USDA Northern Forests Climate Hub
U.S. DEPARTMENT OF AGRICULTURE

VULNERABILITY ASSESSMENT OF AUSTIN'S URBAN FOREST AND NATURAL AREAS

A report from the Urban Forestry Climate Change Response Framework

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Climate Hub Technical Report NFCH-5

ABSTRACT

The trees, developed green spaces, and natural areas within the City of Austin's 400,882 acres will face direct and indirect impacts from a changing climate over the 21st century. This assessment evaluates the vulnerability of urban trees and natural and developed landscapes within the City Austin to a range of future climates. We synthesized and summarized information on the contemporary landscape, provided information on past climate trends, and illustrated a range of projected future climates. We used this information to inform models of habitat suitability for trees native to the area. Projected shifts in plant hardiness and heat zones were used to understand how less common native species, nonnative species, and cultivars may tolerate future conditions. We also assessed the adaptability of planted and naturally occurring trees to stressors that may not be accounted for in habitat suitability models such as drought, flooding, wind damage, and air pollution. The summary of the contemporary landscape identifies major stressors currently threatening trees and forests in Austin. Major current threats to the region's urban forest include invasive species, pests and disease, and development. Austin has been warming at a rate of about 0.4˚F per decade since measurements began in 1938 and temperature is expected to increase by 5 to 10˚F by the end of this century compared to the most recent 30-year average. Both increases in heavy rain events and severe droughts are projected for the future, and the overall balance of precipitation and temperature may shift Austin's climate to be more similar to the arid Southwest. Species distribution modeling of native trees suggests that suitable habitat may decrease for 14 primarily northern species, and increase for four more southern species. An analysis of tree species vulnerability that combines model projections, shifts in hardiness and heat zones, and adaptive capacity showed that only 3% of the trees estimated to be present in Austin based on the most recent Urban FIA estimate were considered to have low vulnerability in developed areas. Using a panel of local experts, we also assessed the vulnerability of developed and natural areas. All areas were rated as having moderate to moderate-high vulnerability, but the underlying factors driving that vulnerability differed by natural community and between East and West Austin. These projected changes in climate and their associated impacts and vulnerabilities will have important implications for urban forest management, including the planting and maintenance of street and park trees, management of natural areas, and long-term planning.

Cover Photo

Colorado River in Downtown Austin. Photo Courtesy April Rose, City of Austin

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VULNERABILITY ASSESSMENT OF AUSTIN'S URBAN FOREST AND NATURAL AREAS

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PREFACE

Context and Scope

This assessment is a fundamental component of the Urban Forestry Climate Change Response Framework project and builds off methods developed for the Chicago Wilderness Urban Forestry Vulnerability Assessment (Brandt et al. 2017). This project builds on lessons learned from the Climate Change Response Framework: a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management. Each project interweaves four components: science and management partnerships, vulnerability assessments, adaptation resources, and demonstration projects. This assessment focuses on both the developed and natural areas within the Austin region.

We designed this assessment to be a synthesis of the best available scientific information. Its primary goal is to inform those that work, study, recreate, and care about the urban forests and natural areas in the Austin region. As new scientific information arises, we expect that new efforts will need to be undertaken to reflect that acquired knowledge and understanding. Most important, this assessment does not make recommendations about how this information should be used.

The scope of the assessment is the urban forest, broadly defined to include both developed and natural settings within the urban landscape.

Author Contributions and Acknowledgements

Leslie Brandt developed the assessment methodology, report structure, and led the writing of chapters 3 and 4. Cait Rottler and Wendy Gordon led the writing of chapter 2 and assembled climate change projections and historical data. April Rose, Lisa O'Donnell, and Stacey Clark led the writing and mapping for chapter 1. Annamarie Rutledge led the writing for chapter 5 with help from Emily King, April Rose, and Lisa O'Donnell.

We wish to thank the municipal foresters, park district representatives, natural areas managers, and others that participated in the vulnerability and adaptation workshops that contributed to this report. We also wish to thank Bill Reiner for his assistance with the species list, and the workshop planning committee.

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Chapter 1: The Contemporary Landscape

This chapter describes the structure and function of Austin's urban forest, the forces that shaped it, and current stressors. This information lays the foundation for understanding how shifts in climate may contribute to changes in Austin's trees and urban forests, and how climate may interact with other stressors present on the landscape.

Key Points

- Austin is composed of two ecoregions: Edwards Plateau to the west and Blackland Prairie to the east.
- Austin's urban forest is made up of approximately 34 million trees with a tree canopy covering about 31% of the city.
- The majority (92%) of trees are native to Texas, and the 10 most common trees account for 84% of all trees.
- Natural areas, including agricultural uses, make up the majority of total land area (57%), while 39% of total land area is considered developed area and the remaining is composed of open water.
- Austin is located on a distinct ecological divide. East Austin includes the Blackland Prairie with deep, rich soils, and West Austin includes the Edwards Plateau, characterized by shallow soils over limestone. These areas support different tree species that are uniquely adapted to each ecoregion. Development, population growth, and land-use change have transformed the area's vegetation structure, composition, and function.
- Additional stressors and threats to Austin's trees and natural areas include drought, alteration of soil, non-native invasive plant species, shifts in fire regime, and insect pests and diseases, including oak wilt, emerald ash borer, Dutch elm disease, and bacterial leaf scorch.
- Managers in Austin's natural and developed areas are working to manage Austin's urban forest to ensure it continues to provide benefits for all members of the community.

Chapter 2: Climate Trends, Projections, and Impacts

This chapter summarizes what we know about how the climate has changed over the historical record, how climate is projected to change over this century, and impacts to Austin's urban forest and natural areas.

Key Points

- Austin has been warming at a rate of about 0.4˚F per decade since measurements began in 1938 and is expected to warm by 5 to 10 degrees by the end of this century compared to the most recent 30-year average.
- Austin has been getting slightly wetter on average, but precipitation can vary widely within and between years, and future projections of precipitation are uncertain.
- It is highly probable there will be both an increase in heavy rain events and severe droughts in the future decades, which will stress the area's trees.
- Overall, the balance of precipitation and temperature may shift Austin's climate to be more similar to the arid Southwest.
- Changes in temperature and precipitation may also exacerbate current stressors such as non-native invasive plants, insect pests, and pathogens.

Chapter 3: Vulnerability of Austin's Trees

This chapter summarizes expected changes in habitat suitability and the adaptive capacity of different species in Austin's developed and natural areas.

Key Points

- Modeling Native Trees: Species distribution modeling of native trees suggests that suitable habitat may decrease for 14 primarily northern species. Suitable habitat was expected to increase for four species.
- Projected Changes from Heat and Hardiness Zone Shifts and Species Ranges: For species for which no model information is available (rare, non-native, or cultivars), shifts in heat and hardiness zones could

have a positive effect on 23 species, while 60 species had either hardiness zone, heat zone, or range limits (or a combination thereof) that may suggest a negative effect.

- Adaptive Capacity of Urban Trees: Adaptive capacity of 104 species was evaluated using scoring systems for planted and natural environments, with many non-native invasive species among those with the highest capacity to adapt to a range of stressors. For planted/developed conditions, 29 species received a high adaptability score, 18 received a low adaptability score, and the remaining 57 received a medium adaptability score. For natural areas (both native and naturalized), 43 species received a high adaptability score, 13 received a low adaptability score, and 48 received a medium adaptability score
- Overall Vulnerability of the Austin Region's Trees: An analysis of vulnerability that combines model projections, shifts in heat and hardiness zones, and adaptive capacity showed that in planted and developed sites many of the same species rated as having high vulnerability in natural areas were also vulnerable in urban areas. Species that were less adapted to urban sites were also listed as vulnerable, indicating that a greater proportion of trees were considered vulnerable in developed sites.

Chapter 4: Vulnerability of Austin's Urban Forest

This chapter focuses on the vulnerability of the urban forest in Austin's developed and natural areas to climate change. Vulnerability is the susceptibility of a system to the adverse effects of climate change and is a function of a system's impacts and adaptive capacity.

Key Points

- Both natural and developed areas in the Austin region show some degree of vulnerability to changes in climate.
- Natural and developed upland areas in West Austin are vulnerable to drought, erosion, and wildfire and have less tree canopy diversity than East Austin.
- Natural and developed areas in East Austin are vulnerable to shrink-swell from precipitation changes and flooding due to their presence at lower elevations but have a greater potential for a diverse tree canopy than West Austin.
- The urban core and other highly developed areas will experience stress not only from changes in climate but also from compounding effects of drought, heat, and local flooding from restricted soil conditions and impervious surfaces.

Chapter 5: Management Considerations

Management considerations in this chapter are summarized by theme and include a range of issues that urban foresters face.

Key Points

- Maintaining species diversity and selecting appropriate species for the projected changes in habitat suitability will become more of a challenge for everyone, from land managers to the nursery industry.
- Given the uncertainties around the effects of climate change it will be important for land managers to continue to observe and document impacts on tree species and refine models and management strategies.
- Climate change challenges will also present opportunities for land managers and other decision-makers to further engage with their communities, develop new partnerships and programs, expand their volunteer base, and make investments in resilient landscapes.

INTRODUCTION

Context

This assessment is a fundamental component of the Urban Forestry Climate Change Response Framework project (https://forestadaptation.org/focus/urban-forests) and is supported jointly by the USDA Southern Plains and Northern Forests Climate Hubs. This project builds on lessons learned from the Climate Change Response Framework: a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management. Each project interweaves four components: science and management partnerships, vulnerability assessments, adaptation resources, and demonstration projects (Fig. X.1). The Austin assessment uses methods developed in the Chicago Wilderness region pilot (Brandt et al. 2017) and also methods developed for assessing vulnerability of natural areas (Brandt et al. 2016).

The overarching goal of all Framework projects is to incorporate climate change considerations into forest management. The overall goal of the Urban project is to ensure that urban forests will continue to provide benefits to the people that live in urban communities as the climate changes. We define the urban forest as all publicly and privately-owned trees within an urban area— including individual trees along streets and in backyards, as well as stands of remnant forest. The Urban project works across organizations, both public and private, to work toward this goal by accomplishing the following objectives:

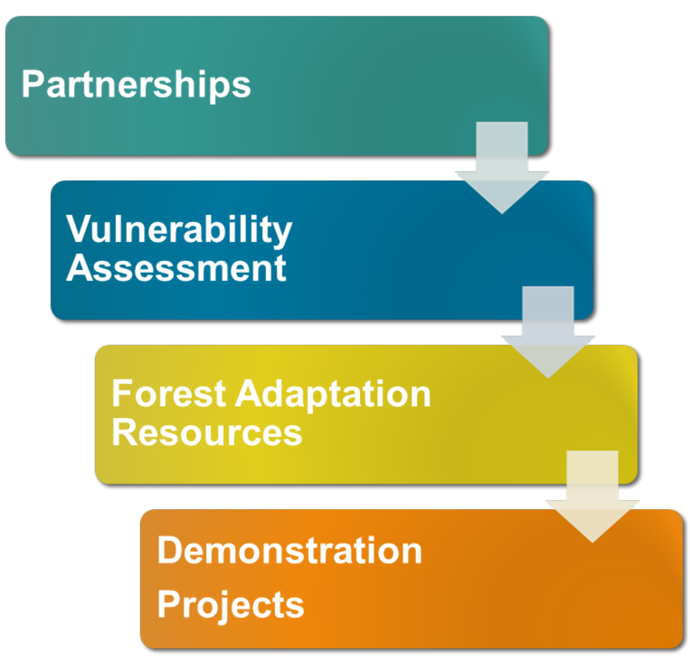

Figure X.1. Climate Change Response Framework components

- Engage with communities that are interested in adapting their urban forest management to climate change.
- Work with these communities to assess the vulnerability of their urban forests to climate change.
- Identify and develop tools to aid adaptation of urban forests to climate change.
- Develop real-world examples of climate-informed management of urban forests.

The tools and approaches developed in the Urban project were originally designed to be applied to areas in the Midwest and Northeast. This report expands that work to the south-central US through a partnership with the Southern Plains Climate Hub.

Current partners in the effort include:

- Northern Institute of Applied Climate Science
- USDA Southern Plains and Northern Forests

Climate Hubs

- USDA Forest Service
- USDA Agricultural Research Service
- USDA Natural Resources Conservation Service
- City of Austin, TX
- Texas A&M Forest Service
- The Nature Conservancy

Austin has a long track record of environmental stewardship; in 2019 the National Wildlife Federation honored Austin as the nation's most wildlife-friendly city, and in 2013, American Forests named Austin one of the 10 Best Cities for Urban Forests. Strong public-private-partnerships provide the benefit of numerous resources that the local community actively leverages to further support the local ecosystem.

Scope and Goals

The primary goal of this assessment is to summarize potential changes to the urban forest of the Austin region under a range of future climates and determine the vulnerability of trees and developed and natural landscapes to those changes. The assessment also includes a synthesis of information about the current landscape as well as projections of climate and vegetation changes used to assess these vulnerabilities. Uncertainties and gaps in understanding are discussed throughout the document. This assessment covers the extraterritorial jurisdictional boundary of the City of Austin and encompasses 400,882 acres (Fig. X.2). Municipalities within this boundary are also included in the assessment.

Assessment Chapters

This assessment comprises the following chapters:

Chapter 1: The Contemporary Landscape describes existing conditions, providing background on the physical environment, ecological character, and current management of developed and natural areas in the Austin region.

Chapter 2: Climate Trends, Projections, and Impacts summarizes our current understanding of past and projected future changes in climate in the Chicago Wilderness region.

Chapter 3: Vulnerability of Austin's Trees summarizes the projected changes in habitat suitability and adaptive capacity for trees found in the Austin region.

Chapter 4: Vulnerability of Austin's Urban Forest summarizes the vulnerability of the urban forest in three developed areas and four natural community types in Austin.

Chapter 5: Management Considerations summarizes implications of climate change for the management of Austin's urban forest.

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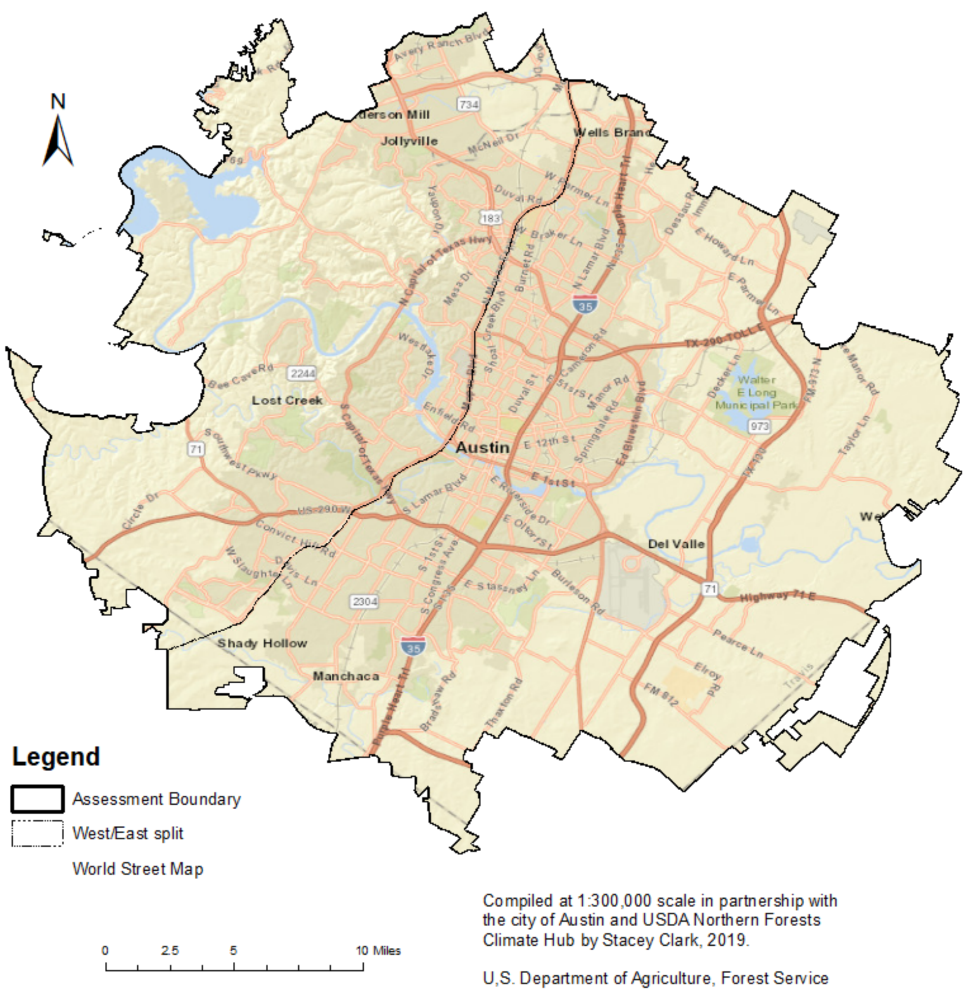

Figure X.2. Assessment Area. The assessment area includes the city of Austin's extra-jurisdictional boundary and all municipalities and ownerships within.

CHAPTER 1

THE CONTEMPORARY LANDSCAPE

The urban forest is defined as all publicly and privately-owned trees within an urban area, including individual trees along streets and in backyards, as well as stands of remnant forest (Nowak et al., 2001). The urban forest of the Austin region can be viewed as two separate but interconnected types: natural areas and developed sites. These areas are managed and maintained in vastly different ways and often by different entities. The urban forest is shaped by ecosystems, landforms, and environmental gradients that existed prior to Euro-American settlement. The ecoregion is defined by the tallgrasses of the Blackland Prairie to the east and the forests, woodlands, of the Edwards Plateau to the west, and is divided by the Balcones fault zone. While much of the region has been developed, its natural history influences current forest composition. In this section we will describe the structure and function of Austin's urban forest, the forces that shaped it, and current stressors. This information lays the foundation for understanding how shifts in climate may contribute to changes in Austin's trees and urban forests, and how climate may interact with other stressors present on the landscape.

Landscape Setting

Austin is a vibrant community, home to many unique cultures and physical landscapes. The city is experiencing rapid growth and change and is projected to continue on this path. Residents are concerned about the impacts of that growth, along with potential impacts from climate change, on their trees and green spaces. In 2019 the city underwent an Urban Forest Vulnerability Assessment to better understand the vulnerability of trees and urban forests to direct and indirect impacts of climate change. This vulnerability assessment follows up on the Urban Forest Inventory and Analysis (Nowak et al., 2016) and the City of Austin's Urban Forest Plan (City of Austin, 2013). This assessment includes all public and private land within the City of Austin and its extraterritorial jurisdiction, which includes the Edwards Plateau and Blackland Prairie ecoregions, as defined by the Texas Parks & Wildlife mapping (Gould, Hoffman, & Rechenthin, 1960). Located in Central Texas, Austin is nestled at the junction of the Edwards Plateau and the Blackland Prairie. It is divided by the Balcones Escarpment fault line (Texas Parks & Wildlife, 2013). The escarpment plays a role in regulating climate in the Austin area; although maximum elevation change is only a few hundred feet, it is the first topographic break inland from the Gulf of Mexico and thus influences weather, making Austin prone to large flood-producing storms (Abbott & Woodruff, 1986). This and other differences in biotic and abiotic characteristics between ecoregions present unique challenges for the city's economic, environmental, climate change–related, and social planning.

Landform, soils, and hydrology

Edwards Plateau

This ecoregion found in the western portion of Austin is an uplifted geological region of thick, mostly flat layers of bedrock composed primarily of hard early Cretaceous limestone (Riskind & Diamond, 1988). Its eastern and

More Information on Trees and Natural Areas in the Austin Region

The resources below provide more information regarding the urban forest and natural areas in Austin:

Austin's Urban Forest (Nowak et al., 2016)
Provides an assessment of Austin's tree composition and their ecosystem service values.

Austin Urban Forest Master Plan (City of Austin, 2013)

Other resources and plans that influence trees and vegetation in the Austin area:

- Land Development Code: www.austintexas.gov/department/austin-city-code-land-development-code
- Environmental Criteria Manual: library.municode.com/tx/austin/codes/environmental_criteria_manual?nodeId=ENCRMA
- ImagineAustin - Green Infrastructure Priority Program: www.austintexas.gov/page/GreenInfrastructure
- Climate Protection Resolution: austintexas.gov/page/climate-protection-resolution
- Invasive Species Management Plan: austintexas.gov/sites/default/files/files/Watershed/invasive/COA-ISMP-Final-7-11-12.pdf
- Watershed Protection Management Plan: www.austintexas.gov/department/watershed-protection-master-plan
- Austin/Travis County Community Wildfire Protection Plan: www.austintexas.gov/wildfireprotectionplan

southern boundaries are defined by a now-inactive fault zone, the Balcones Escarpment (Small, Hanson, & Hauwert, 1996). This ecoregion is largely a dissected limestone plateau that is hillier to the south and east (the "Hill Country"; see Diamond & True, 2008), where it is easily distinguished from bordering ecoregions by the sharp fault line. The eastern edge is characterized by steep limestone karst terrane with a deep, cavernous aquifer (Edwards Aquifer) (Small et al., 1996).

Soil depth varies by topography: hilltops have shallow soils while flat areas and lowlands have thicker soils. Soil textures depend on the underlying parent material and surface vegetation. The Edwards Plateau is prone to high-intensity rainfall events, which can lead to flash-flooding and erosion (Riskind & Diamond, 1988). Due to karst topography (related to dissolution of limestone substrate) and resulting underground drainage, streams are relatively clear and cool in temperature compared to those of surrounding areas (Griffith et al., 2004).

Major water sources in the Austin area include the Edwards Aquifer, the Colorado River and its network of perennial and intermittent streams, and springs, of which the largest (Barton Springs) flows from the base of the Balcones Escarpment. The predominant vegetation association is mature, closed-canopy Ashe juniper-oak forest, although more open woodlands and shrublands also occur in this area. The eastern edge of the Edwards Plateau ecoregion has been identified as a biodiversity "hot spot" with many endemic and imperiled species, including rare plants, cave and spring invertebrates, Eurycea salamanders, and the golden-cheeked warbler (*Setophaga chrysoparia*).

Blackland Prairie

This ecoregion found in the eastern portion of Austin is distinguished from surrounding regions by its fine-textured, clayey soils and predominantly prairie potential natural vegetation (Griffith et al., 2004). Two subregions of Blackland Prairie are found in Austin: the Northern Blackland Prairie and Floodplains and Low Terraces.

The black clay soils are productive, which has led to conversion of much of the terrain into cropland and grazing pastures (Texas Parks & Wildlife, 2013). This region now contains a higher percentage of cropland than adjacent regions; pasture and forage production for livestock is common (Griffith et al., 2004). Large areas of the region are being converted to urban and industrial uses (Griffith et al., 2004). Dominant grasses include little bluestem, big bluestem, yellow Indiangrass, and switchgrass (Griffith et al., 2004). Within the Austin area, the Blackland Prairie ecoregion contains the watersheds, tributaries, and riparian zones of the Colorado River, providing habitat for a variety of wildlife species.

Deciduous bottomland woodland and forest were common along rivers and creeks (Diamond & Smeins, 1993); today pecan, cedar elm, various oaks, and sugarberry dot the landscape, with mesquite invading the edges. Historically important natural landscape-scale disturbances included fire and indigenous wildlife grazing (primarily bison and, to a lesser

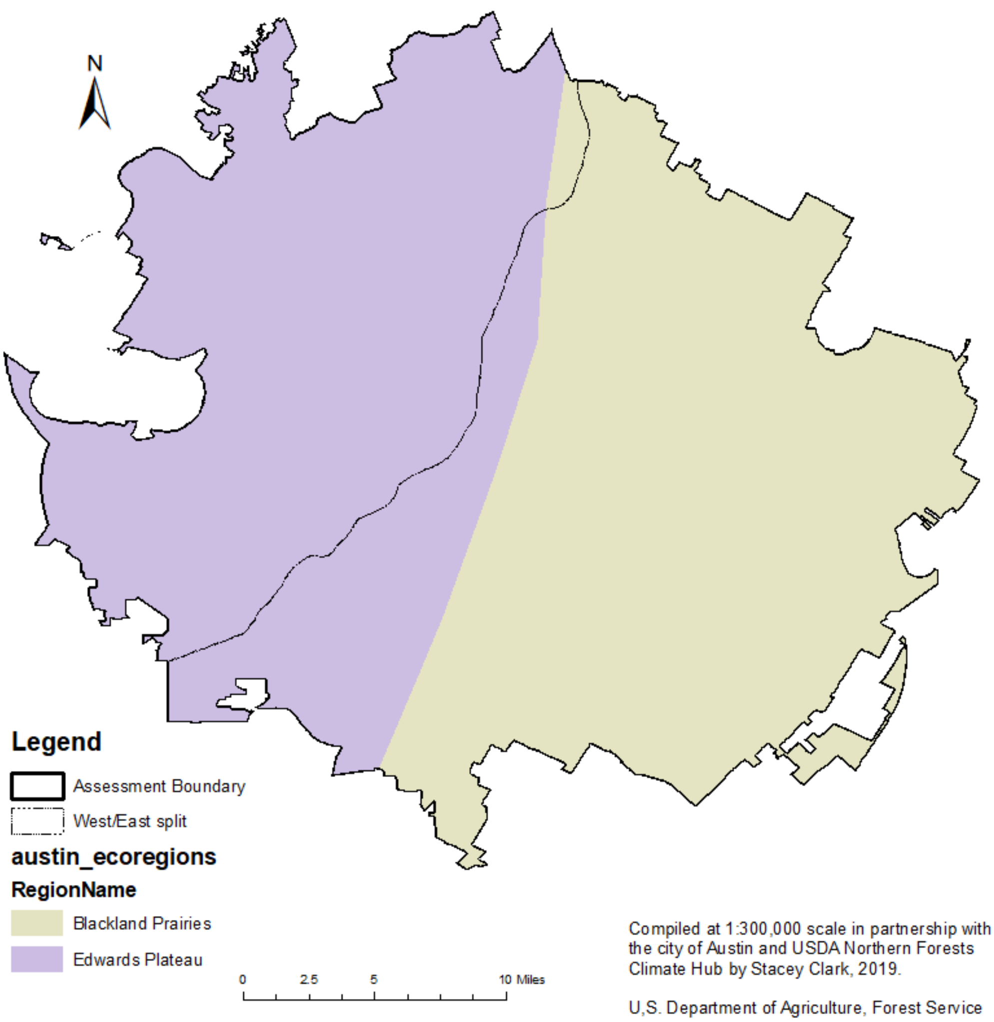

Figure 1.1. Ecological Regions in the Austin, Texas, Assessment Area. From Vegetational Areas of Texas, by F. W. Gould, G. O. Hoffman, & C. A. Rechenthin, C.A. (1960). Created from map in F. W. Gould (1975). Updated by TPWD GIS Lab 1/09/2004. Retrieved August 27, 2019, from https://tpwd.texas.gov/gis/data/baselayers/naturalsubregions-zip/view=

extent, pronghorn antelope). Fire and infrequent but intense short-duration grazing suppressed woody vegetation and invigorated herbaceous prairie species (Eidson & Smeins, 1999). Human settlement and wildfire suppression have also contributed to the invasion of non-native species, such as King Ranch bluestem, bermudagrass, Arrundo, and Chinaberry.

Natural communities

Edwards Plateau: Historical

Fossilized pollen of oak, juniper, other tree species, grasses, and forbs from Friesenhahn Cave in northern Bexar County date to the last ice age, 14,000 to 20,000 years ago (Hall & Valastro, 1995). Eyewitness accounts of early explorers, settlers, and scientists from 1700 to 1900 reported extensive forests dominated by Ashe juniper and other woody species along the eastern edge of the Edwards Plateau (Weniger 1984; Smeins et al 2001; Nelle 2012; O'Donnell, 2019,). These accounts are supported by other documents, including field notes from original land grants, maps, and photographs. Along with land clearing and introduction of livestock, historical records suggest that the extent and frequency of fires increased following European settlement (O'Donnell, 2019; Weniger, 1984), which undoubtedly altered the vegetation communities. In addition to the endangered golden-cheeked warbler, which breeds exclusively in the Ashe juniper-oak forests of Central Texas, observations of the passenger pigeon (*Ectopistes migratorius*) (Lockwood, 2010); flying squirrel (*Pteromys volucella*) (Roemer, 1935); and black bear (*Ursus americanus*) were reported in forests of the Edwards Plateau during the 1800s.

In the Austin area, forests were logged in the late 1800s and early 1900s and are currently in various stages of recovery (Bray, 1904a; Keddy-Hector, 2000). After clearing, much of the topsoil was lost due to subsequent goat and cattle overgrazing and erosion (Marsh and Marsh, 1992). On some steep slopes, this soil loss has greatly reduced the revegetation potential (City of Austin & Travis County, 2018). Current and past over-browsing by white-tailed deer has further reduced understory flora diversity and species abundance (Russell & Fowler, 2004; Russell, Zippin, & Fowler, 2001). While oaks tend to re-sprout following fire, Ashe juniper does not and is slow to recover (Reemts & Hansen, 2008, 2013). However, Ashe juniper can recolonize formerly cleared areas and is a dominant tree on the Edwards Plateau, occuring as both an early successional and climax species (Bray 1904a).

Edwards Plateau: Current

The dominant natural community type currently found in the Edwards Plateau is upland forest, dominated by Ashe juniper, Texas red oak (*Q. buckleyi*), escarpment live oak (*Q. fusiformis*), shin oak (*Q. sinuata var. breviloba*), escarpment black cherry (*Prunus serotina var. eximia*), Texas ash (*Fraxinus texensis*), and cedar elm (*Ulmus crassifolia*). In addition to seedlings of the canopy trees, common understory species include Texas mountain laurel (*Dermatophyllum secundiflorum*), Carolina buckthorn (*Frangula caroliniana*), yaupon holly (*Ilex vomitoria*), red buckeye (*Aesculus pavia var. pavia*), Mexican buckeye (*Ungnadia speciosa*), Lindheimer silk-tassel (*Garrya ovata var. lindheimeri*), and elbowbush (*Forestiera pubescens*) (City of Austin & Travis County, 2018). Texas madrone (*Arbutus xalapensis*) becomes more common on the western edge of the Austin area. Some areas, particularly along riparian corridors, have experienced compositional shifts due to non-native species invasions from species such as privet, Chinaberry, and Chinese Pistache.

Blackland Prairie: Historical

Historical accounts suggest the forested part of the Blackland Prairie region was dominated by flood-tolerant trees along the Colorado River, such as ash, cottonwood, elm, pecan, and willow (De Espinosa, 1930; De Cordova, 1858). Kennedy (1841, page 158) described Onion Creek as flowing "through a fine rolling country of mingled prairie and woodland: about ten miles from its mouth there is a grove of the best description of cypress, to the extent probably of six thousand acres. There are, besides, cedar, southern live oak, white, red, and post oak, hackberry, mulberry, wild peach, & cedar elm." Other creeks were also similarly wooded, with prairie in between. Portions of the Blackland Prairie in East Austin have sandy soil that have historically supported post oak woodlands (Terrell, 1910).

Blackland Prairie: Current

Significant portions of the Blackland Prairie have been converted to rangeland or row crops over the last two centuries. Overgrazed upland pastures are dominated by honey mesquite (*Prosopis glandulosa*), and groves of eastern red cedar (*Juniperus virginiana*) and cedar elm (*Ulmus crassifolia*) are also common in these areas. Shrubland patches can be found in the uplands as well, dominated by legume species like retama (*Parkinsonia aculeata*), catclaws (*Senegalia berlandieri, S. roemeriana, S. wrightii*), and other thorny bushes such as toothache (*Zanthoxylum hirsutum*) and Brasilwood (*Condalia hookeri*). The region is identified as the most altered ecoregion in Texas with 1% of the native Blackland Prairie remaining today (Ramos & Gonzalez, 2011).

Agricultural development in the 19th and 20th centuries likely resulted in considerable degradation of riparian woodlands through both channelization and deforestation. Impacted floodplains left fallow and allowed to recover are typically dominated by cedar elm (*Ulmus crassifolia*), retama

(*Parkinsonia aculeatea*), hackberry (*Celtis occidentalis*), and sugarberry (*Celtis laevigata*) with green ash (*Fraxinus pennsylvanica*) dominating the wetter portions near creek banks and with cottonwood (*Populus deltoides*), American sycamore (*Platanus occidentalis*), and black willow (*Salix nigra*) represented in smaller numbers along with non-native invasive species such as Chinaberry and privet. Seemingly undisturbed riparian remnants are less common and have more complex woody communities that, in addition to the above species, include canopy species such as pecan (*Carya illinoiensis*), American elm (*Ulmus americana*), red mulberry (*Morus rubra*), Anacua (*Ehretia anacua*), gum bumelia (*Sideroxylon lanuginosum*), catalpa (*Catalpa speciosa*), osage orange (*Maclura pomifera*), black walnut (*Juglans nigra*), and honey locust (*Gleditsia triacanthos*). These remnants typically have an understory consisting mostly of roughleaf dogwood (*Cornus drummondii*), Carolina buckthorn (*Frangula caroliniana*), possumhaw (*Ilex decidua*), yaupon (*Ilex vomitoria*), chickasaw plum (*Prunus angustifolia*), Mexican plum (*Prunus mexicana*), and soapberry (*Sapindus saponaria*).

Natural community types within the study area

For the purposes of this urban forest vulnerability assessment, the natural communities within the area of interest were divided into four types: Upland Forest, Upland Woodland, Upland Mixed Shrubland, and Floodplains and Terraces (Figure 1.2). These natural community types have similarities in vegetation species composition, structure, and potential for disturbance (Table 1.1). The four natural community types each include a unique grouping of vegetation types, as described and mapped by the Texas Parks and Wildlife Department's Ecological Mapping Systems Data (Elliott et al., 2009, 2014). Only vegetation types that fell within the area of interest were included for grouping into one of the four natural community types, based on differentiating criteria of overstory cover and species composition, understory species composition, hydrology, productivity, and disturbance potential. If the description of a vegetation type didn't meet the criteria for one of the four natural community type categories, it was included in a fifth, non-assessed category called "Other" (e.g., grasslands, open water, urban, and cropland) (see Table A.1, Appendix 1).

