trees.
- ▶ If possible, stand fallen trees back up and use stakes or guy wires for support until the root system is structurally stable (usually applicable to newly planted trees or trees less than 4 inches in diameter).[183, 316]

- Provide irrigation for stressed trees to encourage formation of new roots.[183, 316]
- Develop a tree salvage plan to maximize the use of woody debris following a disturbance event.[189]

Approach 7.7: Realign severely altered systems toward future conditions

Many urban areas may experience such significant alterations from human- and climate-induced disturbance that it will become difficult to restore systems that reflect native ecosystems of the past. The physical disturbance, altered abiotic conditions, and changed species composition arising from a major disturbance may cause an ecosystem to flip into a fundamentally different state.[407, 408] Management of these systems may be realigned to create necessary changes in species composition and structure to better adapt forests to current and anticipated environments, rather than historical predisturbance conditions.[12, 393, 409, 410] In urban natural areas, it may be beneficial to allow for natural regeneration while also engaging in human-assisted reforestation, with an emphasis on selecting species that are better adapted to weather extremes, such as high winds.[407] In more developed areas, this could mean designing "novel ecosystems" that incorporate both natural and engineered elements and contain entirely new species compositions.[411] In light of recent disasters, some cities are taking a hybrid approach by incorporating green and gray infrastructure in an effort to protect against future damages. This may include nature-based approaches, such as restoring marshes and beaches, and structural protection, such as levees, floodwalls, and pumps.[412] Developing clear plans that establish processes for realigning significantly altered ecosystems before undertaking these actions will allow for more thoughtful discussion and better coordination with other adaptation responses.

EXAMPLE ADAPTATION TACTICS

- Allow community transition by planting future-adapted species within a site that is already declining or is expected to decline (e.g., converting a mesic maple forest to an oak savanna).
- Allow non-native, non-invasive species to remain as part of a novel mix of species, rather than eradicating them.
- Develop monitoring plans of natural regeneration to determine how the ecosystem is changing post-disturbance.[407]
- Assess the quality of the seedbank or regeneration post-disturbance, to determine the need for supplemental planting.
- Design "novel ecosystems" composed of a carefully selected mix of native and non-native species that align with projected future climates.
- Convert areas to green spaces that are expected to be vulnerable to future climate impacts, such as low-lying coastal areas.

Strategy 8: Promote mental and social health in response to climate change

This strategy addresses the personal and community level of interactions of people with nearby nature, and how to build capacities to cope in the face of climate change. The health and well-being of individuals, households, and neighborhoods can be negatively affected by climate change in numerous ways.[413, 414] First, both long-term and abrupt changes in people's lives can bring on mental stress and anxiety. Also, the effects of climate change range from local to global in geography, and our awareness of such conditions can become personal and social stressors. Although many people might first think of trees as an ecological adaptation to address climate, urban forests and green spaces also serve as resources that help people and communities cope and recover.[415] Individuals and communities may receive a wide range of health benefits—from experiences of nearby nature,[416] including faster healing for hospital patients,[417] improved school performance,[418] reduced hypertension,[419] and increased lifespan.[420] Climate change impacts people at different scales, from mental health of individuals[421] to how entire communities react and respond to adversity.[422] Community-based actions to care for and steward ecosystems can foster social connections, acknowledge cultural diversity, and help create places that are meaningful and healing. Urban forestry priorities and plans can be informed by understanding socio-psychological reactions to climate stressors and risks, as well as the healing effects of nature, so that actions can effectively promote mental and social health in any community.[423]

Approach 8.1: Provide nature experiences to ease stress and support mental function

Exposure to trees, forests, and urban greening ease the causes and symptoms of general mental health concerns and can be therapy for clinical conditions,[421, 424] a critical consideration as climate change can affect mental health in multiple ways.[45] Stress disorders, anxiety, and depression are most directly influenced by acute natural disasters and disturbances as people cope with immediate and tragic changes in their lives. Additionally, chronic stress and behavioral change can arise from slowly progressing, long-term conditions, such as rising temperatures and changing precipitation. For instance, high temperatures are associated with an increased incidence of violence, aggression, and suicide, as well as higher rates of treatment for those with psychiatric conditions.[414] Further, living with uncertainty, coping with environmental threats, and experiencing changes in familiar places and personal routines are pathways to multiple health issues,[111] solastalgia (the loss of a sense of place), and changing attitudes about one's self and relationships with others.[114] These effects are expressed across different population groups, depending on how directly exposed or vulnerable people are in their geographical conditions.[425] Exposure to nature can reduce rumination (a propensity to dwell on negative thoughts).[426-428] The presence of surrounding tree canopy and brief walks in forested areas can ease stress and depression.[429-433] Experiences in a more biodiverse outdoor settings may have provide greater benefits.[434, 435] Nature can provide respite and restorative experiences that reduce stress, frustration, and anxiety, thus helping one to think more clearly and make better decisions in challenging situations.[436-438] Finally, nature experiences, especially outdoor walks, can help individuals generate creative solutions to challenges in their lives,communities, and society.[439-441]

EXAMPLE ADAPTATION TACTICS

- Plant and promote more tree canopy cover within a range of 100 meters of homes in residential areas, particularly for neighborhoods that have few trees.[442-444]
- Plant and conserve trees to augment environments that provide quality, short-term restorative nature experiences (e.g., forest views, forest bathing, green streetscapes).[445, 446]
- Develop places for quiet, nature-filled walks of up to 2 miles.[447, 448]
- Implement the principles of Attention Restoration Theory to enhance or create forest and nature spaces that offer opportunity for cognitive and attention recovery,[449-452] including the restorative elements of being away, compatibility, and soft fascination—meaning the outdoor elements that attract our attention without effort, such as water features, wildlife movement, or daily and seasonal changes.[452]
- Promote greater sensory, ecological, and vegetation diversity in nature-experience spaces to enhance mental health and healing.[453-455]
- Plant trees to buffer extreme noise sources and provide natural sounds, as chronic negative sound causes stress, reduces quality of sleep, and impacts social relationships.[456-458]
- Promote nature-based mental health and therapy for various vulnerable populations, such as locating tree projects within or near education, care, or treatment facilities for children[459-463] or older adults.[92, 464]
- Design and implement plantings for nature experiences that support creativity, a psychological resource people call on to address personal and community-level stresses and challenges (examples being garden paths, water features, and outdoor seating).[439, 465, 466]

Approach 8.2: Encourage community and social cohesion to support climate response

