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,

Unless otherwise noted, climate projection data were retrieved from the Climate Mapper tool (Hegewisch, et al., 2019). The tool uses data from the University of Idaho's gridMET meteorological dataset for historical data (Abatzoglou, 2013), and includes downscaled projections from two emissions scenarios (RCP 4.5 and RCP 8.5) and 20 climate models downscaled to a 4km resolution. 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. 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 mode (a model that tends to be hotter and drier than average) with RCP 8.5 to bracket a range of potential futures (Abatzoglou and Brown, 2012).

Climate trend data were retrieved from the NOAA Climate at a Glance tool (NOAA National Centers for Environmental Information 2019). Climate at a Glance was developed at the request of NOAA Headquarters for 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 after further quality assurance measures.

Observed Trends

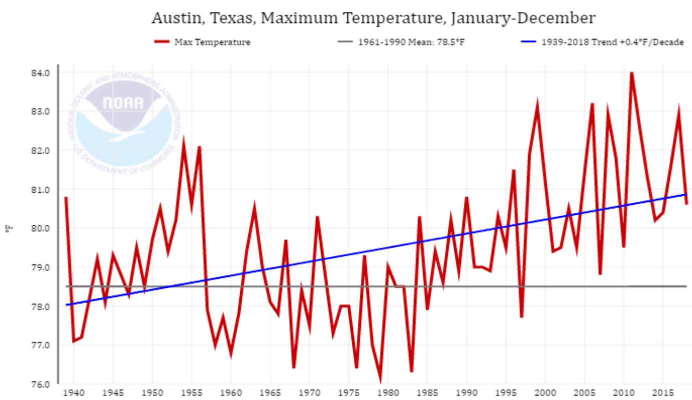
Temperature

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 thirty-year decadal averages, also called "normals." The most recent 30-year normal is 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 out of the year where the heat index exceeded 105ºF.

Temperatures have been increasing over the observational record in Austin, which goes back to 1938. Mean 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 for comparison for examining climate trends ((IPCC), 2019). 2000-2010 was the warmest decade on record for the contiguous United States, and also for Austin. Recent years have been increasingly hot. Seven of the hottest 10 years in Austin have occurred since 2000 (not yet counting 2019 data).

It is unclear how climate change is currently affecting heat wave occurrence, but the number of days with temperatures above 100 ºF has already exceeded the historical average of 13 days per year multiple times this decade. For example, there were 51 days of 100 ºF or more during the summer of 2018. Among the top 10 years with the most 100 ºF days, eight are in the 21st century. Summer 2019 was the second-hottest behind 2011 when drought blanketed much of the western U.S. 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). 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).



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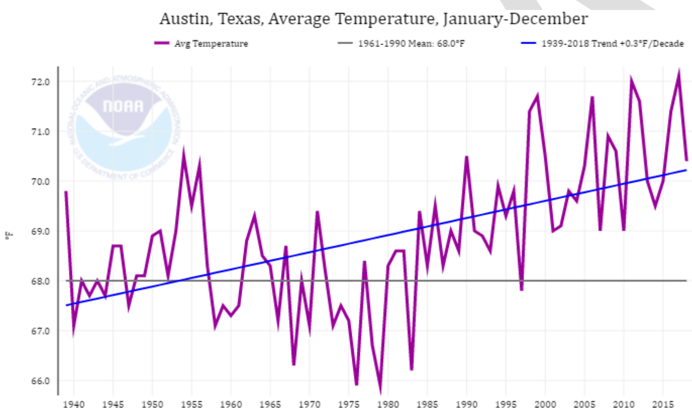

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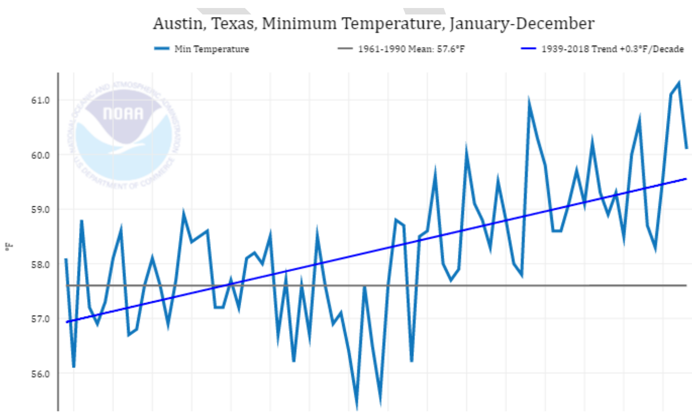