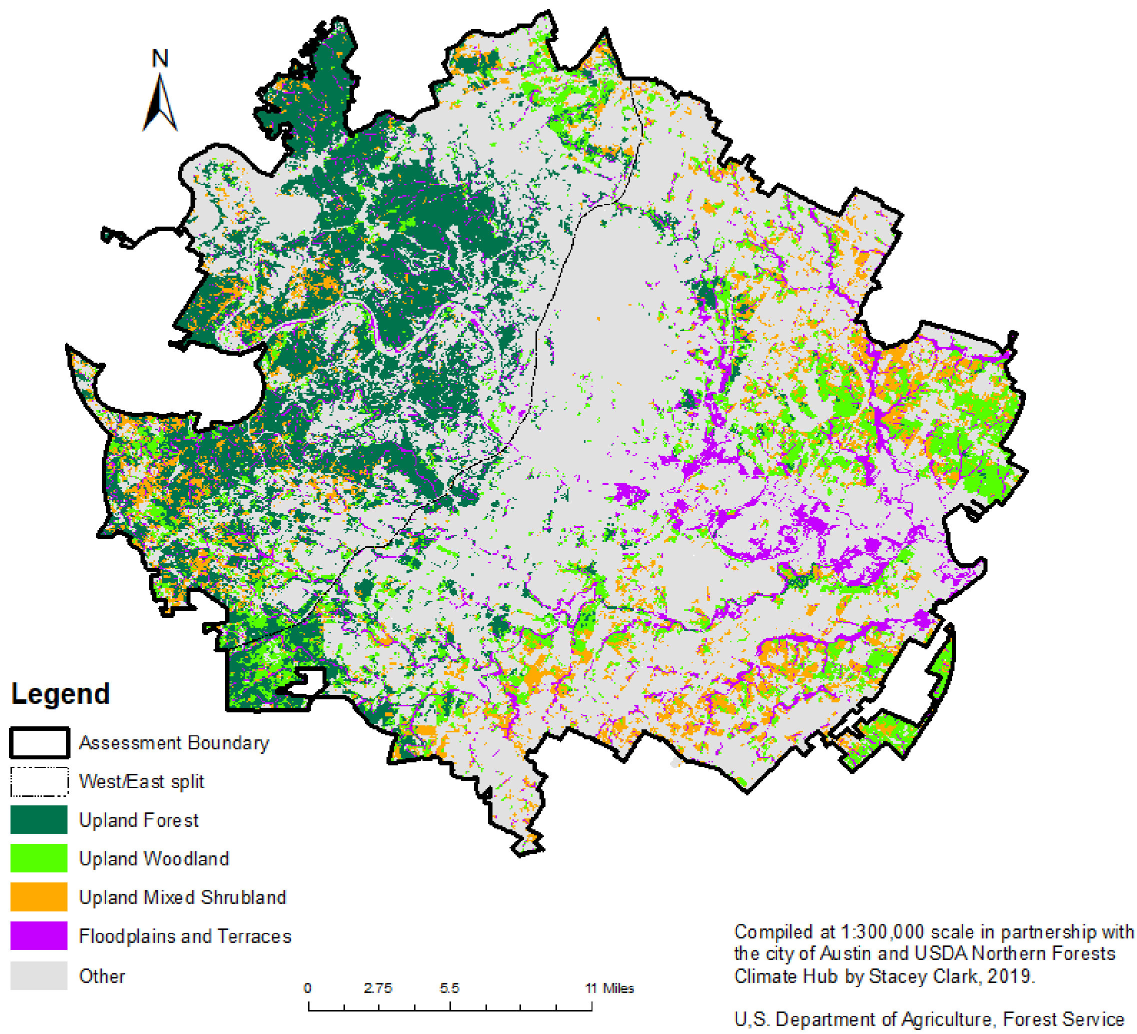

Figure 1.2. Map of the Natural Communities included in the Assessment: Upland Forest, Upland Woodland, Upland Mixed Shrubland, and Floodplains and Terraces. Natural communities were mapped by grouping vegetation types from the Texas Parks and Wildlife Department's Ecological Mapping Systems data (See Table A.1, Appendix 1).

Table 1.1
Natural Community Types, the Defining Characteristics, and Dominant or Indicator Woody Species within Each Type

Natural Community Type	Defining Characteristic	Dominant or Indicator Woody Species
Upland Forest	usually found on flats, steps, and lowlands in steeper slope areas with greater soil depth	Trees: Ashe juniper, Texas red oak, Texas/escarpment live oak, white shin oak, cedar elm, sugarberry, post oak, blackjack oak, Arizona walnut, Escarpment black cherry, Texas ash, gum bumelia, Texas redbud, Carolina buckthorn, rusty blackhaw, red buckeye, Mexican buckeye, Mexican plum, Texas madrone
	mesic microclimates	
	high level of diversity in overstory	
	mixed evergreen and deciduous tree species in the canopy	
	typically >70% canopy tree cover	
	shade, leaf litter, and rocky substrates can limit herbaceous vegetation	Shrubs: shrubby boneset, Lindheimer's silktassel, yaupon, American beautyberry, agarito, Texas mountain laurel, possumhaw, elbowbush, Texas persimmon, catclaw mimosa, evergreen sumac, fragrant sumac
Upland Woodland	usually found on plateau tops and areas with more shallow soils	Trees: Ashe juniper, Texas/escarpment live oak, cedar elm, sugarberry, post oak, white shin oak, blackjack oak, Shumard oak, southern live oak, mesquite, eastern redcedar, gum bumelia
	historically fire driven, removing shrub layer but leaving overstory intact	
	patchy shrub cover intersprsed with pockets of herbaceous cover	Shrubs: Texas persimmon, yaupon, agarita, Texas mountain laurel, whitebrush, flameleaf sumac, elbowbush, catclaw mimosa, fragrant sumac, evergreen sumac
	mixed evergreen and deciduous, or only deciduous, tree species in the canopy	
	typically >70% tree cover	
	overstory trees are usually not as tall as in Upland Forest	
Upland Mixed Shrubland	usually found on xeric sites, slope edges, and along grasslands and woodlands in areas with very shallow soils	Trees: Texas/escarpment live oak, Ashe juniper
	trees do not dominate the canopy or tend to be stunted	Shrubs: Texas persimmon, mesquite, agarita, Texas mountain-laurel, Lindheimer's prickly pear, lotebush, fragrant mimosa, evergreen sumac, Texas colubrina, whitebrush, Lindheimer's silktassel, prairie sumac, Mexcian buckeye, elbowbush, kidneywood
	historically fire driven	
	mixed evergreen and deciduous woody species	
Floodplains and Terraces	located in valley floors of large rivers and perennial streams, and buffer zones of headwaters	Trees: sugarberry, cedar elm, Texas/escarpment live oak, green ash, pecan, American elm, American sycamore, little walnut, western soapberry, Texas oak/Buckley oak, black walnut, Eastern cottonwood, Ashe juniper, Chinaberry, bald cypress, boxelder, Texas ash, Vitex, Chinese elm, wafer ash, mesquite, black willow, Mulberry sp. , Eastern redcedar, gum bumelia
	erosional (riparian) sites are gravelly, cobbly, and rocky	
	depositional (floodplain) sites have alluvial depostion	Shrubs: Zanthoxylum sp., Texas persimmon, common buttonbush, possumhaw, desert willow, huisache, roughleaf dogwood, yaupon, Baccharis, Chinese tallow, Japanese honeysuckle
	historically driven by hydrology and floodplain dynamics	
	loamy, clayey, and sandy bottomland soils are influenced by outwash from surrounding landscape	
	species composition varies by stream order, successional stage, and flooding regime	

Current Conditions in the Austin Region

Land use and ownership

Trees and forests in Austin are arrayed across land cover, use, and ownership, including highly developed, privately owned commercial, mixed-use, or residential locations to publicly owned and managed natural areas. Developed areas make up 39% of the total land area, while natural areas including agricultural uses make up 57% of the total land area. The remaining land area is composed of open water (Table 1.2, Figure 1.3).

Roughly 24% of Austin's total land area is owned by the City of Austin. Figure 1.4 shows the distribution of parks owned by the City of Austin and areas of the Balcones Canyonlands Preserve (all ownerships) within the assessment boundary.

Table 1.2
Land Cover Types in the Assessment Area, based on the National Land Cover Database

Land Cover Type	Percent
Agriculture	10.91%
Developed, High Intensity	4.93%
Developed, Low Intensity	10.78%
Developed, Medium Intensity	10.01%
Developed, Open Space	13.57%
Natural Area	46.63%
Open Water	2.62%
Other	0.56%
Grand Total	**100.00%**

Species composition patterns

The Austin region is a mixture of remnant (pre-settlement) trees, planted trees, and spontaneous recruitment from both sources. Urban forests often have higher tree species diversity than the surrounding native landscapes (Nowak et al., 2016). Parks, natural areas, and other open spaces tend to have a higher proportion of remnant native vegetation, whereas planted trees (both native and non-

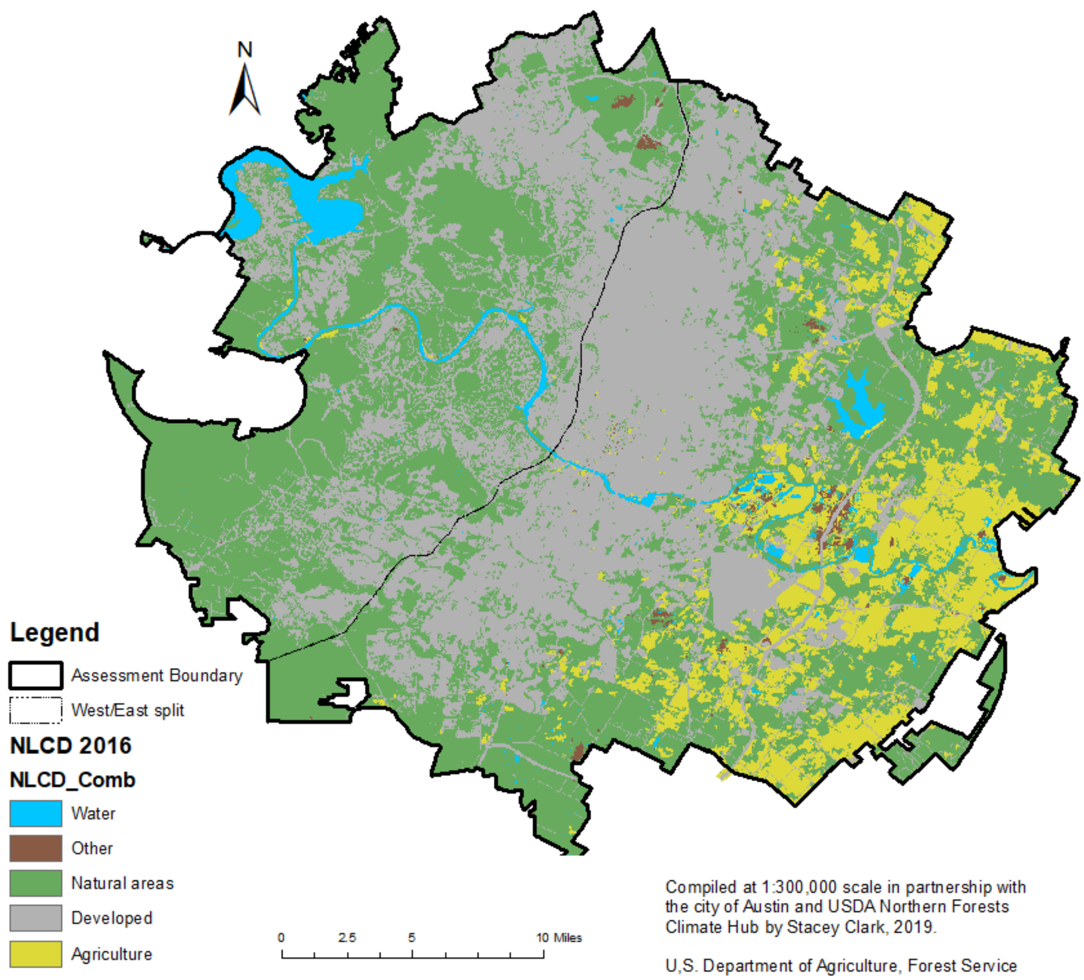

Figure 1.3. Land Cover Classes within the Assessment Area based on the National Land Cover Database. Developed includes residential, commercial, and industrial land.

native) dominate developed areas. Non-native species are found throughout. Because East Austin was historically prairie with the exception of some floodplain forests, there are more tree species planted there that were not present historically. West Austin tends to be more of a mix of remnant native trees such as Ashe juniper, Texas/escarpment live oak, Texas red oak, and cedar elm alongside planted native and non-native trees.

Austin's Urban Forest Inventory and Analysis (FIA) report summarizes the urban forest as of 2014 (Nowak et al., 2016). The analysis gives land managers benchmark data to project trends and advocate for management practices and resources to increase the resilience of the urban forest. The analysis finds that:

- Austin's urban forest contains an estimated 34 million trees.
- Tree canopy covers approximately 31% of the city.
- The most common species are Ashe juniper, cedar elm, southern live oak, sugarberry, and Texas persimmon.
- The 10 most common trees in Austin account for 84% of all trees.
- 92% of trees are native to Texas.
- Trees with diameters less than 5 inches account for 62% of the tree population.
- The largest concentration of trees with a diameter greater than 15 inches are found along the Interstate 35 corridor; while these large-diameter trees are only 3 % of the total population, they comprise 18 % of the total leaf area.
- Large trees are a small proportion but a highly significant part of the ecosystem service benefits of the urban forest.

Evergreen forest comprised largely of southern live oak and Ashe juniper covers 17% of the city. This land cover type is predominantly in the Edwards Plateau of West Austin. It contains 50% of Austin's trees and provides 49% of the leaf surface area (Nowak et al., 2016). Austin has more small trees than large trees, which is a positive indicator of long-term sustainability of tree cover. The most common small-diameter trees (less than or equal to 5 inches) are Ashe juniper, cedar elm, Texas persimmon, sugarberry, live oak, yaupon holly, Texas mountain laurel, glossy privet (ligustrum), chinaberry, and green ash. The most common large-diameter (diameter greater than or equal to 15

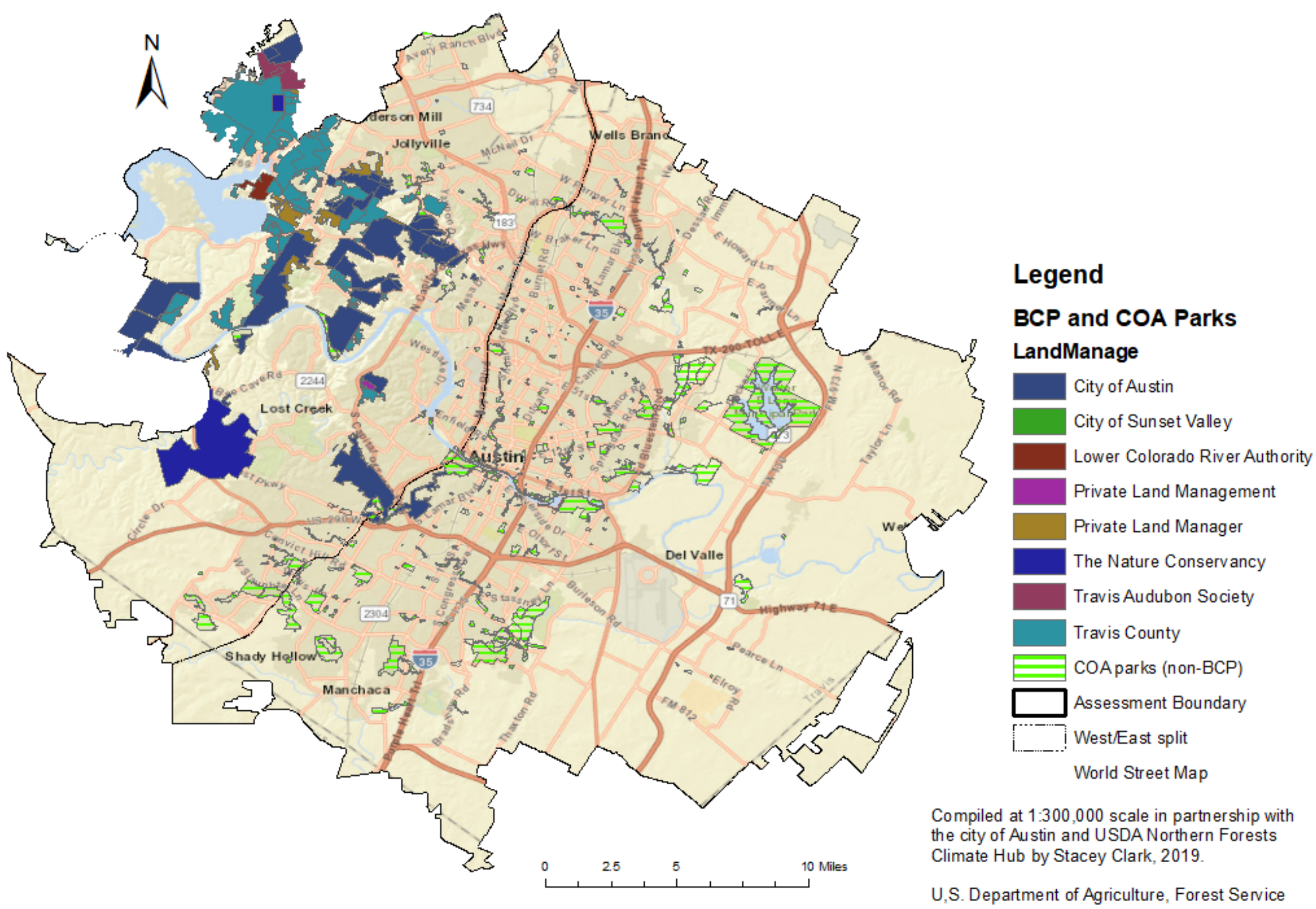

Figure 1.4. Map Showing the Distribution of Parks Owned by the City of Austin and Areas of the Balcones Canyonlands Preserve (All Ownerships) within the Assessment Boundary.

inches) trees are Ashe juniper, southern live oak, cedar elm, pecan, sugarberry, Texas red oak, honey mesquite, Chinaberry, and cottonwood. Many of the most common large-diameter species are not represented in small-diameter species composition (Nowak et al., 2016). If current large-stature trees are not being replaced by other large-stature trees, this may reduce the future potential canopy cover of Austin.

West and East Austin see a few major differences in species composition, with a total of four species forming 10% or more of species composition between both regions (Table 1.3). In other words, two species (Ashe juniper and southern live oak) in West Austin make up 80% of species composition in the area, while four species (Ashe juniper, cedar elm, honey mesquite, and southern live oak) make up 60% of species composition in East Austin. The abundance of the most common species varies between these two regions. In West Austin, Ashe juniper makes up the majority (68%) of species compared to a fifth in East Austin. Cedar elm is more common in East Austin at 18% compared to just 2% in the west. Honey mesquite makes up 10% of species in East Austin, while southern live oak is similar at 12% and 14% in West and East Austin, respectively. There are also unique species found at lower abundances in each region. West Austin contains 11 species that aren't present in the east, while East Austin contains an additional 29 species compared to the west.

Major stressors and threats to Austin's trees and natural areas

Land-use change, development, and fragmentation

Development is the primary driver of forest change in the Austin region. From 2007 to 2017, Austin experienced 34.1% population growth and is projected to continue growing 30% each decade until 2050 (U.S. Census Bureau, 2017). Infrastructure projects such as roadway expansions impact greenspaces. Increasingly, mixed-used and multi-family developments are beginning to infill Austin neighborhoods to accommodate population growth. This "urban infill" may increase pressure on existing trees and natural areas, limit space for new trees, and exacerbate the already challenging urban growing conditions by increasing the heat island effect, radiant heat, and soil moisture evaporation.

Land-use change and development alter natural species composition, distribution, and the functional capacity of the urban forest. While this can be detrimental, Austin has robust tree planting, tree preservation, landscaping, and related environmental regulations that provide mutually beneficial outcomes for the developer, the community, and the urban forest. Tree regulations and the environmental criteria manual prescribe tree species and planting specifications that help preserved and newly planted trees thrive in both current and future conditions. Austin's tree preservation ordinance was one of the first in the country to protect trees on both public and private property. Originally adopted in 1983, the ordinance was updated in 2010 to add protections for "Heritage" trees, a class of select species that are greater than 24 inches in diameter at breast height. As long as Austin has tree preservation and protection regulations, the trees on both public and private property will have the opportunity to provide the community with critical air, water, and public health benefits.

Land-use change and development are also detrimental to genetic diversity and the buffering potential of remnant natural systems. Fragmentation of natural landscapes leads to isolated populations that are unable to migrate easily and exchange genetic material. This can reduce biological and genetic diversity (Fahrig, 2003; Harrison & Bruna, 1999; Robinson, Thompson, Donovan, Whitehead, & Faaborg, 1995). Fragmentation not only results in less connectivity among natural areas but also changes the structure of existing sites. As sites become fragmented and the amount of core ecosystem space is reduced, many plants and animals that rely on core habitat may be extirpated from the region (Saunders, Hobbs, & Margules, 1991). Additionally, habitat edges are more likely to be affected by pollution runoff from nearby roads and industry and are more likely to contain non-native invasive species. Consequently, they tend to be less biologically diverse than core areas and offer less useful habitat for wildlife (Saunders et al., 1991).

Air Pollution

Air pollutants such as ground-level ozone (O3), sulfur oxides (SOX), nitrogen oxides (NOX), and particulate matter (PM) can inflict harm on urban trees both directly and indirectly. Elevated O3 concentrations can cause visible damage to foliage, reduce plant reproduction and growth rates, and reduce tree survival rates. Elevated SOX and NOX concentrations also cause direct injury to vegetation, with indirect impacts on ecosystems due to due to deposition in the environment (for example, nitrogen and sulfur deposition alters soil biochemistry) and secondary formation of fine particulate matter (PM2.5), which also causes harm to vegetation. Fortunately, concentrations of all these pollutants have declined over the past decade and are projected to continue to decline over the next decade due to a combination of federal, state, and local pollution control measures. Overall, the Austin area has seen a 16-17% decrease in ground-level ozone levels compared to 10 years ago. However, while the Austin area's air pollution levels comply with all National Ambient Air Quality Standards (NAAQS), there is evidence that elevated concentrations of these pollutants may harm

Table 1.3
Estimated composition of Tree Species by Common Name across West and East Austin, Texas. Source: Austin Urban Forest Inventory (Nowak et al., 2016). Note: this summary is an estimate based on sample plots and does not represent a complete inventory.

Common Name	Scientific Name	% of Total: West Austin	% of Total: East Austin	Common Name	Scientific Name	% of Total: West Austin	% of Total: East Austin
American elm	*Ulmus americana*	< 1%	1%	Loquat	*Eriobotrya japonica*	< 1%	-
American sycamore	*Platanus americana*	1%	1%	Mescal bean	*Dertmatophyllum secundiflorum*	< 1%	< 1%
Ashe juniper	*Juniperus ashei*	68%	20%	Mexican white oak	*Quercus polymorpha*	-	< 1%
Bald cypress	*Taxodium distichum*	< 1%	-	Mimosa, silktree	*Albizia julibrissin*	-	< 1%
Bastard (white shin, scalybark, Durand) oak	*Quercus sinuata*	1%	-	Northern hackberry	*Celtis occidentalis*	-	2%
Berlandier ash	*Fraxinus berlandieriana*	-	1%	Nutall's oak	*Quercus texana*	-	< 1%
Black walnut	*Juglans nigra*	< 1%	< 1%	Other or unknown live tree		< 1%	-
Boxelder	*Acer negundo*	-	3%	Paper mulberry	*Broussonetia papyrifera*	1%	-
Bur oak	*Quercus macrocarpa*	-	< 1%	Pecan	*Carya illinoiensis*	1%	2%
Cedar elm	*Ulmus crassifolia*	2%	18%	Post oak	*Quercus stellata*	-	< 1%
Cherry and plum spp.	*Prunus spp.*	< 1%	-	Prairie sumac	*Rhus lanceolata*	< 1%	-
Cherry laurel	*Prunus caroliniana*	-	< 1%	Red mulberry	*Morus rubra*	-	< 1%
Chinaberry	*Melia azedarach*	< 1%	1%	River birch	*Betula nigra*	-	< 1%
Chinese elm	*Ulmus parvifolia*	-	< 1%	Roughleaf dogwood	*Cornus drummondii*	-	< 1 %
Chinese pistache	*Pistacia chinensis*	-	< 1%	Shumard oak	*Quercus shumardii*	< 1%	1%
Chinese privet	*Ligustrum sinense*	< 1%	2%	Slippery elm	*Ulmus rubra*	-	< 1%
Chinese tallowtree	*Triadica sebifera*	< 1%	< 1%	Southern live oak	*Quercus virginiana*	14%	12%
Chinkapin oak	*Quercus muehlenbergii*	< 1%	< 1%	Southern magnolia	*Magnolia grandiflora*	-	< 1%
Chittamwood, gum bumelia	*Sideroxylon lanuginosum*	-	1%	Sugarberry	*Celtis laevigata*	1%	8%
Crape myrtle	*Lagerstroemia indica*	1%	1%	Sweet acacia	*Vachellia farnesiana (Acacia farnesiana)*	-	< 1%
Eastern cottonwood	*Populus deltoides*	-	< 1%	Texas ash	*Fraxinus albicans*	1%	-
Eastern red cedar	*Juniperus virginiana*	-	1%	Texas madrone	*Arbutus xalapensis*	< 1%	-
Eastern redbud	*Cercis canadensis*	< 1%	-	Texas persimmon	*Diospyros texana*	1%	2%
Edible fig	*Ficus carica*	-	< 1%	Texas red oak	*Quercus buckleyi*	4%	1%
Florida thatch palm	*Thrinax radiata*	-	< 1%	Texas/escarpment live oak	*Quercus fusiformis*	-	< 1%
Glossy privet	*Ligustrum lucidum*	< 1%	1%	Velvet ash	*Fraxinus velutina*	< 1%	1%
Goldenrain tree	*Koelreuteria paniculata*	-	< 1%	Water oak	*Quercus nigra*	-	< 1%
Green ash	*Fraxinus pennsylvanica*	< 1%	6%	Western soapberry	*Sapindus saponaria var. drummondii*	-	1%
Honey mesquite	*Prosopis glandulosa*	< 1%	10%	White mulberry	*Morus alba*	< 1%	-
Japanese privet	*Ligustrum japonicum*	-	< 1%	Winged elm	*Ulmus alata*	-	1%
Jerusalem thorn	*Parkinsonia aculeata*	-	< 1%	Yaupon	*Ilex vomitoria*	1%	-

urban trees even at levels that are meeting federal standards (CACOG, 2019). An analysis by the Capital Area Council of Governments (CACOG) of local O3 data from 2010-2015 showed a strong negative correlation with humidity (i.e., when the air is drier, O3 concentrations are higher), and a positive correlation with temperature (i.e., O3 concentrations are higher when it is hotter). Consistent with these results, the region experienced high O3 concentrations during 2011 and 2012 when it experienced severe drought conditions. Drought conditions in these years also led to wildfires, which created large amounts of additional air pollution within the region.

Drought

Moderate and severe drought is a normal part of most Texas summers. Drought exacerbates stressful urban conditions including poor soil quality, inadequate soil volume, irregular supplemental water, and the urban heat island effect. Texas experienced the worst drought ever recorded in 2011. The Texas A&M Forest Service estimated that 10% of trees were lost statewide in 2011, and weakened and stressed trees continued to succumb to secondary stressors in subsequent years. Drought stress makes trees more vulnerable to insects and disease. Crouchet, Jensen, Schwartz, and Schwinning (2019) reported a 20% crown mortality for Ashe juniper and 23% for Texas/escarpment live oak on the Edwards Plateau, with tree mortality decreasing with increasing tree size. Ashe juniper is the most common species in the Austin area (Nowak et al., 2016), and thus mortality of this species could have a significant impact on the overall canopy.

Alteration of soil

Changes in land use have altered soils in the region. Although little research is available specific to the Austin region, studies from other urban areas shed light on the likely impacts. In other areas, atmospheric deposition of nitrate, ammonium, calcium, and sulfate ions has been detected in areas nearly 30 miles from the urban core (Lovett et al., 2000). In heavily urbanized sites, soils tend to be compacted, which can decrease the rate at which water enters the soil, increasing rainwater runoff and making it more difficult for trees to grow (Gregory, Dukes, Jones, & Miller, 2006). Development and industrialization have caused the deposition of heavy metals like lead, copper, and nickel (Pouyat, McDonnell, & Pickett, 1995). Heavy metals are more abundant in dense urban cores and are associated with industrial areas, but are also deposited near roadways (Helmreich, Hilliges, Schriewer, & Horn, 2010). Runoff from limestone and concrete causes many urban soils to be more alkaline than is found in most natural areas (Ware, 1990). The most severely altered soil conditions occur in tree pits: cut-outs in the sidewalks or along roads where trees are planted, which are frequently nutrient deficient andheavily compacted (Craul, 1999).

Non-native invasive plant species

Non-native invasive plant species influence the structure, composition, and functioning of forests in the area. Non-native invasive species comprise 5.1% of the tree population, about 1.7 million trees (Nowak et al., 2016). Two non-native invasive trees comprise a significant portion of Austin's urban forest: chinaberry is found throughout Austin and is among the 10 most common small-diameter and large-diameter trees in Austin. Glossy privet (ligustrum) is one of the most common small-diameter trees. It is also found throughout Austin but causes the greatest adverse impacts in natural and riparian areas where its tendency to become a monoculture reduces biodiversity. Glossy privet further impacts the environment by shading out understory vegetation, leaving bare soil prone to erosion during heavy rain or flood events. Nine of the 62 tree species found in Austin are on the regional invasive species list (Watershed Protection Department, n.d.).

Shifts in fire regime

Although historical fire regimes are often assumed, little supporting documentation prior to European settlement exists for either the Blackland Prairie or eastern edge of the Edwards Plateau (Stambaugh, Sparks, & Abadir, 2014). Based on historical eyewitness accounts (O'Donnell, 2019; Weniger, 1984), few fires were mentioned in the 1700s and those that were present appeared to have been small and used to hide or escape and to communicate (smoke signals). While the sample size is small and from a limited area, tree ring analyses collected from 158 tree slabs on the Balcones Canyonlands Preserve suggest an increasing fire frequency on the eastern edge of the Edwards Plateau following European settlement, with a peak in the 1950s, followed by a decreasing trend. Tree ring analyses on the Balcones Canyonlands National Wildlife Refuge show a similar trend (Murray, White, & Yao, 2013).

Combined with logging and introduction of domestic livestock, changing fire frequencies undoubtedly altered the structure and composition of the vegetation in the region, but the full effects are unknown. Bray (1904a, 1904b) discussed soil erosion and drying, oak re-sprouting, and regrowth of Ashe juniper from seed, using areas near what is today the Balcones Canyonlands Preserve as examples. Based on more recent research following a wildfire at Fort Hood Military Reservation, oaks vigorously re-sprouted, while Ashe juniper (which does not re-sprout) has been slow to recover (Reemts & Hansen, 2008, 2013). Comparable studies have not been found for the Blackland Prairie.

Sixty percent of the structures in Austin are in the Wildland Urban Interface (WUI), areas where wildlands and communities mix. Austin Fire Department conducts prescribed burns in wildlands (areas greater than 10 acres) and provides outreach to communities to help them establish Community Wildfire Protection Plans.

Insect pests and diseases

Both native and non-native insect pests and diseases affect trees and forests, especially in developed areas. Trees and forests are often already under stress due to the "urban condition," which usually includes poor soil quality, inadequate volume, and the urban heat island. Stressed trees are more vulnerable to insects and diseases. In Austin, the primary pest and disease threats include oak wilt, emerald ash borer, Dutch elm disease, and bacterial leaf scorch.

Hypoxylon – Hypoxylon is a fungal infection of the sapwood caused by the fungus Biscogniauxia atropunctatum. The fungus is widespread in Austin's natural and developed areas and infects a wide variety of host trees. It invades a tree when resistance is weakened from biotic or abiotic factors, causing white rot decay of the sapwood. There is no cure. We can expect more hypoxylon in Austin's trees due to stress from projected biotic and abiotic conditions.

Oak wilt - Oak wilt is a primary fungal pathogen that invades the vascular system of oak trees. While all oak trees are susceptible, live oak and red oak species are the most commonly affected trees in Austin. Both oak groups are found throughout Austin but are more prevalent in West Austin. Live oak trees are most commonly impacted by the underground spread of the fungus through root graft connections. Naturally occurring escarpment live oak stands with interconnected root systems are found throughout central and West Austin, and they are planted throughout Austin. Red oak trees also become infected and play an important role in fungal spore dispersal and the creation of new infection areas. Increased temperatures could reduce the viability and duration of fungal mats (pressure pads) and spores, and the primary insect vector (Coleoptera: Nitidulidae) may be impacted positively or negatively by higher temperatures. General data and models to project insect transmission of oak wilt are lacking (Jagemann, Juzwik, Tobin, & Raffa, 2018).

Emerald ash borer - The emerald ash borer insect was confirmed 200 miles from Austin in Fort Worth, Texas, in 2018. This insect causes catastrophic loss to all ash species. A major interstate highway connects the two communities; emerald ash borer may already be in Austin but remains undetected. Ash is the ninth most common tree in Austin and comprises 4.2% of the tree canopy. The majority of naturally occurring ash (Fraxinus pennsylvanica, F. texana) exist in riparian areas and undeveloped areas. All of the Arizona ash (F. velutina) were planted and are located in developed and maintained areas. Texas A&M Forest Service has a monitoring program to assist with early detection.