Climate change and disturbance events can shape and test social relationships within communities. Social cohesion is a shared resource that has practical implications for climate response. People in cities often gather in public spaces, including parks and green spaces, to relax, play, learn, and engage in civic events. It is around these multiple informal interactions that social community takes shape.[467] Community also may form around a project or purpose as participants develop differing, yet harmonious, perceptions, skills, or shared interests in a cooperative way to achieve desired outcomes. Social cohesion is the resulting interdependence among members of a community, experienced as shared values, loyalties, and cooperation. Social capital—meaning the networks of social relations characterized by trust and shared give-and-take for mutual benefit— can emerge. Social capital makes it possible to achieve things that cannot be accomplished solely by individuals, and makes achieving community-oriented goals possible.[468] Individuals and groups within communities with strong social cohesion and social capital experience multiple health benefits.[469, 470]

Urban forestry programs and projects can foster the social interactions and dynamics that enable communities to adaptively respond to climate and improve health.[415, 471] At one level, people often pursue intentional, purposeful contact with green space and gardens as a way to summon the capacities to recover during or after a crisis.[472] On a larger scale, sustained programs and activities, such as tree planting and stewardship, can catalyze social cohesion and social capital.[473] The presence of urban green spaces, along with participation in urban forest activities, can encourage positive social interactions,[471] helping people develop the capacity to respond to ongoing risks (such as air quality) or extreme events (such as storms). In times of challenges and crises, local groups can activate their established networks and capacities to become “first responders” to address community and individual needs with local expertise. Social resilience depends upon connectedness and innovation, and daily nature-based experiences and interactions encourage locally relevant and resourceful response. [474, 475]

EXAMPLE ADAPTATION TACTICS

- Engage residents and organizations in tree planting in ways that acknowledge cultural diversity within the community, encourage formation of social relationships and networks, build capacity for communities to address challenges or needs, and nurture place attachment.[476-479]

- Collaborate with residents and local organizations on data assessments that support urban forestry using community science, such as tree inventories, canopy assessment, tree health and risk assessments, and heat mapping or stewardship mapping.[480-483]

- Engage residents in tree-planting programs as stronger connections to nature support more pro-environmental behavior and is related to use of nature for psychological restoration.[484]

- Use trees to create spaces that serve as community gathering spaces used for celebration, festivals, feasts, and other community events, such as Arbor Day and Earth Day.

- Partner with local retail and commercial businesses, civic organizations, and faith centers to foster community-wide networks and capacity for action.

- Collaborate on community-based performance or outcome goals, such as wildlife habitat or sustainability, associated with trees and forest projects to motivate a program of shared community actions and purposes.

- Promote tree projects and green spaces as pathways to immigrant and cross-cultural interactions, understanding local heritage, and welcoming new arrivals to a community.[485, 486] Examples include food forests, nature-based international holiday celebrations, and farm-to-table festivals.

- Engage children and youth in tree projects to nurture their sense of care and stewardship of trees and the environment, including motivating stipends, academic or service credit, or employment for sustained involvement.[487]

- Acknowledge and support trees and green spaces as living memorials and places for grieving following climate disasters or community change, as people often seek nature and gardens to heal from hardship.[488-490]

- Encourage the use of a green space or forests as a sacred space—a place generally shared for solace and contemplative reflection,[491] to connect with communities and places of worship and faith.

- Carefully plan and design green spaces to include creating public environments that discourage crime, instead encouraging perceptions of safety and security, including guiding principles of Crime Prevention Through Environmental Design.[492, 493]

Strategy 9: Promote human health co-benefits in nature-based climate adaptation

This strategy encourages project decisions that support co-design, cultural ecosystem services, and the positive land-use aspects of urban forestry. Although forest and tree health are important to provide long-term climate benefits, additional attention to the placement and configuration of both conserved and newly planted forests can optimize human health. Considering human health benefits when prioritizing nature-based adaptation can significantly increase the influence and value proposition of the investment for human well-being and health promotion. Human health benefits are contingent on locating trees, forests, or parks near where people live or spend time. For example, if tree planting for carbon sequestration and asthma reduction are co-benefits goals, then a schoolyard adjacent to a high-speed road is a good choice for a planting project location. Health promotion includes many things: it refers to the full array of social determinants of human health, including food security, quality housing, and accessibility to nearby nature, and how these factors can support general wellness. It also refers to particular functional benefits, as nature experiences help to prevent specific illnesses, such as attention deficit disorder[494] and depression.[431] Routine physical activity is one of the best ways to improve general health, reduce incidence of chronic disease, and promote healthy aging.[495] As decisions are made about locations of urban forestry projects, plantings that improve streetscapes, trails, or pathways for walking would achieve a co-benefits approach. While response to a climate effect or threat may be the primary purpose of a tree or forest project, a modest amount of additional planning and resources can extend goals to include a wide array of public health benefits.[11] A health co-benefits approach optimizes ecosystem services, offers opportunities to engage with nontraditional public health and community partners, and often provides a compelling case for sustaining urban forestry programs.[496]

Approach 9.1: Co-design large-scale green infrastructure and built systems to promote health

Nature-based and green infrastructure initiatives are increasingly used in urban climate adaptation. Engineered ecosystems integrate the underlying ecological functions of urban natural resources as remedies for multiple short- and long-term climate change effects. As cities progress from a historic emphasis on sanitary systems to more comprehensive and holistic sustainability systems, green infrastructure and urban greening can be imagined and implemented to provide co-benefits through co-design.[497] As one example, green stormwater infrastructure incorporates trees with bioswales or rain gardens, and these natural precipitation management features can be co-designed as micro-parks in a neighborhood. Trees and novel ecosystems can be incorporated into built systems to directly influence healthy responses. This is an important contribution of climate adaptation to health equity because, in many places, health is determined more by where people live than any other factor, including genetics.[498] While public health and wellness is appropriately addressed in city planning and policy, actual design implementation happens across multiple local government departments, such as engineering, transportation, and residential development. The urban forest can be incorporated into the functional details of urban infrastructure and systems at each level of implementation to satisfy public welfare goals at the broadest scale and enhance quality of life for neighborhoods and households. Including the community in co-design wherever possible can increase social cohesion and capital, while it ensures these systems are consistent with perceived social needs.

EXAMPLE ADAPTATION TACTICS

- Adopt a co-design for a co-benefits approach in urban forestry projects so that any tree planting for climate adaptation also optimizes systems or structures that promote public health outcomes,[55, 499] particularly in communities having tree canopy or human health disparities.[500]

- Use tree projects to promote community walkability and physical activity,[501, 502] according to public health guidelines,[503] including routes linking homes to transit stations, schools, and workplaces.

