A Framework for Tree Species Selection in Austin

Topics in Sustainable Development

University of Texas School of Architecture
Spring 2014

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Introduction

The City of Austin sits at the convergence of two distinct ecosystems: the Edwards Plateau to the west, and the Blackland Prairie to the east. The karst limestone formations and varied topography of the former, and the rich soils and rolling hills of the latter, make for a unique distribution of vegetation which has evolved over time in response to changes in land use and population dynamics.

In upcoming years, the southwestern United States (where Austin is located) is expected to become hotter and drier. The region may experience temperature increases exceeding the predicted average rise globally, with decreased annual precipitation between 10 and 30% (Fettig et al., 2013). The climatic envelope of temperature range in which the regional ecosystem thrives will shift geographically, moving north and to higher elevations. When such changes occur, Austin will be situated in a new, warmer and drier climatic envelope unsuitable for many species currently growing in the area. These climate conditions subject trees to a number of stressors; trees can die during droughts due to hydraulic failure, and they can become less resistant to pathogens, resulting in greater forest mortality. These changes could dramatically alter the composition and structure of Austin's urban forests in the coming century.

A significant loss of canopy cover could have economic repercussions. Losing trees means losing the benefits trees provide; the growth of the metro area could stagnate if Austin becomes hotter and simultaneously loses large areas of shade. In 2014, Austin was named a top ten Urban Forest City by American Forests, which cited its park acre to resident ratio and its urban forest master plan as reasons for the recognition. Austin was also named America's fastest growing city by Forbes in 2013. While Austin's population has grown for a number of reasons, researchers have found that many urban residents recognize and appreciate the services trees provide. Pataki, McCarthy, Gillespie, Jenerette, and Pincetl (2013) found that Los Angeles residents strongly prioritized desirable trait-based tree services like shade, tree size, and tree water usage. Residents also had a general awareness and appreciation of trees' value to the landscape.

Urban forests can contribute to a city's long-term sustainability. According to the Brundtland Report's classic definition, "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Cities have promoted urban forests' potential to decrease stormwater runoff (and lower flood risk), to improve water quality, to sequester carbon, and to help mitigate the urban heat island effect (UFMP, 2014), all of which might positively impact urban residents' lives. And unlike traditional infrastructure, an urban forest can increase in value and service level over time (though not without effective management and maintenance), which makes urban forests an especially attractive option to cities like Austin that explicitly identify sustainability as a goal.

Urban forests need effective management in order to provide desired benefits. The management of Austin's urban forest becomes especially critical in light of the forest's potential to attract new residents and its contribution to the city's sustainability. Forest managers must consider increased threats to the forest from future climate change.

Different stakeholders get different utility from urban forests. A city has to consider all perspectives when attempting to maximize the benefits its forest provides. This paper examines the following question: what tree species are both ecologically viable and managerial feasible for Austin's urban forest? To provide an informed context for answering this question, we investigate the economic constraints, ecological considerations, political processes and cultural preferences that influence the city's urban forest.

Literature Review

To prepare to investigate which tree species would be ecologically viable and managerially feasible in a potentially hotter, drier Austin, we looked at literature on three key themes:

- Green infrastructure
- Urban forests
- Novel systems

We selected these areas as our research base because in the urban context, trees and the ecological services they provide can be viewed through the lens of green infrastructure. Because urban forests are a form of green infrastructure, and because they face distinct ecological and managerial challenges, we also decided to incorporate literature specific to urban forests. Finally, because of the differences in these urban sites relative to natural sites in the region, we also explored the literature on novel systems. The ecological shifts associated with climate change make novel systems literature especially relevant.

Green Infrastructure

"Green infrastructure" has developed as a term to describe living systems that are integrated into the built environment, and that provide services to the people living in that environment (Lovell & Taylor, 2013; Madureira & Andresen, 2014). Green infrastructure stands in contrast to grey infrastructure, which denotes conventional single-function systems like storm sewers and power lines. In contrast to static grey infrastructure, green infrastructure is multifunctional; it can provide more than one service at a time (Austin, 2014), helping to mitigate negative consequences of urban design like pollution, flooding, and the urban heat island effect (Hirokawa, 2012; Newell et al., 2013). Green infrastructure adapts more effectively to change and requires less intensive human intervention than its grey counterpart, and facilitates vital urban processes and interactions (Mell, 2009; Austin, 2014). Through biological processes, trees in the urban forest provide shade and sequester atmospheric carbon. They ensure that elements of the larger system—such as water and carbon emissions—are conveyed to places where they are best suited (Mell, 2009; Hirokawa, 2012).

Green infrastructure uses biophysical processes and biota to achieve desired performance measures, from sequestering carbon as a climate mitigation strategy to capturing stormwater to reduce flood risk. It encourages land use practices focused on interconnectivity, sustainability, and support for all life (M'Ikiugu et al., 2012). This approach to urban development uses the natural landscape and existing biophysical processes to meet human needs, while also preserving an urban landscape's ability to support non-human life (Benedict & McMahon, 2006). These human and non-human needs do not necessarily conflict (Kambites & Owen, 2006). While green infrastructure is often used to contain urban sprawl (Benedict & McMahon, 2006; Amati & Taylor, 2010), planners can integrate green space into the urban core by utilizing already existing natural elements (Amati & Taylor, 2010) or by retrofitting urban landscapes (Mell, 2009; Pugh et al., 2012) using strategies such as alley greening (Newell et al., 2013) and street tree planting (Pugh et al., 2012).