Dutch elm disease - Dutch elm disease (DED) is caused by a fungus that infects the vascular system of elm trees. While DED has not been confirmed in Austin, it has been found in several other communities throughout Texas. It is likely that the DED pathogen is more widespread throughout Texas but has simply avoided detection (Appel, 2009). American elm trees are the most vulnerable. They naturally occur in floodplains and low terraces, especially in East Austin. Cedar elm trees have intermediate susceptibility to DED and are found in naturally occurring stands throughout Austin and are also widely planted. Elm bark beetles are a primary vector. They breed in dead and dying elms, where the pathogen forms copious spores in the galleries. As the new populations of beetles emerge from the contaminated galleries, they disperse to feed in twig crotches on healthy elms.

Bacterial leaf scorch - Bacterial leaf scorch (BLS) is a chronic and eventually fatal disease caused by the bacterium Xylella fastidiosa. It is most commonly transmitted by insects with piercing mouthparts including the leafhopper, sharpshooter, or spittlebug, which pierce and suck leaf tissue (Hu, 2018). Leaf and dieback symptoms can appear similar to drought and are most noticeable in late summer and early fall. Susceptible trees in Austin include oaks, pecan, sycamore, sugarberry, mulberry, elm, and olive. There is no cure for BLS, but antibiotic treatments and good cultural practices may help prolong the life of infected trees. High temperatures and drought amplify the stress of BLS. With higher temperatures and drought, the impact of BLS on Austin trees is likely to increase.

Current Management

Management of natural systems in the region

On the Edwards Plateau ecoregion, natural areas consist of the Balcones Canyonlands Preserve (BCP) and Water Quality Protection Lands (WQPL). Both BCP and WQPL are currently developing plans to prepare for climate change with the goal of protecting their vital watershed and habitat services. The BCP is a system of preserves managed under the terms and conditions of the Balcones Canyonlands Conservation Plan, a regional permit issued under the Endangered Species Act in 1996 by the U.S. Fish and Wildlife Service and jointly held by Travis County and the City of Austin. A number of cooperating partners own and manage lands dedicated to the BCP, including the Lower Colorado River Authority, the Nature Conservancy of Texas, Travis Audubon Society, and several private landowners. These partners collectively manage over 31,780 acres as mitigation for seven endangered species (one neotropical migratory songbird and six karst invertebrates) and 28 species of concern (one neotropical migratory songbird, two perennial plants and 25 karst invertebrates). The BCP also provides habitat for many other native plants and animals and contributes to improved air and water quality and quality of life for the people of Austin. Management focuses primarily on protecting and enhancing Ashe juniper-oak forests and karst ecosystems, as well as shrublands. Regenerative strategies to help counter anticipated effects of climate change include promoting healthy soils (including mycorrhizal networks and soil organic matter); the diversity of native plant composition and structure (ground cover, shrub cover, canopy); mesic conditions (by providing shade and capturing, spreading, and sinking rainfall); non-native invasive species removal; restoration of karst ecosystems; reforestation; and connectivity with other forests and protected areas.

The WQPL conserves land in fee title and conservation easement in the Barton Springs contributing and recharge zones. The goal is to maintain and improve the quality and volume of water from project lands to recharge the Barton Springs segment of the Edwards Aquifer. Currently, the WQPL manages over 11,000 acres as fee simple. While most of WQPL is managed for grassland, management of woodlands in preparation for climate change may include promoting old-growth conditions, shaded fuel breaks, diversity planting, strategic thinning to encourage canopy diversity and resource availability, or even pre-transitioning to a more drought-tolerant community type such as an open woodland or shrubland, depending on factors such as endangered species habitat, topography, aspect, soil conditions, access, canopy composition, and proximity to wildland-urban interface.

Selection and management of trees in developed sites

Trees that are planted in developed areas undergo much different stressors than trees in natural areas, and consequently their species composition and management differ as well. Trees selected for planting on streets and other developed areas need to withstand challenging environmental conditions such as urban heat island effects, air pollution, and soils with compaction, high pH, and poor drainage (Nowak, 2012). These considerations can be added to ecological considerations, such as soils and microclimates, which can also limit what species are suitable for planting. For example, species such as shumard oak and southern live oak are better adapted to conditions in East Austin and species such as escarpment live oak and Ashe juniper are better adapted to conditions in West Austin.

Municipal foresters and land managers in Austin adhere to the "right tree, right place" concept when planting new trees, considering factors including the availability of potable or reuse water for establishment, drought tolerance, heat tolerance, mature height, required maintenance, invasive potential, and wildlife benefit. Many urban foresters aim to plant no more than 30% of a given family, 20% of a genus, and 10% of a species (Santamour, 2004). However, recent studies suggest a more nuanced approach to managing for enhanced diversity (Laćan & McBride, 2008). Many municipal foresters have limited budget and capacity for structural pruning and are reluctant to plant trees that require regular pruning to encourage good shape or to prevent against breakage; instead, they prefer trees that can withstand storms with minimal maintenance. Additionally, there may be supply chain limitations. Growers and nurseries may be providing what is currently in demand, not what municipal foresters would like to start incorporating into urban forests.

Austin's Urban Forest Master Plan

The City of Austin completed an Urban Forest Master Plan in 2014 to guide comprehensive management for trees and vegetation on Austin's public property. The requirement for a plan is both codified (Section 6-3-5) and recommended by the 2012 Imagine Austin Comprehensive Plan as a strategy to protect and expand green infrastructure. The Urban Forester and Urban Forestry Board coordinate with forestry programs in various departments to implement the plan, which envisions Austin's urban forest as a healthy and sustainable mix of trees, vegetation, and other components that comprise a contiguous and thriving ecosystem valued, protected, and cared for by the City and its citizens as an essential environmental, economic, and community asset. It provides baseline measurements of the vegetative resource, the community stewardship framework, and resource management policies and practices.

Summary

Austin's urban forest, shaped by ecosystems, land-forms, and environmental gradients, is made up of interconnected natural areas and developed sites. Rapid growth paired with climate change presents a concern for Austin's trees and green spaces. Composed of two ecoregions—Edwards Plateau and Blackland Prairie—and divided by the Balcones Escarpment fault line, Austin is prone to flood-producing storms and unique challenges due to differences in biotic and abiotic factors between the ecoregions. Understanding the structure and function of the landscape setting as well as current conditions, stressors, and management provides a foundation for how a shifting climate may impact Austin's trees, urban forests, and landscape stressors. In terms of tree species composition, the majority of West Austin (68%) is composed of Ashe juniper, followed by southern live oak (14%), while East Austin is composed of Ashe juniper (20%), cedar elm (18%), southern live oak (12%), and honey mesquite (10%). Current stressors and threats to Austin's trees and natural areas include land-use change, development, and fragmentation; drought; alteration of soil; non-native invasive plant species; shifts in fire regime; and insect pests and diseases. Austin's Urban Forest Master Plan (2013) was developed to guide tree and vegetation management on Austin's public property. In addition, partners manage natural systems in the Austin region to preserve plant and wildlife habitat, improve air and water quality, protect and enhance urban forests and shrublands, and develop strategies to counter climate change effects.

Key Points

- Austin is composed of two ecoregions: Edwards Plateau to the west and Blackland Prairie to the east.
- Austin's urban forest is made up of approximately 34 million trees with a tree canopy covering about 31% of the city.
- The majority (92%) of trees are native to Texas, and the 10 most common trees account for 84% of all trees.
- Natural areas, including agricultural uses, make up the majority of total land area (57%), while 39% of total land area is considered developed area and the remaining is composed of open water.
- Austin is located on a distinct ecological divide. East Austin includes the Blackland Prairie with deep, rich soils, and West Austin includes the Edwards Plateau, characterized by shallow soils over limestone. These areas support different tree species that are uniquely adapted to each ecoregion. Development and land-use change have transformed the area's vegetation structure, composition, and function.
- Additional stressors and threats to Austin's trees and natural areas include drought, Development, land-use change, and population growth have transformed the area's vegetation structure, composition, and function.
- Additional stressors and threats to Austin's trees and natural areas include drought, alteration of soil, non-native invasive plant species, shifts in fire regime, and insect pests and diseases, including hypoxylon, oak wilt, emerald ash borer, Dutch elm disease, and bacterial leaf scorch.
- Managers in Austin's natural and developed areas are working to manage Austin's urban forest to ensure it continues to provide benefits for all members of the community.

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CHAPTER 2

CLIMATE TRENDS, PROJECTIONS, AND IMPACTS

Austin's natural areas are strongly influenced by past and current climate, and future changes will likely have far-reaching impacts. Likewise, decision-making around which trees and other vegetation to plant in developed areas is also strongly influenced by temperature and precipitation requirements for certain vegetation. This chapter summarizes what we know about how the climate has changed over the historical record, how climate is projected to change over this century, and impacts to Austin's urban forest and natural areas.

Unless otherwise noted, climate projections were retrieved from the Climate Mapper tool (Hegewisch, Abatzoglou, Chedwiggen, & Nijssen, 2019). The tool uses the University of Idaho's gridMET meteorological dataset of historical data (Abatzoglou, 2013), and includes projections from two emissions scenarios (RCP 4.5 and RCP 8.5) and 20 climate models downscaled to a 4km resolution. The spatial resolution is sufficient for looking at broad climate trends across the metropolitan area, but not fine enough to identify specific microclimates that may be significantly hotter or cooler, such as urban heat islands and north-facing slopes. RCP stands for "representative concentration pathway" and is a scenario of future greenhouse gas concentrations in the atmosphere. RCP 4.5 represents a scenario where greenhouse gas emission rates are dramatically reduced, whereas 8.5 can be considered a "business as usual" scenario; that is, emissions keep growing at the current rate. This report used the CNRM-CM5 model (a model that tends to be cooler and wetter than average projections) with RCP 4.5 and the HadGEM2-ES365 model (a model that tends to be hotter and drier than average) with RCP 8.5 as one attempt to bracket a range of potential futures (Abatzoglou & Brown, 2012).

Historical climate trends were retrieved from the NOAA Climate at a Glance tool (NOAA, 2019). Climate at a Glance was developed to facilitate near real-time analysis of monthly temperature and precipitation data across the contiguous U.S. and intended for the study of climate variability and change. It is important to note that some of the very recent data (last few months) are preliminary, and therefore are subject to change.

Observed Trends

Temperature

Temperatures in the Southern Great Plains, including Texas, have high interannual variability, and the region experiences both heat waves and brief periods of extreme cold. Average climate is often described in 30-year decadal averages, also called "normals." The most recent 30-year normal dates from 1981-2010. Over that period, the average annual temperature in Austin was 52ºF in the winter and 84ºF in the summer, with an average minimum of 40ºF and an average maximum of 98ºF. There were, on average, about 10 days each year where the heat index exceeded 105ºF.

Temperatures have been increasing over the observational record in Austin, which goes back to 1938. Maximum temperature has been increasing at a rate of 0.4˚F per decade, and mean and minimum temperatures have been increasing at a rate of 0.3˚F per decade (Figure 2.1). Since the year 2000, all years have been above the 1961-1990 average, which is a standard baseline period of comparison for examining climate trends (IPCC, 2019). The decade 2000-2010 was the warmest on record for the contiguous United States, and also for Austin. Recent years have been increasingly hot. Six of the hottest 10 years in Austin have occurred between 2000 and 2019.

It is unclear how climate change is currently affecting heat wave occurrence, but the number of days with temperatures above 100ºF has already exceeded the historical average of 13 days per year multiple times this decade. For example, there were 51 days of 100ºF or more during the summer of 2018. Among the top 10 years with the most 100ºF days, eight are in the 21st century. Summer 2019 was the second hottest behind 2011, when drought blanketed much of the western United States. September 2019 was the hottest on record with an average temperature of 88ºF, 8ºF above the 1981-2010 average and 4ºF hotter than the next-warmest Septembers (2011 and 2005). September 2019 was, on average, hotter than June and July of 2019 and had more triple-digit days than July (a total of 19). For that month, overnight lows were 76.1ºF, almost 7ºF warmer than the usual 69.4ºF; 99.8ºF was the average high temperature. The 1981-2010 average high was 90.5ºF (NOAA, 2019).

On the opposite end of the temperature spectrum, cold waves have occurred very infrequently in the past 15 years. Further north, there is a trend toward fewer cold waves, but it is unclear if the same trend is occurring in the southern Great Plains (USGCRP, 2018).

Precipitation

Austin is classified as humid subtropical, meaning it has hot, humid summers and predominantly mild, fairly dry winters. Spring is generally the wettest season in Central Texas and averaged almost 9.5 inches of precipitation from

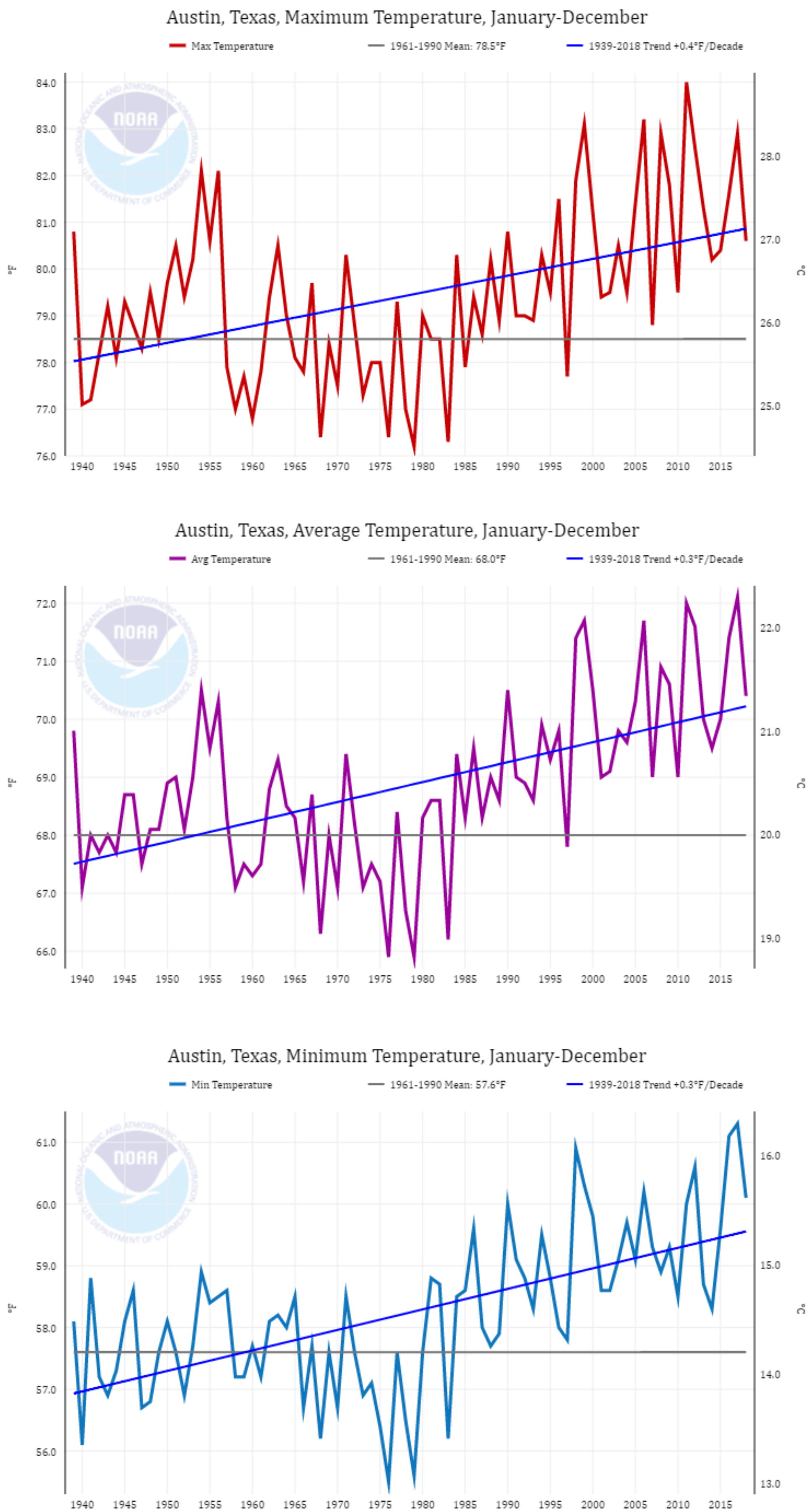

Figure 2.1. Changes in Annual Temperature over the Observational Record from 1938 to 2018 for Austin, Texas. The gray line indicates the 1961–1990 average and the blue line shows the trend over the observational record. A indicates mean annual maximum temperature. B indicates mean annual temperature. C indicates mean annual minimum temperature. Source: NOAA, https://www.ncdc.noaa.gov/cag/

1981 to 2010. Winter is the driest season and averaged less than 7 inches of precipitation during the same time period. Overall, the average yearly rainfall in the Austin area from 1981 to 2010 was 33.5 inches per year. Swings from drought conditions to heavy rains occur regularly, with up to one-third of all droughts in the past 50 years broken by flood-inducing rainy periods (USGCRP, 2018). Over the past several decades (1994-2017), Austin's extreme rainfall events have become more extreme than in the past (Perica et al., 2018).

Overall, precipitation has increased in Austin over the observational record, at a rate of 0.7 inches per decade (Figure 2.2). Changes have not been the same across all seasons, however (see Appendix 2). There has been virtually no change in precipitation in winter, spring, and summer—virtually all gains have been in fall. However, even in fall, these changes have not been consistent, with both extremely dry and extremely wet years occurring in the recent past.

Climate Projections

Temperature

Temperature in the Austin area is expected to increase in the future, regardless of the scenario (Table 2.1). Under the RCP 4.5 scenario, which assumes a drastic reduction in global emissions of greenhouse gases, the average annual temperature is expected to increase by 5ºF by 2100. The maximum summer temperature is expected to increase by 3ºF, and the minimum winter temperature is expected to increase by 5ºF. Increases under the "business as usual" scenario, RCP 8.5, are greater. By 2100, average annual temperature and seasonal maximum temperatures are expected to increase.

Precipitation

In contrast to the effects of climate change on temperature, its effects on precipitation in the Austin region, and the Southern Plains region as a whole, are less clear. Decreases in precipitation are likely, according to different climate models, but the impacts vary by season and scenario. Under RCP 4.5, overall annual precipitation is projected to marginally decrease by 2100, but the effects are primarily expected during summer, winter, and fall, while spring precipitation is expected to increase (Table 2.2). RCP 8.5, on the other hand, projects a similar annual loss, but the decrease is projected for the summer months; the same scenario projects an increase in winter, spring, and fall precipitation (Table 2.2). Models do not project a measurable change in soil moisture content, but the projected increases in temperature coupled with even marginal decreases in precipitation could significantly reduce soil moisture availability. Total runoff is projected to vary seasonally depending on scenario. Finally, it should be noted that although climate models are projecting future decreases in precipitation, the current trend is the opposite (Figure 2.1). Forecasting precipitation in Central Texas is notoriously challenging to meteorologists using present-day weather models due to the atmospheric dynamics of this region. Those same challenges hamper climate modeling of this region.

Some sources also predict that the storms responsible for rain in the southern plains will become more severe (USGCRP, 2018). However, these studies have been carried out on a regional scale, and since the effects are unlikely to be spatially uniform, it is possible that some areas may see no increase in incidence or severity of severe weather. If severe weather does become more common in the Austin area, severe storms (including hail) can be expected to occur more often and be more destructive (USGCRP,

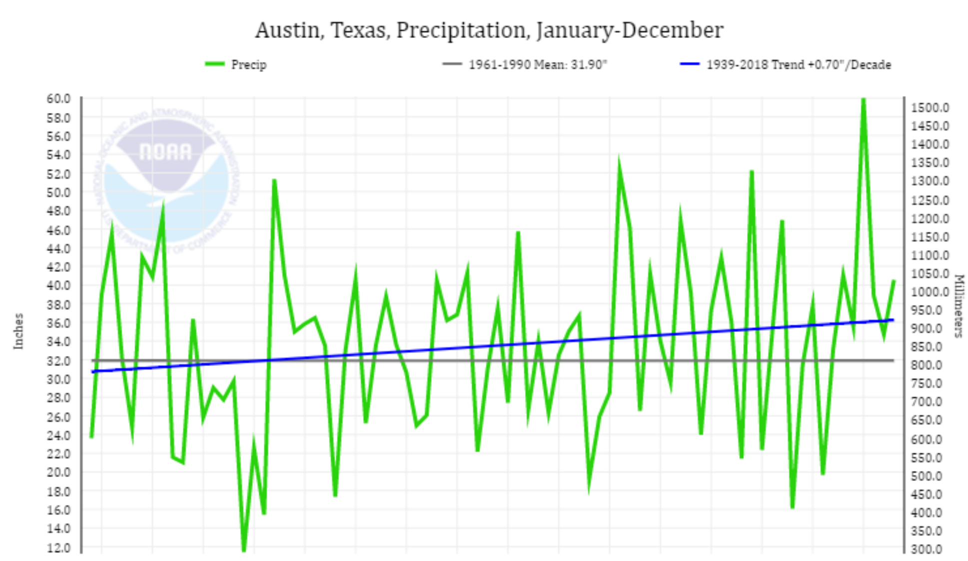

Figure 2.2. Changes in Annual Precipitation over the Observational Record from 1938 to 2018 for Austin, Texas. The gray line indicates the 1961-1990 average and the blue line shows the trend over the observational record. Source: NOAA, https://www.ncdc.noaa.gov/cag/

Table 2.1
Projected Temperatures and Days with Heat Index above 105°F for the Austin Area through 2099

	30-Year Normal	RCP 4.5 w/CNRM-CM 5 (low emissions)			RCP 8.5 w/HadGEM2-ES365 (high emissions)		
	1981–2010	2010–2039	2040–2069	2070–2099	1981–2010	2040–2069	2070–2099
Mean Temperature (˚F)							
Winter	52	54	56	57	55	58	61
Spring	68	70	71	73	71	75	78
Summer	84	85	86	87	88	91	94
Fall	70	72	73	73	74	77	81
Annual	68	70	72	73	72	75	78
Mean Maximum Temperature (˚F)							
Winter	63	65	67	68	66	69	72
Spring	79	81	82	84	82	87	89
Summer	95	96	97	98	99	103	105
Fall	81	83	84	85	86	88	92
Annual	80	82	83	84	82	85	88
Mean Minimum Temperature (˚F)							
Winter	40	43	45	45	44	47	50
Spring	57	59	61	62	60	63	66
Summer	73	74	76	76	76	79	82
Fall	58	60	62	62	63	65	69
Annual	57	59	61	62	60	63	66
Days w/Heat Index >105˚F							
Annual	10	20	33	43	38	86	122

Table 2.2
Precipitation, Soil Moisture, and Runoff for the Austin Area through 2099

	30-Year Normal	RCP 4.5 w/CNRM-CM 5 (low emissions)			RCP 8.5 w/HadGEM2-ES365 (high emissions)		
	1981–2010	2010–2039	2040–2069	2070–2099	1981–2010	2040–2069	2070–2099
Mean Precipitation (inches)							
Winter	6.7	6.7	7.1	6.6	7.6	7.1	8.3
Spring	9.4	9.7	9.5	10.2	9.9	8.1	9.5
Summer	7.9	7.8	8.7	7.5	6.2	4.9	5.6
Fall	9.1	8.2	8.8	8.6	9.2	9	9.7
Annual	33.5	33	34	33	33	29	33
% Change in Precipitation							
Winter		-4.4	0.7	-5.6	4.6	-0.9	14.2
Spring		1.2	-0.8	6.1	14.1	-7.1	9.3
Summer		1	13.9	-3.5	-28	-42.6	-35.2
Fall		-9.9	-2.6	-6.4	0.1	-2.4	5
Annual		-3.1	2.4	-2	-2.5	-13.5	-2.1
	Averages	**Soil Moisture Content (inches)**					
Winter	19	18	18	19	19	18	18
Spring	19	18	19	19	19	19	18
Summer	18	18	18	18	18	17	17
Fall	17	17	17	18	17	17	17
Annual	18	18	18	18	18	18	17
	Averages	**Total Runoff (inches)**					
Winter	n/a	13	17	15	20	14	15
Spring	n/a	20	20	17	19	13	18
Summer	n/a	17	18	17	12	8	10
Fall	n/a	12	20	21	13	14	15
Annual	n/a	16	19	18	16	12	14

2018). Over the past several decades (1994-2017), Austin's extreme rainfall events have become more extreme than in the past (Perica et al., 2018). The formerly 500-year storm event is now the 100-year storm event. Likewise, what was the 100-year storm event is now the 25-year storm event. It is not clear whether this is a result of climate change, but it is consistent with the expectation that climate change will make extreme events more common.

Physical Impacts on the Area's Trees and Green Spaces

Shifts in Heat Tolerance and Cold Hardiness Zones

Climate change is expected to result in shifts in plant hardiness zones and heat tolerance zones (Table 2.3). Hardiness zones are determined by the average minimum temperature over a 30-year period, whereas heat zones are determined by the number of days over 86˚F. By 2100, Austin is expected to shift from cold hardiness zone 8b to either 9a (lower emissions scenario) or 9b (higher emissions scenario). With warming winter temperatures, the growing season, as determined by the number of days above freezing, could potentially increase to 300-359 days compared to the current 278 days. Thus, for the high emissions/hotter scenario, the growing season would be virtually year-round. Summer temperatures will also increase, resulting in a higher risk of heat stress. Austin is expected to shift from its current heat-tolerance zone of 9 to zone 11 or 12 by 2100, exceeding the tolerance of many species currently present.

Heat Stress

The number of hot days (over 100˚F) is projected to increase, particularly under RCP 8.5 (USGCRP, 2018). Based on historical data (1971-2000), the Camp Mabry weather station in Austin averaged 13 days per year over 100˚F. By late in the 21st century, if no reductions in emissions take place, the region is projected to experience 30-60 more days per year above 100˚F than it did at the end of the 20th century (USGCRP, 2018).

Increases in temperature from climate change can be exacerbated in urban areas (Wilby, 2008). Urban areas with one million or more people can be 1.8 to 5.4˚F warmer than their surrounding rural areas due to the "urban heat island effect" from heat-absorbing infrastructure such as pavement and buildings (Akbari, 2005). The heat island effect can make urban areas one or more hardiness zones warmer than the surrounding area, facilitating the growth of more southern species (USDA, 2012). In addition to ameliorating winter temperatures, heat island effects can also make summer temperatures higher, especially near dark pavements and buildings. A recent study of the city of Austin showed that areas around downtown and major highways and development were several degrees warmer than areas in the city with dense tree cover or large rivers (City of Austin, 2019).

The combination of climate change and the urban heat island will affect the growth and survival of Austin's trees. Trees that are intolerant of extreme heat will be that much more vulnerable in urban settings with an urban heat island effect. Species already present in the landscape such as Texas mountain laurel, Jerusalem thorn (retama), Mexican white oak, honey mesquite, Texas madrone, yaupon, and sweet acacia (huisache) can tolerate extremely high heat and may be able to withstand even higher summer temperatures.

Drought Stress and Aridification

The 100th meridian is a distinct belt that marks the transition from the wet eastern U.S. to the dry west, so named because it was closely aligned with the 100th meridian of longitude. However, that transition zone is no longer aligned with the 100th meridian; it has migrated about 140 miles to the east, about the location of the 98th meridian, due to rising temperatures and shifting winds affecting rainfall pattern (Seager et al., 2018). Historically, Austin was described as being within that distinct belt between the dry deserts of the American Southwest and the lush, green, more humid regions of the American Southeast. In the past decade, Austin has experienced a combination of drier summers (in some years) and increased evapotranspiration due to higher temperatures (in most years). Increases in evapotranspiration are expected to exacerbate aridity if they aren't balanced with increases in precipitation (USGCRP, 2018). Austin, located at 97.7˚W, is just east of the current dry line. If the dry line continues its eastward migration in the coming decades as projected, Austin could find itself in the desert Southwest. This is significant because the concept of drought in the

Table 2.3
Heat Tolerance, Cold Hardiness, and Growing Season Length in the Austin Area through 2099

	Average	RCP 4.5			RCP 8.5		
	1971–2000	2010–2039	2040–2069	2070–2099	2010–2039	2040–2069	2070–2099
Plant Heat-Tolerance Zone	9	10	11	11	10	11	12
Cold Hardiness Zone	8b	8b	9a	9a	8b	9a	9b
Growing Season Length (Days)	278	276	286	300	299	319	359

desert Southwest is increasingly replaced by the concept of aridification, i.e., a transition to from a temporary state of dryness to a permanent one (USGCRP, 2018).

Short- and long-term changes in moisture availability can have dramatic impacts on the Austin region's urban forest. The drought from 2010 to 2011 led to a loss of 10% of Austin's trees. Statewide, the drought had the highest impact in post oak woodlands, pinyon-juniper shrublands, and Ashe juniper woodlands (Schwantes et al., 2017). The severity of the drought led to losses of some species that are often considered relatively drought-tolerant, such as Ashe juniper, Texas persimmon, and Texas/escarpment live oak. Habitat conditions will undoubtedly affect tree vulnerability and susceptibility to climate change. For example, one study suggests that severe drought could kill a large fraction (18-85%) of intermediate- to large-sized Ashe juniper trees growing in full sun in Central Texas savannas (Polley, Johnson, & Jackson, 2018), while another (Crouchet, Jensen, Schwartz, & Schwinning, 2019) found larger trees had higher survival than saplings in closed-canopy woodlands. Studies have also shown that water sources used by trees (e.g., rainwater, soil water, groundwater) vary by tree species, time of year, edaphic conditions, and other factors (Estrada-Medina et al., 2013; Carrière et al. 2020). McCole and Stern (2007) found that Ashe juniper uses primarily soil water most of the year but changes to deeper water sources during summer. Studies have shown that the ability of species such as Ashe juniper, Texas/escarpment live oak, and mesquite to tap deep water sources may be constrained by local geology (Jackson, Moore, Hoffman, Pockman, & Linder, 1999; Litvak, Schwinning, & Heilman, 2010). Future increases in temperature and vapor pressure deficit, especially under a higher-emissions scenario, could create conditions for another high-mortality event by the end of the century (Schwantes et al., 2017).

Trees in developed areas, such as residences and street trees, may be less susceptible to drought due to reduced competition and increased maintenance and/or irrigation. However, some street trees planted in confined spaces could also experience drought stress if there is insufficient soil volume or if they are not properly cared for.

Hurricanes, Tornadoes, and Other Severe Storms

Overall, the number of hurricanes developing in the Gulf of Mexico is not expected to change, but the average intensity of hurricanes is expected to increase due to rising sea surface temperature (Bender et al., 2010). Being several hundred miles inland from the coast, Austin rarely experiences hurricane conditions, though storms accompanied by high winds and extreme rainfall are not infrequent during spring conditions when the atmosphere can be highly unstable, and during the fall tropical storm season. In fact, Central Texas has been the site of numerous record rainfalls.

Trees can vary greatly by species in their ability to survive severe storms. Based on surveys following hurricanes in Florida, trees exhibiting high survival after storms that are also found in Austin include southern magnolia, southern live oak, sweetgum, and crape myrtle (Duryea, Kampf, & Littell, 2007). Species with lower survival included cherry laurel, sycamore, Chinese tallowtree, and pecan. Because of its unique climate and geology, Austin comprises a mix of deeply rooted species that can potentially withstand high winds and shallowly rooted species that have the potential to blow over. Our assessment of adaptive capacity in the next chapter suggests some of the most wind-vulnerable trees in Austin include sugarberry, velvet ash, Ashe juniper, littleleaf/goldenball leadtree, and escarpment black cherry, particularly when growing on particularly when growing on steep slopes or as single trees (closed canopy forests help to protect individual trees from wind damage). Chinese pistache and Chinese tallowtree are considered among the most wind resistant. Location of a tree, such as on a steep slope, and the depth of its root system may ultimately be more important than species in determining survival under severe storm conditions.

Flooding and Stormwater Runoff

Urban environments are more susceptible to stormwater runoff due to the high concentration of impervious surfaces. Increases in impervious cover can dramatically increase the size and frequency of flood events (Hollis, 1975). However, Austin has always been highly flood-prone due to its topography and karst geology. In fact, this region of Texas is known as "flash flood alley." The risk of flooding in Austin has increased in the past few decades (Perica et al., 2018), and could become higher if heavy rains increase in frequency and intensity.

Typically, urban floods are short-lived, but extended flooding can stress trees, leading to leaf yellowing, defoliation, crown dieback, and even death. Extended soil saturation can also make trees more susceptible to being blown over in high winds. In addition, flooding can lead to secondary attacks by insect pests and diseases (Bratkovich et al., 1993). Some species are more tolerant of flooding than others. Flood-intolerant species include upland species such as catclaw, Texas madrone, Anacacho orchid tree, and others that are more adapted to dry, well-drained soils. Species that are generally tolerant of flooding include species that are adapted to floodplains and riparian areas such as boxelder, sugarberry, desert willow, green ash, possumhaw, yaupon, Arizona walnut, sweetgum, Mexican and American sycamore, Shumard oak, black willow, western soapberry, bald cypress, Montezuma cypress, and American elm. In addition to differences among species, age class and vigor can also affect flood-related damage and mortality.