- Plan, design, and activate facilities and programs that support and motivate physical activity, as more intentional engagement of nearby residents and users through activities such as community walking programs and yoga sessions facilitates and motivates more healthful behaviors and outcomes.[504-506]

- Use forest plantings, restoration, and conservation to enhance connectivity of existing green spaces and align with transportation, utilities, riparian, and other urban corridors to expand functional connectivity of ecological, sociocultural, and active living systems to include walking/running paths, hiking trails, and bike routes.[448, 507]

- Engage engineers, urban planners, and sustainability officers, along with other allied professionals, to pursue co-benefits project designs that integrate trees and expand open space in communities to promote health, such as green stormwater infrastructure, cloudburst management plans, and utilities projects.[55]

- As cities implement multi-modal transportation projects, including Complete Streets,[508, 509] provide shaded sidewalks and bike lanes so people are comfortable and safe when choosing to walk, bike, or access public transit.

- Plan projects to encourage longer nature encounters near residential areas and user facilities to provide optimal nature "dosage" opportunities of 15 to 60 minutes.[445, 450, 510, 511]

- Promote greater biodiversity in projects—in terms of forest structure and vegetation composition—for greater psychological and physiological human health benefit.[434, 512]

Approach 9.2: Provide micro-scale nature experiences to promote health and healing

People can gain health advantages from remarkably brief experiences while in nearby nature spaces of even limited size.[513, 514] These small, yet frequent, micro-scale experiences may become increasingly important as climate changes challenge health.[45] Urban forest conservation, restoration, or planting policies and programs may be expansive in scope, but implementation may entail multiple small-scale projects. Small spaces, such as hospital gardens, are valuable resources for healing, therapy, and stress recovery.[417, 515] Simply having window views of nature from homes, schools, and workplaces provide health benefits.[516] Tree plantings at the parcel level on private and public properties in cities can have important cumulative effects on both climate and human health, especially if adjacent to residential centers or facilities that serve vulnerable populations or imbedded within disadvantaged communities. In all these situations, additional thought can be given to how a tree project that is primarily oriented to biological or ecological functions might also be configured to promote human health. Modest additional planning can help ensure residents and users are engaged in the stewardship activities that provide healthful experiences and social cohesion benefits.

EXAMPLE ADAPTATION TACTICS

- Optimize access to nature settings of any size; plant and manage so that residents and visitors find such spaces to be accessible, secure, safe, and support experiences of fitness, adaptability, and delight.[517, 518]

- Conserve large trees, as this has numerous benefits; multiple studies indicate human preferences for large trees over small, and both the health and ecological benefits quotient is many times greater for large trees compared to small ones.[519]

- Optimize nature views from windows and interactions in and around the common spaces of civic service facilities, such as libraries, community centers, and government buildings, to model climate-friendly landscapes and create restorative opportunities as people engage in meetings, wait for service providers, take breaks, and arrive or depart from the building.[520]

- Optimize nature views and interactions in places where people work on focused tasks—including workplaces, schools, healthcare centers, and campuses—as brief, frequent nature encounters improve creativity and restore cognitive capacity for task attention and focus.[460, 520-522]

- Collaborate with transportation and public works departments to promote shady corridors, create Green Streets or Complete Streets,[523] and provide comfortable connecting spaces for "10 Minute Walks"—a nature and health metric being adopted by many local governments—to parks and green spaces.[524]

- Plan and reinforce access to forests, groves, and significant trees for forest therapy and bathing programs, as some of the most rigorous studies of nature and health indicate that this activity supports multiple health improvements, including stress reduction, improved immune function, and reductions in symptoms of diabetes and cardiovascular disease.[525, 526]
- Select tree species to provide community food supplement,[527] expressed as cultural food groves,[528] food arboretums, or food forests,[529] and include food trees in urban forest management plans.[530, 531]
- Incorporate information about trees, forests, and urban greening and human health response in environmental and ecological interpretive materials, such as signs, brochures, and project outreach.
- Collaborate to support tree plantings in healthcare and clinical care settings, as nature provides therapeutic and healing benefits to patients[417, 424, 532] and reduces stress in healthcare providers.[515]
- Use tree planting and species selection to optimize protection from ultraviolet (UV) ray exposure by shading waiting areas or high-use outdoor spaces, such as sports fields, festival areas, and bus stops.[135, 533, 534]

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Adaptation: Adjustments, both planned and unplanned, in natural and human systems in response to climatic changes and subsequent effects. Ecosystem-based adaptation activities use a range of opportunities for sustainable management, conservation, and restoration.

Adaptive capacity: 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. Adaptive capacity can be an inherent property, or it could have been developed because of previous policy, planning, or design decisions.

Adaptive management: A dynamic approach to forest management in which the effects of treatments and decisions are continually monitored and used, along with research results, to modify management on a continuing basis to ensure that objectives are being met.

Afforestation: Converting land to forest.

Age class: An interval into which the age range of trees is divided for classification or use.

Amenity trees: Trees with recreational, functional, environmental, ecological, social, health, or aesthetic value rather than for production purposes.

At-risk species: A species that has been determined to be vulnerable to observed or projected changes in climate or other stressors.

Biological legacy: Individual trees of a variety of species retained from harvest in order to maintain their presence on the landscape, provide a potential seed source for both species and genotypes that are expected to be better adapted to future conditions, and serve as future nurse logs for regeneration of some species.

Biomass: The mass of living organic matter (plant and animal) in an ecosystem. Biomass also refers to organic matter (living and dead) available on a renewable basis for use as a fuel; biomass includes trees and plants (both terrestrial and aquatic), agricultural crops and wastes, wood and wood wastes, forest and mill residues, animal wastes, livestock operation residues, and some municipal and industrial wastes.

Bioswale: A landscape feature designed to filter silt and pollution from surface runoff, consisting of a shallow drainage course with gently sloped sides and filled with vegetation.

Brownfield: Previously developed land potentially contaminated by a pollutant, hazardous substance, or other contaminant. The term may also be used to describe former industrial or commercial sites where its future expansion, reuse, or redevelopment is affected by known or perceived environmental pollution, such as soil contamination.

Carbon sequestration: The process of storing carbon in a carbon pool.

Climate: The statistical description of the weather in terms of the mean and variability of relevant quantities (usually temperature, precipitation, and wind) over periods of several decades (typically three decades). In a wider sense, the "climate" is the description of the state of the climate system.