Table 1: Green infrastructure: definitions and forms of implementation

Definitions	"Green infrastructure is taken, therefore, to encompass connected networks of multifunctional, predominantly unbuilt, space that supports both ecological and social activities and processes." *Kambites & Owen, 2006* "Green infrastructure… is a scientific approach to determining the best use of the land to support both the natural processes that exist on the landscape and the infrastructure and recreational needs of the people who live there." *Benedict & McMahon, 2006* "Natural or built ecosystems, elements, and concepts that encourage land-use planning and practices that focus on interconnectivity to support sustainability and confer life support benefits to nature and people." *M'Ikiugu et al., 2012* "Urban biophysical networks... that provide ecosystem services critical to enhancing cities' resilience." *Schäffler & Swilling, 2013* "An approach that focuses on supporting different interests by maintaining landscape resources across urban, urban-fringe and rural areas in order to develop resilient landscapes that support ecological, economic, and human interests by maintaining the integrity of, and promoting landscape connectivity, whilst enhancing the quality of life, place and the environment across different landscape boundaries." *Mell, 2009* "A continuous network of corridors and spaces, planned and managed to sustain healthy ecosystem functions"; its "context… is suburban and urban, but optimally connects to wild nature and fully functioning ecosystems." *Austin, 2014*
Forms	Urban forests (street trees, woodlands), greenbelts, greenways (trails, wildlife corridors), green roofs, green walls, alley greening, green streets, gardens, urban agriculture, parks, wildlife refuges/nature preserves, waterways (rivers, streams), wetlands, permeable paving, renewable energy facilities, rainwater harvesting and storage facilities, bioswales, vegetation, vacant lots, yards

Green infrastructure is strategically planned and managed, and is often conceptualized as a network that connects natural spaces fragmented by urban growth (M'Ikiugu et al., 2012; Benedict & McMahon, 2006; Lovell & Taylor, 2013). Unplanned open space in public and private realms, such as domestic gardens and vacant lots, can also be considered green infrastructure (Lovell & Taylor, 2013). An integrated planning approach at the community or regional level is vital to incorporate green infrastructure into the urban environment in ways that simultaneously enhance the viability of human and natural activity, and balance the requirements and values of different stakeholders (Kambites & Owen, 2006; Hirokawa, 2012; Newell et al., 2013).

Formal planning considers how a green infrastructure system can become greater than the sum of its parts when its components support one another to provide system-wide benefits (Schäffler & Swilling, 2013). Sometimes planners must prioritize certain ecosystem functions over others, and spatially apply green infrastructure through strategic policy (Madureira & Andresen, 2014; Kousky et al., 2013). The planning participants may include multiple governments whose jurisdictions overlap the planning area (Kambites & Owen, 2006), and various environmental governance groups in the public, private and nonprofit sectors (Young & McPherson, 2013).

At specific sites, green design can increase land use potential (Amati & Taylor, 2010), given the use that planners have designated for the site, and enable more opportunities for natural processes and residents' urban livelihoods to flourish (M'Ikiugu et al., 2012). This reflects the shift in rationale behind green infrastructure planning over time, from original goals of landscape preservation, to the current emphasis on improving urban quality of life (Benedict & McMahon, 2006). Thus, green infrastructure promotes the resilience and renewal of urban systems by using natural resources more efficiently, productively, and positively (Mell, 2009; M'Ikiugu et al., 2012).

A core consideration for planners is to develop and maintain urban forests to reap tree-based benefits that include shade, recreational retreat, wildlife habitat, air pollutant removal, and increased property values (Hirokawa, 2012). Such benefits, especially those that offer relief from intense urban activity, are crucial for cities such as Austin that are predicted to be hotter and drier in the near future (Jiang & Yang, 2012). However, the literature still lacks empirical assessments of the ability of landscapes, including urban forests, to provide these services under rapidly changing environmental conditions. Thus, the continued functionality of urban forests over the long-term is unclear given current design, maintenance, and municipal investment practices.

Multifunctionality

The numerous benefits provided by biogenic green infrastructure (including urban trees), positively affect the ecological, economic, and social aspects of urban life (Newell et al., 2013; M'Ikiugu et al., 2012; Madureira & Andresen, 2014). For municipalities, designing multifunctional landscapes that complement and often counterbalance existing grey infrastructure can be justified economically. Shrinking city budgets following the 2008 recession (Nelson, 2012), have put pressure on cities like Austin to reduce infrastructure expenditures. Cities increasingly see landscapes that reduce environmental risk and provide many benefits for humans and the surrounding ecosystem as win-win propositions (Kousky et al., 2013). They are harnessing green infrastructure as a tool for adapting to future environmental problems like increased urban temperatures or pollution (Lovell & Taylor, 2013; Kousky et al., 2013).