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Figure 2.1— Changes in annual temperature over the observational record from 1938 to 2018 for Austin, TX. The gray line indicates the 1961-1990 average and the blue line shows the trend over the observational record. A. Mean maximum temperature, B.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

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 in of precipitation from 1981-2010. Winter is the driest season, and averaged less than 7 in of precipitation during the same time period. Overall, the average yearly rainfall in the Austin area from 1981-2010 was 33.5 in per year. Drastic swings from drought to flood occur regularly, with up to one-third of all droughts in the past 50 years being followed directly by flood events (USGCRP, 2018). These "whiplash" events and the frequency of flood events has increased especially in the past 30 years(Christian, et al., 2015, USGCRP, 2018).

Overall, precipitation has increased in Austin over the observational record, at a rate of 0.7 inches per decade. Changes have not been the same across all seasons, however (see appendix). There has been virtually no change in precipitation in winter, spring, and summer, and 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.

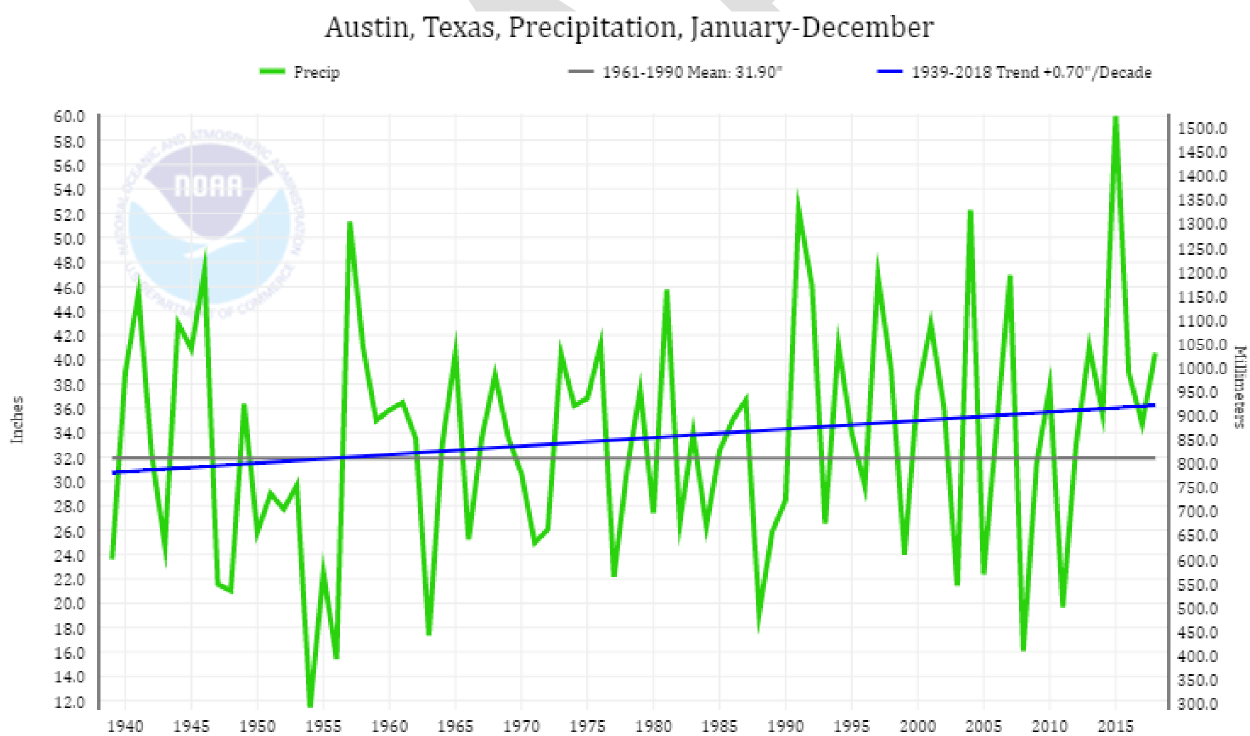

Figure 2.1— Changes in annual precipitation over the observational record from 1938 to 2018 for Austin, TX. The gray line indicates the 1961-1990 average and the blue line shows the trend over the observational record. Source: NOAA https://www.ncdc.noaa.gov/cag/

CLIMATE PROJECTIONS

Temperature

The temperature in the Austin,TX 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, while the minimum winter temperature is expected to increase by 5ºF. Increases under the "business as usual" scenario, RCP 8.5, are greater. By 2100, the average annual temperature and across most seasons is expected to increase 10ºF. The positive effects of a shorter, warmer winter are expected to be offset by the effects of longer, hotter summers and increased pressure on limited water and energy supplies for irrigation and air conditioning (USGCRP 2018). Increased summer temperatures will lead to higher evaporative stress on plants, and higher summer lows will affect the ability of trees to recover from high daytime temperatures.

Table 2.1 -Temperatures and Days with Heat Index above 105ºF for the Austin area through 2099

	30-Year Normal	**RCP 4.5 w/ CNRM-CM5 (low emissions)**			**RCP 8.5 w/HadGEM2-ES365 (high emissions)**		
	1981-2010	2010-2039	2040-2069	2070-2099	2010-2039	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

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 expected to marginally decrease by 2100, but the effects are primarily expected during summer, winter, and fall, while spring precipitation is expected to increase. RCP 8.5, on the other hand, predicts a similar annual loss, but it is all expected to affect summer precipitation; the same scenario projects an increase in winter, spring, and fall precipitation (Table 2.2). Model projections available do not project a measureable change in soil moisture content, but the coupled change in temperature with even marginal decreases in temperature could reduce soil moisture availability. Total runoff is projected to vary seasonally depending on scenario.