Climate change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.

Climate refugia: Areas that are buffered from the impacts of climate change, and may allow for the persistence of physical, ecological, and socio-cultural resources. For example, variations in topography can create cooler areas in the landscape where sensitive species may be better able to persist into the future.

Disturbance: Stresses and destructive agents, such as invasive species, diseases, and fire; changes in climate and serious weather events, including hurricanes and ice storms; pollution of the air, water, and soil; real estate development of forest lands; and timber harvest.

Diversity: The variety and abundance of life forms, processes, functions, and structures of plants, animals, and other living organisms, including the relative complexity of species, communities, gene pools, and ecosystems at spatial scales that range from local through regional to global. There are commonly five levels of biodiversity: (1) genetic diversity—the genetic variation within a species; (2) species diversity—the variety of species in an area; (3) community or ecosystem diversity—the variety of communities or ecosystems in an area; (4) landscape diversity—the variety of ecosystems across a landscape; and (5) regional diversity—the variety of species, communities, ecosystems, or landscapes within a specific geographic region.

Ecological function: The sum of physical conditions (e.g., depth of water and soil type) and ecological processes (such as nutrient cycling and sediment movement) that make up an ecosystem and, ultimately, habitats on which species depend. A loss of ecological function is the removal or disruption of an ecological process that produces a certain physical condition or the loss of or damage to a physical condition.

Ecological processes: Processes fundamental to the functioning of a healthy and sustainable ecosystem, usually involving the transfer of energy and substances from one medium or trophic level to another (e.g., water flows and movement, nutrient cycling, sediment movement, and predator–prey relationships).

Ecosystem: A system of living organisms interacting with each other and their physical environment. The boundaries of an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.

Ecosystem resilience: The capacity of a system to absorb disturbance and reorganize while undergoing change yet retain essentially the same function, structure, identity, and feedbacks.

Ecosystem services: Ecological processes or functions having monetary or nonmonetary value to individuals or society at large. These are frequently classified as (1) supporting services, such as productivity or biodiversity maintenance; (2) provisioning services, such as food or fiber; (3) regulating services, such as climate regulation or carbon sequestration; and (4) cultural services, such as tourism or spiritual and aesthetic appreciation.

Equity: Equity is the principle of fairness in burden-sharing and is a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in equal ways. It is often aligned with ideas of equality, fairness, and justice, and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations, and gender, as well as in the sense of who participates and controls the processes of decision-making.

Evapotranspiration: The process by which plants and soils release moisture into the atmosphere.

Fragmentation: A disruption of ecosystem or habitat connectivity, caused by human or natural disturbance, creating a mosaic of successional and developmental stages within or between forested tracts of varying patch size, isolation (distance between patches), and edge (cumulative length of patch edges).

Functional groups: A set of similar species that have similar traits. In trees, typical functional groups are conifers, deciduous broadleaf trees, and evergreen broadleaf trees.

Gene flow: Transfer of genetic material from one population to another, resulting in a changed composition of the gene pool of the receiving population.

Genetic diversity: Genetic variation within a species.

Gray infrastructure: Constructed structures that are often made of concrete such as dams, pipes, roads, seawalls, sewer systems. treatment facilities, storage basins, or stormwater systems.

Green infrastructure: A water management approach that mimics, restores, or protects the natural water cycle using measures such as landscaping, permeable pavement, plant or soil systems, or stormwater harvest and reuse.

Greenhouse gas: Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases present in the atmosphere, such as halocarbons and other chlorine- and bromine-containing substances

Health Impact Assessment: Widely used policy analysis tools that evaluate the potential health impacts of a project or policy and provide recommendations to increase positive health co-benefits and mitigate negative health impacts. These assessments include a broad definition of health; consideration of economic, social, or environmental health determinants; application to a broad set of policy sectors; involvement of affected stakeholders; explicit concerns about social justice; and a commitment to transparency.

Health outcomes: Changes in health that result from specific health care investments or interventions. Positive health outcomes include a general sense of well-being, as well as functioning well mentally, physically, and socially. Population-level health outcome metrics include life expectancy and self-reported level of health and function.

Hydrologic processes: The processes that occur as part of the water cycle, including evapotranspiration, condensation, infiltration, precipitation, and runoff. Earth's water circulates continuously between the oceans, atmosphere, and land.

Invasive species: A species that is not native to an area and whose introduction causes, or is likely to cause, economic or environmental harm or harm to human health.

Landscape fragmentation: A process in which larger areas of habitat or natural land cover are broken into smaller, more isolated patches. This generally occurs due to land-use change for agriculture, urban development, and road building.

Migration: The movement of genes, individuals, or species from one population or geographic location to another. Tree migration is largely influenced by dispersal ability, landscape connectivity, and climatological and other factors.

Mitigation (of climate change): A human intervention to reduce emissions or enhance the terrestrial sequestration of carbon dioxide (CO_2) and other greenhouse gases

Monitoring: The collection of information over time, generally on a sample basis, by measuring change in an indicator or variable to determine the effects of resource management treatments in the long term.

Native species: A species that been present in a given place for a long enough period that it has adapted to the physical environment and developed complex relationships with other organisms in an ecological community

Novel ecosystem: A unique assemblage of species and environmental conditions resulting from human actions, both intentional and unintentional.

Nutrient cycling: The biological, geological, and chemical processes involved in the transfer and movement of energy and matter between living organisms and nonliving matter. Water, carbon, oxygen, and nitrogen are examples of major nutrient cycles.

Realignment: The process of tuning ecosystems or habitats to current and anticipated future conditions in such a way that they can respond adaptively to ongoing change.

Refugia: Locations and habitats that support populations of organisms that are limited to small fragments of their previous geographic range.

Regeneration: The vegetative (e.g., sprouting from clonal root structures and coppicing) or sexual regeneration of a plant species.

Reserve: Natural areas with little to no harvest activity, unless required to maintain the system, that do not exclude fire management or other natural disturbance processes.

Resistance: An adaptation option intended to improve the defenses of an ecosystem against anticipated changes or directly defend the forest against disturbance to maintain relatively unchanged conditions.

Restoration: The process of returning ecosystems or habitats to their original structure and species composition.

Riparian: Related to, living, or located in conjunction with a wetland, on the bank of a river or stream, or at the edge of a lake or tidewater. The riparian community significantly influences, and is significantly influenced by, the neighboring body of water.