Green infrastructure affects communities in different ways and at multiple scales (Mell, 2009), providing different services to cities, neighborhoods, and individual homes (Newell et al., 2013). The ecological and social conditions present in a specific setting influence what infrastructure functions are needed and wanted by local residents; communities have to set priorities and establish clear goals for the function of each green infrastructure project. Local site conditions also affect how a piece of a wider green infrastructure network (like an urban forest) performs locally (M'Ikiugu et al., 2012; Pugh et al., 2012). Across different neighborhoods, changing soil quality and plantable space can create different levels of viability for street trees, while residents may express differing levels of favorability toward street trees. Green infrastructure is thus an ecological, economic, and social issue, framed as both a *product* that generates multiple functions and a *process* grounded in the social, political, and ecological dimensions of urban communities (Schäffler & Swilling, 2013).

However, the variable purposes of green infrastructure can also create conflict between different functions (Madureira & Andresen, 2014), and between the goals of different public agencies responsible for regulating and allocating these functions (Newell et al., 2013; M'Ikiugu et al., 2012). For example, a city's interest in stocking trees to promote carbon sequestration and lessen climate change effects can run up against water conservation measures, such as Austin's irrigation restrictions, during periods of drought—which future climate effects may make more severe.

Ecosystem Services

Cities invest in green infrastructure because of the ecosystem services that infrastructure provides. Ecosystem services are defined as any benefit that people obtain from ecosystems (Millennium Ecosystem Assessment, 2005); these are classified as: provisioning services such as food, water, and timber; regulating services that affect climate, floods, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling. While many of these services can be provided by grey infrastructure, green infrastructure is unique in that it is multifunctional, and has the potential to increase in value and provide greater services as time passes (Hirokawa, 2012).

While ecosystems can provide benefits, they can also negatively affect urban environments. Certain kinds of green infrastructure can increase pollen production, aggravating human and animal allergies. Irrigated vegetation can deplete water resources, and urban forests can cause physical damage to people and structures when tree limbs fall during storms. When tree roots damage sidewalks, they can increase a city's liability to trip and fall lawsuits (Lovell and Taylor, 2013; Hirokawa, 2012).

Researchers have evaluated green infrastructure's ability to provide beneficial ecosystem services. Pugh et al. (2012) found that green walls and green roofs reduced concentrations of air pollutants and pollutant deposition rates in dense urban environments with distinct wind patterns through street canyons. Newell et al. (2013) found that green alleys can help to manage stormwater runoff and improve local water quality. Open spaces can reduce flood damages (Kousky et al., 2013), and urban forests provide shade, reduce buildings' cooling costs, provide wildlife habitat, have aesthetic and spiritual value, and can increase property values (Hirokawa, 2012).

Communities are increasingly putting a dollar value on the ecosystem services green infrastructure projects provide (Kousky et al., 2013; Hirokawa, 2012). Monetizing these benefits allows communities to internalize previously externalized costs and gives them the ability to compare costs and benefits. Communities therefore have the ability to assess the expected benefits of a green infrastructure project relative to its costs and cost savings. The city of Austin, for instance, has used the i-Tree Street program to estimate that its street trees provide over ten million dollars in benefits; the city estimates that every dollar it invests in trees produces $9.87 in benefits (Urban Forest Master Plan, 2014).

Governance

Urban environments are both politically and ecologically complex (Madureira and Andresen, 2014). Cities must decide which landscape functions to prioritize, and which infrastructure projects deserve funding; governance therefore critically affects both initial investment in green infrastructure (including urban forests) and that infrastructure's ongoing management and maintenance. The urban and metropolitan governance structures responsible for the management of green infrastructure must balance the functionality, maintenance, and planning of these systems. Much of the complexity in urban governance of green infrastructure stems from the need to design and plan in relation to other infrastructure in a rapidly-changing landscape. Green infrastructure in urban environments crosses boundaries between public and private land, spanning multiple legal and policy realms (Young & McPherson, 2013). Finally, governance strategies are constrained by perceptions of value, political support, and financial and environmental resource uncertainty (Young & McPherson, 2013).

Research on green infrastructure has assessed the transparency, accountability, and capacity of local governments and governance strategies in managing green infrastructure. In municipalities, urban governance roles are typically filled by public sector bodies (Newell et al., 2013, Young & McPherson, 2013) rather than private or non-profit entities. Public sector governance is often housed in city parks departments, but management and oversight can also come from mayoral offices and advisory boards (Young & McPherson, 2013). Governance strategies includes protecting green infrastructure with police power, developing green infrastructure strategic plans to gain consensus in local communities, designing regulations through city-wide programs, permits, and overlay zones, and coordinating regulation with other programs such as stormwater control, neighborhood revitalization, and habitat protection (Hirokawa, 2012).