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

	30-Year Normal	RCP4.5 w/ CNRM-CM5 (low emissions)			RCP8.5 w/HadGEM2-ES365 (high emissions)		
	1981-2010	2010-2039	2040-2069	2070-2099	2010-2039	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		13	17	15	20	14	15
Spring		20	20	17	19	13	18
Summer		17	18	17	12	8	10
Fall		12	20	21	13	14	15
Annual		16	19	18	16	12	14

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, 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 could potentially increase to be 300 to 359 days long (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 higher risks from 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.

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

	Average	**RCP4.5**			**RCP8.5**		
	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

Heat Stress

The number of hot days (over 100°F) is projected to increase, particularly under a higher as compared to lower emissions scenario and by later compared to earlier time periods (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 an additional 30–60 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 zone warmer than the surrounding area, allowing some more southern species to be planted (USDA, 2012). In addition to milder winters, however, heat island effects can also make summer temperatures higher, especially near dark pavements and buildings. A recent study for the city of

Austin showed that areas around downtown and major highways and development areas were several degrees warmer than areas in the city with high tree cover or large rivers (Austin, 2019). Trees that are intolerant of extreme heat are thus more vulnerable in these areas with an elevated urban heat island effect. Some trees can tolerate extremely high heat, and may be able to withstand high summer temperatures, such as Texas mountain laurel, Jerusalem thorn (retama), Mexican white oak, honey mesquite, Texas madrone, yaupon, and sweet acacia (huisache).

Drought Stress

In the late 1800s, the explorer John Wesley Powell observed a distinct belt that marked the transition of the wet east from the dry west. That transition line became known as the “100th Meridian” because it was closely aligned with the 100th meridian of longitude. However, it 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 located 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 been experiencing a combination of drier summers (in some years) and increased evapotranspiration due to higher temperatures (in most years) that is expected to exacerbate aridity (USGCRP, 2018). Austin, being 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, Austin could find itself lumped into the desert southwest. This is significant because the concept of drought in the desert Southwest is increasingly being replaced by the concept of aridification, i.e., a transition to from a temporary state of dryness to a permanent one (Group, 2018, USGCRP, 2018).