Risk: The chance of something happening that will have an impact on objectives, often specified in terms of an event or circumstance and the consequences that may flow from it. Measured in terms of the consequences of an event and their likelihoods, risk may have a positive or negative impact.

Silvicultural practices: Management actions taken to guide the establishment, growth, composition, health, and quality of forests to meet the needs for timber, wildlife habitat, restoration, and recreation. Treatments may include actions such as thinning, prescribed burning, planting, pruning, and harvesting.

Social determinants of health: The social, economic, and physical conditions in the places people are born, live, work, educate, and play that affect a wide range of health and quality-of-life risks and outcomes. Health outcomes can be significantly impacted by social determinants—resources that enhance quality of life, such as affordable housing, access to nutritious food, quality education, a healthy environment, and access to nature/natural surroundings.

Soft fascination: Natural scenes can easily and almost effortlessly hold people's attention, while allowing room in the mind for other thoughts and reflection. These qualities play an important role in the restorative quality of nature. In contrast, "hard" fascination, such as watching television, fully occupies the mind, leaving little space for contemplation. Sunsets, clouds, and wind blowing through trees are examples of soft fascination.

Soil profile: The vertical cross-section of soil layers.

Stormwater infiltration: The ability of excess water during storm events to soak into the soil and increase groundwater recharge, rather than quickly running off the surface and into nearby water bodies.

Taxonomic diversity: A measure of biodiversity that includes the number and relative abundance of species in a given area.

Transition: An adaptation option intended to accommodate change and enable ecosystems to adaptively respond to changing and new conditions.

Upstream health planning: Considers the social, economic, and environmental origins of population-level health outcomes. Addressing the fundamental, root causes of poor health, rather than focusing merely on correcting symptoms, often requires governmental interventions and policy-change approaches. Housing, neighborhood conditions, and socioeconomic status are all upstream factors that play a fundamental causal role in health outcomes.

Urban resilience: The ability of an urban system—and all its constituent socioecological and sociotechnical networks across temporal and spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, adapt to change, and quickly transform systems that limit current or future adaptive capacity.

Volatile organic compounds (VOCs): Natural and human-made chemicals that are emitted as gases from various solids and liquids; plants developed a communication system to convey information based on VOCs and emit various compounds while communicating.

Vulnerability: The susceptibility of a system to the adverse effects of climate change. Vulnerability is a function of the magnitude of climatic change, the sensitivity of a system, and the ability of the system to adapt.

Wildland-urban interface (WUI): Any area where manmade improvements are built close to, or within, natural terrain and flammable vegetation; there may be a higher potential for wildland fire in these areas.

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APPENDIX 1

Adaptation Workbook Steps in Brief

This is a brief outline of the Adaptation Workbook (Fig. 5) process. Find the full process in the "Forest Adaptation Resources: Climate change tools and approaches for land managers, 2nd edition"[21] and as an online tool at www.adaptationworkbook.org.

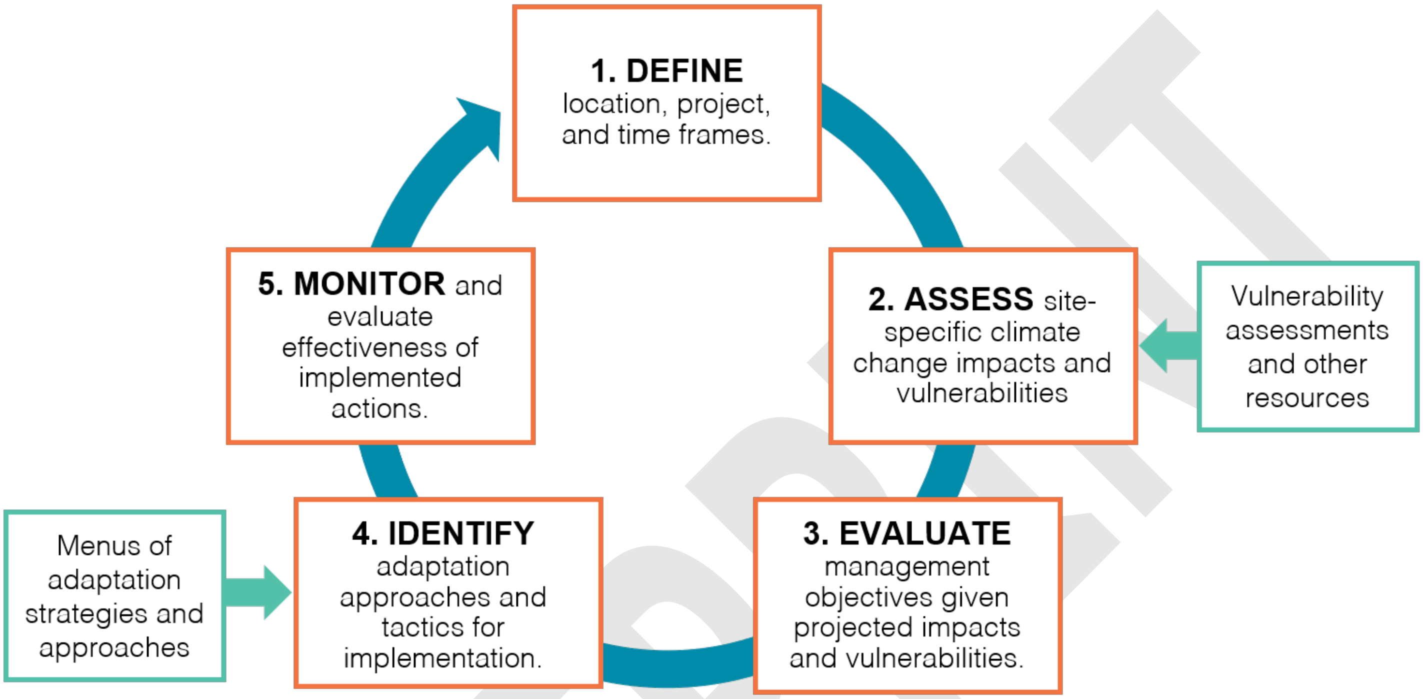

Figure 5—The Adaptation Workbook21 describes an assessment and decision process that is used in conjunction with vulnerability assessments, local knowledge, and adaptation strategies menus. The results are site-specific actions that address explicit management and conservation objectives under a range of potential future climates.

Step 1: DEFINE location, project, and time frames

"What are your management goals and objectives for the project area?"