Municipal departments involved in green infrastructure governance often hold divergent perspectives on the value of green infrastructure (M'Ikiugu et al., 2012). Differing perceptions of the economic, social, and environmental value of trees also influences political and budgetary support for green infrastructure initiatives. Because green infrastructure provides multifunctional services, managing it is more complicated than managing traditional grey infrastructure. Regulating green infrastructure requires institutional integration across diverse city departments, and between public and private actors (Young & McPherson, 2013, Mell, 2009). Research suggests that effective governance requires coordination between government agencies, advocacy groups, and the community (Newell et al., 2013) and that community-based governance structure may support a green infrastructure system that provides a more equitable distribution of benefits (Lovell & Taylor, 2013).

In an era of diminishing public financial resources, municipal governance and public sector management may not be economically feasible. Recently, large green infrastructure initiatives in urban centers, like PlaNYC and the Los Angeles Million Tree program, have relied on public-private partnerships (PPP) to address economic challenges. PPPs require an integrated approach to green infrastructure planning and management, and treat green infrastructure as a municipal financial investment where costs and benefits are shared (Young & McPherson, 2013, Kousky et al., 2013).

Urban Forests

One of the most visible forms of green infrastructure, and one that has garnered significant attention in large American cities in recent years, is the urban forest. The US Census Bureau applies the term ‘urban’ to geographic areas bounded by municipal jurisdiction that have a population exceeding 50,000 (US Census Bureau, 2013). Cities have placed particular importance on the economic benefits and ecosystem services that urban forests provide. Municipalities manage urban forests with ordinances regulating the quantity, type, health, and distribution of tree populations on public and private land (Hirokawa, 2012). Be it in millennium tree planting initiatives (Young & McPherson, 2013), forest master plans (Austin Urban Forest Plan, 2014), or municipal strategic plans (Imagine Austin, 2012), urban forests and urban forestry have increasingly been targeted as worthy candidates of focus and funding. The functions, benefits, and governance needs of urban forests can differ greatly from those of other forms of green infrastructure, and between varying urban environments (Pincetl, 2010).

An urban forest is more than just a collection of trees; municipal policies and plans can define urban forests to include all public or 'community vegetation and green spaces' within a city, and their 'associated resources' (Sustainable Urban Forest Coalition, 2013; Nowak, 2005; Austin Urban Forest Plan, 2014). Communities manage these natural resources through the practice of urban forestry, which works to maintain and enhance the health, extent, and targeted benefits of urban forests (Nowak, 2010).

The rise in municipal policy, planning, and management related to urban forests is driven by the assumption that forests have the capacity to provide extensive ecological, sociocultural and economic benefits to cities, and that these benefits exceed potential liabilities (McPherson note 11 in Hirokawa, 2012). Urban forests have been designated by municipalities as capable of providing wildlife habitat, heat island mitigation, stormwater management, air pollution reduction, and carbon sequestration (Lawrence, 1993; Bartens, 2009; Hirokawa, 2012). Urban forests can also reduce crime (Troy, 2012), increase property values (Kadish, 2012), and add to the overall aesthetic quality of the urban realm.

While claims about urban forests' benefits are widespread (Hirokawa, 2012; Austin Urban Forest Plan, 2014), the benefits actually delivered by forests are often difficult to demonstrate empirically (Dobbs, 2011). Recent studies have challenged trees' capacity to filter air pollution (Pataki, et al., 2011), and have suggested that the urban forest's ability to 'climate proof' is limited (Hall, 2012).

There are several additional challenges and disservices that are not always considered in municipal urban forest planning. Forests require water and energy inputs, and can have substantial financial costs. Trees have to be purchased, pruned, nourished, removed, and disposed of. This involves monetary expenditures for human labor, as well as the cost and maintenance of the equipment necessary to perform these duties. Furthermore, the root and branching structures of trees affect infrastructure above and below ground; these effects incur costs in the preventative maintenance of trees and in the repair to damaged infrastructure. Trees can also impose liability burdens on cities (McPherson et al., 2005).

From an ecological perspective, trees generate green waste or leaf litter, which adds to the cost of maintenance. Trees can emit volatile organic compounds (VOCs), which can increase ground-level ozone concentrations, and they produce pollen, which can induce allergies. (Escobedo, 2011; Hirokawa, 2013). The use of scarce water resources to sustain urban forests in arid environments raises additional ecological concerns (in addition to the economic costs of watering trees). Trees are a tax on the water resources of a city; also, the fertilizer used to help develop healthy forest stands in urban environments can negatively affect the water quality of local stormwater runoff.

From a social standpoint, cultural attitudes frame whether urban forests are perceived as assets or nuisances. Troy (2012) found a set of correlations between trees and crime rates: some species and vegetation structures had negative correlations to crime, whereas others had positive correlations (Troy, 2012).

As cities begin to think of trees as infrastructure rather than decoration, their management approach will change. Like more traditional infrastructure, urban forests require planning. Cities have a range of management tools available to them, including street tree programs, tree removal permits, requirements for landscaping plans, and ordinances to protect trees during construction. While cities certainly have the capacity to manage trees located on public land, U.S. courts have also upheld well-designed ordinances for preserving trees on private land (Hirokawa, 2012). Ordonez et al. (2012) suggested that successful management should be guided by metrics like ecosystem health, biodiversity, and resilience, instead of being guided exclusively by canopy cover area. Managers must consider which tree species are best adapted for a specific environment (McCarthy et al., 2010). Urban foresters and arborists have typically encouraged the planting of native species, but there is current debate over whether that approach will remain viable in an era of changing climate.