Severe and long-term droughts can have dramatic impacts on the Austin region’s urban forest. Species known for their drought tolerance may experience less of a negative effect than species that are adapted to more mesic environments. 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 escarpment live oak. One study suggests that severe drought could kill a large fraction (18–85%) of intermediate- to large-sized Ashe juniper trees in central Texas savannas (Polley, et al., 2018). Studies have shown that the ability of species such as Ashe juniper, escarpment live oak, and mesquite to tap deep water sources may be constrained by local geology (Jackson, et al., 1999, Litvak, et al., 2011) . Future increases in temperature and vapor pressure deficit, especially under a higher emissions scenario, could create conditions for another high mortality event by 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 in their ability to survive severe storms by species. Based on surveys following hurricanes in Florida, trees exhibiting high survival after storms that are also found in Austin include southern magnolia, live oak, sweetgum, and crapemyrtle (Duryea, et al., 2007). Species with lower survival included cherry laurel, sycamore, Chinese tallowtree, and pecan. Because of its unique climate and geology, Austin is an mix of deeply rooted species (in search of water) that can potentially withstand high winds and shallowly-rooted species (due to surficial geology) that have the potential to blow over. Location of the tree, whether deeply rooted in thick soil or exposed in shallow soil, may ultimately be more important than species in determining overall survival.

Wind Damage

On average, urban areas tend to have lower wind speeds than surrounding rural areas (Mishra, et al., 2015), but buildings and other urban infrastructure can create "street canyons" with localized areas of altered wind speed and turbulence (Rotach, 1995). Wind damage to trees can be particularly problematic in urban areas because of the increased risk to human life and property. When the urban forest experiences severe wind disturbance, falling limbs and trees can result in loss of electric service, displacement of families and businesses, and impede emergency vehicles from accessing damaged areas. Several factors influence the resilience of trees to wind damage. Trees that have defects (co-dominant stems, decay, severed roots, etc.) are more likely to be damaged or uprooted by strong winds. Large trees sustain greater amounts of damage due to having a larger crown exposure to wind. Furthermore, wind speeds increase with increased distance from the ground, thereby exerting greater force on taller trees. Wind related damage and mortality can also be species-specific and depend on factors such as tree architecture and wood material properties. Our assessment of adaptive capacity suggests some of the most wind-vulnerable trees in Austin include sugarberry, velvet ash, Ashe juniper, littleleaf/goldenball leadtree, and escarpment black cherry. Chinese pistache and Chinese tallow tree were considered among the most wind-resistant.

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 so-called 100-year flood events (Hollis, 1975). This effect will likely be exacerbated by the increase in heavy rain events that is already occurring (Atlas 14) and projected to increase even more in the area from a changing climate (Perica, et al., 2018). Typically, urban floods are short-lived, but extended flooding can stress trees, leading to leaf yellowing, defoliation, and crown dieback. If damage is severe, mortality can occur. 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, and sulfur dioxide can all affect tree health. Elevated temperatures can increase the rate of ground-level ozone formation (Jacob and Winner, 2009, Nowak, et al., 2016), leading to leaf damage and secondary damage from insects and disease. Regional increases in summer temperatures could worsen effects already experienced due to the heat island effect (Wilby, 2008). However, new air quality standards could help reduce this effect (Reitze Jr, 2015), and 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). Trees can also contribute to air pollution via the production of volatile organic carbons (VOCs), which can be precursors to ozone production. The major emitters of VOCs in the Austin region are oak and juniper species. VOC emissions depend partially on temperature. Thus, it could be expected for VOC emissions to increase as summer temperatures increase.