The first step is to describe the project area and your management objectives before considering the potential effects of climate change. This may include identifying:

- Any ecosystem types, stands, or other distinct areas that you want to consider individually
- Any short- or long-term milestones that can be used to evaluate progress

Step 2: ASSESS site-specific climate change impacts and vulnerabilities

"What climate change impacts and vulnerabilities are most important to this particular site?"

Climate change will have a wide variety of effects on the landscape, and not all places will respond similarly. List site-specific factors that may increase or reduce the effects of climate change in your project area, such as:

- Site conditions, including topographic position, soils, or hydrology
- Past and current management
- Forest composition and structure
- Increasing exposure to pests, diseases, or other stressors

Step 3: EVALUATE management objectives given projected impacts and vulnerabilities

"What management challenges and opportunities may occur as a result of climate change?"

This step explores management challenges and opportunities that may arise under changing conditions. For each of your management objectives, consider:

- Management challenges and opportunities given the climate impacts you identified previously
- The feasibility of meeting each management objective under current management
- Other considerations (e.g., administrative, legal, or social considerations) beyond climate change that may affect your ability to meet your management objectives

Step 4: IDENTIFY adaptation approaches and tactics for implementation

"What actions can enhance the ability of the ecosystem to adapt to anticipated changes and meet management goals?"

Generate a list of adaptation tactics—prescriptive actions specifically designed for your project area or property and your unique management objectives. Use the Urban Forest Climate and Health Adaptation Menu as a starting point for identifying specific management tactics (e.g., what, how, and when) that you can implement. As you develop tactics, consider the following:

- Benefits, drawbacks, and barriers associated with each tactic
- Effectiveness and feasibility of each tactic

Step 5: MONITOR and evaluate effectiveness of implemented actions.

"What information can be used to evaluate if the selected actions were effective and inform future management?"

Monitoring metrics can help you determine if you are making progress on your management goals and evaluate the effectiveness of those actions. When identifying monitoring items, work to identify monitoring items that:

- Identify if your management goals and objectives were achieved
- Evaluate if the adaptation tactics had the intended effect
- Are realistic to implement

APPENDIX 2

Adaptation Demonstration: Climate and Human Health Adaptation on a Neighborhood Scale in Providence, Rhode Island

Adaptation demonstrations are examples of organizations applying the Adaptation Workbook[21] process and adaptation menus to their real-world natural resource management projects to generate explicit adaptation tactics in alignment with their objectives. More than 400 adaptation demonstration projects have been generated using other adaptation menus and are available online. The following demonstration was used in December 2020 to evaluate the Urban Forest Climate and Health Adaptation Menu (Menu).

Project Area and Management Goals

As public and private urban forest managers working in partnership to build a more equitable and robust urban forest, the Providence Parks Department and the Providence Neighborhood Planting Program (PNPP) aim to engage residents and neighborhood stakeholders in developing and implementing community-driven tree planting and stewardship solutions focused on climate adaptation and human health in Upper & Lower South Providence, two low-canopy and low-income neighborhoods disproportionately burdened by the impacts of climate change and environmental injustice. The general project area is primarily residential and light commercial, bordered by Interstate 95 (I-95) and the industrial Port of Providence to the east and hospital campuses to the north, which are surrounded by large areas of surface parking lots.

The primary management focus is on right-of-way and front-of-property planting sites along streets between Broad Street, Eddy Street, Dudley Street, and I-95. The existing canopy cover is relatively low (20 percent) and lacks diversity. The most common tree species include callery pear (*Pyrus calleryana*), red maple, Japanese zelkova (*Zelkova serrata*), and honey locust (*Gleditsia triacanthos*). There are many highly disturbed and polluted sites in the neighborhood; residents battle poor air quality and high asthma rates. The eight census block groups that make up the project area have a population of 8,493, with 94 percent identifying as non-Caucasian. The average unemployment rate is 17 percent, and 69 percent of the population has a household income that falls below 200 percent of the poverty line.

Natural resource professionals from the City of Providence and the PNPP used the Adaptation Workbook and the Menu to consider climate change effects on the project area as part of meeting their management goals and objectives. The Northern Institute of Applied Climate Science (NIACS) professionals worked with the Providence team to translate the goals and climate change impacts into adaptation tactics.

The team identified five primary management goals:

- Increase and enhance canopy cover throughout the project area by involving community stakeholders in tree planting and ensuring newly planted street trees survive, ultimately improving the health environment (heat and air quality) for people who reside, work, and attend school in the project area.

- Decrease localized street flooding and stormwater runoff.
- Engage residents, community groups, and institutions within the project area in planning and implementation of tree planting and stewardship activities.
- Expand on existing program models and pilot new initiatives and practices (e.g., community youth tree watering and job-training partnerships) that will increase and improve tree canopy while also serving as tools for outreach and education regarding the urban forest. Outreach and education tools will link to climate and health, increasing awareness of the benefits trees provide to our communities. They will also support the development of the citywide PVD Tree Plan, which is a collaborative, equity-focused action plan for Providence's urban forest. The PVD Tree Plan is currently in development by PNPP in partnership with a coalition of core stakeholders.
- Protect existing tree canopy in the project area and prevent future canopy loss due to extreme weather events, such as heavy storms and high winds.

Managers from the Providence Parks Department and PNPP plan to address these goals by selecting and planting climate-adapted trees (30-50 in the project area through PNPP's Neighborhood Street Tree Planting model), identifying the most vulnerable sites and implementing tree pit projection, installing stormwater tree pits (five tree filter pits in the project area), and implementing community and stakeholder engagement strategies. Such strategies could include developing partnerships, cultivating new resident PNPP Tree Leaders, and involving residents, students, and community groups in tree stewardship.

Climate Change Impacts and Providence

The Providence team used their knowledge of the local landscape to examine regional climate change impacts and assess how these impacts will increase or decrease vulnerabilities in the project area. The team identified four key climate change impacts affecting the project area.

- Temperatures in New England are projected to increase 3.5 to 8.5 °F by the end of the 21st century, with the greatest warming expected to occur during winter.[535] This increase could have detrimental effects on human and ecosystem health, leading to a chain reaction of changes among plants, animals, weather patterns, and more. The project area is affected by Providence's urban heat islands and battles poor air quality that amplifies breathing issues. In addition, the area has relatively low access to cooling via public cooling centers and air conditioning, which may further exacerbate heat-related health problems.
- Altered hydrology is another concern. Annual precipitation is projected to increase and there is potential for reduced growing season precipitation. Intense precipitation events will continue to become more frequent, and the timing and amount of stream flow is expected to change. Compacted soil, fewer lawn strips, and more pavement may result in lower

water capture and higher runoff containing pollutants.