Novelty is the New Normal

As a result of human activity, landscapes are currently undergoing unprecedented transformations (Foley, Defries, & Asner, 2005; Lugo, Carlo, & Wunderle, 2012; Parmesan, 2006; Williams and Jackson, 2007), characterized by the decoupling of historic ecological relationships and interactions, resulting in the emergence of new, previously unseen ecological communities (Higgs, 2012; Hobbs, Arico, & Aronson, 2006; Hobbs, Higgs, & Hall, 2013; Lindenmayer et al., 2008; Suding & Leger, 2012; Williams and Jackson 2007). The relationships within trophic webs and the interactions between species are being re-configured due to changing local climate regimes, new chemical inputs, and new (or introduced) species (Seastedt, Hobbs, & Suding, 2008). Novel communities (Williams and Jackson, 2007), are compositionally unlike any found today, falling outside the conventional gradient of pristine to degraded ecosystems (Lindenmayer et al., 2008).

Earth is no stranger to change—novel communities are not unique contemporary phenomena. Species have migrated and expanded their home ranges over the last 18,000 years, moving at different rates and directions during interglacial transitions (Overpeck, Bartlein, & Webb, 1991). The resulting landscapes possess unique plant communities without historic precedents (Lindenmayer et al., 2008), indicating that even in the absence of human intervention, landscapes cyclically transition from known, to hybrid, to fully novel systems. Recent estimates claim novel landscapes cover approximately 35% of the globe (based on urban and agricultural land uses) (Marris, 2009), and are predicted to increase most notably in tropical and subtropical region by 2100 under various International Panel on Climate Change (IPCC) climate scenarios (Williams & Jackson, 2007).

Current landscape change is distinguished from historical landscape change based on: (a) faster rates of change due to anthropocentric drivers (e.g., carbon emissions), (b) increased intensities of chemical inputs (fertilizers, pollutants), and (c) expanding spatial patterns of landscape fragmentation due to development. In the contemporary context, ecologists predict that novel landscapes will become the new normal (Williams & Jackson, 2007).

Ecosystem novelty is particularly relevant to urban foresters because urban ecosystems are already fundamentally altered sites (Kowarik, 2011). Urban ecosystems have typically been subjected to increased forces of climate change, microclimate effects, pollution, and anthropogenic use (Hobbs et al. 2009; Kaye et al. 2006). These forces can fundamentally alter ecosystem dynamics in urban sites, creating purely novel systems through both biotic and abiotic shifts (Hobbs et al. 2009).

Some scholars argue that ecologists should accept novelty as a fact due to an ever-changing global ecology in which species composition shifts with environmental changes (Starzomski, 2013). This is particularly true in light of the rapid rate of climate change the planet is currently undergoing (Kaye et al. 2006). If urban ecologists can expect novelty to be the new normal, then they may need to consider how the forces that create novel landscapes affect the suitability of species, both native and nonnative, in the urban ecosystem (Fettig et al. 2013), and shift the focus away from native tree species to species that provide specific, desired ecological functions.

Conservation vs. Performance

Researchers acknowledge the dilemma posed by novel ecosystems. There is a choice between either pursuing traditional species conservation, or optimizing ecosystem performance. These two ideals cannot co-exist, as engineering a novel ecosystem to maintain its original species balance (i.e. conservation) could potentially cause environmental disruption and, therefore, decreased ecosystem performance. In spaces where physical, chemical, and biological changes have made a landscape partially or wholly uninhabitable to native species, returning to an all-native regime would be impossible. For example, non-native species that now hold an essential place in the food chain cannot be readily removed without harming others that now rely on those species for food or habitat (Hobbs et al. 2009).

Many intervention ecologists consider cities to be fundamentally altered sites, and argue that cities and urban forests should be planned for and managed with a strong focus on function, and less of a focus on native species conservation. These researchers argue that green infrastructure and ecological restoration projects should be developed with an understanding of and respect for how non-native species contribute to urban ecosystems—specifically, how they provide ecosystem services and social benefits, and how they contribute to biodiversity (Kowarik, 2011). In some cases, non-native species may be better adapted than native plants to rapidly-changing urban conditions (Crooks, 2002). In light of urban growth and the changing climate, novelty cannot be ignored (Starzomski, 2013).

Managing Urban Forests for Function and Performance

New considerations arise when urban forest management is reframed in terms of performance and novelty. The services and sustainability of the ecosystem take precedence over native species composition. Heterogeneity and habitat complexity are emphasized as strategies for ecological viability as well as performance (Crooks, 2002). Species selection is viewed according to ecosystem function, and the fact that some non-native species provide more effective functionality must be acknowledged (Kowarik, 2011; Seastedt et al. 2008). Preserving the ecosystem functions and ensuring the long-term ecological health of a landscape subjected to ongoing environmental change requires advanced planning, including better collaboration between land managers, scientists, and policy makers (Seastedt et al. 2008).