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 percent of Travis county's 2007 carbon emissions (McCaw, 2012). Increasing temperature may be leading to increased aridification, which could reverse the carbon sink effect. Increased carbon dioxide in the atmosphere may also directly affect tree growth and water use efficiency. Carbon dioxide 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 paloverde) exposed to twice ambient levels of CO_2 had significantly larger mass than those grown under ambient concentrations (Tischler, et al., 2004). Experimentation under a gradient of CO_2 has shown that CO_2 enrichment may favor the establishment of honey mesquite into grasslands (Polley, et al., 2002). Other studies have concurred that honey mesquite seedlings possess the capacity to respond markedly to CO2 enrichment, particularly through greater rooting depth, and that may yield a competitive advantage over grass seedlings (Derner, et al., 2005). Nutrient and water availability, ozone pollution, and tree age and size all play major roles in the ability of trees to capitalize on carbon dioxide fertilization (Ainsworth and Rogers, 2007).

Fire

Fires are determined directly by climate conditions as well as through changes in fuels. The worst wildfire in Texas history occurred in 2011, destroying more than 1000 homes and burning more than 1.5 million trees Bastrop County (Hanna 2011). The unusual severity of the wildfire was partially caused by an ongoing drought as well as high winds from a tropical storm. As drought and becomes more common, fuel for catastrophic wildfires is likely to become more available. In addition, the number of dry days and days with extremely high temperatures will result in increased drying of fuel, further increasing the danger of wildfires. Along with increases in severity of fires, the amount of area burned in Austin can be expected to increase going into the middle of the century. Projections for the end of the century are much less certain, and predict both an increase and decrease in severity and area burned, depending on the climate model (Geos Institute 2016). A study by Stambaugh (2018) examined future fire probability in the central plains using three different climate models. The results as to whether fire probability would increase or decrease in the Edwards Plateau and Blackland Prairie depended on the climate model used, and point to the fact that fires in this area can be at the tipping point between reactant (fuels) limited and reaction (temperature) limited.

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. Austin is located at roughly 30 degrees north latitude, the dividing line between the north temperate zone and the tropics (Borchert, et al., 2005). Deciduous trees in temperate climates 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. The dividing line between these two patterns is roughly 7 ℃ average January temperature (Borchert, et al., 2005). Average January minimum temperatures in Austin over the past 30 years is 41.4 ℉, or 5.2 ℃. If January temperatures increase as projected to above the 7 ℃ (45 ℉) 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 hackberry, green ash, and some oak species (Borchert, et al., 2005).

Invasive Plant Species

Invasive plant species can out-compete native species in natural areas in the Austin region as mentioned in the previous chapter. 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 had 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 tree is projected to expand northward and its future range is in part determined by winter minimum temperatures (Gan, et al., 2009, Wang, et al., 2011). A few species were considered moderately vulnerable to increases in temperature based on published heat and hardiness zone tolerances. These species were 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, et al., 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 studies suggest that increasing temperatures between 30 degrees north and south latitude may decrease the number of invasive species in areas like Texas.

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 high-mortality disease of oaks in the region and important determinant of golden-cheeked warbler habitat (Stewart, et al., 2014). Oak wilt benefits from cool, moist conditions for transmission and hot, dry conditions for disease progression. Thus wetter springs followed by hot dry summers could make oak wilt a larger problem in the Austin region in the coming decades. Although oak wilt was thought to be limited by extremely high temperatures, evidence has shown it to survive under extremely hot conditions in Texas (Appel, 1995). 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 and Appel, 2009). Wood boring beetles are pests that can infest oaks and other species if they are showing declines in health (Drees, et al.), 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 species found in Ashe juniper communities in the Edwards Plateau. Modeling of the effects of future climate conditions by the National Audubon Society suggests that nearly all of its current range will be lost within the next few decades (National AudubonSociety, 2013). The species is highly dependent on Ashe juniper, and it could potentially persist in areas with remaining Ashe juniper habitat. However, these habitats are also considered vulnerable to climate change based on this assessment.

Some wildlife species can have negative effects on natural areas through browsing and disruption of soil. Feral hogs can disrupt soil and vegetation by rooting and wallowing. Conditions are already favorable for feral hogs in Texas, and they are only expected to expand their range further north as climate conditions continue to warm (Snow, et al., 2017). White-tailed deer can also reduce recruitment of oaks into adult size classes on the Edwards Plateau (Andruk, et al., 2014, Russell and 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.