Air and Soil Pollution

Air and soil pollution from ozone, nitrogen deposition, dust, heavy metals, nitrogen and phosphorus deposition, application of fertilizers, herbicides, and pesticides, and sulfur dioxide can all affect tree health. Elevated temperatures, as are projected to occur from both the urban heat island and climate change, can increase the rate of ground-level ozone formation (Jacob & Winner, 2009; Nowak et al., 2016), leading to leaf damage and secondary damage from insects and disease. It is estimated that the trees currently present in Austin help reduce ozone pollution by over 1,000 tons per year at a value of $1.6 million (Nowak et al., 2016). However, trees can also contribute to air pollution via the production of volatile organic carbons (VOCs), which can be precursors to ozone production as well as harmful to human health. However, the role of trees in regulating ozone levels is complex, as trees emit biogenic volatile organic carbons (BVOCs) that, which can contribute to decomposition of ozone but can also be precursors to ozone production in the presence of nitrogen oxides (Wiedinmyer et al. 2001; Aydin et al., 2014; Fitsky et al., 2019). Isoprene is the BVOC with the highest potential to contribute to ozone formation and is typically emitted by broad-leaved species, and monoterpenes typically emitted by conifers may also be pre-cursors (Aydin et al., 2014; Fitsky et al., 2019). The major emitters of these BVOCs in the Austin region include oak (isoprene) and juniper (monoterpenes) species. The quantity and compositions of emissions are affected by environmental stressors (Anderson et al., 2000; Fitsky et al., 2019). For example, BVOC emissions depend partially on temperature, and thus could potentially increase as summer temperatures increase. In an urban setting, increases in BVOCs along with nitrogen oxide could lead to the formation ozone, which would could be harmful to some ozone-sensitive trees as well as have negative implications for human health. (Fitsky et al., 2019). Benefits of BVOCs (the aromatic compounds released from plants) include their role in cloud formation (Zhao et al., 2017), plant signaling and defense (Holopainen and Blande, 2013), and reduced stress and improved immune function in humans (Li et al., 2008). While some modeling shows that projected increases in drought conditions could lead to an increase of 1-6% for ground-level ozone in the US by 2100 compared to the 2000s (Silva et al., 2017), the most recent National Climate Assessment from 2018 suggests that climate change may actually reduce summertime O3 concentrations in Central Texas (USGCRP, 2018).

Carbon Cycling

The urban forest in the Austin region is estimated to absorb about 92,000 tons of carbon per year (Nowak et al., 2016), and the natural areas in Austin are currently acting as carbon sinks, with the potential of storing up to 1.6% of Travis County's 2007 carbon emissions (McCaw, 2012). Increasing temperature may be leading to increased aridification, which could reverse the carbon sink effect. However, increased carbon dioxide in the atmosphere may also positively affect tree growth and water use efficiency. Carbon dioxide (CO2) enrichment experiments that have been performed on Central Texas species show positive growth effects. For instance, seedlings of five woody legume species (honey mesquite, huisache, honey locust, Eve's necklace, and retama) exposed to twice ambient levels of CO2 had significantly larger mass than those grown under ambient concentrations (Tischler et al., 2004). Experimentation under a gradient of CO2 has shown that CO2 enrichment may favor the establishment of honey mesquite into grasslands (Polley, Tischler, Johnson, & Derner, 2002). Other studies have shown that honey mesquite seedlings may increase rooting depth and yield a competitive advantage over grass seedlings under elevated CO2 (Derner, Tischler, Polley, & Johnson, 2005). However, these studies have focused only on a few species that are adapted to hot, dry conditions over a short period, and thus it is unclear how CO2 enrichment may affect Austin's urban forest as a whole.

Fire

Fires are determined directly by climate conditions as well as through changes in fuel loads. The worst wildfire in Texas history occurred in 2011 in Bastrop County, destroying more than 1,000 homes and burning more than 1.5 million trees (Hanna, 2011). The unusual severity of the wildfire was partially caused by an ongoing drought and fuel buildup as well as high winds from a tropical storm. As drought and mortality become more common, fuel for catastrophic wildfires is likely to become more available. In addition, the projected increase in the number of dry days and days with extremely high temperatures could result in increased drying of vegetation, further increasing the risk of wildfire. Along with increases in fire severity, the area at risk of burning in Austin is projected to increase by the middle of the century. Projections for the end of the century are much less certain, with some models showing an increase and some a decrease in severity and area burned (Geos Institute, 2016). A study by Stambaugh, Guyette, Stroh, Struckhoff, and Whittier (2018) examined future fire probability in the central plains using three different climate models. The results also showed that whether fire probability would increase or decrease in the Edwards Plateau and Blackland Prairie depended on the climate model used. Some suggested an increase due to an increase in temperature, and others suggested a decrease due to a potential decrease in fuel loads.

Biological Impacts on the Area's Trees and Green Spaces

Shifts in Phenology

Climate change may lead to shifts in the timing of leafout, flowering, fruit production, and senescence in urban trees. The growing season length in Austin, as determined by first and last frost, was 278 days on average from 1971 to 2000. Climate projections mentioned earlier in this chapter suggest that the frost-free season could become nearly year-round under RCP 8.5 by the end of the century. Leafout of many species in southern areas like Texas is determined by a short-term increase in temperature, making trees susceptible to "false springs" when a hard frost occurs after leafout (Allstadt et al., 2015). Currently, false springs are relatively common occurrences in Texas, but increasing temperatures and a shift to a nearly year-round frost-free season could reduce the probability of false springs in the future (Allstadt et al., 2015).

Austin is located at roughly 30°N latitude, the dividing line between the North Temperate Zone and the tropics. Deciduous trees in temperate climates often rely on a chilling period followed by spring temperature increases to determine budbreak. Trees in tropical climates, however, rely on other cues, such as daylength, dry season, and leaf age to determine leaf fall and budbreak. Interestingly, research has found that temperate broad-leaved species can shift their phenology to become similar to that of tropical trees when they are grown in tropical climates (Borchert, Robertson, Schwartz, & Williams-Linera, 2005). The dividing line between these two patterns is roughly 45°F average January temperature (Borchert et al., 2005). Average January minimum temperatures in Austin over the past 30 years is 41.4°F. If January temperatures increase as projected to above the 45°F threshold, this could cause a shift from phenological cues being determined by temperature to being determined by other factors in Austin, especially for temperate trees such as northern hackberry, green ash, and some oak species (Borchert et al., 2005).

Non-Native Invasive Plant Species

Non-native invasive plant species out-compete native species in natural areas in the Austin region as mentioned in the previous chapter particularly along riparian areas and degraded sites. Of the species we evaluated for vulnerability (next chapter), all of the invasive woody plant species that currently threaten natural areas in the Austin region have a high adaptive capacity. This means they will be among those most successful in a changing climate. Some species may benefit from warmer temperatures. For example, Chinese tallow is projected to expand northward and its future range is in part determined by winter minimum temperatures (Gan, Miller, Wang, & Taylor, 2009; Wang et al., 2011). A few species are considered moderately vulnerable to increases in temperature based on published heat and hardiness zone tolerances. These species are cherry laurel, silktree/mimosa, white mulberry, glossy privet, Chinese pistache, Chinese/lacebark elm, and Chinese privet. A study examining future suitable habitat for Chinese privet found that its most suitable habitat may shift north and east to areas like Virginia, Kentucky, Tennessee, and North Carolina (Bradley, Wilcove, & Oppenheimer, 2010). However, many of these species are known to have invaded areas south of Austin and could potentially tolerate higher temperatures than their zone tolerances indicate. Nevertheless, some recent modeling suggests that increasing temperatures between 30°N and S latitude may decrease the number of invasive species in areas like Texas (Bellard et al., 2013).

Insect Pests and Pathogens

Warmer temperatures and stressed trees may increase the abundance of pests and pathogens that are currently present in the Austin region. Oak wilt is a highly infectious tree disease found in the region caused by the fungus Bretziella fagacearum, which disables the water-conducting system in susceptible oak trees. The fungus is generally transmitted by beetles active in the spring. Red oaks (Southern red oak, Shumard oak, and blackjack oak) are the most susceptible and play a unique role in the establishment of new oak wilt infection areas. Live oaks are less susceptible than red oaks but are the most seriously infected species due to its grafted root systems that allow the fungus to spread among adjacent trees. The fungus benefits from cool, moist conditions to form mats. Thus, wetter springs could make oak wilt a larger problem in the Austin region in the coming decades. In addition, a milder winter could lengthen the season of insect-vectored transmission. Although oak wilt was thought to be limited by extremely high temperatures, evidence has shown it capable of surviving under extremely hot conditions in Texas (Appel, 1995).

In addition to oak wilt, other pests and pathogens may also become more problematic with changes in climate. Hypoxylon canker is a fungus that can infect stressed or injured oak trees, and conditions such as heat, drought, and flooding (which are all projected to increase in the coming decades) can predispose trees to infection (McBride & Appel, 2009). Wood boring beetles are pests that can infest oaks and other species if they are showing declines in health (Drees, Jacman, & Merchant, n.d.), and, thus, stress from a changing climate or extreme weather events could make some trees more vulnerable. Bacterial leaf scorch is another disease of oaks, along with several other species such as elm and sycamore, and appears to benefit in part from hot, dry periods (Howard, 2019). Thus, it could be expected that bacterial leaf scorch will become more problematic as temperatures increase and soil moisture decreases.

Tree- and Forest-dependent Wildlife

Wildlife that depend on trees and natural areas in the Austin region may also experience the effects of climate change. Suitable habitat for wildlife may shift due to both direct effects of temperature and precipitation and indirect effects through changes in vegetation and food sources upon which they depend. The golden-cheeked warbler is a federally listed endangered species found in Ashe juniper communities in the Edwards Plateau. One modeling study suggests under a scenario of less warming, the warbler could still retain some breeding habitat in the Austin area, but scenarios of moderate and severe warming could lead to habitat loss (National Audubon Society, 2019).

Some wildlife species have negative effects on natural areas through browsing and disruption of soil. Feral hogs, which are a non-native invasive species, disrupt soil and vegetation by rooting and wallowing. Feral hogs are already widespread throughout South and Central Texas and are considered a serious nuisance. White-tailed deer can also reduce recruitment of oaks into adult-size classes on the Edwards Plateau (Andruk, Schwope, & Fowler, 2014; Russell & Fowler, 2004). Because white-tailed deer ranges extend far into Central America, it appears unlikely that warming temperatures will have a noticeable effect on deer populations in Austin. However, breeding seasons are somewhat dependent on climate conditions, and could shift slightly in response to warming or changing precipitation patterns. Increases in temperature may also affect pathogens and parasites, and these changes could, in turn, affect wildlife populations though no research is currently available pertaining to the Austin area.

Nutrient Cycling

A changing climate may result in altered rates of decomposition and nutrient cycling, which has important implications for trees in both natural and developed areas. As soil warms, the rate of nutrient cycling generally increases. However, the cycling of nutrients in soil, such as carbon, nitrogen, and phosphorus, could be disrupted by the increased aridity expected in Central Texas. Reduced soil moisture, either due to increased air temperature driving higher rates of evapotranspiration, extended periods of drought, or both, could reduce productivity and slow decomposition rates, which, in turn, would reduce nutrient cycling (Steven, McHugh, & Reed, 2017). Microbial nutrient cycling in arid environments often occurs following brief pulses of precipitation. Research on the Texas Edwards Plateau indicates that microbial communities from historically arid environments respond more readily to these pulses than those from areas that historically received higher precipitation (Averill et al., 2016). Thus, Austin's soil biota may be less able to take advantage of brief periods of moisture if Austin becomes more arid than it was historically with intermittent heavy rains, further reducing nutrient cycling.

Across dryland locations around the globe, aridity has been shown to have a negative impact on the concentration of organic carbon and total nitrogen but a positive effect on the concentration of inorganic phosphorus (Delgado-Baquerizo et al., 2013). Aridity can reduce plant density, which may promote physical processes, such as rock weathering and photodegradation, over biological decomposition. A decrease in nitrogen concentrations with increasing aridity may, for example, further decrease the plant productivity beyond that caused by water limitations.

Summary

Temperatures in Austin have been increasing and are projected to continue to increase throughout the rest of the 21st century, leading to more extremely hot days and fewer extremely cold periods. Precipitation has also been increasing, but there is a great amount of variability within and among years. Austin can experience both extreme drought and extremely wet precipitation events, which can make conditions extremely stressful for its resident trees. Austin may experience both an increase in the frequency in severity and frequency of these extremely wet and dry conditions, though model projections have some uncertainty. Warmer temperatures are projected to lead to a longer growing season and more evaporative losses from the soil, along with effects on biological stressors such as non-native invasive plants and insect pests.

Key Points

- Austin has been warming at a rate of about 0.4°F per decade since measurements began in 1938 and is expected to increase by 5 to 10 degrees by the end of this century compared to the most recent 30-year average.
- Austin has been getting slightly wetter on average, but precipitation can vary widely within and between years, and future projections of precipitation are uncertain.
- It is highly probable there will be both an increase in heavy rain events and severe droughts in the future decades, which will stress the area's trees.
- Overall, the balance of precipitation and temperature may shift Austin's climate to be more similar to the arid Southwest.
- Changes in temperature and precipitation may also exacerbate current stressors such as invasive plants, insect pests, and pathogens.

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CHAPTER 3

VULNERABILITY OF AUSTIN'S TREES

Changes in climate have the potential to profoundly affect Austin's trees in both developed and natural areas. Many tree species that are currently present may experience declines in habitat suitability under warmer temperatures and altered precipitation patterns. Other species may experience improved habitat suitability under these conditions. Some species not currently present could potentially be planted in the area. In addition, climate change can have indirect effects on the urban forests in the region by changing insect pests, pathogens, and non-native invasive species, as well as the probability, severity, and extent of severe storms. Tree species will differ in their capacity to adapt to stressors. This chapter summarizes expected changes in habitat suitability and the adaptive capacity of different species in Austin's developed and natural areas.

Modeled Projections of Habitat Suitability

Climate change has the potential to alter habitat suitability for tree species. Scientists can project future habitat suitability using species distribution models (SDMs). SDMs establish a statistical relationship between the current distribution of a species or ecosystem and key attributes of its habitat. This relationship is used to make projections about how the range of the species will shift as climate change affects those attributes. SDMs are much less computationally expensive than process models, which model ecosystem and tree species dynamics based on interactive mathematical representations of physical and biological processes. Because of their relative computational ease, SDMs can typically provide projections for the suitable habitat of many species over a larger area. Users should be aware of some caveats, however (Wiens, Stralberg, Jongsomjit, Howell, & Snyder, 2009). SDMs use a species' realized niche instead of its fundamental niche. The realized niche is the actual habitat a species occupies given predation, disease, and competition with other species. A species' fundamental niche, in contrast, is the habitat it could potentially occupy in the absence of competitors, diseases, or predators. Given that a species' fundamental niche may be greater than its realized niche, SDMs may underestimate current niche size and future suitable habitat. In addition, species distributions in the future might be constrained by competition, disease, and predation in ways that do not currently occur. If so, SDMs could overestimate the amount of suitable habitat in the future. If some constraints are removed due to future change, the opposite could also occur. Furthermore, fragmentation or other physical barriers to migration may create obstacles for species otherwise poised to occupy new habitat. With these caveats in mind, SDMs can still be a useful tool for projecting changes in habitat suitability across species.

Modeling Native Trees

Suitable habitats for tree species native to the eastern United States were modeled in the Austin region using the DISTRIB-II model, an SDM that is an updated version of the Tree Atlas toolset (Iverson, Peters, Prasad, & Matthews, 2019; Iverson, Prasad, Matthews, & Peters, 2008; Peters, Iverson, Prasad, & Matthews, 2019; Prasad, Iverson, Matthews, & Peters, 2014). DISTRIB-II measures relative abundance, referred to as importance values, for 134 eastern tree species (note that only 31 of these were of interest to the Austin region because they are currently present or expected to gain habitat in the area). Inputs include tree species distribution data from the U.S. Forest Service Forest Inventory and Analysis (FIA) program and environmental variables (pertaining to climate, soil properties, elevation, land use, and fragmentation), which are used to statistically model current species abundance with respect to current habitat distributions. DISTRIB-II then projects future importance values and suitable habitat for individual tree species using projections of future climate conditions on a 12-by-12-mile grid (Peters et al., 2019). For this assessment, the DISTRIB-II model uses an average of three downscaled climate models (CCSM4, Hadley, and GFDL) and two representative concentration pathways (4.5 and 8.5). Note that this model does not account for projected changes in human population, land use, or the urban heat island effect.

Table 3.1 shows the projected change in potential suitable habitat for 31 species within a 1-by-1-degree latitude/longitude area (30 to 31 °N and 97 to 98 °W, approximately 69 miles north-south and 60 miles east-west) that includes the city of Austin. The table includes species that are either currently present in the region or expected to gain suitable habitat in the region for the years 2070 to 2099 compared to present values. Species were categorized based upon whether the results from the two climate-RCP scenarios projected an increase, decrease, or no change in suitable habitat compared to current conditions, or if the model results were mixed. Further, some tree species that are currently not present in the assessment area were identified as having potential suitable habitat in the future under one or both scenarios.

When examining these results, it is important to keep in mind that model reliability was generally higher for more common species than for rare species (see Appendix 3).

Of the 31 species examined for the Austin region, suitable habitat for 14 of them was projected to decline under both high and low scenarios. Species expected to decline that are currently found in Austin based on urban FIA data include American sycamore, black walnut, bur oak, eastern red cedar, post oak, and mulberry.

For three of the species examined, model results were slightly unclear of the direction of change. There was a small projected increase for cedar elm under a low-emissions scenario, a large increase under the high-emissions scenario for chittamwood/gum bumelia, and a large decrease for honey locust under the low-emissions scenario. For each of the species, the alternate scenario suggested no change in habitat suitability.

Suitable habitat for 10 species was projected to remain relatively stable under both scenarios. Common species in Austin that fell under this category include American elm, Ashe juniper, boxelder, green ash, northern hackberry, southern live oak (Q. virginiana), and winged elm. Four species were projected to experience a gain in suitable habitat. These were blackjack oak, pecan, sugarberry, and water oak.

Note that these projections are only available for native species and are based on data collected from phase II plots every 6,000 acres in natural areas through the U.S. Forest Service FIA program. Thus, these projections are not directly applicable to native species planted in highly developed cultivated settings that may have very different soils, microclimates, and management. For more discussion on modeling methods, see Iverson et al. (2019) Peters et al. (2019).

Projected Changes from Heat and Hardiness Zone Shifts and Species Ranges

Model information is not available for all species and cultivars that are found in the Austin region or for many of the species being considered for future planting. These species are usually either too rare in the region to be modeled reliably, have a range that extends outside of the U.S., are not native to North America, or are cultivars. To understand how climate change may affect these species, one approach is to examine hardiness and heat zone ranges of the species to see how they compare to projected future zones in the region. Species that are currently present in the area based on urban FIA (Nowak et al., 2016) or expert knowledge were evaluated (Table 3.2). Species that are only hardy to zone 8 or higher may experience benefits from milder winters. Species that can only tolerate a heat zone of 10 or lower may experience negative effects from hotter summers. See Chapter 2 for projections of heat and hardiness zones in the area. Note that using heat and hardiness zones to estimate which species will benefit or fare worse in a changing climate is not as informative as the species distribution models described above because SDMs take into account changes in precipitation, seasonal climate changes, and other habitat requirements such as soil texture. This analysis is only meant to provide a coarse estimate of potential changes in habitat suitability based on temperature extremes.

We also examined species' current ranges by county using the Biota of North America Program North American Plant Atlas (Kartesz, 2015). Based on climate projections, the climate of Austin is projected to be more similar to areas that are currently located south and west of the city over the coming decades. Thus, we assumed species commonly found in areas south and west of Austin may be better suited to future climate conditions than those common north and east of Austin. If a species is currently at the northern and/or eastern extent of its range in Travis County (more common to the southwest), it was considered to likely be positively affected by climate change. If a species is at the southern and/or western extent of its range (more common to the northeast), it was considered likely to be negatively affected.

Based on this method, 23 species may benefit from milder winters (indicated by a shift in hardiness zone) over the next century (Table 3.2). The most common species expected to benefit is southern live oak (Q. virginiana), followed by Texas mountain laurel. Other species that were commonly found in the urban FIA assessment that may experience positive effects include loquat, Mexican (Berlandier) ash, Jerusalem thorn (retama), Mexican white oak, and sweet acacia (huisache).

Sixty species had either hardiness zone, heat zone, or range limits (or a combination thereof) that may suggest a negative impact from an increase in temperature. Many of Austin's most common species are included in this category, including Ashe juniper, cedar elm, sugarberry/hackberry, yaupon, green ash, Texas red oak (Q. buckleyi), boxelder, bastard/white shin oak (Q. sinuata), pecan, western soapberry, crapemyrtle, winged elm, American sycamore, and Texas live oak (Q. fusiformis).

Twenty-one of the species evaluated did not have a strongly anticipated effect of temperature. Species included in this category were Texas persimmon, honey mesquite, and Texas ash. However, these species could be affected by other climate-related changes, such as shifts in precipitation or insect or disease outbreaks.

Table 3.1
Projected Changes in Habitat Suitability for Trees Native to the 1-by-1-degree Latitude/Longitude Area around the Austin Region based on the DISTRIB-II Model

Species with lower model reliability are associated with less confidence in the direction of change. This list is limited to only species represented in the DISTRIB-II model. Note that some of the species listed may be native to part of the 1-by-1-degree latitude/longitude area, but outside of Austin. See Appendix 3 for more information.

Common Name	Scientific Name	Model Reliability	Change Class-Low Emissions (RCP 4.5)	Change Class-High Emissions (RCP 8.5)
		DECREASE UNDER BOTH SCENARIOS		
American sycamore	*Platanus occidentalis*	Low	Small decrease	Small decrease
bitternut hickory	*Carya cordiformis*	Low	Large decrease	Large decrease
Black cherry	*Prunus serotina*	Medium	Small decrease	Small decrease
black oak	*Quercus velutina*	High	Small decrease	Small decrease
black walnut	*Juglans nigra*	Low	Small decrease	Small decrease
bur oak	*Quercus macrocarpa*	Medium	Small decrease	Large decrease
eastern redcedar	*Juniperus virginiana*	Medium	Small decrease	Small decrease
flowering dogwood	*Cornus florida*	Medium	Large decrease	Large decrease
loblolly pine	*Pinus taeda*	High	Small decrease	Small decrease
post oak	*Quercus stellata*	High	Small decrease	Small decrease
red mulberry	*Morus rubra*	Low	Small decrease	Small decrease
Shumard oak	*Quercus shumardii*	Low	Small decrease	Small decrease
slippery elm	*Ulmus rubra*	Low	Small decrease	Small decrease
white ash	*Fraxinus americana*	Medium	Small decrease	Small decrease
		MIXED RESULTS		
cedar elm	*Ulmus crassifolia*	Medium	Small increase	No change
chittamwood/gum bumelia	*Sideroxylon lanuginosum ssp. lanuginosum*	Low	No change	Large increase
honeylocust	*Gleditsia triacanthos*	Low	Large decrease	No change
		NO CHANGE		
American elm	*Ulmus americana*	Medium	No change	No change
Ashe juniper	*Juniperus ashei*	High	No change	No change
black hickory	*Carya texana*	High	No change	No change
boxelder	*Acer negundo*	Low	No change	No change
green ash	*Fraxinus pennsylvanica*	Low	No change	No change
northern hackberry	*Celtis occidentalis*	Medium	No change	No change
southern live oak	*Quercus virginiana*	High	No change	No change
Osage-orange	*Maclura pomifera*	Medium	No change	No change
winged elm	*Ulmus alata*	Medium	No change	No change
		INCREASE		
blackjack oak	*Quercus marilandica*	Medium	Small increase	Small increase
pecan	*Carya illinoinensis*	Low	Small increase	Large increase
sugarberry	*Celtis laevigata*	Medium	Large increase	Large increase
water oak	*Quercus nigra*	High	Small increase	Small increase

Table 3.2
Potential Effects of Hardiness and Heat Zone (Where Available) Changes and Range Position for Species That Are Currently Found in the Austin Region or Are Being Considered for Planting in the Area

Estimated number of trees is based on 2014 Urban FIA sample (Nowak et al. 2016). Species hardiness/heat zone range is the range of zones in which the species is considered suitable for planting. Climate change was considered to have a positive effect on habitat suitability if the lowest zone for which the species was hardy was 8 or higher and/or it was at the northern and/or eastern extent of its range. Climate change was considered to have a negative effect on habitat suitability if the highest heat zone the species can tolerate was 10 or lower and/or it was at the southern and/or western extent of its range. See Chapter 2 for projected changes in heat and hardiness zones. [i] = non-native invasive species; n/a= not available

Common Name	Scientific Name	Native?	Estimated Trees in Austin	Hardiness Zone	Heat Zone	Position in Range	Climate Change Effect
American elm	*Ulmus americana*	Yes	72,039	3 to 9	9 to 1	West	Negative
American smoketree	*Cotinus obovatus*	Yes		4 to 8	N/A	South	Negative
American sycamore	*Platanus occidentalis*	Yes	132,468	5 to 9	9 to 3	Southwest	Negative
anacacho orchid tree	*Bauhinia lunarioides*	No		9 to 11	N/A	North (rare)	Positive
Arizona walnut	*Juglans major*	Yes		N/A	N/A	East	Negative
Arroyo sweetwood	*Myrospermum sousanum*	No		8 to 10	N/A	N/A	Positive
Ashe juniper	*Juniperus ashei*	Yes	13,315,759	6 to 9	10 to 7	South	Negative
Asian persimmon	*Diospyros kaki*	No		7 to 10	N/A	Center	No effect
baldcypress	*Taxodium distichum*	Yes	12,725	5 to 11	12 to 5	West	Negative
bastard/white shin oak (scalybark oak)	*Quercus sinuata*	Yes	243,656	7 to 9	N/A	South	Negative
black hickory	*Carya texana*	Yes		5 to 9	N/A	Southwest	Negative
black walnut	*Juglans nigra*	Yes	105,106	4 to 9	9 to 3	South	Negative
black willow	*Salix nigra*	Yes		4 to 9	N/A	Southwest	Negative
blackjack oak	*Quercus marilandica*	Yes		6 to 9	N/A	Southwest	Negative
boxelder	*Acer negundo*	Yes	367,930	2 to 8	8 to 3	South	Negative
Brazilian bluewood	*Condalia hookeri var. hookeri*	Yes		8 to 11	N/A	North or range	Positive
bur oak	*Quercus macrocarpa*	Yes	6,363	3 to 8	9 to 1	South	Negative
Carolina basswood	*Tilia americana var. caroliniana*	Yes		6 to 9	N/A	West	Negative
Carolina buckthorn	*Frangula caroliniana*	Yes		5 to 9	N/A	Southwest	Negative
catclaw	*Senegalia roemeriana (acacia roemeriana)*	Yes		7 to 11	N/A	Northeast	Positive
catclaw mimosa (fragrant mimosa)	*Mimosa aculeaticarpa var. biuncifera*	Yes		3 to 10	N/A	East	No effect
cedar elm	*Ulmus crassifolia*	Yes	4,583,201	7 to 9	9 to 6	South/central	Negative
cherry laurel[i]	*Prunus caroliniana*	Yes	78,107	6 to 9	9 to 6	West	Negative
Chinaberry[i]	*Melia azedarach*	No	538,729	8 to 15	12 to 7	Center	Positive
Chinese elm (lacebark elm)[i]	*Ulmus parvifolia*	No	78,107	5 to 9	9 to 1	South	Negative
Chinese pistache[i]	*Pistacia chinensis*	No	17,322	6 to 9	9 to 6	North	Negative
Chinese privet[i]	*Ligustrum sinense*	No	123,994	7 to 9	9 to 6	South	Negative
Chinese tallow tree[i]	*Triadica sebifera*	No	28,029	8 to 10	10 to 8	Center	No effect

Common Name	Scientific Name	Native?	Estimated Trees in Austin	Hardiness Zone	Heat Zone	Position in Range	Climate Change Effect
chinkapin oak	*Quercus muehlenbergii*	Yes	10,959	4 to 8	8 to 2	South	Negative
chittamwood (gum bumelia)	*Sideroxylon lanuginosum*	Yes	89,955	6 to 10	N/A	South	Negative
common hoptree (wafer ash)	*Ptelea trifoliata*	Yes		4 to 9	N/A	South	Negative
crapemyrtle	*Lagerstroemia indica*	No	174,401	7 to 9	9 to 6	N/A	Negative
desert willow	*Chilopsis linearis*	No		7 to 11	N/A	East of range	Positive
Eastern cottonwood	*Populus deltoides*	Yes	15,862	3 to 9	9 to 1	South	Negative
Eastern red cedar	*Juniperus virginiana*	Yes	38,457	3 to 9	9 to 1	South	Negative
Eastern redbud	*Cercis canadensis*	Yes	6,248	3 to 9	9 to 6	South	Negative
edible fig	*Ficus carica*	No	22,984	6 to 10	10 to 6	Center	No effect
escarpment black cherry	*Prunus serotina var. eximia*	Yes		7 to 9	N/A	South	Negative
Eve's necklace	*Styphnolobium affine*	Yes		7 to 9	N/A	Center	No effect
evergreen sumac	*Rhus virens*	Yes		8 to 11	N/A	East	Positive
fragrant sumac (skunkbush sumac)	*Rhus aromatic*	Yes		N/A	N/A	South-central	No effect
glossy privet[i]	*Ligustrum lucidum*	No	623,890	7 to 9	9 to 6	South	Negative
goldenrain tree[i]	*Koelreuteria paniculata*	No	6,363	5 to 9	9 to 1	N/A	Negative
green ash	*Fraxinus pensylvanica*	Yes	751,788	3 to 9	9 to 1	South	Negative
honey mesquite	*Prosopis glandulosa*	Yes	655,950	6 to 9	12 to 1	East-center	No effect
Japanese privet[i]	*Ligustrum japonicum*	No	17,322	7 to 10	10 to 7	Center	No effect
Jerusalem thorn (retama)	*Parkinsonia aculeata*	Yes	10,199	9 to 12	12 to 10	North	Positive
Lacey oak	*Quercus laceyi*	Yes		7 to 9	N/A	East	No effect
Lindheimer's silktassel	*Garrya ovata var. lindheimeri*	Yes		8 to 11	N/A	East	Positive
little walnut	*Juglans microcarpa*	Yes		6 to 8	N/A	East	Negative
littleleaf/goldenball leadtree	*Leucaena retusa*	No		7 to 9	N/A	East	No effect
loquat	*Eriobotrya japonica*	No	312,427	8 to 11	12 to 8	North	Positive
lotebush	*Ziziphus obtusifolia*	Yes		8 to 11	N/A	East	Positive
Mexican ash (Berlandier ash)	*Fraxinus berlandieriana*	Yes	184,758	7 to 8	N/A	North	Positive
Mexican buckeye	*Ungnadia speciosa*	Yes		7 to 9	N/A	Center	No effect
Mexican olive	*Cordia boissieri*	No		9 to 11	N/A	North or range	Positive
Mexican plum	*Prunus mexicana*	Yes		6 to 8	N/A	Southwest	Negative
Mexican redbud	*Cercis canadensis var. mexicana*	No		6 to 8	N/A	Northeast of range	Positive
Mexican sycamore	*Platanus mexicana*	No		5 to 9	N/A	North of range	Positive
Mexican white oak	*Quercus polymorpha*	No	84,966	7 to 10	12 to 8	North	Positive
Meyer lemon	*Citrus meyeri*	No		9 to 11	N/A	n/a	Positive
mimosa silktree[i]	*Albizia julibrissin*	No	4,720	6 to 9	9 to 6	Center	Negative

Common Name	Scientific Name	Native?	Estimated Trees in Austin	Hardiness Zone	Heat Zone	Position in Range	Climate Change Effect
mockernut hickory	*Carya tomentosa*	No		4 to 9	N/A	Southwest	Negative
Montezuma cypress	*Taxodium mucronatum*	No		8 to 11	N/A	North of range	Positive
netleaf hackberry	*Celtis laevigata var. reticulata*	Yes		3 to 9	N/A	East	Negative
northern hackberry	*Celtis occidentalis*	Yes	161,569	2 to 9	9 to 1	South	Negative
Osage orange	*Maclura pomifera*	Yes		4 to 9	N/A	South	Negative
paper mulberry[i]	*Broussonetia papyrifera*	No	335,755	6 to 11	N/A	Center	No effect
pecan	*Carya illinoinensis*	Yes	196,132	5 to 9	9 to 1	South	Negative
pomegranate	*Punica granatum*	No		8 to 11	12 to 4	n/a	Positive
possumhaw (deciduous holly)	*Ilex decidua*	Yes		5 to 9	N/A	Southwest	Negative
post oak	*Quercus stellata*	Yes	86,286	5 to 9	9 to 4	South	Negative
prairie sumac (flameleaf sumac)	*Rhus lanceolata*	Yes	77,093	5 to 8	N/A	Center	No effect
red bay	*Persea borbonia*	Yes		7 to 11	12 to 8	West	Negative
red buckeye	*Aesculus pavia var. pavia*	Yes		6 to 9	N/A	Southwest	Negative
red mulberry	*Morus rubra*	Yes	124,975	5 to 9	9 to 4	Southwest	Negative
roughleaf dogwood	*Cornus drummondii*	Yes	59,882	4 to 9	N/A	South	Negative
rusty blackhaw	*Viburnum rufidulum*	Yes		5 to 9	8 to 1	Southwest	Negative
Shumard oak	*Quercus shumardii*	Yes	43,137	5 to 10	9 to 1	South	Negative
slippery elm	*Ulmus rubra*	Yes	12,725	3 to 10	10 to 1	Southwest	Negative
Southern live oak (coast live oak)	*Quercus virginiana*	Yes	2,862,523	8 to 11	11 to 6	Center	Positive
Southern magnolia	*Magnolia grandiflora*	No	6,363	7 to 10	11 to 1	West	Negative
sugarberry	*Celtis laevigata*	Yes	2,058,386	5 to 10	N/A	South	Negative
sweet acacia (huisache)	*Vachellia farnesiana (acacia farnesiana)*	Yes	4,597	8 to 10	12 to 10	North	Positive
sweetgum	*Liquidambar styraciflua*	No		6 to 9	N/A	Southwest	Negative
Texas ash	*Fraxinus albicans*	Yes	438,216	3 to 9	9 to 4	Center	No effect
Texas crab apple	*Malus ioensis var. texana*	No		N/A	N/A	N/A	Unknown
Texas Hercules' club (prickly-ash, tickle-tongue)	*Zanthoxylum hirsutum*	Yes		4 to 8	N/A	Center	No effect
Texas kidneywood	*Eysenhardtia texana*	Yes		8 to 11	N/A	Northeast	Positive
Texas live oak (escarpment live oak, plateau live oak)	*Quercus fusiformis*	Yes	101,848	6 to 10	10 to 6	Center	No effect
Texas madrone	*Arbutus xalapensis*	Yes	6,189	7 to 11	12 to 3	North	No effect
Texas mountain laurel	*Dermatophyllum secundiflorum*	Yes	648,060	8 to 15	12 to 10	Northeast	Positive
Texas mulberry	*Morus microphylla*	Yes		5 to 9	N/A	East	No effect
Texas persimmon	*Diospyros texana*	Yes	2,014,199	7 to 9	N/A	North	No effect
Texas pistache	*Pistacia mexicana*	No		7 to 9	N/A	North	No effect
Texas red oak	*Quercus buckleyi*	Yes	419,812	7 to 10	10 to 1	South	Negative

Common Name	Scientific Name	Native?	Estimated Trees in Austin	Hardiness Zone	Heat Zone	Position in Range	Climate Change Effect
Texas redbud	*Cercis canadensis var. texensis*	Yes		5 to 9	N/A	Center	No effect
velvet ash	*Fraxinus velutina*	Yes	59,326	6 to 9	9 to 6	East	Negative
water oak	*Quercus nigra*	Yes	4,597	6 to 9	9 to 7	Southwest	Negative
Western soapberry	*Sapindus saponaria var. drummondii*	Yes	192,371	6 to 9	N/A	Southeast	Negative
white mulberry[i]	*Morus alba*	No	13,790	4 to 8	8 to 1	Center	Negative
winged elm	*Ulmus alata*	No	134,185	6 to 9	N/A	South	Negative
yaupon	*Ilex vomitoria*	Yes	833,143	7 to 11	12 to 7	Southwest	Negative

Adaptive Capacity of Urban Trees

The results presented above provide information on potential changes in tree species habitat suitability across a range of projected future temperature and precipitation regimes (in the case of DISTRIB-II) or extreme high and low temperatures (in the case of hardiness and heat zones), but do not account for factors such as changes in flood regime, extreme weather events, insects and disease, and non-native invasive species. To understand the capacity of tree species and cultivars in the area to adapt to these other effects of climate change, we relied on a scoring system developed by Matthews, Iverson, Prasad, Peters, and Rodewald (2011) called "modification factors." Other scoring systems have been developed (Roloff, Korn, & Gillner, 2009), but we found the system developed by Matthews et al. to be the most comprehensive for all potential climate change–related stressors. Modification factors can include life history traits or environmental factors that make a species more or less likely to persist on the landscape (Matthews et al., 2011). Examples of modification factors include fire or drought tolerance, dispersal ability, shade tolerance, site specificity, and susceptibility to insect pests and diseases (Table 3.3). These factors can then be weighted by their intensity, the level of uncertainty about their impacts, and relative importance to future changes to tree mortality and survival to arrive at a numerical score (see Appendix 4). Modification factors are highly related to the adaptive capacity of a species: the ability to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (IPCC 2014). A species with a large number of positive modification factors would have a high adaptive capacity, and a species with a large number of negative modification factors would have a low adaptive capacity.