Communities can use cost-benefit analyses to assess the performance of specific tree species and the capacities of local jurisdictions to manage for specified performance levels (e.g., total amount of atmospheric carbon sequestered) (Belnap et al. 2012). These economic analyses are similar to those that cities use to determine the return on investment for grey infrastructure. However, CBAs can also assess trees' provision of services not typically associated with conventional infrastructure; residents may prioritize trees for their beauty, ease of maintenance, fruit production, and their effects on line of sight/privacy. Economic analyses can strategically value species' physiological traits in light of these priorities (Pataki et al. 2013).

To better prepare urban planners as their cities undergo major landscape management projects in the 21st century, more research is needed on how urban systems affect ecosystem novelty (Kaye et al. 2006; Crooks, 2002). Also needed is a better understanding of the regional transformations that will take place due to ongoing climate change (Fettig et al., 2013). Redefining urban landscapes as inherently novel (Kaye et al. 2006; Kowrik, 2011) and acknowledging climate change as a major factor in the development of novel ecosystems over the coming century (Starzomski, 2013) would help inform urban forest management decisions, and potentially result in an urban forest more in tune with the aesthetic desires, stakeholder priorities, and structural necessities of Austin.

Research Design

Our research questions are as follows:

- What tree species can be considered ecologically viable – that is, able to persist under future conditions of urban growth and climatic variability in the Austin greater metropolitan region?
- What tree species can Austin feasibly maintain, manage, and regulate under current and future conditions of urban growth and climatic variability?
- What are novel systems, and how might an urban forest become novel? How might the concept of novelty impact how cities invest in, regulate, design, and manage urban forests?

Methods

We used a mixed methods research design to approach these questions. Our methods included archival research, interviews with individuals and organizations involved with Austin's urban forests, and geospatial mapping of the Austin area.

Archives

We conducted archival research to provide social and historical context for the report. We collected financial data on tree-related expenditures in Austin by both government and private organizations through online public records, websites including Guidestar.org, and direct contact with the organizations. Media articles from the past five years from the Austin American Statesman and press releases from Austin-area nonprofit organizations highlighting drought in Texas were compiled, and we analyzed those media articles for key themes. We used government and online sources to research estimates on tree mortality, and changes in mortality rates in the region. We data mined the United States Forest Service Inventory and Analysis Tool for tree mortality data for the state of Texas from 2008 to 2012. Journal articles housed in the University of Texas Library System provided insight into the main causes of tree mortality in regions such as Austin, as well as which tree and plant species that cities with similar climates are using to replace struggling native species. We further researched potential novel species for the Austin area by exploring the City of Austin's Grow Green program.

Table 2: Archival sources

Financial data	• City of Austin budgetary information, 2010 - 2013 • Draft compilation of tree-related municipal department budgets for the city of Austin, 2014 • Austin Urban Forest Master Plan • Tax form 990 for: • Austin Parks Foundation • TreeFolks • Keep Austin Beautiful • Friends of the Parks of Austin • Town Lake Trail Foundation • Austin Parks Foundation, Future Forests Project Report • Budgetary information from email and/or phone correspondence with: • TreeFolks • Austin Parks Foundation • Barton Creek Greenbelt Guardians • Hill Country Alliance • Austin Heritage Tree Foundation
Media coverage pre- and post-drought	Press Releases from: • The Nature Conservancy • Hill Country Alliance • Hill Country Conservancy • The Ladybird Johnson Wildflower Center • Texas Land Conservancy • Austin American Statesman
Tree mortality information	• Texas A&M Forest Service • United States Forest Service Inventory • Journal Articles in UT Library System • City of Austin Grow Green Program Information • Urban Forest Master Plan • TreeFolks Recommended Plant Documentation
Climate data	• Class Journal Articles • StateImpact Texas (NPR) • Texas Drought Monitor

Interviews

The interview team developed a purposive sampling strategy to identify potential interviewees by targeting individuals and organizations believed to have valuable expertise or information related to our research questions. Nineteen potential interviewees were contacted by email and phone, and we conducted twelve interviews with individuals representing public, private, and nonprofit institutions. The pool of interviewees had diverse professional backgrounds, relationships to the urban forest, and perspectives on how effectively Austin's trees are being managed. They also had different recommendations for optimal strategies for preserving the city's forest. A list of interviewees is provided in table 3.