- Storm events will continue to become more frequent and severe, including the increased possibility of tornados, hurricanes, and other tropical storms. Older trees in the existing canopy become susceptible to breakage due to wind as well as uprooting due to high water saturation, while localized flooding events, paired with a combined sewer system, could lead to water issues.

- Warmer temperatures, combined with varied precipitation, may alter soil moisture and increase drought risk. Changes in temperature and precipitation are projected to alter soil moisture patterns throughout the year, with the potential for both wetter and drier conditions depending on the location and season. In addition, forest vegetation may face increased risk of moisture deficit and drought during the growing season.

A comparison of the climate and health tree species list (appendix 3) with street tree inventory data from the project area indicates that none of the tree species planted are considered highly vulnerable to climate change, and most trees have low or low-moderate vulnerability. Red maple and Norway maple (*Acer platanoides*) are some of the most common species in the project area and are projected to experience a decline in habitat suitability. Although these species are beneficial for carbon storage and shade, they also have high allergenicity and volatile organic carbon emissions that could have negative human health implications. Thus, the large presence of Norway and red maple could contribute further to vulnerability of both the tree canopy and the human population in the neighborhood.

Overall, neighborhood vulnerability is higher compared to some others in Providence due to lower income, low canopy, low home ownership rates, high impervious surfaces, and urban heat island effects. In terms of adaptive capacity factors, the project area does not have a lot of connected green space or biodiversity. The low-income neighborhood and low rates of home ownership result in lower private tree care compared to other areas in the city because trees are costly to maintain. On the other hand, age class diversity of tree canopy is varied, and the City of Providence already has a pruning cycle established through the 15 wards in the city, each divided into 10 areas based on tree inventory. Ten percent of each ward is pruned each year. The Division of Forestry and PNPP jointly manage a program called Providence Community Tree Keepers that trains residents to act as stewards of the city's young trees. While the program currently has little participation within the project area, there are opportunities to build that capacity in the near future.

Challenges and Opportunities for Management

A changing climate will present challenges and opportunities for accomplishing the management objectives. Each management objective was evaluated keeping the list of climate change impacts in mind and many challenges were based on the vulnerabilities identified in the previous step.

CHALLENGES

The primary challenge for meeting the project goals is the overall difficulty and uncertainty of tree establishment in the face of increased drought risk and increased storm and wind events. It may be difficult to identify tree species that meet all criteria, such as climate adaptability, resilience, health concerns, and the conditions of bioswale pits. Planting days may be impacted with additional storms, and hot/dry weather may make it more difficult to get residents outside for tree watering and other maintenance. It may also be difficult to ensure the survival of trees in bioswales and maximize tree size and longevity in stormwater installations.

A changing climate can create more challenges for community engagement. Increased storms and wind events may result in more tree damage, which can increase hesitation and negative views toward trees. As a result, recruiting participants for activities such as tree planting and maintenance may be more difficult.

OPPORTUNITIES

Climate change may also create opportunities in the project area. When selecting tree species, there will be an opportunity to select and grow nursery stock that is more adaptable to climate change. Providence has well-established relationships with local nursery growers that can adjust their stock based on city requests. In addition, urban forest managers may be able to extend the planting season with a longer growing season that results in earlier springs and delayed autumns. A longer growing season may also aid in growth and establishment of young trees.

Burgeoning concern about climate change among residents and professionals alike may create opportunities to collaborate with different partners, pilot ideas, and work with young residents who are concerned by and interested in climate change. Providence's newly established Green Justice Zones may be used to build more capacity and community organizing around climate. Stormwater runoff, one of the primary concerns, is a "hot topic" due to climate change, which may present an additional opportunity to obtain more funding for management goals. Lastly, heat and flood impacts in the neighborhood can be used to deliver more effective messaging and make connections to urban trees.

Adapting to Climate Change

Adaptation actions were identified with the previous information in mind (Table 3). Several adaptation approaches were selected that addressed the biggest climate change impacts and challenges while also capitalizing on opportunities to meet project goals. Approaches and tactics were selected related to four main themes. The first theme focused on tree species selection to align with future climate conditions, making use of a more diverse palette of future-adapted trees in tree-planting initiatives. The second theme focused on increasing water infiltration and soil quality. The urban forest land managers were interested in exploring several tactics to increase herbaceous ground cover as a way of increasing soil organic matter and infiltration. The third theme is related to increasing concern about extreme storms and wind affecting the existing tree canopy, which prompted the project partners to consider doing a local tree canopy risk assessment to identify trees that may need additional care or removal. Finally, concerns about climate-change effects to the area's residents prompted the urban forest land managers to consider exploring the idea of creating

Table 3—Selected proposed adaptation actions identified for the neighborhood project area in Providence, Rhode Island.

Management Area/Topic	Climate Change Impacts	Adaptation Approach	Proposed Adaptation Tactics
Expanding tree canopy	▸ Extreme heat, reduced soil moisture in summer	▸ Approach 7.3: Introduce species, genotypes, and cultivars that are expected to be adapted to future conditions	▸ Select drought-adapted and wind-tolerant trees by examining adaptive capacity scores for individual tree species
Stormwater/ street flooding	▸ Increased heavy rain events and flooding, reduced soil moisture in summer	▸ Approach 4.1: Maintain or restore soils and nutrient cycling in urban areas ▸ Approach 5.1: Reduce impacts from extreme rainfall and enhance stormwater infiltration and storage ▸ Approach 9.1: Co-design large-scale green infrastructure and built systems to promote health ▸ Approach 9.2: Provide micro-scale nature experiences to promote health and healing	▸ Select flood-adapted trees for use in bioswales ▸ Increase biodiversity of ground cover and widen tree pits around existing trees ▸ Plant multiple trees in larger beds and change soil within the beds over time ▸ Implement more lawn strips ▸ Provide homeowners with education/ guidance for planting and recommend planting a layer under their trees ▸ Look into products such as mycorrhizae packets, hydrogel, and biochar
Maintaining existing tree canopy	▸ More extreme storms and wind, more severe hurricanes	▸ Approach 5.2: Reduce risk of damage from extreme storms and wind	▸ Maintain current systematic pruning program ▸ Consider planting windbreaks that help other trees survive on the property and reduce drying ▸ Conduct additional tree risk assessments to identify hazardous trees for removal in priority areas ▸ Treat trees that could become a hazard
Community/ stakeholder engagement **(mixed land-use types)**	▸ Extreme heat and air quality effects on people, climate-related trauma, and stress	▸ Approach 1.3: Address climate and health challenges of disadvantaged communities and vulnerable populations ▸ Approach 8.1: Provide nature experiences to ease stress and support mental function	▸ Develop communication strategies using the local school and organizations (e.g., Boys & Girls Club), and send the children home flyers ▸ Implement additional door-to-door canvassing and events/programming around trees ▸ Identify heritage trees and bring attention to them ▸ Create small green spaces that incorporate nature and are designed by the community

a small space for engagement with nature as a source of community healing. This would require additional input from residents regarding what type of space would be wanted, where it could be located, and how to engage local artists to help design the space.