We used the modification factors developed for the Chicago Wilderness vulnerability assessment to better capture the unique environment of urban areas (Brandt et al., 2017). As in the Chicago assessment, we created separate scores for developed and natural areas. For the most part, we used the same categories and weights as in Chicago but eliminated the road salt category as road salt is not used in Austin. We also put extra weight on both flooding and drought in natural areas because Austin is more susceptible to these effects than Chicago. We developed modification factor scores for 104 species and varieties. Scores were then converted to categories of high, medium, and low adaptive capacity. It is important to note that modification factors are meant to be used as a general summary of a species' adaptive capacity across its entire range, and not meant to capture site-specific factors that may enhance or reduce a species ability to withstand stressors.

For planted/developed conditions, 29 species received a high adaptability score, 18 received a low adaptability score, and the remaining 57 received a medium adaptability score (Table 3.4). Common native species with high adaptability scores in planted environments include cedar elm, Texas mountain laurel, yaupon, possumhaw, hoptree/wafer ash, chittamwood/gum bumelia, and Eve's necklace. Factors that tended to enhance adaptive capacity included tolerance to a wide range of disturbances, ability to be planted on a wide range of sites, and ease of propagation in a nursery. Common species that received low adaptability ratings were pecan, black walnut, and several oak species. These species tended to receive low adaptability ratings because they were susceptible to pests or diseases and were intolerant of a variety of urban sites and/or pollution.

For natural areas (both native and naturalized), 43 species received a high adaptability score, 13 received a low adaptability score, and 48 received a medium adaptability score (Table 3.5). Not surprisingly, many of the most adaptable species are non-native invasive species, such as Chinese tallowtree, Japanese and Chinese privet, Chinese elm, glossy privet, chinaberry, paper and white mulberry, mimosa/silktree, Chinese pistache, and goldenrain tree. Native species with high adaptability scores include sugarberry, sumac species, boxelder, possumhaw, roughleaf dogwood, southern live oak, yaupon, cedar elm, and hoptree/wafer ash.

Table 3.3
Trait Codes for Adaptability Tables

Traits are listed if they were among the main contributors to the overall adaptability score. N = applies to naturally occurring trees; P = applies to planted trees. See Appendix 4 for more information.

Factor	Code	Type	Description (if positive)	Description (if negative)
Air pollution	AIP	N, P	Tolerant of air pollution	Intolerant of air pollution
Browse	BRO	N, P	Resistant to browsing	Susceptible to browsing
Competition-light	COL	N, P	Tolerant of shade or limited light conditions	Intolerant of shade or limited light conditions
Disease	DISE	N, P	Disease-resistant	Has a high number and/or severity of known pathogens that attack the species
Dispersal	DISP	N	High ability to effectively produce and distribute seeds	Low ability to effectively produce and distribute seeds
Drought	DRO	N, P	Drought-tolerant	Susceptible to drought
Edaphic specificity	ESP	N, P	Wide range of soil tolerance	Narrow range of soil requirements
Environmental habitat specificity	EHS	N	Wide range of slopes/aspects/topographic positions	Small range of slopes/aspects/topographic positions
Flood	FLO	N, P	Flood-tolerant	Flood-intolerant
Fire regeneration	FRG	N	Regenerates well after fire	N/A
Fire topkill	FTK	N	Resistant to fire topkill	Susceptible to fire topkill
Ice	ICE	N, P	N/A	Susceptible to breakage from ice storms
Insect pests	INS	N, P	Pest-resistant	Has a high number and/or severity of insects that may attack the species
Invasive plants	INPL	N, P	N/A	Strong negative effects of non-native invasive plants on the species, either through competition for nutrients or as a pathogen
Invasive potential	INPO	P	N/A	Species has the potential to become invasive and thus disfavored for planting
Land-use and planting site specificity	LPS	P	Can be planted on a wide variety of sites	Can only be planted in a narrow range of sites or as a specimen
Maintenance required	MAR	P	Little pruning, watering, or cleanup required	Requires considerable pruning, watering, or cleanup of debris
Nursery propagation	NUP	P	Easily propagated in nursery and widely available	Not easily propagated/not usually available
Planting establishment	PLE	P	Easily transplanted and requires little care to establish	Difficult to transplant or requires considerable care to establish
Restricted rooting conditions	RRC	P	Can tolerate restricted rooting conditions	Intolerant of restricted rooting conditions
Seedling establishment	SES	N	High ability to regenerate with seeds to maintain future populations	Low ability to regenerate with seeds to maintain future populations
Soil and water pollution	SWP	N, P	Tolerant of soil and/or water pollution	Intolerant of soil and/or water pollution
Temperature gradients	TEM	N, P	Wide range of temperature tolerances	Narrow range of temperature requirements
Vegetative reproduction	VRE	N	Capable of vegetative reproduction through stump sprouts or cloning	Not capable of vegetative reproduction
Wind	Win	N, P	N/A	Susceptible to breakage from windstorms

Table 3.4
Adaptability Scores for Trees in Developed Areas

See Table 3.3 for trait codes. See Appendix 4 for descriptions of Disturb, Bio and, Adapt scoring system. A negative disturb score indicates a species is highly susceptible to one or more disturbances such as drought, flooding, or pests and vice versa. A negative bio score indicates a species has a very limited range of soil, light, and other environmental requirements and vice versa. Adapt scores are all positive. A score below 3.5 is low, above 4.5 is high, and between 3.5 and 4.5 is a medium adapt class. [i] =non-native invasive species

Common Name	Scientific Name	Planted Disturb Score	Planted Bio Score	Planted Adapt Score	Planted Adapt Class	Planted Positive Factors	Planted Negative Factors
American elm	*Ulmus americana*	-2.2	1	3.83	Medium	TEM NUP	DISE DRO
American smoketree	*Cotinus obovatus*	-0.75	1	3.86	Medium	DRO LPS RRC	AIP
American sycamore	*Platanus occidentalis*	-0.75	0.56	3.85	Medium	FLO TEM NUP	DRO
Anacacho orchid tree	*Bauhinia lunarioides*	-0.34	-1	3.62	Medium		FLO AIP
Arizona walnut	*Juglans major*	-0.77	-0.66	3.53	Medium	FLO	DRO AIP
Arroyo sweetwood	*Myrospernum sousanum*	-0.57	-0.94	3.57	Medium	DRO	FLO AIP INPO
Ashe juniper	*Juniperus ashei*	0.66	0.09	4.46	Medium	AIP ESP RRC DRO	FLO ICE WIN
Asian persimmon	*Diospyros kaki*	-1.86	0	3.3	Low		FLO AIP LUP
bald cypress	*Taxodium distichum*	0.2	2	5	High	FLO RRC NUP	AIP
Bastard/white shin oak (scalybark oak)	*Quercus sinuata*	-0.3	-1	3.4	Low	DRO	AIP
Berlandier ash	*Fraxinus berlandieriana*	-2.43	1	3.94	Medium		INS DRO AIP INPO
bigtooth maple	*Acer grandidentatum*	0.82	0.22	4.64	High	TEM	
Black hickory	*Carya texana*	-1.45	-2	2.92	Low		FLO AIP NUP
black walnut	*Juglans nigra*	-1.18	-1.78	2.88	Low		DISE AIP COL LPS RRC
black willow	*Salix nigra*	-1.55	-0.38	3.3	Low	FLO	SRO AIP RRC
Blackjack oak	*Quercus marilandica*	-1.16	-2	2.87	Low	DRO TEM	DISE FLO AIP LPS RRC NUP
boxelder	*Acer negundo*	0.02	0	4.34	Medium	DRO FLO TEM	INS INPO
Brazilian bluewood	*Condalia hookeri var. hookeri*	-0.75	-0.28	3.53	Medium	DRO	FLO AIP
bur oak	*Quercus macrocarpa*	0.55	0.84	4.49	High	DRO TEM AIP LPS NUP	FLO
Carolina basswood	*Tilia americana var. caroliniana*	-1.23	0.19	3.86	Medium	COL	AIP
Carolina buckthorn	*Frangula caroliniana*	-1	1	4.17	Medium		DRO TEM
catclaw	*Acacia roemeriana*	-0.89	0	3.63	Medium	DRO	FLO COL AIP
Catclaw mimosa	*Mimosa biuncifera*	0.45	-1	3.68	Medium	DRO	AIP INPO

Common Name	Scientific Name	Planted Disturb Score	Planted Bio Score	Planted Adapt Score	Planted Adapt Class	Planted Positive Factors	Planted Negative Factors
cedar elm	*Ulmus crassifolia*	0.98	3.63	5.82	High	FLO AIP EPS LPS RRC NUP DRO	
cherry laurel[i]	*Prunus caroliniana*	-0.2	0.47	4.55	High	NUP	FLO RRC INPO
Chinaberry	*Melia azedarach*	1.11	-1.41	4.12	Medium	DRO FLO RRC PES	LPS NUP INPO
Chinese elm[i]	*Ulmus parvifolia*	1.39	2	5.5	High	DRO TEM EDS LPS RRC NUP	INPO
Chinese pistache	*Pistacia chinensis*	1.23	0.56	4.86	High	DRO LPS RRC	FLO MAIN INPO
Chinese privet[i]	*Ligustrum sinense*	-1.5	0.69	4.14	Medium	TEM NUP	INPO
Chinese tallowtree[i]	*Triadica sebifera*	0.2	2	5	High	DRO FLO WIN LPS RRC NUP	DISE AIP INPO
chinkapin oak	*Quercus muehlenbergii*	-0.27	1	4.48	Medium	DRO TEM	AIP
chittamwood (gum bumelia)	*Sideroxylon lanuginosum*	-0.36	1.75	4.53	High	DRO TEM	AIP
Common hoptree (wafer ash)	*Ptelea trifoliata*	-0.66	1.22	4.48	Medium	TEM RRC NUP	AIP
crape myrtle	*Lagerstroemia indica*	-0.95	3	4.71	High	DRO TEM LPS RRC NUP	FLO AIP
Desert willow	*Chilopsis linearis*	0.34	-0.66	3.76	Medium	DRO FLO	AIP
Eastern cottonwood	*Populus deltoides*	-1.43	-0.38	3.15	Low	TEM NUP	DIS INS AIP LPS RRC
Eastern red cedar	*Juniperus virginiana*	0	2	4.65	High	DRO TEM LPS RRC	AIP
Eastern redbud	*Cercis canadensis*	0	2	4.65	High	FLO TEM LPS RRC	AIP
edible fig	*Ficus carica*	-2.05	-1	2.84	Low		FLO AIP
escarpment black cherry	*Prunus serotina var. eximia*	-1.18	-3	2.73	Low	TEM	WIN AIP ESP LPS NUP
Eve's necklace	*Styphnolobium affine*	-0.16	2	4.89	High	DRO LPS NUP	FLO AIP
evergreen sumac	*Rhus virens*	-0.84	1	4.23	Medium	DRO	FLO AIP DISE
Fragrant sumac	*Rhus aromatica*	0.3	2	4.9	High	DRO TEM ESP LPS NUP	
glossy privet[i]	*Ligustrum lucidum*	0.48	2	4.92	High	TEM LPS RRC NUP	INPO
goldenrain tree[i]	*Koelreuteria paniculatan*	0.48	1	4.55	High	DRO TEM LPS RRC NUP	INPO
green ash	*Fraxinus pennsylvanica*	-1.2	0.81	3.86	Medium	FLO LPS NUP	INS MAIN
Honey mesquite	*Prosopis glandulosa*	0.57	-2	3.63	Medium	DRO	AIP INPO
Japanese privet[i]	*Ligustrum japonicum*	-1.5	1	4.14	Medium	TEM NUP	INPO
Jerusalem thorn (retama)	*Parkinsonia aculeata*	0.59	1.69	4.98	High	DRO LPS RRC NUP	INPO
Lacey oak	*Quercus laceyi*	-0.07	-0.16	3.94	Medium	DRO	FLO SIP

Common Name	Scientific Name	Planted Disturb Score	Planted Bio Score	Planted Adapt Score	Planted Adapt Class	Planted Positive Factors	Planted Negative Factors
Lindheimer's silktassel	*Garrya ovata var. lindheimeri*	-0.3	0	3.96	Medium		FLO AIP
little walnut	*Juglans microcarpa*	-0.98	-0.66	3.47	Low	FLO	DRO AIP
littleleaf (goldenball leadtree)	*Leucaena retusa*	-0.2	-1	3.57	Medium	DRO	WIN AIP INPO
loquat	*Eriobotrya japonica*	-1.45	0	3.76	Medium		AIP INPO
Lotebush	*Ziziphus obtusifolia*	0.25	0.47	4.36	Medium	DRO	AIP INP
Mexican buckeye	*Ungnadia speciosa*	-0.16	2	4.95	High	DRO TEM RRC NUP	AIP
Mexican olive	*Cordia boissieri*	-1.68	0.28	3.45	Low	DRO	FLO AIP
Mexican plum	*Prunus mexicana*	-0.09	1	4.59	High	DRO LPS	AIP
Mexican redbud	*Cercis canadensis L. var. mexicana*	-1.32	-0.09	3.66	Medium	DRO	FLO AIP
Mexican sycamore	*Platanus mexicana*	0.93	-1.41	4.26	Medium	FLO AIP	LPS RRC
Mexican white oak	*Quercus polymorpha*	0.14	2	4.59	High	DRO LPS NUP	AIP
Meyer lemon	*Citrus meyeri*	-1.18	0.94	3.81	Medium	NUP	FLO
mimosa (silktree)[i]	*Albizia julibrissin*	-0.77	-2.28	2.88	Low	DRO FLO TEM EDS	DISE AIP INPO LPS RRC INPO
Mockernut hickory	*Carya tomentosa*	-0.46	-0.59	3.68	Medium		AIP
Montezuma cypress	*Taxodium mucronatum*	0.86	-1	4.05	Medium	DRO FLO	AIP
Netleaf hackberry	*Celtis laevigata var. reticulata*	-0.64	-0.59	3.66	Medium	DRO FLO TEM AIP	WIN
Northern hackberry	*Celtis occidentalis*	0.25	1.66	4.64	High	DRO TEM LPS NUP	
Osage orange	*Maclura pomifera*	0.61	2.66	5.26	High	INS DRO TEM RRC NUP	AIP
paper mulberry[i]	*Broussonetia papyrifera*	0.3	-0.63	4.12	Medium	FLO TEM	INPO
pecan	*Carya illinoinensis*	-1.85	0	3.15	Low		AIP LPS RRC
Pomegranate	*Punica granatum*	-0.93	0.94	3.82	Medium	DRO RRC NUP	FLO
Possumhaw	*Ilex decidua*	1.14	1	4.95	High	FLO TEM	AIP
post oak	*Quercus stellata*	-1.39	-2	2.92	Low	TEM	DISE FLO AIP LPS NUP
prairie flameleaf sumac	*Rhus lanceolata*	1.14	-0.38	4.12	Medium	DRO TEM	AIP
prickly-ash (tickle-tongue)	*Zanthoxylum hirsutum*	-0.36	-1	3.57	Medium		AIP LPS INPO
Red bay	*Persea borbonia*	-0.5	2	4.74	High	TEM NUP	AIP
Red buckeye	*Aesculus pavia var. pavia*	-1.18	0.09	3.81	Medium		AIP

Common Name	Scientific Name	Planted Disturb Score	Planted Bio Score	Planted Adapt Score	Planted Adapt Class	Planted Positive Factors	Planted Negative Factors
red mulberry	*Morus rubra*	-1.05	0.38	4.02	Medium	TEM NUP	AIP
roughleaf dogwood	*Cornus drummondii*	0.61	0	4.31	Medium	TEM FLO	AIP RRC
rusty blackhaw	*Viburnum rufidulum*	-0.11	1	4.39	Medium	DRO TEM LPS	FLO RRC
Shumard oak	*Quercus shumardii*	-0.3	2	4.22	Medium	FLO LPS RRC NUP	DISE
slippery elm	*Ulmus rubra*	-1.36	0	3.92	Medium	TEM	DISE AIP INPO
Southern live oak	*Quercus virginiana*	-0.75	2	4.54	High	TEM LPS RRC NUP	DISE AIP
Southern magnolia	*Magnolia grandiflora*	-1.43	-0.72	3.57	Medium	NUP	DRO LPS RRC
sugarberry	*Celtis laevigata*	-0.02	0	4.03	Medium	DRO FLO TEM	WIN
sweet acacia (huisache)	*Vachellia farnesiana*	-0.89	-1	3.13	Low	DRO	FLO INPO
sweetgum	*Liquidambar styraciflua*	-0.48	-0.28	3.72	Medium	FLO	INS DRO RRC
Texas (escarpment, plateau) live oak	*Quercus fusiformis*	-1.75	-2	2.76	Low		DISE INS FLO AIP LPS RRC
Texas ash	*Fraxinus albicans*	-0.82	2.16	4.69	High	TEM LPS RRS NUP	INS FLO
Texas crab apple	*Malus ioensis var. texana*	-1.86	0	3.51	Medium		FLO AIP
Texas kidneywood	*Eysenhardtia texana*	-0.48	0	3.84	Medium	DRO	FLO AIP
Texas madrone	*Arbutus xalapensis*	-1.3	1.09	4.25	Medium	DRO RRC	FLO AIP PLE
Texas mountain laurel	*Dermatophyllum secundiflorum*	0.2	3	5.15	High	DRO LPS RRC NUP	AIP
Texas mulberry	*Morus microphylla*	-1.45455	-1.13	3.4	Low		AIP
Texas persimmon	*Diospyros texana*	-0.52	1	4.43	Medium	RRC	AIP
Texas pistache	*Pistacia mexicana*	-0.43	0	3.69	Medium	DRO	DIS AIP
Texas red (Buckley) oak	*Quercus buckleyi*	-0.43	1	4.18	Medium	TEM	DISE FLO
Texas redbud	*Cercis canadensis var. texensis*	-1.36	1	4.03	Medium	RRC LPS DRO	AIP FLO
velvet ash	*Fraxinus velutina*	-0.14	2	4.44	Medium	DRO AIP LPS RRS NUP	INS WIN MAIN
water oak	*Quercus nigra*	-1.02	0.34	3.55	Medium	FLO TEM NUP	DISE AIP
Western soapberry	*Sapindus saponaria var. drummondii*	2.09	-1.88	4.69	High	DRO FLO TEMP AIP	NUP
white mulberry[i]	*Morus alba*	0.36	-0.22	3.41	Low	NUP	LPS INPO
winged elm	*Ulmus alata*	-1.77	1.44	4.17	Medium	FLO LPS RRC	DISE AIP INPO
yaupon	*Ilex vomitoria*	0.32	3	5.46	High	ESP LPS RRC NUP	High

Table 3.5
Adaptability Scores for Trees in Natural Areas

See Table 3.3 for trait codes. See Appendix 4 for descriptions of Disturb, Bio and, Adapt scoring system. See Appendix 4 for descriptions of Disturb, Bio and, Adapt scoring system. A negative disturb score indicates a species is highly susceptible to one or more disturbances such as drought, flooding, or pests and vice versa. A negative bio score indicates a species has a very limited range of soil, light, and other environmental requirements and vice versa. Adapt scores are all positive. A score below 3.5 is low, above 4.5 is high, and between 3.5 and 4.5 s a medium adapt class. [i] = non-native invasive species

Common Name	Scientific Name	Natural Disturb Score	Natural Bio Score	Natural Adapt Score	Natural Adapt Class	Natural Positive Factors	Natural Negative Factors
American elm	*Ulmus americana*	-2.19	2	4.64	High	EHS	DISE INSP DRO AIP
American smoketree	*Cotinus obovatus*	-0.85	-1	3.35	Low	DRO	AIP EHS
American sycamore	*Platanus occidentalis*	-1.46	-0.21	3.49	Medium	FLO	DRO EHS
Anacacho orchid tree	*Bauhinia lunarioides*	-0.56	-1.5	3.38	Low	DRO	FLO COL EHS
Arizona walnut	*Juglans major*	-0.87	0	3.61	Medium	FLO	DRO AIP EHS
Arroyo sweetwood	*Myrospernum sousanum*	-0.63	0	3.61	Medium	DRO SES	FLO AIP EHS
Ashe juniper	*Juniperus ashei*	-0.79	3	5.12	High	DRO ESP EHS DISP SES	FLO FTK
Asian persimmon	*Diospyros kaki*	-2.19	-0.11	3.36	Low		FLO AIP DISP
bald cypress	*Taxodium distichum*	-1.31	0	3.81	medium	FLO	DRO AIP EHS
Bastard/white shin oak (scalybark oak)	*Quercus sinuata*	-0.44	0	4.02	Medium	DRO VRE FRG	AIP COL DISP
Berlandier ash	*Fraxinus berlandieriana*	-3.13	2.36	4.23	Medium	FTK AIP VRE	INS DRO DISP SES
bigtooth maple	*Acer grandidentatum*	0.15	2	4.87	High	COL EHS	
black hickory	*Carya texana*	-1.9	0	3.52	Medium	SES	FLO AIP COL
black walnut	*Juglans nigra*	-1.25	0	3.85	Medium	SES	DISE COL
black willow	*Salix nigra*	-1.79	-1.29	3.26	Low	FLO	DRO FTK AIP COL
Blackjack oak	*Quercus marilandica*	-1.37	2	4.67	High	DRO SES VRE	DISE FLO AIP COL
boxelder	*Acer negundo*	-0.13	4.61	5.64	High	DRO FLO TEM COL DISP SES	AIP
Brazilian bluewood	*Condalia hookeri var. hookeri*	-0.96	0.32	4.02	Medium	DRO	FLO AIP COL
bur oak	*Quercus macrocarpa*	0.23	1	4.73	High	DRO AIP	FLO
Carolina basswood	*Tilia americana var. caroliniana*	-1.54	-1	3.49	Low	COL	AIP EHS SES
Carolina buckthorn	*Frangula caroliniana*	-1.12	1	4.18	Medium	COL SES	DRO AIP
catclaw	*Acacia roemeriana*	-1.19	0	3.93	Medium	DRO	FLO COL AIP
Catclaw mimosa	*Mimosa biuncifera*	0.63	0	4.24	Medium	DRO EHS VRE	AIP COL

Common Name	Scientific Name	Natural Disturb Score	Natural Bio Score	Natural Adapt Score	Natural Adapt Class	Natural Positive Factors	Natural Negative Factors
cedar elm	*Ulmus crassifolia*	0.12	4	5.61	High	DRO FLO AIP ESP EHS DISP SES FRE	
cherry laurel[i]	*Prunus caroliniana*	-0.92	2.46	4.74	High	COL DISP SES	FLO VRE
Chinaberry	*Melia azedarach*	0.81	2	5.19	High	DRO FLO DISP SES VRE	COL
Chinese elm[i]	*Ulmus parvifolia*	0.67	3	5.44	High	DRO ESP EHS SES	
Chinese pistache	*Pistacia chinensis*	0.83	1	4.87	High	DRO WIN AIP EHS	FLO VRE
Chinese privet[i]	*Ligustrum sinense*	-1.52	5	5.81	High	COL EHS DISP SES VRE	AIP
Chinese tallowtree[i]	*Triadica sebifera*	0.6	4.71	6	High	DRO FLO WIN COL EHS DISP SES VRE	DISE AIP
chinkapin oak	*Quercus muehlenbergii*	-0.58	1.07	4.5	Medium	DRO TEM	
chittamwood (gum bumelia)	*Sideroxylon lanuginosum*	-0.69	0.54	4.22	Medium	DRO TEM	AIP COL
Common hoptree (wafer ash)	*Ptelea trifoliata*	-1.58	1	4.29	Medium	TEM COL DISP	FTK AIP VRE
Crape myrtle	*Lagerstroemia indica*	-0.75	3	5.16	High	DRO EHS DISP SES VRE	FLO COL
desert willow	*Chilopsis linearis*	0.42	0.75	4.46	Medium	DRO FLO SES	AIP COL
Eastern cottonwood	*Populus deltoides*	-1.52	1	3.93	Medium	TEM	DIS INS AIP
Eastern red cedar	*Juniperus virginiana*	-0.38	0	4.03	Medium	DRO	FTK COL
Eastern redbud	*Cercis canadensis*	-0.5	2.36	4.98	High	FLO	AIP
edible fig	*Ficus carica*	-2.35	-1.39	2.62	Low		FLO AIP VRE
escarpment black cherry	*Prunus serotina var. eximia*	-1.5	0.32	3.61	Medium	DISP SES	WIN AIP ESP EHS
Eve's necklace	*Styphnolobium affine*	-0.17	0	3.78	Medium	DRO COL	FLO AIP DISP
evergreen sumac	*Rhus virens*	-0.73	3	5.34	High	DRO DISP SES VRE FRG	FLO AIP DISE
Fragrant sumac	*Rhus aromatica*	0.33	3.86	5.72	High	DRO TEM ESP EHS DISP SES VRE	AIP
glossy privet[i]	*Ligustrum lucidum*	-0.4	3	5.22	High	TEM EHS DISP SES	
goldenrain tree[i]	*Koelreuteria paniculatan*	-0.21	2	4.7	High	DRO DISP SES	COL
green ash	*Fraxinus pennsylvanica*	-1.37	1.18	4.46	Medium	FLO	INS COL
honey mesquite	*Prosopis glandulosa*	0.13	1.39	4.68	High	DRO SES FRE	AIP COL
Japanese privet[i]	*Ligustrum japonicum*	-1.52	4.71	5.81	High	COL EHS DISP SES VRE	AIP
Jerusalem thorn (retama)	*Parkinsonia aculeata*	0.12	-0.75	3.74	Medium	DRO SES	COL VRE
Lacey oak	*Quercus laceyi*	-0.33	-1.07	3.38	Low	DRO SES	FLO AIP EHS DISP

Common Name	Scientific Name	Natural Disturb Score	Natural Bio Score	Natural Adapt Score	Natural Adapt Class	Natural Positive Factors	Natural Negative Factors
Lindheimer's silktassel	*Garrya ovata var. lindheimeri*	-0.75	0.21	4.04	Medium		FLO AIP
little walnut	*Juglans microcarpa*	-1.67	-1	2.73	Low	FLO SES	DRO FTK AIP EHS DISP VRE
littleleaf (goldenball leadtree)	*Leucaena retusa*	-0.71	2	4.33	Medium	DRO DISP SES	FLO WIN AIP VRE
loquat	*Eriobotrya japonica*	-1.62	2	4.34	Medium		AIP
Lotebush	*Ziziphus obtusifolia*	0.4	4	5.67	High	DRO EHS DSIP SES VRE	AIP
Mexican buckeye	*Ungnadia speciosa*	-0.46	-0.11	4.03	Medium	COL	AIP EHS SES
Mexican olive	*Cordia boissieri*	-1.46	0	3.61	Medium	DRO	FLO AIP COL
Mexican plum	*Prunus mexicana*	-0.73	1.07	4.13	Medium	DRO COL EHS	VRE
Mexican redbud	*Cercis canadensis L. var. mexicana*	-1.27	2	4.67	High	DRO SES	FLO AIP
Mexican sycamore	*Platanus mexicana*	0.27	3.54	5.59	High	FLO AIP EHS DISP SES	
Mexican white oak	*Quercus polymorpha*	0.02	0	3.87	Medium	DRO SES	AIP DISP
Meyer lemon	*Citrus meyeri*	-1.75	-0.32	3.53	Medium		FLO COL
mimosa (silktree)[i]	*Albizia julibrissin*	-0.88	2.89	4.99	High	DRO FLO EDS EHS SES	DISE AIP COL
mockernut hickory	*Carya tomentosa*	-0.81	1	4.46	Medium		FTK COL
Montezuma cypress	*Taxodium mucronatum*	0.98	-2.79	3.39	Low	DRO FLO	AIP COL EHS DISP
netleaf hackberry	*Celtis laevigata var. reticulata*	-0.92	5	5.74	High	COL ESP EHS DISP SES	AIP
northern hackberry	*Celtis occidentalis*	-0.44	2.36	4.9	High	DRO	FTK
Osage orange	*Maclura pomifera*	-0.21	2.04	4.94	High	DRO EDS EHS	
paper mulberry[i]	*Broussonetia papyrifera*	-0.42	3	5.1	High	FLO COL SES	
pecan	*Carya illinoinensis*	-2.46	-1	3.12	Low		FTK COL
Pomegranate	*Punica granatum*	-1.21	-0.21	3.2	low	DRO EHS SES	FLO COL DISP VRE
possumhaw	*Ilex decidua*	0.69	2.25	4.89	High	FLO COL EHS SES	AIP DISP
post oak	*Quercus stellata*	-1.42	1	4.17	Medium	TEM	DISE FLO AIP COL
prairie flameleaf sumac	*Rhus lanceolata*	0.98	3	5.48	High	DRO TEM EHS DISP SES VRE FRG	AIP COL
prickly-ash (tickle-tongue)	*Zanthoxylum hirsutum*	-0.69	2.68	5.07	High	EHS VRE	
red bay	*Persea borbonia*	-0.98	1.39	4.46	Medium		AIP
Red buckeye	*Aesculus pavia var. pavia*	-0.79	2	4.83	High	COL FLO	AIP

Common Name	Scientific Name	Natural Disturb Score	Natural Bio Score	Natural Adapt Score	Natural Adapt Class	Natural Positive Factors	Natural Negative Factors
red mulberry	*Morus rubra*	-1.71	1.93	4.44	Medium	COL	FTK AIP
roughleaf dogwood	*Cornus drummondii*	0.15	2	4.9	High	FLO COL	AIP
rusty blackhaw	*Viburnum rufidulum*	-0.38	1.07	4.36	Medium	DRO COL	FLO VRE
Shumard oak	*Quercus shumardii*	-1.19	0	3.81	Medium	FLO	DISE FTK COL
slippery elm	*Ulmus rubra*	-1.83	2	4.5	High	COL	DISE FTK AIP
Southern live oak	*Quercus virginiana*	-0.79	2	5.07	High	FTK VRE FRG	DISE AIP
Southern magnolia	*Magnolia grandiflora*	-1.56	1	4.29	Medium	COL SES	DRO FLO EHS
sugarberry	*Celtis laevigata*	-0.92	4.5	5.74	High	COL ESP EHS DISP SES	AIP
sweet acacia (huisache)	*Vachellia farnesiana*	-1.21	-1.82	2.99	Low	DRO	FLO COL
sweetgum	*Liquidambar styraciflua*	-1.46	1.82	4.63	High	FLO EHS VRE	INS DRO FTK AIP COL
Texas ash	*Fraxinus albicans*	-1.69	1	4.17	Medium	SES	INS FLO
Texas crab apple	*Malus ioensis var. texana*	-2.19	-2.14	2.56	Low		FLO AIP COL EHS
Texas kidneywood	*Eysenhardtia texana*	-1.02	0.75	4.09	Medium	DRO EHS	FLO AIP COL
Texas live oak	*Quercus fusiformis*	-1.87	3	4.86	High	FTK SES VRE FRG	DISE INS FLO AIP
Texas madrone	*Arbutus xalapensis*	-1.02	1.29	4.54	High	DRO	FLO AIP SES
Texas mountain laurel	*Dermatophyllum secundiflorum*	-0.1	1.29	4.43	Medium	DRO EHS DISP	AIP
Texas mulberry	*Morus microphylla*	-1.73	1	3.93	Medium	COL	AIP
Texas persimmon	*Diospyros texana*	-1.1	3.54	5.31	High	COL EHS DISP	AIP
Texas pistache	*Pistacia mexicana*	-0.52	0.86	4.13	Medium	DRO	DISE AIP
Texas red (Buckley) oak	*Quercus buckleyi*	-1.48	1	4.13	Medium	TEM VRE SES FRG	DISE FLO FTK DISP
Texas redbud	*Cercis canadensis var. texensis*	-1.42	1	3.97	Medium	DRO	FLO AIP
velvet ash	*Fraxinus velutina*	-0.25	0	3.93	Medium	DRO AIP SES	INS WIN COL VRE
water oak	*Quercus nigra*	-1.6	0.75	3.93	Medium	FLO	DISE FTK AIP COL
Western soapberry	*Sapindus saponaria var. drummondii*	1.56	-1	4.49	Medium	DRO FLO AIP DISP VRE	FTK EHS SES
white mulberry[i]	*Morus alba*	0.13	2.46	4.98	High	DISP SES	
winged elm	*Ulmus alata*	0	0	0	Medium	FLO COL	DISE AIP
yaupon	*Ilex vomitoria*	-0.5	4	5.68	High	COL ESP EHS DISP SES	AIP

Overall Vulnerability of the Austin Region's Trees

Vulnerability is the susceptibility of a system to the adverse effects of climate change (Parry, Canziani, Palutikof, Van der Linden, & Hanson, 2007). Vulnerability is a function of potential climate change impacts and the adaptive capacity of the system. Overall vulnerability of trees in the Austin region was estimated by considering the impacts on individual tree species using changes in heat and hardiness zone and species range limits (climate change effect column in table 3.2), together with the adaptive capacity of tree species as described in the previous section (adapt class in Tables 3.4 and 3.5) in a matrix (Table 3.6).