Nutrient Cycling

A changing climate may result in altered rates of decomposition and nutrient cycling. Changes can be driven by a single climate factor or multiple factors acting in concert that alter the distribution, abundance, phenology, physiology and behavior of species, and the diversity, structure, and function of ecosystems. For example, changes in temperature, precipitation, soil moisture, and relative humidity can affect the above-ground diversity and productivity of plants and animals as well as the below-ground diversity and activity of soil microorganisms. As soil warms, the rate of microbial decomposition is sped up. 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, will reduce productivity and slow decomposition rates, which, in turn, will reduce 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 (Delgado-Baquerizo, et al., 2013). Aridity can reduce plant density, which may promote physical processes, such as rock weathering, over biological processes, such as litter decomposition. Physical processes are linked to phosphorus production and biological processes to carbon and nitrogen availability. A decrease in nitrogen concentrations with increasing aridity may, for example, further decrease the plant productivity beyond that caused by water limitations.

In the background is still increasing rates of nitrogen deposition due to human activity. Although biodiversity is often shown to decline when nitrogen deposition is high (Bobbink, et al., 2010, Pardo, et al., 2011), the compounding effects of multiple stressors are difficult to predict. Warming and changes in water availability have been shown to interact with nitrogen in additive or synergistic ways to exacerbate biodiversity loss (Porter, et al., 2013).

------start text box---

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.
- Changes in temperature and precipitation may also exacerbate current stressors such as invasive plants, insect pests, and pathogens.

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LITERATURE CITED

(IPCC), I.P.o.C.C. 2019. Data Distribution Center Frequently Asked Questions.
Abatzoglou, J.T. 2013. Development of gridded surface meteorological data for ecological applications and modelling. International Journal of Climatology 33: 121-131. doi:10.1002/joc.3413.
Abatzoglou, J.T. and T.J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology 32: 772-780. doi:10.1002/joc.2312.
Ainsworth, E.A. and A. Rogers. 2007. The response of photosynthesis and stomatal conductance to rising CO2 : mechanisms and environmental interactions. Plant Cell and Environment 30: 258-270. doi:10.1111/j.1365-3040.2007.01641.x.
Akbari, H. 2005. Energy saving potentials and air quality benefits of urban heat island mitigation. Ernest Orlando Lawrence Berkeley NationalLaboratory, Berkeley, CA (US).
Andruk, C.M., C. Schwope and N.L. Fowler. 2014. The joint effects of fire and herbivory on hardwood regeneration in central Texas woodlands. Forest Ecology and Management 334: 193-200. doi:10.1016/j.foreco.2014.08.037.
Appel, D.N. 1995. The Oak Wilt Enigma: Perspectives from the Texas Epidemic. Annual Review of Phytopathology 33: 103-118. doi:10.1146/annurev.py.33.090195.000535.
Austin, C.o. 2019. Urban Heat Island: City of Austin.
Bender, M.A., T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner, et al. 2010. Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. Science 327: 454. doi:10.1126/science.1180568.
Bobbink, R., K. Hicks, J. Galloway, T. Spranger, R. Alkemade, M. Ashmore, et al. 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecological Applications 20: 30-59. doi:10.1890/08-1140.1.
Borchert, R., K. Robertson, M.D. Schwartz and G. Williams-Linera. 2005. Phenology of temperate trees in tropical climates. International Journal of Biometeorology 50: 57-65.
Bradley, B.A., D.S. Wilcove and M. Oppenheimer. 2010. Climate change increases risk of plant invasion in the Eastern United States. Biological Invasions 12: 1855-1872. doi:10.1007/s10530-009-9597-y.
Bratkovich, S., L. Burban, S. Katovich, C. Locey, J. Pokorny and R. Wiest. 1993. Flooding and its effect on trees.
Christian, J., K. Christian and J.B. Basara. 2015. Drought and Pluvial Dipole Events within the Great Plains of the United States. Journal of Applied Meteorology and Climatology 54: 1886-1898. doi:10.1175/jamc-d-15-0002.1.
Delgado-Baquerizo, M., F.T. Maestre, A. Gallardo, M.A. Bowker, M.D. Wallenstein, J.L. Quero, et al. 2013. Decoupling of soil nutrient cycles as a function of aridity in global drylands. Nature 502: 672.
Derner, J.D., C.R. Tischler, H.W. Polley and H.B. Johnson. 2005. Seedling growth of two honey mesquite varieties under CO2 enrichment. Rangeland Ecology & Management 58: 292-298. doi:10.2111/1551-5028(2005)58[292:sgothm]2.0.co;2.
Drees, B.M., J.A. Jacman and M.E. Merchant. Wood-boring