Table 3: Interviewees

Interviewee	Position Title	Organizational Affiliation
Angela Hanson	Urban Forester	City of Austin (CoA) Parks & Recreation Dept
Greg Mast	Community Forester	TreeFolks (local urban forestry nonprofit)
Daniel Woodroffe	President, Founder, & Lead Designer	dwg. (landscape architecture design firm)
Eric Courchesne	Program Director, Future Forest Project	Austin Parks Foundation
Jim Carse	Assistant Manager of Urban Forestry	UT Sustainability Office
Margaret Valenti	Manager, Austin Community Tree Program	CoA Planning and Development Review Dept
Joanna Wolaver	Executive Director	Shoal Creek Conservancy (local nonprofit)
Matt Hollon	Environmental & Conservation Program Manager	CoA Watershed Protection Dept
Zach Baumer	Austin Climate Program Manager	CoA Office of Sustainability
Keith Mars	City Arborist	CoA Planning and Development Review Dept
Dave Nowak	Project Leader / Research Forester	U.S. Forest Service, Northern Research Station
Patrick Brewer	District Manager, Austin office; ex-chair, CoA Urban Forestry Board	Bartlett Tree Experts (tree care services provider)

We structured our interviews to ensure that we could compare information from interviewees. We asked each interviewee questions that explored topics like: their professional role in relation to urban forests; factors that affect the ecology of Austin's urban trees and their management; the predominant challenges to urban forest vitality in Austin now and in the future; and proven or promising ways to combat those challenges. The core interview questions are provided in Appendix A. Although the interviews were exempt from Institutional Review Board (IRB) requirements and did not require approval, we obtained consent from each interviewee to use their names and responses in the report.

All interviews were audio-recorded, transcribed, and coded. To facilitate the coding process, we used the qualitative data analysis software HyperResearch, which allowed us to aggregate our interview transcriptions, and store codes in a central database. The final database contained 40 different codes grouped under 3 broad categories. Each code was meant to capture interviewees' perspectives on challenges facing Austin's urban forest, the opportunities available for better management and enhancement of urban forest viability, and general observations on the value of the urban forest. The code structure was organized by opportunities, challenges, and observations, as follows:

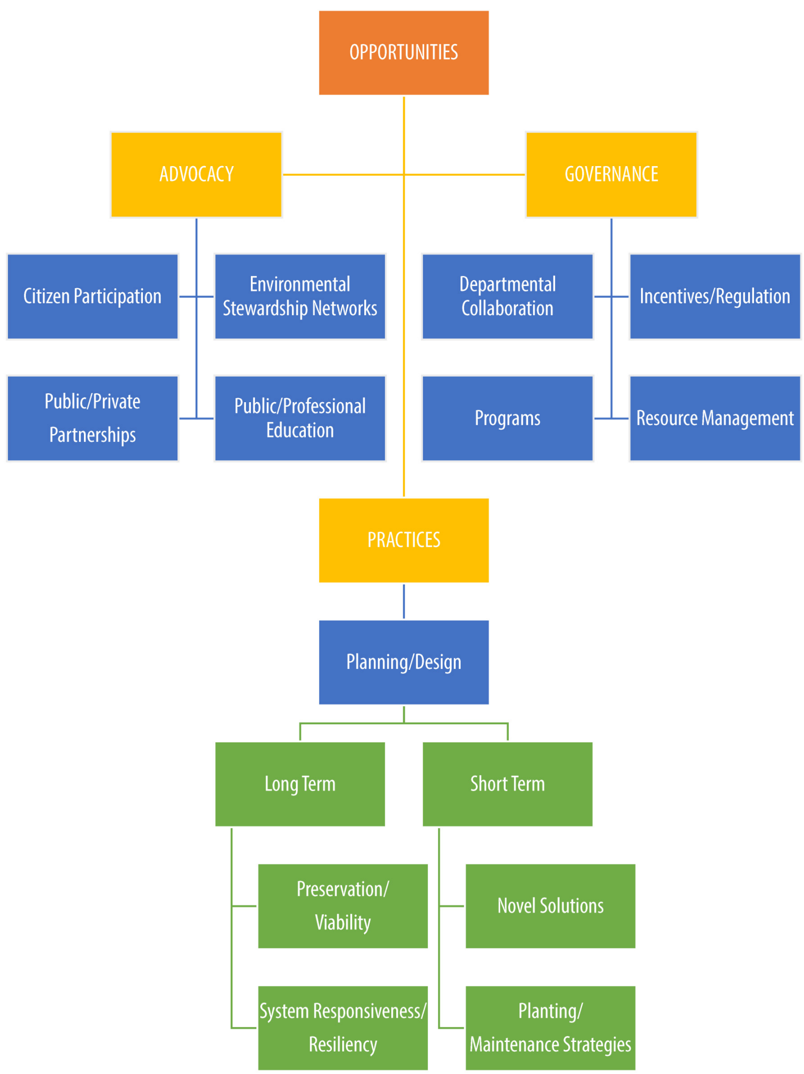

Figure 1- coding structure for opportunities.

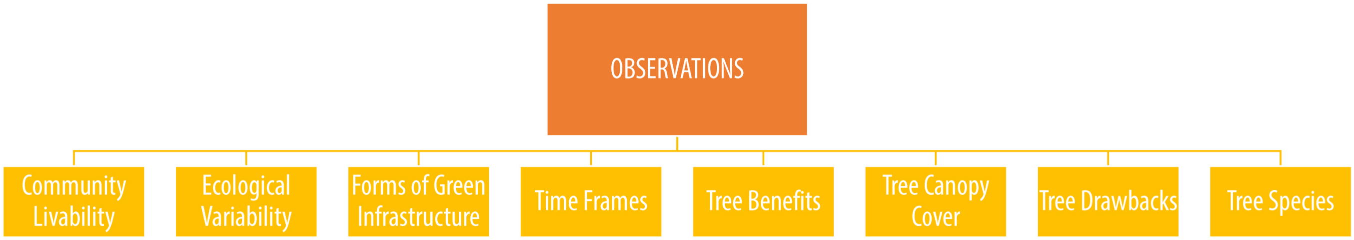

Figure 2- coding of observations.