One hundred two species and cultivars were evaluated for their vulnerability, of which 58 were recorded as being present in the 2014 urban FIA data collection (Nowak et al., 2016). This overall approach is meant to give a coarse picture of vulnerability, and readers should consider the relative confidence in vulnerability estimates based on the level of information available.

Each species was given a separate vulnerability rating for natural areas versus planted/developed sites (Table 3.7). For natural areas, the most vulnerable species were American smoketree, bastard oak, black willow, and Texas red oak. These species make up a small proportion (less than 2 percent) of the total trees in Austin based on the recent urban FIA assessment. The least vulnerable species, making up about 11 percent of the total trees in Austin, included Texas persimmon, Texas Hercules' club (prickly-ash, tickle-tongue), lotebush, and several sumac species. Also rated as having low vulnerability were several non-native invasive species (chinaberry, paper mulberry, privet species) and species native to areas farther south (Mexican redbud, Mexican sycamore). The majority of the trees present in Austin fell into the moderately vulnerable category, in large part because Ashe juniper and cedar elm are in that category.

Many of the species rated as having high vulnerability in natural areas were also vulnerable in planted and developed sites. However, species less adapted to urban sites also were listed as highly vulnerable (e.g., post oak, black walnut, black hickory, and eastern cottonwood). In developed sites, native species considered to have low vulnerability included Texas mountain laurel, Mexican white oak, Jerusalem thorn (retama), red bay, Eve's necklace, Mexican buckeye, and Texas persimmon. Only 3% of the trees estimated to be present in Austin based on the most recent Urban FIA estimate were considered to have low vulnerability in developed areas.

Table 3.6
Vulnerability scoring matrix based on Brandt et al. (2017)

Climate Change Effect	**Adapt Class**		
	Low	Medium	High
Negative	High Vulnerability	Moderate-high Vulnerability	Moderate Vulnerability
No Effect	Moderate-high Vulnerability	Moderate Vulnerability	Low-moderate Vulnerability
Positive	Moderate Vulnerability	Low-moderate Vulnerability	Low Vulnerability

Table 3.7
Vulnerability Ratings for Natural and Developed Areas for Trees in the Austin Region. Estimated number of trees is based on 2014 Urban FIA sample (Nowak et al., 2016)

Common Name	Scientific Name	Estimated Trees Present in Austin	Vulnerability in Natural Areas	Vulnerability in Developed Areas
American elm	*Ulmus americana*	72,039	Moderate	Moderate-High
American smoketree	*Cotinus obovatus*		High	High
American sycamore	*Platanus occidentalis*	132,468	Moderate-High	Moderate-High
Anacacho orchid tree	*Bauhinia lunarioides*		Moderate	Low-Moderate
Arizona walnut	*Juglans major*		Moderate-High	Moderate-High
Arroyo sweetwood	*Myrospermum sousanum*		Low-Moderate	Low-Moderate
Ashe juniper	*Juniperus ashei*	13,315,759	Moderate	Moderate-High

Common Name	Scientific Name	Estimated Trees Present in Austin	Vulnerability in Natural Areas	Vulnerability in Developed Areas
Asian persimmon	*Diospyros kaki*		Moderate-High	Moderate-High
bald cypress	*Taxodium distichum*	12,725	Moderate-High	Moderate
bastard oak	*Quercus sinuata var. sinuata*	166,563	High	High
black hickory	*Carya texana*		Moderate-High	High
black walnut	*Juglans nigra*	105,106	Moderate-High	High
black willow	*Salix nigra*		High	High
blackjack oak	*Quercus marilandica*		Moderate	Moderate-High
boxelder	*Acer negundo*	367,930	Moderate	Moderate-High
Brazilian bluewood	*Condalia hookeri var. hookeri*		Low-Moderate	Low-Moderate
bur oak	*Quercus macrocarpa*	6,363	Moderate	Moderate
Carolina basswood	*Tilia americana var. caroliniana*		High	Moderate-High
Carolina buckthorn	*Frangula caroliniana*		Moderate-High	Moderate-High
catclaw	*Senegalia roemeriana (acacia roemeriana)*		Low-Moderate	Low-Moderate
catclaw mimosa (fragrant mimosa)	*Mimosa aculeaticarpa var. biuncifera*		Low-Moderate	Low-Moderate
cedar elm	*Ulmus crassifolia*	4,583,201	Moderate	Moderate
cherry laurel	*Prunus caroliniana*	78,107	Moderate	Moderate
Chinaberry	*Melia azedarach*	538,729	Low	Low-Moderate
Chinese elm (lacebark elm)	*Ulmus parvifolia*	78,107	Moderate	Moderate
Chinese pistache	*Pistacia chinensis*	17,322	Moderate	Moderate
Chinese privet	*Ligustrum sinense*	123,994	Low	Moderate-High
Chinese tallowtree	*Triadica sebifera*	28,029	Moderate	Moderate
chinkapin oak	*Quercus muehlenbergii*	10,959	Moderate-High	Moderate-High
chittamwood (gum bumelia)	*Sideroxylon lanuginosum*	89,955	Moderate-High	Moderate
common hoptree (wafer ash)	*Ptelea trifoliata*		Moderate-High	Moderate-High
crape myrtle	*Lagerstroemia indica*	174,401	Moderate	Moderate
desert willow	*Chilopsis linearis*		Low-Moderate	Low-Moderate
Eastern cottonwood	*Populus deltoides*	15,862	Moderate-High	High
Eastern red cedar	*Juniperus virginiana*	38,457	Moderate-High	Moderate
Eastern redbud	*Cercis canadensis*	6,248	Moderate	Moderate
edible fig	*Ficus carica*	22,984	Moderate-High	Moderate-High

Common Name	Scientific Name	Estimated Trees Present in Austin	Vulnerability in Natural Areas	Vulnerability in Developed Areas
escarpment black cherry	*Prunus serotina var. eximia*		Moderate	High
Eve's necklace	*Styphnolobium affine*		Low-Moderate	Low
evergreen sumac	*Rhus virens*		Low	Low-Moderate
fragrant sumac (skunkbush sumac)	*Rhus aromatica*		Low	Low
glossy privet	*Ligustrum lucidum*	623,890	Moderate	Moderate
goldenrain tree	*Koelreuteria paniculata*	6,363	N/A	N/A
green ash	*Fraxinus pensylvanica*	751,788	Moderate-High	Moderate-High
honey mesquite	*Prosopis glandulosa*	655,950	Low	Low-Moderate
Japanese privet	*Ligustrum japonicum*	17,322	Low	Low-Moderate
Jerusalem thorn (retama)	*Parkinsonia aculeata*	10,199	Low-Moderate	Low
lacey oak	*Quercus laceyi*		Moderate-High	Moderate
Lindheimer's silktassel	*Garrya ovata var. lindheimeri*		Low-Moderate	Low-Moderate
little walnut	*Juglans microcarpa*		Moderate-High	Moderate-High
littleleaf (goldenball leadtree)	*Leucaena retusa*		Moderate-High	Moderate-High
loquat	*Eriobotrya japonica*	312,427	Moderate	Moderate
lotebush	*Ziziphus obtusifolia*		Low	Low-Moderate
Mexican ash (berlandier ash)	*Fraxinus berlandieriana*	184,758	Low-Moderate	Low-Moderate
Mexican buckeye	*Ungnadia speciosa*		Moderate	Low
Mexican olive	*Cordia boissieri*		Low-Moderate	Moderate
Mexican plum	*Prunus mexicana*		Moderate-High	Moderate
Mexican redbud	*Cercis canadensis L. var. mexicana*		Low	Low-Moderate
Mexican sycamore	*Platanus mexicana*		Low	Low-Moderate
Mexican white oak	*Quercus polymorpha*	84,966	Low-Moderate	Low
Meyer lemon	*Citrus meyeri*		Low-Moderate	Low-Moderate
mimosa (silktree)	*Albizia julibrissin*	4,720	Moderate	High
mockernut hickory	*Carya tomentosa*		Moderate-High	Moderate-High
Montezuma cypress	*Taxodium mucronatum*		Moderate	Low-Moderate
northern hackberry	*Celtis occidentalis*	161,569	Moderate	Moderate
Osage orange	*Maclura pomifera*		Moderate	Moderate
paper mulberry	*Broussonetia papyrifera*	335,755	Low	Low-Moderate

Common Name	Scientific Name	Estimated Trees Present in Austin	Vulnerability in Natural Areas	Vulnerability in Developed Areas
pecan	*Carya illinoinensis*	196,132	Moderate-High	Moderate-High
pomegranate	*Punica granatum*		Moderate-High	Moderate
possumhaw (deciduous holly)	*Ilex decidua*		Moderate	Moderate
post oak	*Quercus stellata*	86,286	Moderate-High	High
prairie sumac (flameleaf sumac)	*Rhus lanceolata*	77,093	Low	Low
red bay	*Persea borbonia*		Low-Moderate	Low
red buckeye	*Aesculus pavia var. pavia*		Moderate	Moderate-High
red mulberry	*Morus rubra*	124,975	Moderate-High	Moderate-High
roughleaf dogwood	*Cornus drummondii*	59,882	Moderate	Moderate
rusty blackhaw	*Viburnum rufidulum*		Moderate-High	Moderate-High
Shumard oak	*Quercus shumardii*	43,137	Moderate-High	Moderate-High
slippery elm	*Ulmus rubra*	12,725	Moderate	Moderate-High
Southern live oak (coast live oak)	*Quercus virginiana*	2,862,523	Low-Moderate	Low-Moderate
Southern magnolia	*Magnolia grandiflora*	6,363	Moderate	Moderate-High
sugarberry	*Celtis laevigata*	2,058,386	Moderate	Moderate-High
sweet acacia (huisache)	*Vachellia farnesiana (acacia farnesiana)*	4,597	Moderate	Moderate
sweetgum	*Liquidambar styraciflua*		Moderate	Moderate-High
Texas ash	*Fraxinus albicans*	438,216	Moderate-High	Moderate
Texas crab apple	*Malus ioensis var. texana*		Moderate-High	Moderate
Texas Hercules' club (prickly-ash, tickle-tongue)	*Zanthoxylum hirsutum*		Low	Low-Moderate
Texas kidneywood	*Eysenhardtia texana*		Low-Moderate	Low-Moderate
Texas live oak (escarpment live oak, plateau live oak)	*Quercus fusiformis*	101,848	Moderate	Moderate-High
Texas madrone	*Arbutus xalapensis*	6,189	Moderate-High	Low-Moderate
Texas mountain laurel	*Dermatophyllum secundiflorum*	648,060	Low-Moderate	Low
Texas mulberry	*Morus microphylla*		Low-Moderate	Moderate
Texas persimmon	*Diospyros texana*	2,014,199	Low	Low-Moderate
Texas pistache	*Pistacia mexicana*		Low-Moderate	Low-Moderate
Texas red oak	*Quercus buckleyi*	419,812	High	Moderate-High
Texas redbud	*Cercis canadensis var. texensis*		Low-Moderate	Low-Moderate

Common Name	Scientific Name	Estimated Trees Present in Austin	Vulnerability in Natural Areas	Vulnerability in Developed Areas
velvet ash	*Fraxinus velutina*	59,326	Moderate-High	Moderate-High
water oak	*Quercus nigra*	4,597	Moderate	Moderate
Western soapberry	*Sapindus saponaria var. drummondii*	192,371	Moderate-High	Moderate
white mulberry	*Morus alba*	13,790	Moderate	High
white shin oak (scalybark oak)	*Quercus sinuata var. breviloba*	243,656	High	High
winged elm	*Ulmus alata*	134,185	Moderate-High	Moderate-High
yaupon	*Ilex vomitoria*	833,143	Moderate	Moderate

Summary

Results from species distribution modeling suggest that habitat suitability for many tree species found in the Austin area may shift across the region, leading to declines in some species and increases in others. Species at the southern and western extent of their range are generally projected to decline in suitable habitat. Species at the northern and eastern extent of their range or currently native to areas south could experience an increase in suitable habitat, especially in areas where there is an urban heat island effect. Factors not included in the models, such as changes in extreme events, insects, and diseases, may also affect the survival of particular trees and make them more or less adaptable to climate change–induced pressures than the species distribution models otherwise suggest. Going forward, the vulnerability of trees and the surrounding urban forest will need to be gauged based on the complex interaction of multiple stressors and benefits.

Key Points

- Modeling Native Trees: Species distribution modeling of native species suggests that suitable habitat may decrease for 14 of 31 primarily northern species and remain stable for 10 species. Suitable habitat was expected to increase for four species.
- Projected Changes from Heat and Hardiness Zone Shifts and Species Ranges: For species for which no model information is available (rare, non-native, or cultivars), shifts in heat and hardiness zones could have a positive effect on 23 species, while 60 species had either hardiness zone, heat zone, or range limits (or a combination thereof) that may suggest a negative effect.
- Adaptive Capacity of Urban Trees: Adaptive capacity of 104 species was evaluated using scoring systems for planted and natural environments, with many non-native invasive species among those with the highest capacity to adapt to a range of stressors. For planted/developed conditions, 29 species received a high adaptability score, 18 received a low adaptability score, and the remaining 57 received a medium adaptability score. For natural areas (both native and naturalized), 43 species received a high adaptability score, 13 received a low adaptability score, and 48 received a medium adaptability score.
- Overall Vulnerability of the Austin Region's Trees: An analysis of vulnerability that combines model projections, shifts in heat and hardiness zones, and adaptive capacity showed that in planted and developed sites many of the same species rated as having high vulnerability in natural areas were also vulnerable in urban areas. Species that were less adapted to urban sites were also listed as vulnerable, indicating that a greater proportion of trees were considered vulnerable in developed sites.

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CHAPTER 4

VULNERABILITY OF AUSTIN'S URBAN FOREST

This chapter focuses on the vulnerability of the urban forest in Austin's developed and natural areas to climate change. Vulnerability is the susceptibility of a system to the adverse effects of climate change (Parry, Canziani, Palutikof, Van der Linden, & Hanson, 2007). It is a function of potential climate change impacts and the adaptive capacity of the system. We consider both developed and natural urban forests to be vulnerable if they are anticipated to suffer substantial declines in health or productivity. In urban forests with a more natural composition of native species, systems are also vulnerable if climate change would fundamentally alter their composition or character (Brandt et al., 2016b). For this assessment, we defined developed urban forests as trees occurring in any areas (e.g., parks, streets, residential yards, campuses) that are classified as "developed" using the national landcover database within the city of Austin's extraterritorial boundary. We defined natural areas as those that are classified as forest or shrubland by the national landcover database within the city of Austin's extraterritorial boundary. Natural and developed urban forests were evaluated for their vulnerability using the same methods used for assessing natural ecosystems in rural areas (Brandt et al., 2016b), but social, economic, and organizational factors were weighed more heavily for developed areas due to the greater influence of and on humans (Brandt et al., 2016a, 2017; Ordonez & Duinker, 2014).

We evaluated vulnerability using two key components: impacts and adaptive capacity (Swanston et al., 2016). Climate change impacts are the direct and indirect effects of climate change on the system in question. To assess impacts, we evaluated how climate change would affect the key characteristics, dominant species, and current stressors of a system (Brandt et al., 2016b). Adaptive capacity is the ability of a species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption. For natural areas, we focused on the ecological adaptive capacity of the systems, including factors such as species and topographic diversity and connectivity. For developed areas, we also included social, economic, and organizational factors that could affect the capacity to adapt the management of the urban forest.

To assess vulnerability, we assembled a panel of experts on the ecology and management of Austin's urban forest, including developed and natural areas, for a two-day workshop. Twenty-five people attended the workshop, including representatives from the U.S. Department of Agriculture, City of Austin, Regenerative Environmental Design, The Nature Conservancy, Travis County, University of Texas at Austin, Texas A&M Forest Service, and the City of San Marcos. Participants were presented information on current trends and projected changes in climate and preliminary results from the tree species assessment. We then used a facilitated process to identify key impacts and adaptive capacity factors for three developed areas and four natural areas based on the presented climate information and expert knowledge of the ecology and management of Austin's urban trees.

Areas for evaluation were predetermined by a workshop planning team as being distinctive enough to have different ecology, management, composition, stressors, and/or climate change impacts that may make them vary in their vulnerability to climate change. The key characteristics, dominant species, and current stressors were then described by workshop participants and summarized. The group then discussed how climate change may affect key characteristics, dominant species, and stressors and what key adaptive capacity factors each area had. Participants had time to deliberate on what they perceived as the key factors contributing to that area's impacts and adaptive capacity. They were asked to rate the overall vulnerability and the amount of evidence and agreement among that evidence contributing to their rating. Ratings from each individual were then discussed to determine an overall vulnerability and confidence rating for each area. See Brandt et al. (2016b) for a more detailed description of the assessment process.

The areas in the Austin region tended to be rated in the moderate vulnerability range, indicating that there wasn't one specific area type that was more vulnerable than others (Table 4.1). However, the underlying factors that contributed to their vulnerability varied greatly. These contributing factors are summarized for each area evaluated in this chapter.

Urban Core

Moderate - High Vulnerability; Medium Agreement, Medium Evidence

Low canopy cover and high impervious surface make this area vulnerable to high temperatures and localized flooding, and the area has limited adaptive capacity due to low species diversity and lack of mature trees.

Table 4.1
Summary of Impacts, Adaptive Capacity, and Vulnerability for Areas Evaluated in the Austin Region

Developed or Natural Area	Impacts	Adaptive Capacity	Vulnerability	Evidence	Agreement
Urban Core	Moderately Disruptive	Moderate	Moderate-High	Medium	Medium
West Austin	Moderate	Moderate	Moderate	Medium	Medium
East Austin	Moderate	Moderate-High	Moderate	Medium	Medium
Floodplains and Terraces	Moderately Disruptive	Moderate-High	Moderate	Medium	Medium-High
Upland Mixed Shrubland	Moderately Disruptive	Low-Moderate	Moderate-High	Medium	Low
Upland Woodland and Savanna	Moderate	Moderate	Moderate	Limited-Medium	Low-Medium
Upland Forest	Moderately Disruptive	Moderate	Moderate-High	Medium	Low

Potential Impacts: Moderately Disruptive

Key characteristics

The urban core has a lower canopy cover (less than 30%) and higher impervious surface cover compared to the rest of Austin. Both of these factors, along with waste heat from buildings and vehicles, contribute to a more pronounced urban heat island effect in the area. Thus, the urban core is thought to be the most vulnerable to increases in temperature, especially nighttime temperatures. This area also has highly altered soils and hydrology, which can make trees more susceptible to reduced soil moisture and fertility as well as localized flooding, both of which are expected to become more pronounced under future climate conditions.

Dominant species

Species commonly found in the urban cores that may be particularly vulnerable include pecan, eastern cottonwood, post oak, American sycamore, Texas red (Buckley) oak, cedar elm, and green ash. Species that are considered the least vulnerable are Texas mountain laurel and Mexican white oak.

Stressors and threats

Damage from development and construction that is typical in the urban core can make trees more susceptible to pests, disease, and other stressors, including extreme heat and fluctuating precipitation, expected under a changing climate. Typical pests and pathogens observed in the urban core include hypoxylon, bacterial leaf scorch, oak wilt, and root decay fungi such as Armillaria. There is no current evidence that changes in temperature and precipitation projected for Austin will worsen these biological stressors although heat and drought will increase tree stress which will make trees more vulnerable to opportunistic pests and diseases. Trees in the urban core that were not planted at the correct depth or with insufficient rooting space may also be susceptible to anticipated climate changes.

Adaptive Capacity: Moderate

Trees in the urban core tend to be short-lived, and thus there are more small, young trees with less-established root systems that may be more vulnerable to precipitation extremes. Because only a few species are tolerant of the harsh urban conditions, species and genetic diversity tends to be lower than in other parts of Austin. However, the trees that are planted tend to be relatively resilient to a variety of stressors including heat and drought. The urban core tends to have high investment of resources per tree and high visibility, which enables early detection, treatment, and replacement of trees when problems arise.

West Austin

Moderate Vulnerability; Medium Agreement, Medium Evidence

High canopy cover and moderate biodiversity can help protect this area from extreme heat and losses of productivity, but its position in the wildland-urban interface may make it susceptible to future wildfire in some areas if best management practices are not maintained.

Impacts: Moderate

Key characteristics

West Austin tends to have higher canopy cover (exceeding 50% on average) than other developed parts of the Austin area. This higher canopy cover helps keep the area cooler, more humid, and protected from wind. This area was developed on upland, thin limestone soils over karst, which can make it susceptible to erosion and can sometimes

Colorado River in Downtown Austin. Photo courtesy of April Rose, City of Austin.

make the establishment of new trees difficult. Much of this area is in the wildland urban interface (WUI). Although fires are rare in closed canopy juniper-oak forests (White, 2009; Miller et al., 2017), increases in tree mortality, heat, and drought could make it more susceptible to wildfire in the future.

Dominant species

Ashe juniper is the most dominant species in West Austin, making up 68% of the trees there, and is considered to be moderately vulnerable. Several species of oak are also common, with varying levels of vulnerability. Other moderately to highly vulnerable species common in West Austin include pecan, cedar elm, and velvet ash. Species common to West Austin that are considered most adaptable include yaupon, Eve's necklace, and Texas mountain laurel.

Current stressors

The position of West Austin in the WUI exposes the area to both human and ecological stressors. Development and landscaping practices such as overuse of fertilizer or improper irrigation practices can stress trees and make them more vulnerable to the direct and indirect effects of climate change. Feral hogs, deer, and other wildlife can also disrupt vegetation through activities such as rooting and browsing. It is unclear how these wildlife species may be affected by changes in temperature and precipitation, but the stress they place on vegetation and soil can make the area more susceptible to mortality and erosion. In addition, concerns about wildfire risk can lead people to clear vegetation around their properties, reducing tree cover.

Adaptive Capacity: Moderate

Although Ashe juniper dominates in this area, there is a considerable richness of other species (both planted and naturally occurring). There also tends to be moderate genetic diversity and high diversity of tree sizes and ages. West Austin is dominated by higher-income owner-occupied households. Thus, there is a relatively high capacity for people to care for and replace stressed trees if they are informed of best practices. There are also some restrictions on development in this area, which could help maintain its tree canopy. Because this area is already heavily forested, there may be reduced need to enhance canopy or biodiversity from current levels.

East Austin

Moderate Vulnerability; Medium Evidence, Medium Agreement

Although this area has a lower tree canopy than west Austin, a rich diversity of planted trees that are adapted to hot, dry climates may help the urban forest withstand increases in temperature and drought.

West Austin landscape. Photo courtesy of Wendy Gordon, Climate Action Texas.

Impacts: Moderate

Key characteristics

East Austin was developed on an area that was historically prairie, and thus tree canopy tends to be much lower than West Austin (25% or less). Impervious cover is higher than West Austin but less than the urban core. This area is flatter and dominated by soils with higher clay content, which can make them susceptible to shrink-swell from changes in moisture, a phenomenon that is expected to become more pronounced as precipitation becomes more variable. However, the position in a floodplain and on former prairie contributes to a deep layer of soil rich in organic matter, which could help reduce drought vulnerability. Parts of this area are in a floodplain and are vulnerable to increased flashiness and severity of flooding associated with increased heavy rain events. This area interfaces with agricultural and rangelands, which could make it susceptible to grass fires during hot, dry periods and agriculture runoff during periods of heavy rain.

Dominant species

East Austin has a wide variety of species, although Ashe juniper is still the most common species. Species considered particularly vulnerable in the area are pecan, black walnut, eastern cottonwood, post oak, and black willow. Species that are considered less vulnerable include southern live oak, yaupon, Mexican white oak, Texas mountain laurel, Jerusalem thorn (retama), Texas persimmon, honey mesquite, and Mexican sycamore.

Stressors and threats

This area has experienced a history of environmental injustice, which has led to local pollution of the soil, water, and air from industries such as the Holly St. Power Plant .This area is experiencing rapid development, which could further reduce canopy cover and increase the urban heat island effect and interact with current and projected temperature increases from climate change to increase temperatures at a more rapid rate.

Adaptive Capacity: Moderate

Because this was formerly prairie, there are more tree species that were not historically present in the area. The range of species that was planted in East Austin tends to be diverse, with a greater number of species adapted to hot, dry conditions than what is found in West Austin. Trees common in floodplains are also widely present and may be more able to withstand increases in flooding. Housing lots tend to be smaller and average income is lower than in West Austin, limiting the resources that can be allocated to tree care and planting but also reducing the number of trees each resident needs to care for. There is currently more opportunity to increase tree canopy and open space conservation, but also risks associated with increased development.

East Austin neighborhood. Photo by Leslie Brandt USDA Forest Service.

Floodplains and Terraces

Moderate Vulnerability; Medium Evidence, Medium-High Agreement

These areas are vulnerable to increased flashiness from heavy rain events and are susceptible to non-native invasive species, but high biodiversity and connectivity along with extensive management enhances their adaptive capacity.

Impacts: Moderately Disruptive

Key characteristics

These systems include forests in large alluvial floodplains along the Colorado River and its tributaries with bottomland soils influenced by outwash from the surrounding landscape. They are also riparian forests along smaller streams that tend to have more gravelly erosional soils along steep slopes. In both areas, flood regime tends to be the dominant driver of species composition and structure. These areas could be extremely vulnerable to increased flashiness from periods of extremely high rain followed by periods of drought.

Dominant species

Because these areas receive frequent flooding, common species intolerant of flooding may be particularly vulnerable, such as roughleaf dogwood, Texas red (Buckley) oak, Texas/escarpment live oak, and Ashe juniper. In addition, some flood-adapted species may not be able to withstand higher temperatures, such as sugarberry, possumhaw, Chinese tallowtree, boxelder, American elm, black willow, green ash, American sycamore, eastern cottonwood, and western soapberry. Species common in floodplains and low terraces that may be most adaptable to both increased temperature and flooding are desert willow, yaupon, and the non-native invasive Chinaberry.

Stressors and threats

This area is susceptible to invasion by non-native woody species (Chinaberry, Chinese tallow, glossy privet) and grasses (bermudagrass, King Ranch bluestem, Johnsongrass, arundo). These non-native invasive species may be able to take advantage of increased disturbed area from flash floods and erosion and colonize new areas. Hydrology of many of these areas has been altered through structures such as dams and reservoirs, making the systems less adapted to natural flood regimes. In some areas, a lack of tree seed sources, among other factors, has converted some riparian and floodplain forests to herbaceous plant community types. This type of conversion could become more common if tree seedling recruitment and survival are reduced with higher temperatures and altered flood regimes.

Adaptive Capacity: Moderate-High

Riparian and floodplain forests tend to have a high species diversity and connectivity to enable gene flow and species migration. In the alluvial floodplains, soils tend to be deep and more resilient to changes in moisture. Erosional, rocky areas may be more susceptible to soil moisture extremes. The species present in these areas tend to be well adapted to flooding. There is also high community support for restoration of riparian and floodplain forests.

Riparian area along the Colorado River in East Austin. Photo by Leslie Brandt USDA Forest Service.

Upland Mixed Shrubland

Moderate-High Vulnerability; Medium Evidence, Low Agreement

Shrubs and grasses in these systems are tolerant of hot, dry conditions, but these areas are heavily fragmented and exist on dry, shallow soils and are thus at risk for conversion to grassland or desert.

Impacts: Moderately Disruptive

Key characteristics

Shrublands tend to occur on more xeric sites with shallow soils. These areas were historically cleared and/or burned due to anthropogenic or natural causes. Due to the shallow soils, trees do not dominate the canopy and tend to be stunted. With grasses interspersed among the shrubs, these areas tend to be higher risk for wildfire (White 2009). Although climate change could potentially increase conditions for wildfire, there may be fewer opportunities for prescribed fire. Grazing and browsing also shape this system.

Dominant species

Many of the dominant species are adapted to hot, dry conditions including prairie flameleaf and evergreen sumac, lotebush, honey mesquite, Texas persimmon, Texas mountain-laurel, Lindheimer's silktassel, and catclaw acacia. However, Ashe juniper, Texas/escarpment live oak, and white shin oak are all expected to be somewhat vulnerable to increases in temperature. Texas kidneywood and Mexican buckeye are considered less drought-tolerant. It is also important to note that even some drought-tolerant species like Texas persimmon suffered negative effects during the most recent 2011 drought, and thus even seemingly drought-tolerant species may be vulnerable to extreme and exceptional droughts.

Stressors and threats

Shrublands are threatened primarily from loss of habitat and fragmentation as well as altered disturbance regimes (lack of fire, overgrazing/browsing). Overgrazing/browsing may Fragmentation may decrease the ability of shrubland species to colonize newly suitable habitat. Altered disturbance regimes have led to a reduction in species diversity and loss of dominance of some species that may be better adapted to warmer conditions. As herbivores prefer deciduous trees, they are selectively removed, leading to the dominance of evergreens such as Ashe juniper, one species that is relatively vulnerable to climate change. Feral hogs are also highly disruptive to these systems, and their rooting activities could increase the vulnerability of soil to erosion and loss with increased heavy rain events.

Adaptive Capacity: Low-Moderate

Shrublands are typically adapted to hot, dry conditions that may be more common in the coming decades. However, biodiversity is relatively low compared to other habitat types. These tend to be located on very dry, rocky sites, where conditions may become so severe that few species can tolerate them, potentially shifting the structure to a grassland or desert. Because many shrublands provide habitat for the black-capped vireo (Vireo atricapilla), which was formerly listed as endangered but delisted in 2018 based in part on the ongoing habitat management programs for this species, efforts to maintain these shrublands are expected to continue.

Upland Woodland and Savanna

Moderate Vulnerability; Limited-Medium Evidence, Low-Medium Agreement

These systems are relatively tolerant of hot, dry conditions, but extreme heat and drought may limit regeneration of oak trees, making them vulnerable to loss of canopy in the long-term.

Impacts: Moderate

Key characteristics

Woodlands and savannas are characterized as having low-moderate tree canopy cover but still retain large canopy trees as part of their structure. Soil types and topography can vary between woodlands and savannas in East Austin (Blackland Prairie) and West Austin on the Edwards Plateau. Soils tend to be deeper in the Blackland Prairie and shallower and more susceptible to drought on the Edwards Plateau. These systems are historically adapted to fire but are now maintained through management using tools such as prescribed fire. Conditions for wildfire may increase, but opportunities for prescribed fire may decrease, limiting the opportunity to maintain this community type. Because these areas have less canopy cover, they are more vulnerable to heat and evaporative losses.

Dominant species

Most species dominant in woodlands and savannas are considered drought-tolerant. Cedar elm, sugarberry, and oak species like blackjack, Shumard, white shin, escarpment, and post oak are considered drought-tolerant but are vulnerable to increases in temperature, whereas southern live oak may be able to withstand temperature increases but is not drought-tolerant. Adaptable species include yaupon, fragrant and evergreen sumac, Texas persimmon, honey mesquite, catclaw mimosa, and Texas mountain laurel.

Stressors and threats

These systems are threatened by altered fire regimes, overgrazing, and loss of habitat. In the east, these systems may be particularly vulnerable to development. Oak wilt has led to declines in oaks in the area. Although there is no clear link between changes in climate and oak wilt, the pathogen coupled with heat and drought stress could lead to increased oak mortality. Woodlands and savannas in lower-lying areas may also be susceptible to increased flood risk.

Upland mixed shrubland at the Vireo Preserve, Austin. Photo courtesy of Annamarie Rutledge.

Savanna at McKinney Falls State Park. Photo courtesy of April Rose, City of Austin.