insects of trees and shrubs. Texas

A&M Agrilife Extention, College

Station, TX.
Duryea, M.L., E. Kampf and R.C. Littell. 2007. Hurricanes and the urban forest: I. Effects on southeastern United States coastal plain tree species. Arboriculture and Urban Forestry 33: 83.
Gan, J., J.H. Miller, H. Wang and J.W. Taylor. 2009. Invasion of tallow tree into southern US forests: influencing factors and implications for mitigation. Canadian Journal of Forest Research 39: 1346-1356. doi:10.1139/X09-058.
Group, C.R.R. 2018. WHEN IS DROUGHT NOT A DROUGHT?

DROUGHT, ARIDIFICATION, AND THE "NEW NORMAL".

Hegewisch, K.C., J.T. Abatzoglou, O. Chedwiggen and B. Nijssen. 2019. Climate Mapper web tool: NW Climate Toolbox

Hollis, G.E. 1975. The effect of urbanization on floods of different recurrence interval. Water Resources Research 11: 431-435.

Howard, Z. 2019. Bacterial leaf scorch in oaks.

information, N.N.C.f.E. 2019. Climate at a Glance: City Time Series.

Jackson, R.B., L.A. Moore, W.A. Hoffmann, W.T. Pockman and C.R. Linder. 1999. Ecosystem rooting depth determined with caves and DNA. Proceedings of the National Academy of Sciences of the United States of America 96: 11387-11392. doi:10.1073/pnas.96.20.11387.

Jacob, D.J. and D.A. Winner. 2009. Effect of climate change on air quality. Atmospheric Environment 43: 51-63. doi:10.1016/j.atmosenv.2008.09.051.

Litvak, M.E., S. Schwinning and J.L. Heilman. 2011. Woody plant rooting depth and ecosystem function of savannas: a case study from the Edwards Plateau Karst, Texas. Ecosystem Function in savannas 117: 134.

Mcbride, S. and D. Appel. 2009. *Understanding, Recognizing and Keeping Hypoxylon Canker of Oaks at Bay* . . Texas AgriLife Extension Service.

McCaw, W.M. 2012. Sequestration vs. Emissions: on the Carbon Sequestration Potential of the Natural Areas of the City of Austin, Texas. Natural Areas Journal 32: 86-95. doi:10.3375/043.032.0110.

Mishra, V., A.R. Ganguly, B. Nijssen and D.P. Lettenmaier. 2015. Changes in observed climate extremes in global urban areas. Environmental Research Letters 10: 024005.

NOAA. 2019. Data Tools: 1981-2010 Normals.

Nowak, D.J., A.R. Bodine, R.E. Hoehn, C.B. Edgar, D.R. Hartel, T.W. Lister, et al. 2016. Austin's urban forest, 2014. Resource Bulletin NRS-100. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station. 55 p. http://dx. doi. org/10.2737/NRS-RB-100 100: 1-55.

Pardo, L.H., M.E. Fenn, C.L. Goodale, L.H. Geiser, C.T. Driscoll, E.B. Allen, et al. 2011. Effects of nitrogen deposition and empirical nitrogen critical loads for ecoregions of the United States. Ecological Applications 21: 3049-3082. doi:10.1890/10-2341.1.

Perica, S., S. Pavlovic, M. St. Laurent, C. Trypaluk, D. Unruh and O. Wilhite. 2018. Precipitation-Frequency Atlas of the

United States: Texas. In: N. O. a. A. Administration, editor Sliver Spring, MD. p. 283.