Monitoring

The project partners identified several monitoring items that could help inform future management. PNPP will monitor the number of new species planted and inventory the

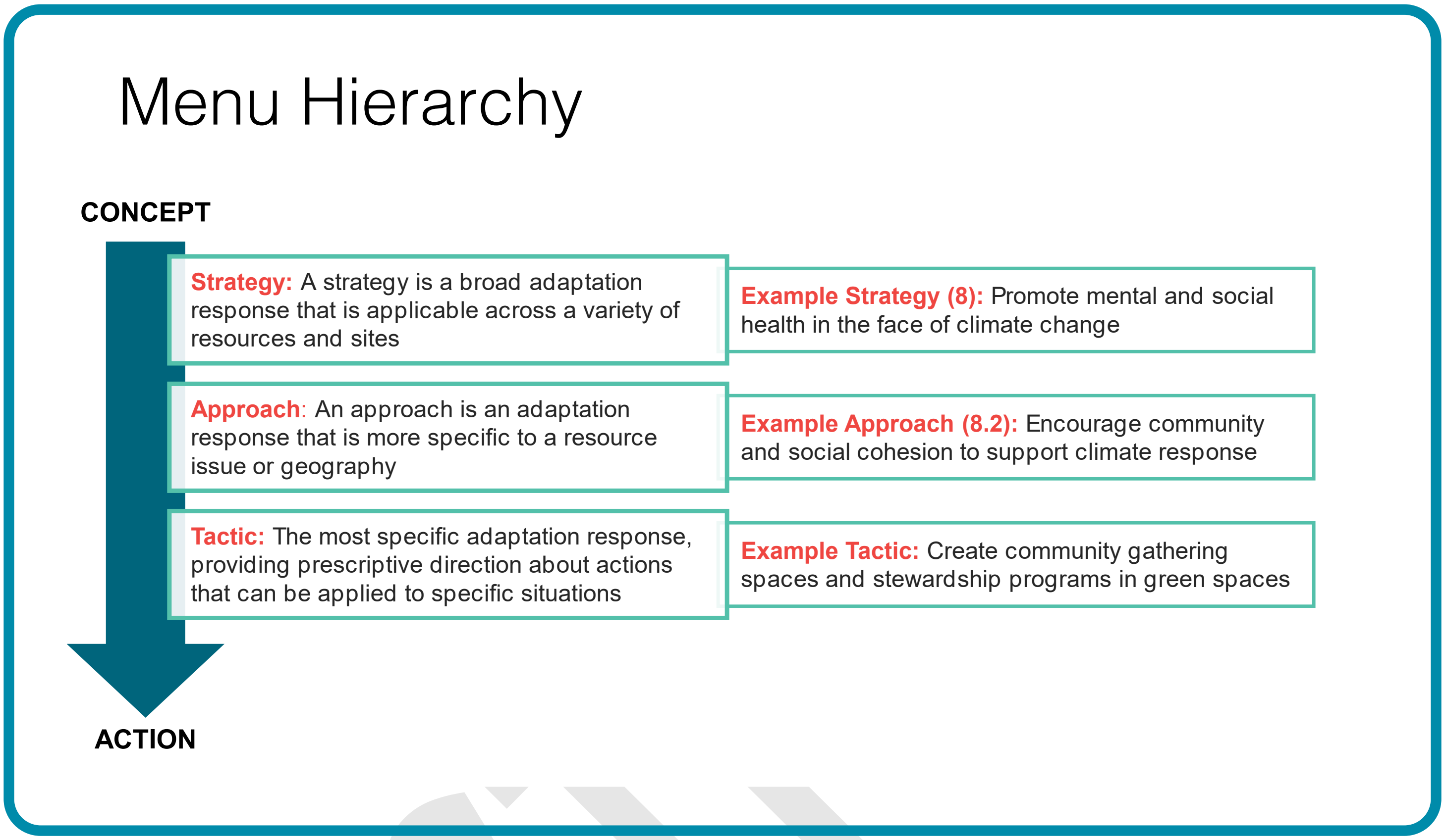

Figure 5—The Adaptation Workbook[21] describes an assessment and decision process that is used in conjunction with vulnerability assessments, local knowledge, and adaptation strategies menus. The results are site-specific actions that address explicit management and conservation objectives under a range of potential future climates.

diversity and survival of trees over 2 years. Organic matter content and microbial biomass in the soil also can be measured in addition to bioswale monitoring that is already conducted, which evaluates the infiltration of stormwater through a partnership with researchers at the Rhode Island School of Design.

Stewardship and maintenance activities will be tracked by measuring the number of volunteers who participate in stewardship within the neighborhood and the number of trees maintained by volunteers. The number of risk assessments and emerald ash borer treatments conducted also can be documented.

Community engagement will be measured by the number of residential sites that request a tree planting, and the number of presentations, events, pamphlets, and general outreach activities can be documented as well. Depending on the green space designed as a pocket park, urban forest land managers can determine community surveying methods to measure the impact, such as the number of engagements with a particular aspect of the space.

More Information

Information on this adaptation demonstration is available at www.forestadaptation.org/pnpp.

APPENDIX 3

Rhode Island Tree Species List for Climate and Health

Because individual tree species will respond differently to climate change, assessing the vulnerability of individual tree species can provide useful information to urban foresters and municipalities in managing the urban forest. Gathering information on the biological traits of tree species and their sensitivity to varying stressors helps to identify which species may be at greatest risk, as well as locations or neighborhoods that are susceptible to greater loss of forest canopy.

A tree species vulnerability assessment was created for urban forests in Rhode Island to consider how climate change would affect tree species used in urban forestry projects, and also to outline the benefits of various tree species on human health and carbon mitigation.

Rhode Island Climate and Health Tree List