Adaptive Capacity: Moderate

These systems tend to have low taxonomic diversity as they are typically dominated by just a few oak species in the canopy. Based on ongoing studies of oak regeneration, the City of Austin has found that shade during hot summer months is critical for seedling survival of white shin oak (O'Donnell et al. 2020), Texas red oak, and escarpment plateau live oak (unpublished data). Thus, replacement of existing canopy trees could decline over time. These systems are adapted to fire and drought, which both could become more common with projected changes in climate. However, lack of opportunities for prescribed fire and extreme drought or wet conditions could be detrimental to these systems. In addition, severe fires could exceed the tolerance of many of the dominant species.

Upland Forest

Moderate-High Vulnerability; Medium Evidence, Medium Agreement

These systems have a higher number of vulnerable species, but high canopy cover along with topographic and species diversity may help protect these systems from extreme losses.

Impacts: Moderately Disruptive

Key characteristics

Upland forests in Austin are concentrated on steep slopes and plateaus on the Edwards Plateau. South-facing slopes and areas with more shallow soil may be more vulnerable to drought stress and mortality as temperatures increase, whereas north-facing slopes and areas with deeper soils may be more protected. The structure and composition of these forests have made them historically resistant to fire. However, fire risk could increase in these areas if future climate conditions lead to tree mortality (from drought, pests and disease, or storms) and a subsequent increase in fuels. By definition, canopy cover in forests is high, which may help buffer some climate change effects. For example, higher canopy cover can help create cooler microclimates through shading and evapotranspiration. Upland forests are composed of a mix of evergreen and deciduous species, and sites that are completely deciduous tend to be more mesic and less vulnerable to drought.

Dominant species

Many of the dominant upland forest species are susceptible to drought and/or heat-based mortality. Species that are considered the most vulnerable include Texas red (Buckley) oak, white shin oak, and Arizona walnut. Moderately vulnerable species include Carolina buckthorn, Ashe juniper, Texas/escarpment live oak, post oak, gum bumelia, escarpment black cherry, and red buckeye. Species that may be the most adaptable are evergreen and fragrant sumac, Texas persimmon, Texas madrone, and Texas mountain laurel.

Stressors and threats

Upland forests in Austin are located in the wildland urban interface (WUI), which makes them vulnerable to non-native species invasion and human-ignited fires as well as development pressure. Non-native woody species like Chinaberry and glossy privet could benefit from newly created habitat post-disturbance. Human-ignited fires could become more problematic as warmer, and possibly drier, conditions that are favorable for the spread of wildfire become more common. Development, when it occurs, can lead to increased soil erosion and a lowered water table with a concomitant loss of vegetation.

Adaptive Capacity: Medium

Upland forests tend to have greater native species and topographic diversity and larger patch sizes than other natural areas in Austin, all of which could help enhance their adaptive capacity. The evergreen canopy can sequester carbon year-round, and soils under the tree canopy are rich in organic matter. Thick organic soil layers in some locations can help capture large quantities of rainfall and help reduce vulnerability to drought and fire. Mycorrhizal networks tend to be abundant, which can facilitate nutrient uptake and sharing of resources. A large seedbank of native species in the soil could help these systems resist non-native species invasion and ensure that some native species are able to continue to grow and regenerate. Despite these factors that enhance capacity, these systems are also located at the WUI, which could increase future fragmentation and wildfire risk and reduce capacity for expansion to newly suitable areas.

Key Points

- Both natural and developed areas in the Austin region show some degree of vulnerability to changes in climate.
- Natural and developed upland areas in West Austin are vulnerable to drought, erosion, and wildfire and have less tree canopy diversity than East Austin.
- Natural and developed areas in East Austin are vulnerable to shrink-swell from precipitation changes and flooding due to their presence at lower elevations but have a greater potential for a diverse tree canopy than West Austin.
- The urban core and other highly developed areas will experience stress not only from changes in climate but also from compounding effects of drought, heat, and local flooding from restricted soil conditions and impervious surfaces.

Upland Forest at Reicher Canyon. Photo courtesy of Bill Riemer, City of Austin.

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CHAPTER 5

MANAGEMENT CONSIDERATIONS

A changing climate presents both challenges and opportunities for urban forest management. Increases in temperature, drought, and extreme precipitation events may impact tree species planting lists and current management of existing trees—both native and non-native species—as well as alter public outreach and engagement efforts. This chapter provides an overview of climate change impacts on management decisions and practices related to urban and community forestry in the Austin region. This chapter does not make recommendations as to how management should be adjusted to account for these changes. A separate document, Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers, 2nd edition (Swanston et al., 2016), has been developed to assist forest managers in a decision-making process to adapt their land management to projected impacts. Management considerations in this chapter are summarized by theme and include a range of issues that urban foresters face. These themes, along with their descriptions, are not meant to be comprehensive. Instead, they provide a jumping-off point for thinking about the management implications of climate change in an urban setting. The More Information sections located throughout the chapter provide links to key resources for urban forestry professionals about the impacts of climate change on that theme.

Natural Areas

Natural areas in the Austin region will be impacted by a changing climate. The growing season is expected to become nearly year-round, and the heat tolerance zone is expected to shift from 9 to 11 or 12 by the year 2100. Increases in temperature paired with extended growing seasons will likely benefit many non-native invasive species, increase evapotranspiration, and increase plant stress. Management objectives may include preserving and improving habitat for endangered species, increasing soil stability, managing pests and non-native invasive species, and maintaining healthy forests and species diversity. These objectives will be met with challenges such as changes to phenology and survivorship, difficulty establishing some native species, and increases in heat, drought, and flooding.

Prescribed burns are used as a management tool in some ecosystems. An increase in temperatures and drought stress may result in fewer possible days to conduct prescribed burns. Higher temperatures and lower humidity could create more "red flag days" where burning is restricted. While a lengthened growing season may increase the vegetative fuel load, heavy rain events may reduce the number of days when burning is possible. Prescribed burns could also potentially exacerbate aridification of some systems in a warming climate.

Preserving oak and juniper woodlands may become more challenging on some sites due to changes in habitat suitability for dominant species along with other climate-related stressors. A distinct challenge will be management in juniper-oak karst ecosystems in the Edwards Plateau, where there are shallower soils and reduced soil moisture compared to the east side of Austin.

Projected changes in climate suggest there may be mortality of some drought-intolerant species, shifts toward more arid conditions, and increases in drought-tolerant species. Current management is focused on promoting mesic regimes through soil restoration and increasing shading to help counter increasingly dry conditions. Additional strategies that could be employed to overcome these challenges may include installing weather stations for real-time monitoring, reforesting degraded landscapes, restoring karst ecosystems, promoting pollinator habitat and connectivity with other forests, composting or mulching dead biomass of non-native invasive plants in situ, promoting land stewardship, increasing native plant and structural diversity, protecting native seed banks, removing non-native invasive species, and ongoing research and monitoring.

More Information

- The Balcones Canyonlands Preserve is a multi-agency conservation effort focused on wildlife habitat restoration: www.austintexas.gov/bcp
- The Community Wildfire Protection Plan includes information about prescribed burning and other vegetation management strategies: www.austintexas.gov/page/austintravis-county-community-wildfire-protection-plan

Street Trees

As temperature increases associated with climate change exacerbate urban heat island effects, street trees will take on increased importance to the communities that live within these areas. Species selected will need to withstand climate-related stressors such as drought, extreme precipitation, and pest and disease outbreaks. Areas that lack diversity in species or age classes may be more vulnerable to climate change impacts and may increase the vulnerability of residents living within these areas to heat-related illness and other negative health outcomes. Common goals for street tree managers include diversifying species planted, increasing and maintaining canopy cover, supporting urban forest health through best practices, and providing up-to-date decision-making information for the public. These goals can be met by promoting tree planting and maintenance along the public right of way, developing a proactive inspection and maintenance program, and regularly updating the tree planting lists and public engagement materials. Tree planting lists may be based on the available nursery stock (see Nursery Industry section), and these lists may need to be updated according to projections of future conditions. There will always be some uncertainty concerning which species to recommend and plant. However, there will be an opportunity to introduce new species that are more heat- and drought-tolerant and create materials to engage residents in planting recommended tree species on their property.

More Information

- TreeFolks provides tree education, programs, and resources such as neighborhood tree adoption events in Central Texas: www.treefolks.org/

Municipal Parks

Municipal parks, found in developed as well as more natural areas, provide active and passive recreational opportunities while simultaneously reducing the urban heat island effect. These parks face similar climate change challenges and management considerations to those of natural areas and street trees. Increases in heat may attract more visitors who want to utilize the shade and water features of municipal parks. Projected increases in extreme precipitation events could result in flooding of parks, leading to a reduction in park use or availability. As park use shifts in response to a changing climate, planting and stormwater management decisions may shift as well.

More Information

- Austin Parks Foundation is a local nonprofit that advocates for Austin's parks, and supports park adoption groups that steward their local parks: austinparks.org
- "How Cities Use Parks for Climate Change Management" discusses the benefits city parks provide, such as storing carbon and reducing the urban heat island effect: www.planning.org/publications/document/9148693

Wildlife

Austin strives for a balanced, healthy, urban environment for both people and wildlife including various birds, reptiles, mammals, amphibians, and invertebrates. Wildlife habitat is an essential benefit provided by urban trees and natural areas, but climate change poses significant risks. Shifts in the phenological patterns of trees and the spread of non-native invasive species may reduce the capacity of Austin's trees and urban forests to provide wildlife habitat. Changing climate trends will decrease habitat for some species of wildlife and increase habitat for others.

The phenological patterns of trees, such as spring leaf out, flowering, fruiting, and leaf drop, are expected to be affected by climate change (Lipton et al., 2018). Many animals use environmental cues for migration, hibernation, or reproduction. The degree to which different species will be affected by shifts in resource availability will vary based on their level of specialization as well as life history traits. However, there is an emerging trend: The rate of phenological change varies between trophic levels, causing resource mismatches and altered species interactions (Lipton et al., 2018). Migratory species, common in Austin, are more vulnerable to phenological mismatch if their primary food sources are unavailable when they migrate to their feeding grounds or if they are unable to shift to other sources (Lipton et al., 2018).

More Information

- Wildlife Austin promotes wildlife habitat creation and conservation through community collaboration and public education: austintexas.gov/wildlifeatx
- The National Audubon Society has interactive visualizers to view the projected impacts of climate change on bird populations: www.audubon.org/climate/survivalbydegrees
- The National Phenology Network has tons of resources for analyzing phenological change and for participating in monitoring activities: www.usanpn.org

Species Diversity

One of the primary management challenges for urban foresters will be maintaining and increasing diversity of native and cultivated tree species. As suitable habitat declines for some species, new species adapted to current and future climate may be introduced. The introduction of new species, often called "assisted migration" can create new risks, however. These species may suffer mortality if a cold snap occurs or if they are unable to adapt to the area's soils or moisture regimes. If they do survive, they could outcompete native species, alter wildlife and pollinator habitat, or potentially introduce novel pests or diseases.

Regeneration techniques that promote genetic diversity of native trees may also need to be expanded, especially in natural areas. There are also the challenges of promoting a diverse age structure if it becomes harder to establish young trees or mortality of older trees increases. Finally, the spread of non-native invasive species in a changing climate could lead to losses of native species, altering existing ecological communities and the composition of Austin's tree canopy.

More Information

- The Texas Natural Diversity Database provides information on rare species, native plant communities, and animal aggregations: tpwd.texas.gov/huntwild/wild/wildlife_diversity/txndd/
- The US Forest Service Climate Change Resource Center Assisted Migration topic page, provides information and tools related to assisted migration: www.fs.usda.gov/ccrc/topics/assisted-migration

Nursery Industry

With projected changes in habitat suitability and shifts in heat and hardiness zones, land managers and homeowners may want to select species expected to be less vulnerable to these changes. However, species selection will be largely dependent upon nursery stock available. Small, local nurseries often rely on large, wholesale nurseries for their supply. Wholesalers can be located in different regions of the country and may not be familiar with local needs. Economic incentives for nursery growers such as contract growing may encourage the production of new species or cultivars. However, uncertainty among climate model projections as well as the financial risks tied to expanding the diversity of species offered for changing conditions—for instance, anticipating when and where those new markets are—will pose challenges. As a result, nursery growers may choose to develop cultivars adapted to a wide range of climate conditions rather than niche plants. As an alternative, managers in Austin will have the option of collecting seed or transplants from other geographic areas in the southwest adapted to the expected changes in climate. This can be a costly and time-consuming endeavor, however, and may not be feasible for some organizations.

More Information

- "Native Tree Growing Guide for Central Texas" contains information about what, when, and where to plant native tree species as well as a tree selection chart: www.austintexas.gov/sites/default/files/files/Watershed/growgreen/2_8_12_native_tree_growing_guide_for_central_texas.pdf
- "Texas Tree Planting Guide" provides a tree species database outlining tree details such as water needs, tolerances, and problems: texastreeplanting.tamu.edu/ViewAllTrees.aspx?let=O
- "Native Plant Information Network" provides a database of plant information including cultural requirements, wildlife associations, and nursery availability: www.wildflower.org/plants-main
- Texas Nursery and Landscape Association is the membership organization that supports the Texas plant growers and nursery industry: www.tnlaonline.org

Private Properties

Larger private properties such as golf courses, cemeteries, college and corporate campuses, and commercial and industrial holdings will also be subject to the stressors of a changing climate. Changes in habitat suitability will impact which trees and other plants can be grown on their land. Green infrastructure incorporated into these locations, such as green roofs or rain gardens, may also need to be reconsidered in light of changing temperature and precipitation regimes. For example, rain gardens may need to be designed to absorb more precipitation, and green roofs may need to withstand higher temperatures than they had in the past. Development pressures may also decrease the amount of urban green space and put an increased demand on existing trees and spaces to provide essential ecosystem services.

Homeowners and renters often lack the expert knowledge, skills, and resources to manage trees on their property in relation to a changing climate. With an increase in temperature, trees will provide more value to residential properties by supplying cooling and shade, therefore reducing energy costs. Educating the public will be important to ensure that they are providing adequate care for their existing tree canopy, are planting species expected to survive in the projected climate, and are adequately managing invasive species, pests, and pathogens. Training and assistance may be needed to support homeowners and renters in their tree species selection and tree care and maintenance efforts.

More Information

- The City of Austin provides tree care resources to help plan for, care for, and preserve trees on your property: austintexas.gov/department/tree-resources
- Travis County AgriLife Extension, and their Master Gardener program, provides free education and outreach about trees and plants: travis-tx.tamu.edu/horticulture/

- The City of Austin has a variety of rebates to promote green infrastructure improvements including rain cisterns, and rain gardens: www.austintexas.gov/department/rebates-free-stuff-grants
- "The Climate-Friendly Gardener: A Guide to Combating Global Warming from the Ground Up" gives practical tips for cultivating a climate-friendly garden to help reduce climate change impacts: www.ucsusa.org/resources/climate-friendly-gardener

Landscaping Features and Green Infrastructure

Green infrastructure can range from site design approaches (e.g., rain gardens and green roofs) to regional planning approaches (e.g., land conservation and urban tree canopy) (U.S. Environmental Protection Agency, 2019). As part of the Imagine Austin Comprehensive Plan, one of the city's priorities is to "use green infrastructure to protect environmentally sensitive areas and integrate nature into the city" (City of Austin, 2012). A goal of this priority program is to manage Austin's urban and natural ecosystems by increasing environmental protection, improving tree cover, improving the watershed, increasing access to parks, and linking resources in the city. This program was organized into three groups: open space acquisition, regulatory policy, and public lands management.

Faced with a changing climate, green infrastructure may increase in importance while also requiring new approaches to adapt, such as berms, mulching, bioswales, and refugia. By reducing the rate of surface runoff, berms can help with erosion control and sedimentation, while mulching techniques can help retain soil moisture, contribute to soil health, and protect against temperature changes. Bioswales can assist with improving water quality, reducing flood potential, and moving stormwater away from critical infrastructure. Identifying and creating refugia within specific ecological communities can protect against climate-related disturbances such as heat, wildfires, and flooding. Recognizing which features and where to employ them will be an ongoing land management component for urban foresters.

More Information

- Climate Vulnerability in Austin, A multi-risk assessment. This report shows the which communities in Austin are most at risk to wildfire, flooding and heat: www.austinindicators.org/wp-content/uploads/2020/02/Austin-Climate-Vulnerability-Report_Bixler-and-Yang-2020.pdf
- The City of Austin provides additional information about programs and resources on green roofs, rain gardens, and landscaping design: www.austintexas.gov/department/green-roofs, www.austintexas.gov/department/rain-gardens-keeping-water-land, www.austintexas.gov/landscapedesign
- The City of Austin highlights six green strategies to reduce the urban heat island effect: www.austintexas.gov/urban-heat

Equity and Environmental Justice

Climate change adaptation practices can offer opportunities to improve quality of life, but practitioners will also need to be sensitive to how these practices may inadvertently benefit some individuals and communities over others. Low-income and communities of color are expected to be more adversely affected by climate change than other populations because they are often living in areas with lower canopy cover and older infrastructure that is more vulnerable to failure. Climate change is a social, scientific, economic, political, historical, and equity issue. When thinking about activities to increase canopy cover or incorporate green infrastructure, urban foresters may need to consider historical issues of racial segregation and environmental effects on disparate populations in Austin (City of Austin, 2019).

More Information

- The City of Austin launched a Community Climate Ambassadors program to engage with members of Austin's diverse community on climate topics: www.austintexas.gov/climateambassadors

Planning and Partnerships

Climate change will remain an important component of planning as new challenges are created by droughts, flooding, wildfires, pests, pathogens, non-native invasive species, runoff, soil erosion, tree mortality, and shifting vegetation. Austin already has made great progress in planning for climate change and a strong tree canopy through its Community Climate Plan and Urban Forest Plan. Work to integrate climate change considerations into all aspects of planning and updating plans as new information becomes available can help the city prepare in the long term. Regional and state-wide efforts to address climate change and the urban tree canopy are areas of potential growth to address these challenges beyond municipal boundaries.

Climate change puts pressure on limited resources, elevating the importance of partnerships. Creating partnerships and working groups to coordinate large, regional planning efforts can enhance climate adaptation progress and increase landscape connectivity through strategic land acquisitions and restoration. Volunteer-based organizations may provide assistance with the planting and care of trees in cities, parks, and natural areas. For example, Austin has a long-standing and robust relationship with Tree Folks. Land managers may also work with utility companies to create educational programs and rebates to retain tree canopy. Lastly, collaborating with others to expand public outreach to diverse audiences may also help with challenges such as oak wilt and wildfire prevention.

More Information

- Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers, 2nd edition, is a tool that can assist in incorporating climate change considerations into planning: www.nrs.fs.fed.us/pubs/52760
- The Austin Community Climate Plan is a resource for understanding how engaged individuals within the community fit into plans, policies, and strategies for carbon neutrality: austintexas.gov/sites/default/files/files/Sustainability/FINAL_-_OOS_AustinClimatePlan_061015.pdf
- The City of Austin's Urban Forest Plan provides a master plan for parks, natural areas, residential yards, green spaces, and street trees: www.austintexas.gov/sites/default/files/files/Parks/Forestry/AUFP_Final_DRAFT_01-07-14_No_Appendices.pdf

Summary

A changing climate can have significant impacts on the management of urban forests in developed and natural areas in the Austin region. Maintaining species diversity and selecting appropriate species for the projected changes in habitat suitability will become more of a challenge for everyone, from land managers to the nursery industry. Increased short-term financial investments may be needed for the development of landscaping materials and restoration practices that will help maintain the urban forest in the long term. Climate change challenges will also present opportunities for land managers and other decision-makers to further engage with their communities, develop new partnerships and programs, expand their volunteer base, and make investments in resilient landscapes.

Key Points

- Maintaining species diversity and selecting appropriate species for the projected changes in habitat suitability will become more of a challenge for everyone, from land managers to the nursery industry.
- Given the uncertainties around the effects of climate change it will be important for land managers to continue to observe and document impacts on tree species and refine models and management strategies.
- Climate change challenges will also present opportunities for land managers and other decision-makers to further engage with their communities, develop new partnerships and programs, expand their volunteer base, and make investments in resilient landscapes.

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GLOSSARY OF TERMS

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 as a result of previous policy, planning, or design decisions.

alluvial a fine-grained fertile soil deposited by water flowing over flood plains or in riverbeds

aquifer an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt)

atmospheric deposition the process whereby precipitation (rain, snow, fog), particles, aerosols, and gases move from the atmosphere to the earth's surface

berm a narrow shelf, path, or ledge typically at the top or bottom of a slope

bioswales linear channels designed to concentrate and convey stormwater runoff while removing debris and pollution

channelization a method of river engineering that widens or deepens rivers to increase the capacity for flow volume at specific sections of the river

climate normal the arithmetic mean of a climatological element computed over three consecutive decades.

cultivar a plant variety that has been produced in cultivation by selective breeding

crown dieback recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds toward the trunk

emissions scenario a plausible representation of the future development of emissions of greenhouse gases and aerosols that are potentially radiatively active, based on certain demographic, technological, or environmental developments.

evapotranspiration the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants

flashiness sensitivity to a rapid increase in flow shortly after onset of a precipitation event, and an equally rapid return to base conditions shortly after the end of the precipitation event

forb an herbaceous flowering plant other than a grass

fragmentation the process during which a large expanse of habitat is transformed into a number of smaller patches of smaller total area isolated from each other by a matrix of habitats unlike the original

fungal mat a dense aggregation of fungal hyphae

hardiness zone a geographically defined area in which a specific category of plant life is capable of growing, defined by the average annual winter minimum temperature.

heat zone a geographically defined area in which a specific category of plant life is capable of growing, defined by the number of days above 86 degrees Fahrenheit.

impact the direct and indirect consequences of climate change on systems, particularly those that would occur without adaptation

importance value an index of the relative abundance of a species in a given community (0 = least abundant, 50 = most abundant)

karst landscape underlain by limestone which has been eroded by dissolution, producing ridges, towers, fissures, sinkholes and other characteristic landforms

mesic (of an environment or habitat) containing a moderate amount of moisture

microclimate the climate of a very small or restricted area, especially when this differs from the climate of the surrounding area.

mycorrhizal pertaining to the symbiotic association between a fungus and a plant

neotropical relating to, or constituting the tropical New World biogeographic region that extends south, east, and west from the central plateau of Mexico

overstory the uppermost layer of foliage in a forest, forming the canopy

parent material the underlying geological material (generally bedrock or a superficial or drift deposit) in which soil horizons form

phenology the study of the timing of the biological events in plants and animals

refugia areas in which a population of organisms can survive through a period of unfavorable conditions

Representative Concentration Pathway (RCP) a greenhouse gas concentration (not emissions) trajectory adopted by the Intergovernmental Panel on Climate Change for its fifth Assessment Report in 2014

riparian relating to or situated on the banks of a river

seedbank the natural storage of seeds, often dormant, within the soil of most ecosystems

taxonomic relating to the classification of organisms into groups based on shared characteristics and genetics

terrace an earthen embankment, ridge or ridge-and-channel built across a slope to slow water runoff, therefore reducing soil erosion and phosphorus loss

trophic level the position an organism occupies in a food web

understory a layer of vegetation beneath the main canopy of a forest

urban heat island an urban area that is significantly warmer than its surrounding rural areas due to human activities.

urban infill the rededication of land in an urban environment, usually open space, to new construction

vulnerability the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the impacts and adaptive capacity of a system

water table the upper level of an underground surface in which the soil or rocks are permanently saturated with water

wildland-urban interface the zone of transition between wildland and human development

xeric of an environment containing little moisture; very dry

LIST OF SPECIES NAMES

Common Name	Scientific Name
agarita	*Berberis trifoliolata*
American beautyberry	*Callicarpa americana*
American elm	*Ulmus americana*
American smoketree	*Cotinus obovatus*
American sycamore	*Platanus occidentalis*
American sycamore	*Platanus occidentalis*
anacacho orchid tree	*Bauhinia lunarioides*
anacua	*Ehretia anacua*
Arizona ash	*Fraxinus velutina*
Arizona walnut	*Juglans major*
arroyo sweetwood	*Myrospernum sousanum*
arundo	*Arundo donax*
Ashe juniper	*Juniperus ashei*
Asian persimmon	*Diospyros kaki*
bald cypress	*Taxodium distichum*
bastard oak (white shin)	*Quercus sinuata var. breviloba*
bermudagrass	*Cynodon dactylon*
big bluestem	*Andropogon gerardi*
bigtooth maple	*Acer grandidentatum*
bitternut hickory	*Carya cordiformis*
black cherry	*Prunus serotina*
black hickory	*Carya texana*
black oak	*Quercus velutina*
black walnut	*Juglans nigra*
black willow	*Salix nigra*
blackjack oak	*Quercus marilandica*
boxelder	*Acer negundo*
Brazilian bluewood	*Condalia hookeri var. hookeri*
bur oak	*Quercus macrocarpa*
Carolina basswood	*Tilia americana var. caroliniana*
Carolina buckthorn	*Frangula caroliniana*
catalpa	*Catalpa speciose*
catclaw	*Senegalia roemeriana (acacia roemeriana)*
catclaw mimosa (fragrant mimosa)	*Mimosa aculeaticarpa var. biuncifera*
cedar elm	*Ulmus crassifolia*
cherry laurel	*Prunus carolinianai*
chickasaw plum	*Prunus angustifolia*
Chinaberry	*Melia azedarach*
Chinese elm (lacebark elm)	*Ulmus parvifolia*
Chinese pistache	*Pistacia chinensis*
Chinese privet	*Ligustrum sinense*
Chinese tallowtree	*Triadica sebifera*
chinkapin oak	*Quercus muehlenbergii*
chittamwood (gum bumelia)	*Sideroxylon lanuginosum*
common buttonbush	*Cephalanthus occidentalis*
common hoptree (wafer ash)	*Ptelea trifoliata*
crape myrtle	*Lagerstroemia indica*
desert willow	*Chilopsis linearis*
eastern cottonwood	*Populus deltoides*
eastern red cedar	*Juniperus virginiana*
eastern redbud	*Cercis canadensis*
edible fig	*Ficus carica*
elbowbush	*Forestiera pubescens*
escarpment black cherry	*Prunus serotina var. eximia*
Eve's necklace	*Styphnolobium affine*
evergreen sumac	*Rhus virens*
flameleaf sumac	*Rhus copallina*
Florida thatch palm	*Thrinax radiata*
flowering dogwood	*Cornus florida*
fragrant mimosa	*Mimosa borealis*
fragrant sumac (skunkbush sumac)	*Rhus aromatica*
giant reed	*Arundo donax*
glossy privet	*Ligustrum lucidumi*
goldenrain tree	*Koelreuteria paniculata*
green ash	*Fraxinus pennsylvanica*
Hercules' club (prickly ash, toothache tree)	*Zanthoxylum hirsutum*
honey locust	*Gleditsia triacanthos*
honey mesquite	*Prosopis glandulosa*
Japanese honeysuckle	*Lonicera japonica*
Japanese privet	*Ligustrum japonicum*
Johnsongrass	*Sorghum halepense*
King Ranch bluestem	*Bothriochloa ischaemum*
lacey oak	*Quercus laceyi*
Lindheimer's prickly pear	*Opuntia lindheimeri*
Lindheimer's silktassel	*Garrya ovata var. lindheimeri*
little bluestem	*Schizachyrium scoparium*
little walnut	*Juglans microcarpa*
littleleaf (goldenball leadtree)	*Leucaena retusa*
loblolly pine	*Pinus taeda*
loquat	*Eriobotrya japonica*
lotebush	*Ziziphus obtusifolia*
Mexican (berlandier) ash	*Fraxinus berlandieriana*
Mexican buckeye	*Ungnadia speciosa*
Mexican olive	*Cordia boissieri*
Mexican plum	*Prunus mexicana*
Mexican redbud	*Cercis canadensis L. var. mexicana*
Mexican sycamore	*Platanus mexicana*
Mexican white oak	*Quercus polymorpha*

Common Name	Scientific Name
Meyer lemon	*Citrus meyeri*
mimosa silktree	*Albizia julibrissin*
mockernut hickory	*Carya tomentosa*
Montezuma cypress	*Taxodium mucronatum*
netleaf hackberry	*Celtis laevigata var. reticulata*
northern hackberry	*Celtis occidentalis*
northern hackberry	*Celtis occidentalis*
Osage orange	*Maclura pomifera*
paper mulberry	*Broussonetia papyrifera*
pecan	*Carya illinoiensis*
pomegranate	*Punica granatum*
possumhaw (deciduous holly)	*Ilex decidua*
post oak	*Quercus stellata*
prairie flameleaf sumac	*Rhus lanceolata*
red bay	*Persea borbonia*
red buckeye	*Aesculus pavia var. pavia*
red mulberry	*Morus rubra*
red oak	*Quercus rubra*
retama (Jerusalem thorn, palo verde)	*Parkinsonia aculeata*
river birch	*Betula nigra*
roughleaf dogwood	*Cornus drummondii*
rusty blackhaw	*Viburnum rufidulum*
shin oak	*Q. sinuata var. breviloba*
shrubby boneset	*Ageratina havanensis*
Shumard oak	*Quercus shumardii*
silktassel	*Garrya elliptica*
slippery elm	*Ulmus rubra*
Southern live oak (coast live oak)	*Quercus virginiana*
southern magnolia	*Magnolia grandiflora*
sugarberry	*Celtis laevigata*

Common Name	Scientific Name
sweet acacia (huisache)	*Vachellia farnesiana (Acacia farnesiana)*
sweetgum	*Liquidambar styraciflua*
switchgrass	*Panicum virgatum*
Texas (escarpment, plateau) live oak	*Quercus fusiformis*
Texas ash	*Fraxinus albicans*
Texas colubrina	*Colubrina texensis*
Texas crab apple	*Malus ioensis var. texana*
Texas kidneywood	*Eysenhardtia texana*
Texas madrone	*Arbutus xalapensis*
Texas mountain laurel (mescal bean)	*Dermatophyllum secundiflorum*
Texas mulberry	*Morus microphylla*
Texas persimmon	*Diospyros texana*
Texas pistache	*Pistachia texana*
Texas red oak	*Quercus buckleyi*
Texas red oak/Buckley oak	*Quercus buckleyi*
Texas redbud	*Cercis Canadensis var. texensis*
velvet ash	*Fraxinus velutina*
vitex	*Vitex agnus-castus*
water oak	*Quercus nigra*
western soapberry	*Sapindus saponaria var. drummondii*
white ash	*Fraxinus americana*
white mulberry	*Morus alba*
white shin oak	*Quercus sinuata var. breviloba*
whitebrush	*Aloysia gratissima*
winged elm	*Ulmus alata*
yaupon holly	*Ilex vomitoria*
yellow Indiangrass	*Sorghastrum nutans*

APPENDIX 1

NATURAL COMMUNITY CROSSWALK WITH TEXAS PARKS AND WILDLIFE VEGETATION TYPES

Table A1.1
Natural Community Types and the Texas Parks and Wildlife Vegetation Types (Elliott et al., 2014) Found within Each Type

Natural Community Type	Vegetation Types
Upland Forest	Edwards Plateau: Ashe Juniper Motte and Woodland
	Edwards Plateau: Ashe Juniper Slope Forest
	Edwards Plateau: Oak - Ashe Juniper Slope Forest
	Edwards Plateau: Oak - Hardwood Slope Forest
	Native Invasive: Juniper Woodland
	Edwards Plateau: Deciduous Oak - Evergreen Motte and Woodland
Upland Woodland	Edwards Plateau: Live Oak Motte and Woodland
	Edwards Plateau: Oak - Hardwood Motte and Woodland
	Edwards Plateau: Post Oak Motte and Woodland
	Post Oak Savanna: Live Oak Motte and Woodland
	Post Oak Savanna: Post Oak - Yaupon Motte and Woodland
	Post Oak Savanna: Post Oak Motte and Woodland
	Native Invasive: Deciduous Woodland
	Edwards Plateau: Wooded Cliff/Bluff
Upland Mixed Shrubland	Edwards Plateau: Ashe Juniper-Live Oak Shrubland
	Edwards Plateau: Ashe Juniper-Live Oak Slope Shrubland
	Edwards Plateau: Shin Oak Shrubland
	Edwards Plateau: Shin Oak Slope Shrubland
	Native Invasive: Juniper Shrubland
	Native Invasive: Mesquite Shrubland

Table A1.1 (continued)
Natural Community Types and the Texas Parks and Wildlife Vegetation Types (Elliott et al., 2014) Found within Each Type

Natural Community Type	Vegetation Types
Floodplains and Terraces	Central Texas: Floodplain Deciduous Shrubland
	Central Texas: Floodplain Evergreen Forest
	Central Texas: Floodplain Evergreen Shrubland
	Central Texas: Floodplain Hardwood - Evergreen Forest
	Central Texas: Floodplain Hardwood Forest
	Central Texas: Floodplain Live Oak Forest
	Central Texas: Riparian Deciduous Shrubland
	Central Texas: Riparian Evergreen Shrubland
	Central Texas: Riparian Hardwood - Evergreen Forest
	Central Texas: Riparian Hardwood Forest
	Central Texas: Riparian Live Oak Forest
	Central Texas: Riparian Evergreen Forest
	Central Texas: Riparian Live Oak Forest
	Central Texas: Riparian Evergreen Forest
	Edwards Plateau: Floodplain Ashe Juniper Forest
	Edwards Plateau: Floodplain Ashe Juniper Shrubland
	Edwards Plateau: Floodplain Deciduous Shrubland
	Edwards Plateau: Floodplain Hardwood - Ashe Juniper Forest
	Edwards Plateau: Floodplain Hardwood Forest
	Edwards Plateau: Floodplain Live Oak Forest
	Edwards Plateau: Riparian Ashe Juniper Forest
	Edwards Plateau: Riparian Ashe Juniper Shrubland
	Edwards Plateau: Riparian Deciduous Shrubland
	Edwards Plateau: Riparian Hardwood - Ashe Juniper Forest
	Edwards Plateau: Riparian Hardwood Forest
	Edwards Plateau: Riparian Live Oak Forest

APPENDIX 2

SEASONAL CLIMATE TRENDS

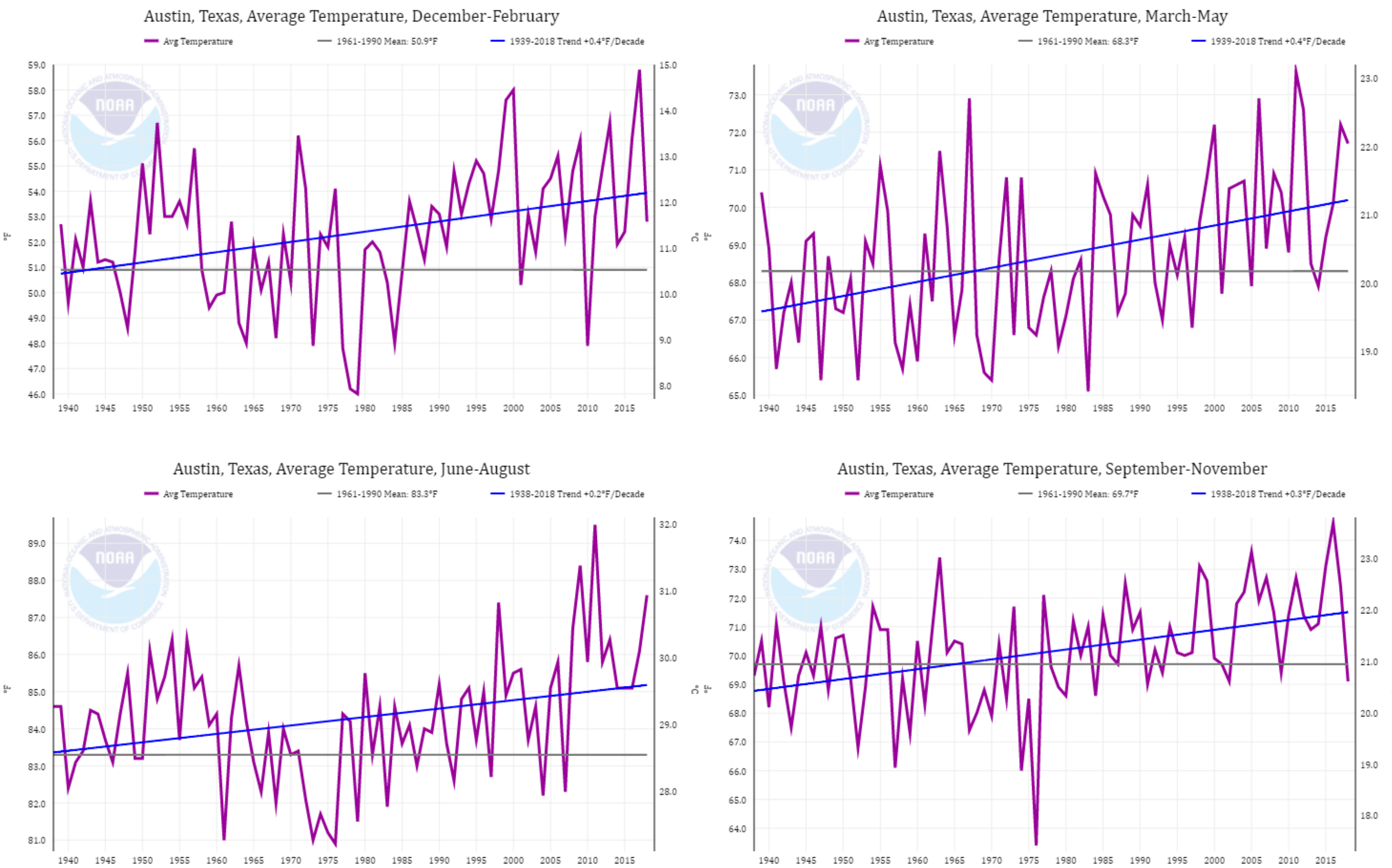

Figure A2.1. Seasonal Trends in Mean Temperature for Austin. Source: NOAA Climate-at-a-glance tool.