Polley, H.W., D.M. Johnson and R.B. Jackson. 2018. Projected drought effects on the demography of Ashe juniper populations inferred from remote measurements of tree canopies. Plant Ecology 219: 1259-1267. doi:10.1007/s11258-018-0876-5.

Polley, H.W., C.R. Tischler, H.B. Johnson and J.D. Derner. 2002. Growth rate and survivorship of drought: CO2 effects on the presumed tradeoff in seedlings of five woody legumes. Tree Physiology 22: 383-391.

Porter, E.M., W.D. Bowman, C.M. Clark, J.E. Compton, L.H. Pardo and J.L. Soong. 2013. Interactive effects of anthropogenic nitrogen enrichment and climate change on terrestrial and aquatic biodiversity. Biogeochemistry 114: 93-120. doi:10.1007/s10533-012-9803-3.

Reitze Jr, A.W. 2015. The National Ambient Air Quality Standards for Ozone. Ariz. J. Envtl. L. & Pol'y 6: 420.

Rotach, M.W. 1995. PROFILES OF TURBULENCE STATISTICS IN AND ABOVE AN URBAN STREET CANYON. Atmospheric Environment 29: 1473-1486. doi:10.1016/1352-2310(95)00084-c.

Russell, F.L. and N.L. Fowler. 2004. Effects of white-tailed deer on the population dynamics of acorns, seedlings and small saplings of Quercus buckleyi. Plant Ecology 173: 59-72. doi:10.1023/b:vege.0000026329.47461.99.

Schwantes, A.M., J.J. Swenson, M. Gonzalez-Roglich, D.M. Johnson, J.C. Domec and R.B. Jackson. 2017. Measuring canopy loss and climatic thresholds from an extreme drought along a fivefold precipitation gradient across Texas. Global Change Biology 23: 5120-5135. doi:10.1111/gcb.13775.

Seager, R., N. Lis, J. Feldman, M. Ting, A.P. Williams, J. Nakamura, et al. 2018. Whither the 100th Meridian? The once and future physical and human geography of America’s arid–humid divide. Part I: The story so far. Earth Interactions 22: 1-22.

Snow, N.P., M.A. Jarzyna and K.C. VerCauteren. 2017. Interpreting and predicting the spread of invasive wild pigs. Journal of Applied Ecology 54: 2022-2032. doi:10.1111/1365-2664.12866.

Society, N.A. 2013. Developing

a Management Model of the Effects of Future Climate Change on Species: A Tool

for the Landscape Conservation Cooperatives. p. 258.
Stambaugh, M.C., R.P. Guyette, E.D. Stroh, M.A. Struckhoff and J.B. Whittier. 2018. Future southcentral US wildfire probability due to climate change. Climatic Change 147: 617-631. doi:10.1007/s10584-018-2156-8.
Stewart, L.R., M.L. Morrison, D.N. Appel and R.N. Wilkins. 2014. Spatial and Temporal Distribution of Oak Wilt in Golden-Cheeked Warbler Habitat. Wildlife Society Bulletin 38: 288-296. doi:10.1002/wsb.395.
Tischler, C.R., J.D. Derner, H.W. Polley and H.B. Johnson. 2004. Responses of seedlings of five woody species to carbon dioxide enrichment. Hild, Ann L.; Shaw, Nancy L.; Meyer, Susan E: 12-16.
USDA. 2012. USDA Plant Hardiness Zone Map.
USGCRP. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. In: D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, Stewart and B.C., editors, U.S. Global Change Research Program, Washington, DC, USA. p. 1515.
Wang, H.-H., W.E. Grant, T.M. Swannack, J. Gan, W.E. Rogers, T.E. Koralewski, et al. 2011. Predicted range expansion of Chinese tallow tree (Triadica sebifera) in forestlands of the southern United States. Diversity and Distributions 17: 552-565. doi:10.1111/j.1472-4642.2011.00760.x.
Wilby, R.L. 2008. Constructing climate change scenarios of urban heat island intensity and air quality. Environment and Planning B: Planning and Design 35: 902-919.