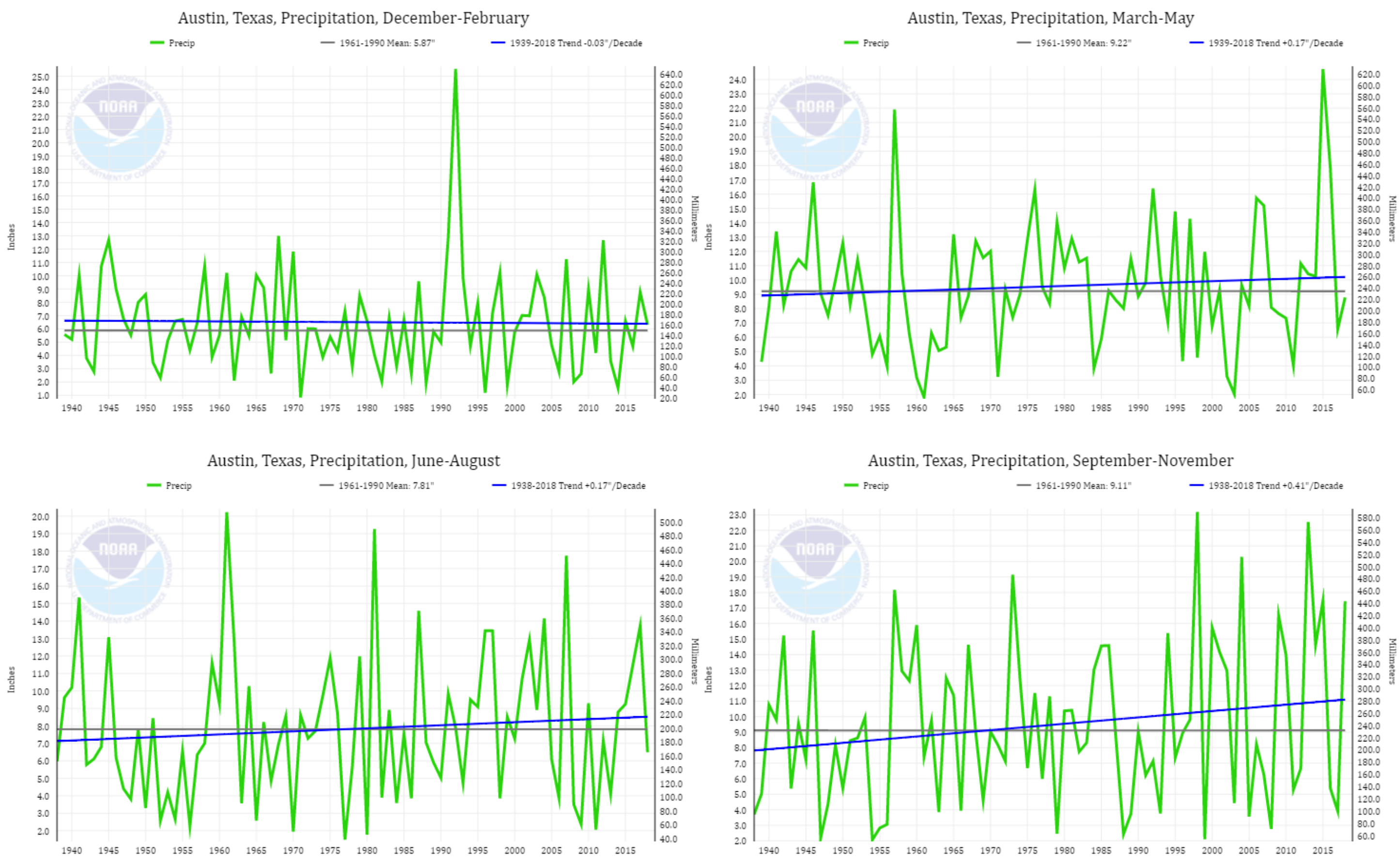

Figure A2.2. Seasonal Trends in Total Precipitation for Austin. Source: NOAA Climate-at-a-glance tool.

APPENDIX 3

MODELED PROJECTIONS OF HABITAT SUITABILITY

The table below provides the current and modeled importance values for the species modeled using the DISTRIB-II species distribution model for trees in the 1-by-1-degree latitude/longitude grid cell bounded by 30 degree south and 97 degrees west. This list is limited to only species represented in the DISTRIB-II model and may include species that are found in the larger 1x1 grid cell but outside of the City of Austin. Definitions for headings and supporting documentation are below.

Common Name	Scientific Name	Model Reliability	FIAsum	FIAiv	G45i	G85i	G45r	G85r	ChngCl45	ChngCl85
Ashe juniper	*Juniperus ashei*	High	1368.3	38.07	1247.31	1241.76	0.86	0.85	No change	No change
American elm	*Ulmus americana*	Medium	13	2.95	12.48	15.39	0.91	1.12	No change	No change
bitternut hickory	*Carya cordiformis*	Low	0	0.08	0	0	0	0	Lg. dec.	Lg. dec.
black cherry	*Prunus serotina*	Medium	2	0.79	0.74	0.77	0.4	0.42	Sm. dec.	Sm. dec.
black hickory	*Carya texana*	High	1	0.36	3.19	3.46	2.53	2.75	No change	No change
black oak	*Quercus velutina*	High	5.68	3.16	2.33	2.33	0.39	0.39	Sm. dec.	Sm. dec.
black walnut	*Juglans nigra*	Low	20.02	21.3	9.74	9.72	0.46	0.46	Sm. dec.	Sm. dec.
blackjack oak	*Quercus marilandica*	Medium	40	5.83	50.52	50.95	1.2	1.21	Sm. inc.	Sm. inc.
boxelder	*Acer negundo*	Low	2.17	9.23	1.61	1.61	0.7	0.7	No change	No change
bur oak	*Quercus macrocarpa*	Medium	0	1.47	0.14	0.04	0.39	0.12	Sm. dec.	Lg. dec.
cedar elm	*Ulmus crassifolia*	Medium	334	15.5	433.93	406.72	1.22	1.14	Sm. inc.	No change
chittamwood/gum bumelia	*Sideroxylon lanuginosum ssp. lanuginosum*	Low	20	3.9	17.1	18.78	0.79	0.87	Sm. dec.	No change
eastern redcedar	*Juniperus virginiana*	Medium	235.27	13.87	161.26	169.59	0.64	0.68	Sm. dec.	Sm. dec.
flowering dogwood	*Cornus florida*	Medium	0.18	0.11	0.03	0.02	0.18	0.12	Lg. dec.	Lg. dec.
green ash	*Fraxinus pennsylvanica*	Low	29	5.65	25.55	30.38	0.84	1	No change	No change
honeylocust	*Gleditsia triacanthos*	Low	0	0.14	0.21	0.94	2.28	10.16	No change	Lg. inc.
loblolly pine	*Pinus taeda*	High	124	26.76	57.63	57.75	0.44	0.44	Sm. dec.	Sm. dec.
northern hackberry	*Celtis occidentalis*	Medium	43.24	8.25	52.54	53.57	1.14	1.16	No change	No change
Osage-orange	*Maclura pomifera*	Medium	5.95	5.17	10.94	15.71	1.73	2.48	No change	No change
pecan	*Carya illinoinensis*	Low	35.2	13.46	66.75	75.65	1.78	2.02	Sm. inc.	Lg. inc.
post oak	*Quercus stellata*	High	431	23.41	243.79	236.93	0.53	0.52	Sm. dec.	Sm. dec.
red mulberry	*Morus rubra*	Low	3.15	3.35	1.9	1.74	0.57	0.52	Sm. dec.	Sm. dec.
Shumard oak	*Quercus shumardii*	Low	5.49	3.73	2.88	2.86	0.49	0.49	Sm. dec.	Sm. dec.
slippery elm	*Ulmus rubra*	Low	0.86	0.31	0.5	0.5	0.55	0.55	Sm. dec.	Sm. dec.
southern live oak	*Quercus virginiana*	High	743	23.37	846.3	828.55	1.07	1.05	No change	No change
sugarberry	*Celtis laevigata*	Medium	27.53	4.74	74.17	84.24	2.53	2.88	Lg. inc.	Lg. inc.
sycamore	*Platanus occidentalis*	Low	14	14.77	5.71	5.78	0.39	0.39	Sm. dec.	Sm. dec.
water oak	*Quercus nigra*	High	3.07	1.03	17.73	23.51	5.42	7.19	Sm. inc.	Sm. inc.
white ash	*Fraxinus americana*	Medium	1.34	0.57	0.49	0.48	0.34	0.34	Sm. dec.	Sm. dec.
winged elm	*Ulmus alata*	Medium	5	2.85	5.27	12.04	0.94	2.14	No change	No change

Definitions

Heading	Heading Definition
Common Name	Species common name used by FIA.
Scientific Name	Species scientific name used by FIA.
Model Reliability	The model reliability of the species' model predicting current and future suitable habitat (High, Medium, Low) (see Peters et al., 2019).
FIAsum	The area-weighted sum of the importance values (IV) per 100 sq km, so it is based on both abundance and area occupied within the zone, calibrated to 10,000 sq km, the approximate area of 1x1 degree zone at 35 degrees latitude. This is the primary variable to sort on for ranked abundance of species within the region. These values have been corrected for partial 1x1 degree zones (to 10,000 sq km), and for varying sizes north to south (curvature of earth makes zones narrower toward the poles), or partial coastal grids, according their proportion of a full 1x1 degree zone at mid latitudes (35 degrees).
FIAiv	The average importance value (IV) according to FIA records for the species. This provides indication of abundance of the species where it is found, not including where it is absent.
G45i or G85i	The area-weighted sum of importance values (IV) per 100 sq km according to a Random Forest model for the species within cells, under the Representative Concentration Pathway (RCP) 4.5 (relatively low emission future) or 8.5 (high emission pathway) average of 3 general circulation models (GCMs) by 2100. The 0-100 score is based on number of stems and basal area.
G45r or G85r	The ratio of future (2070-2099) suitable habitat (G45i or G85i) to actual (2001-2016) habitat (=act_sumIV), so that a ratio of 1 indicates no change in suitable habitat, <1 indicates a potential loss in habitat, and >1 indicates a potential gain in habitat by 2100 according to the lower (or higher) emissions scenario, average of 3 GCMs.
ChngCl45	Class of potential change in habitat suitability by 2100 according to the ratios of future (2070-2099) suitable habitat for an average of 3 GCMs to current (1981-2010) modeled habitat at RCP4.5.
ChngCl85	Class of potential change in habitat suitability by 2100 according to the ratios of future (2070-2099) suitable habitat for an average of 3 GCMs to current (1981-2010) modeled habitat at RCP8.5.

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APPENDIX 4

MODIFICATION FACTORS FOR ASSESSING THE ADAPTIVE CAPACITY OF TREE SPECIES IN URBAN AREAS

Modification Factor scores, based on Matthews et al. (2011), were developed for 105 species that are either already present or have the potential to gain habitat in the Austin region (defined as Travis County and all adjacent counties). The purpose of these scores is to provide managers and policy-makers regional information about individual species which will allow potential suitable habitat distribution models to be considered in a local context based on specific variables within their jurisdiction. This approach will assist interpretation of modeled outputs as published on the Climate Change Atlas (Landscape Change Research Group, 2014) and other species distribution models.

Several assumptions associated with climate change over the next 50 years in the Austin region were made to develop the scores. We assume, based on the literature reviews in this assessment:

- More drought conditions throughout the region because growing season average temperatures are projected to be higher in the future with only minimal increases in precipitation during this time in most scenarios.
- Higher exposure to fire events in natural areas due to higher average temperatures.
- Higher incidence of flooding due to more extreme precipitation patterns.
- Higher wind damage due to more intense pressure differences.
- Increase in several air and soil pollutants over the next 50 years as the area population increases and industry and transportation increase, which will be especially harsh in urban areas.
- Disease, insects, herbivory from deer (especially in natural areas), and invasive plants will increase or remain steady.
- Tree removal (harvest) will be primarily for restoration efforts, risk reduction, and for new land development.

There are several limitations to these scores. Landscapes—natural, urban, and rural—contain many diverse interactions between processes and patterns that influence the species that inhabit them. Although this analysis uses common factors that influence habitat at the local level to modify large-scale projections, some factors that are not included might and should be considered by local managers where applicable.

It is also important to understand that severe events can influence many factors used to modify habitat projections. A long drought can influence dispersal, fire, insect development, and seedling establishment. Therefore these modifications are somewhat dynamic and should be updated as needed by managers.

Scoring System

Each species was given individual scores for each Modification Factor that was then weighted and converted into an overall Disturbance, Biological, and Adaptability score.

Below are the definitions for the scoring system:

FactorType - One of two influential Factor Types (Biological and Disturbance) that describe the variables used to modify the outputs of individual species distribution models.

ModFactor - A Modification Factor that is considered to affect the establishment, growth, mortality rate, and regeneration of a species and that could reduce or increase the habitat suitability or future abundance for that species. See below for specific details relating to each ModFactor for planted and naturally occurring trees.

Score - A score, given as an integer ranging from -3 (negative effect on reproduction, growth, or survival) to +3 (positive effect on reproduction, growth, or survival), that relates to the potential influence a ModFactor has on the species throughout its range at the present.

Uncert - A default score (multiplier on Score) of how uncertain the ModFactor is in influencing the distribution of the species. Scores are 0.5 = highly uncertain; 0.75 = somewhat uncertain; 1.0 = low uncertainty that the ModFactor will provide the influence. These values are also assigned preliminarily by the modeling team based on literature research. For example, if there is contradictory information in the literature, the score would be 0.5.

FutureRelevance - A value (also a multiplier to Score) referring to the likely potential Future Relevance that a particular ModFactor could have on the distribution of a species, over the next 50 years in a changing climate. Values range from 1 = not highly relevant over next 50 years to 5 = likely to be an extremely important ModFactor.

Weighted - A weighted score based on multiplication of the three default values (ScoreX UncerX FutureRelevance) for the species throughout its range.

Average Disturbance Score - The average of all the Weighted Disturbance Factor Scores—and relates to the relative overall impact of these factors.

Average Biological Score - The average of all the Weighted Biological Factor Scores—and relates to the relative overall impact of these factors.

Converted Dist Score - The average of all Disturbance Factor Scores (unweighted) +3 to remove negative values. Values can range from 0 to 6.

Converted Bio Score - The average Biological Factor Scores (unweighted) +3 to remove negative values. Values can range from 0 to 6.

Adapt Score - The hypotenuse of a right triangle created from the Converted Dist and Bio Score. Values can range from 0 to 8.5.

Adapt Class - Categories assigned based on Adapt Score. Low: less than 3.5. Moderate: 3.5-4.5. High: more than 4.5.

Factors for Trees in Natural and Other Undeveloped Areas

These scores were developed for native, naturalized, and invasive species in the Austin region for use in natural areas and others where trees naturally regenerate. Scores for native species were primarily based on those developed by Matthews et al. (2011), with most information derived from Burns and Honkala (1990). For invasive species, information was gleaned from various sources, including the USDA Plants Database (USDA, 2015) and invasive species fact sheets developed by Federal and state agencies. Additional information for wind and ice storm susceptibility was taken from Hauer et al. (2006) and Duryea et al. (2007).

Defaults were kept consistent with Matthews et al. (2011), with a few exceptions. Insect and disease scores were modified to account for local pest and disease influences such as oak wilt and hypoxylon.

Factors that received a weighted score of less than -4.5 or greater than 4.5 were listed as contributing negatively or positively to the species' overall adaptability score in tables. Weighted scores between these two values were not listed.

Disturbanc Factors:

Disease - Accounts for the number and severity of known pathogens that attack a species. If a species is resistant to many pathogens, it is assumed that it will continue to be so in the future. If the mortality rate is low it is assumed that the species is not greatly affected by diseases. Thus, those species would receive positive scores. Defaults for all species: -1 Score, 0.75 Uncert, and 2 FutureRelevance.

Insect Pests - Accounts for the number and severity of insects that may attack the species. If a species is resistant to attacks from known insect pests now or is adapted to cope with them, then it is assumed to be at least partially resistant in the future. This factor, although highly uncertain in overall effects, is likely to be very important over the next 50 years. Defaults for all species: -1 Score, 0.5 Uncert, and 4 FutureRelevance.

Browse - The extent to which browsing (by deer or other herbivores) has an effect on the species, either positive by promoting growth or by effective strategies for herbivory avoidance, or negative by over-browsing. Defaults for all species: -2 Score (+1 if promoted by browsing), 0.75 Uncert, and 1 FutureRelevance.

Invasive Plants - The effects of invasive plants on the species, either through competition for nutrients or as a pathogen. This factor is not yet well researched as to effects on individual tree species but could be very important in the future as invasives are usually more readily adapted to changing environments and can form monotypic stands that restrict regeneration. Defaults for all species: -3 Score, 0.5 Uncert, and 4 FutureRelevance.

Drought - Extended periods without sufficient access to water. Certain species are better adapted to drier conditions, allowing them to survive more frequent or prolonged droughts. Defaults for all species: -1 Score, 0.75 Uncert, and 5 FutureRelevance.

Flood - Frequent or prolonged periods of standing water. Species adapted to sustained flooding will be positively affected while species vulnerable to flooding will be negatively affected by the assumed greater flooding exposures under climate change. Defaults for all species: -1 Score, 0.75 Uncert, and 4 FutureRelevance.

Ice - The damaging effects of ice storms and potential for ice heaving on a species. Defaults for all species: -1 Score, 0.5 Uncert, and 2 FutureRelevance.

Wind - The damaging effects of windstorms and uprooting potential (and top breakage) of a species: -1 Score, 0.75 Uncert, and 2 FutureRelevance. If a species is susceptible to windthrow the standard default is -2 (Score); if resistant to windthrow, Score is +1.

Fire Topkill - The effects of fire or fire suppression on the larger stems of a species (poles and sawtimber). Species adapted to fire will be positively affected by the assumed greater fire exposure under climate change, while species vulnerable to fire will be negatively affected. As a first approximation, bark thickness relates directly to this ModFactor. Defaults for all species: -1 Score, 0.75 Uncert, and 2 FutureRelevance.

Harvest - If the species is harvested using best management practices, is the species generally enhanced or diminished through time? If the best management practice includes replanting, that is included in the ranking. If the species is not a target species currently being managed within a harvest context, consider how the species responds when it is an incidental species in harvested stands. Since harvesting is generally low in urban areas, this defaults to 0 and is not factored in unless there is an active attempt at managing this species (e.g., removal of woody invasives). Defaults for all species: 0 Score, 0.5 Uncert, and 2 FutureRelevance.

Temperature Gradients - The effects of variations in the temperature gradient associated with a species. Species that currently occupy regions with a diverse range of temperatures are assumed to be better adapted to warmer and highly variable climates than species occupying regions with a small range of temperatures. Defaults for all species: 1 Score, 0.75 Uncert, and 2 FutureRelevance.

Air Pollution - Airborne pollutants that affect, mostly negatively, a species' growth, health, and distribution. Includes acid rain, ozone. Defaults for all species: -2 Score, 0.75 Uncert, and 3 FutureRelevance.

Soil/Water Pollution - Pollutants in the soil and water that that affect, mostly negatively, a species' growth, health, and distribution. Defaults for all species: -1 Score, 0.5 Uncert, and 1 FutureRelevance.

Biological Factors:

Competition-Light - The tolerance of a species towards light. Does the species grow better in shade, partial shade, or full sun? Default values depend on species tolerance level, and all with FutureRelevance of 3. Species intolerant to shade receive -3 (Score) 0.75 (Uncert), Intermediate either -1, 0, 1 (Score) 0.5 (Uncert). Intermediate default is 0, with flexibility to go +1 or -1. Tolerant species have scores of +3 (Score) 0.75 (Uncert).

Edaphic Specificity - The specific soil requirements (e.g., pH, texture, organic content, horizon thickness, permeability) for a species to survive in a suitable habitat. Includes long-term soil moisture capacities of the soil. Species with general requirements have positive scores, and species with specific requirements have negative defaults. Unsuitable soils north of the current range of a species can be a barrier to migration. Defaults for all species: 0 Score, 0.75 Uncert, and 2 FutureRelevance.

Environmental Habitat Specificity - Considers the range of non-edaphic environmental characteristics (e.g., slope, aspect, topographic position, climatic modulation, specific associates) that the species requires. Also considers whether the species may be able to survive a changed climate in relatively small refugia (e.g., coves, N-facing slopes). Defaults for all species: 0 Score, 0.75 Uncert, and 3 FutureRelevance.

Dispersal - The species' ability to effectively produce and distribute seeds; considers viability, production, production intervals, seed banking, dispersing agents (even humans), and other factors related to moving seeds across the landscape. Defaults for all species: 1 Score, 0.5 Uncert, and 3 FutureRelevance.

Seedling Establishment - The ability of the species to regenerate with seeds to maintain future populations; considers the conditions required for establishment of seedlings and survival rates for seedlings, but not necessarily to the sapling stage. Defaults for all species: 1 Score, 0.75 Uncert, and 4 FutureRelevance.

Vegetative Reproduction - The ability of the species to regenerate by means of stump sprouts or cloning (not necessarily growing into sapling sizes). Species that can reproduce vegetatively have positive defaults, and those that cannot have negative defaults. Defaults assume some vegetative reproduction, so for all species: 1 Score, 0.75 Uncert, and 2 FutureRelevance.

Fire Regeneration - The capability of the species to be enhanced in regeneration through fire, usually surface fires. This score will never be < 0 as it is only used if there is an extra benefit in fire to regenerate the species, above seedling establishment and vegetation reproduction. Defaults are 0 Score, 0.75 Uncert, and 2 FutureRelevance.

Below is an example natural score for boxelder (Table A4.1).

Table A4.1
Example of Natural Modification Factor Scores Generated for the Species Boxelder

Factor Type	ModFactor	Score	Uncert	FutureRelevance	Weighted
Disturbance	Disease	-1	0.75	4	-3.00
Disturbance	Insect pests	-1	0.5	4	-2.00
Disturbance	Browse	-1	0.75	1	-0.75
Disturbance	Invasive plants	-1	0.5	4	-2.00
Disturbance	Drought	3	0.75	4	9.00
Disturbance	Flood	2	0.75	3	4.50
Disturbance	Ice	-2	0.5	1	-1.00
Disturbance	Wind	-2	0.75	2	-3.00
Disturbance	Fire topkill	-2	0.75	2	-3.00
Disturbance	Harvest	0	0.5	2	0.00
Disturbance	Temperature gradients	3	0.75	2	4.50
Disturbance	Air pollution	-2	0.75	3	-4.50
Disturbance	Soil & water pollution	-1	0.5	1	-0.50
Biological	Competition-light	2	0.75	3	4.50
Biological	Edaphic specificity	2	0.75	2	3.00
Biological	Environmental habitat specificity	1	0.75	3	2.25
Biological	Dispersal	3	1	3	9.00
Biological	Seedling establishment	3	0.75	4	9.00
Biological	Vegetative reproduction	2	0.75	2	3.00
Biological	Fire regeneration	1	0.75	2	1.50
	Average dist score				-0.09
	Average bio score				-0.13
	Converted dist score				2.62
	Converted bio score				5.00
	Adapt score				5.64
	Adapt class				high

Factors for Planted Trees in Developed Areas

We created separate scores for trees planted in developed areas. Factors, scores, and weighting were modified from naturally occurring trees to account for the different environments experienced by trees in more developed areas. Many biological factors were also altered to account for the fact that dispersal and natural reproduction are not typically factors for planted trees. Most information for native species was derived from Burns and Honkala (1990) with supplementary material relevant to cultivated environments from Gilman and Watson (1993). Most information for cultivars and non-natives was taken from Gilman and Watson (1993). Additional information for wind and ice storm susceptibility were taken from Hauer et al. (2006) and Duryea et al. (2007).

Factors that received a weighted score of less than -4.5 or greater than 4.5 were listed as contributing negatively or positively to the species' overall adaptability score in tables. Weighted scores between these two values were not listed.

Disturbance Factors:

Disease - Same as natural scores.

Insect Pests - Same as natural scores.

Browse - Same as natural scores, but defaults to -1 because it is assumed herbivory would be lower in planted environments (primarily because larger trees are planted).

Invasive Plants - Same as natural scores, but defaults to 0 because it is assumed that for the most part planted trees will be shielded from competition from invasive species.

Drought - Same as for natural scores, but future relevance is reduced from 5 to 3 because it is assumed that many planted trees will be watered during drought periods.

Flood - Same as natural scores.

Ice - Same as natural scores.

Wind - Same as natural scores.

Temperature Gradients - Same as natural scores, except future relevance was increased from 2 to 3 because of the urban heat island effect.

Air Pollution - Same as natural scores, but default is reduced to -3 to account for the increased air pollution in developed areas.

Soil/Water Pollution - Same as natural scores, but default is reduced to -2 to account for greater pollution in developed areas.

Biological Factors:

Competition-Light - Same as natural scores.

Edaphic Specificity - Same as natural scores.

Land-Use/Planting Site Specificity - The ability for the species to be planted in a variety of site types (street, residential, park, campus). Also considers the range of non-edaphic environmental characteristics (e.g., slope, aspect, topographic position, climatic modulation, specific associates) that the species requires. Defaults for all species: 0 Score, 0.75 Uncert, and 3 FutureRelevance.

Restricted Rooting Conditions and Coil Compaction - The ability of a species to grow and survive in narrow boulevards and other constrained spaces. Defaults for all species: -1 Score, 0.75 Uncert, and 3 FutureRelevance.

Nursery Production Potential - The ease and/or cost of producing the species in a nursery. Also relates to how widely available it is. Future Relevance is high for this factor because it will largely determine the extent to which the species is widely propagated and planted. For all species: 0.75 Uncert, and 4 FutureRelevance. If stock is widely available, Score is +2. If not currently available, Score is -2.

Planting Establishment - The ease with which the species establishes itself after planting. Also relates to the amount of care required to establish. Defaults for all species: 1 Score, 0.75 Uncert, and 2 FutureRelevance. -1 Score if not easily established.

Maintenance Required - The degree to which pruning or other maintenance is needed after establishment. Negative score indicates that maintenance is required. Defaults for all species: -1 Score, 0.75 Uncert, and 2 FutureRelevance. 1 Score if minimal maintenance required.

Invasive Potential - Likelihood the species could become invasive if planted. Applies to both native and non-native species. Negative score indicates that a species is known to be or has the potential to be invasive. Defaults for all species: 0 Score, 0.75 Uncert, and 3 FutureRelevance. -3 Score if species is known to be invasive.

Below is an example planted score for boxelder (Table A4.2).

Table A4.2
Example of Planted Modification Factor Scores Generated for the Species Boxelder

Factor Type	ModFactor	Score	Uncert	FutureRelevance	Weighted
Disturbance	Disease	-1	0.75	2	-1.50
Disturbance	Insect pests	-3	0.5	5	-7.50
Disturbance	Browse	-1	0.75	1	-0.75
Disturbance	Invasive plants	0	0.5	2	0.00
Disturbance	Drought	3	0.75	3	6.75
Disturbance	Flood	2	0.75	3	4.50
Disturbance	Ice	-1	0.5	2	-1.00
Disturbance	Wind	-1	0.75	2	-1.50
Disturbance	Temperature gradients	3	0.75	3	6.75
Disturbance	Air Pollution	-2	0.75	3	-4.50
Disturbance	Soil & Water Pollution	-2	0.5	1	-1.00
Biological	Competition-light	2	0.5	1	1.00
Biological	Edaphic specificity	2	0.75	2	3.00
Biological	Land use & planting site specificity	1	0.75	3	2.25
Biological	Restricted rooting conditions	1	0.75	3	2.25
Biological	Nursery propagation	-1	0.75	4	-3.00
Biological	Planting establishment	2	0.75	2	3.00
Biological	Maintenance required	-1	0.75	2	-1.50
Biological	Invasive potential	-3	0.75	3	-6.75
	Average dist score				0.02
	Average bio score				0.03
	Converted dist score				2.83
	Converted bio score				3.38
	Adapt score				4.41
	Adapt class				medium

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The trees, developed green spaces, and natural areas within the City of Austin's 400,882 acres will face direct and indirect impacts from a changing climate over the 21st century. This assessment evaluates the vulnerability of urban trees and natural and developed landscapes within the City Austin to a range of future climates. We synthesized and summarized information on the contemporary landscape, provided information on past climate trends, and illustrated a range of projected future climates. We used this information to inform models of habitat suitability for trees native to the area. Projected shifts in plant hardiness and heat zones were used to understand how less common native species, nonnative species, and cultivars may tolerate future conditions. We also assessed the adaptability of planted and naturally occurring trees to stressors that may not be accounted for in habitat suitability models such as drought, flooding, wind damage, and air pollution. The summary of the contemporary landscape identifies major stressors currently threatening trees and forests in Austin. Major current threats to the region's urban forest include invasive species, pests and disease, and development. Austin has been warming at a rate of about 0.4°F per decade since measurements began in 1938 and temperature is expected to increase by 5 to 10°F by the end of this century compared to the most recent 30-year average. Both increases in heavy rain events and severe droughts are projected for the future, and the overall balance of precipitation and temperature may shift Austin's climate to be more similar to the arid Southwest. Species distribution modeling of native trees suggests that suitable habitat may decrease for 14 primarily northern species, and increase for four more southern species. An analysis of tree species vulnerability that combines model projections, shifts in hardiness and heat zones, and adaptive capacity showed that only 3% of the trees estimated to be present in Austin based on the most recent Urban FIA estimate were considered to have low vulnerability in developed areas. Using a panel of local experts, we also assessed the vulnerability of developed and natural areas. All areas were rated as having moderate to moderate-high vulnerability, but the underlying factors driving that vulnerability differed by natural community and between East and West Austin. These projected changes in climate and their associated impacts and vulnerabilities will have important implications for urban forest management, including the planting and maintenance of street and park trees, management of natural areas, and long-term planning.

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