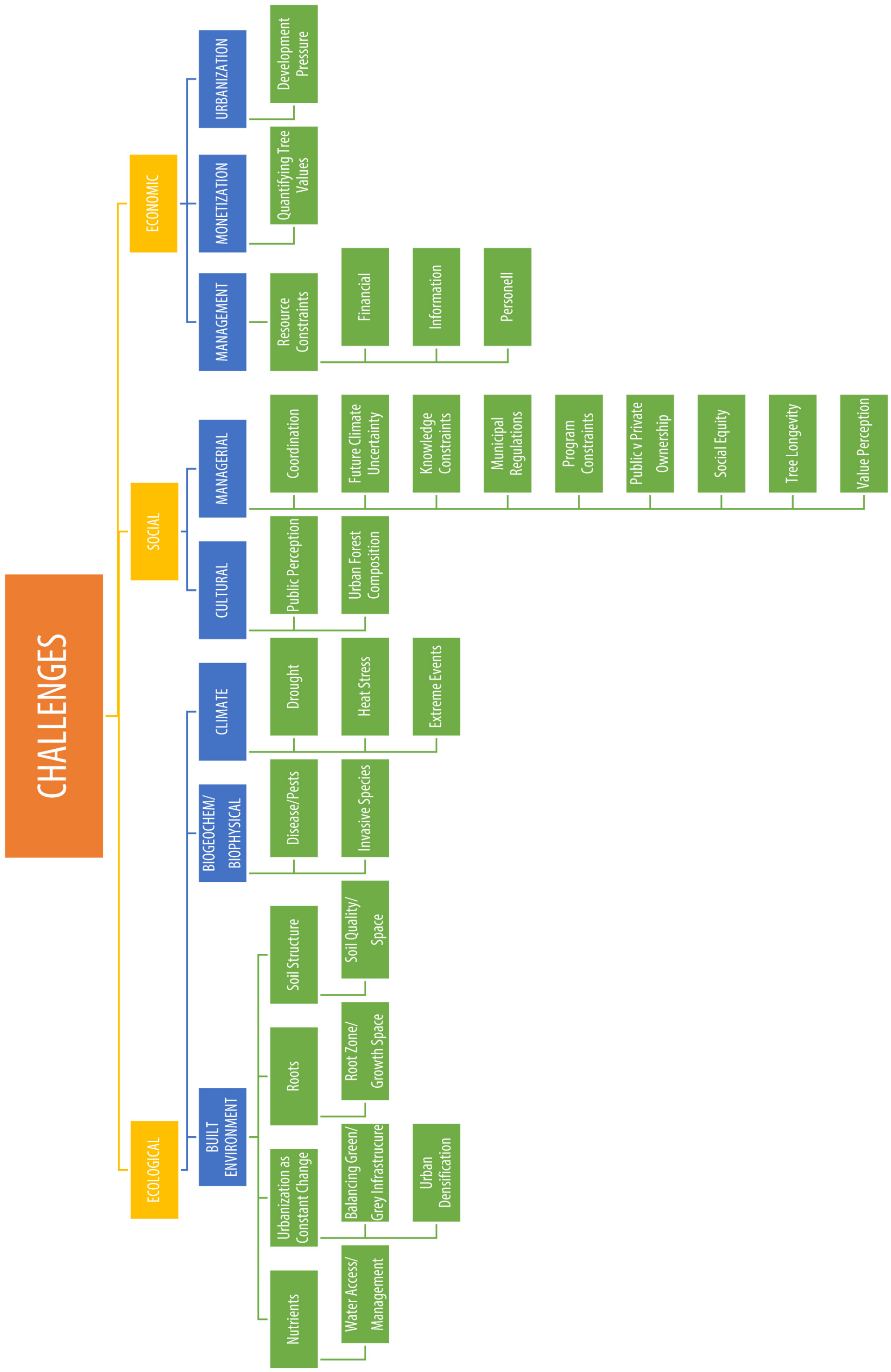

Figure 3- coding of challenges

Geographic Information Systems

We used geospatial analysis to spatially contextualize the distribution of Austin's urban forest, and complement our qualitative archival and observational data. We queried tree canopy cover, land use, and socio-economic data sets to model how land use and ownership might impact ecological viability and managerial feasibility.

We used ArcMap 10.1 to analyze GIS tree canopy cover data from 2006 and 2010. The 2006 and 2010 data sets were produced by the City of Austin Watershed Protection and Development Review Department using ERDAS Imagine and color infrared aerial photography. To limit our data set to land that falls within the City's management scope, we clipped 2006 and 2010 canopy cover shapefiles to Austin's municipal boundary, and excluded land pertaining to Austin's 'ETJ,' or Extraterritorial Jurisdiction[1]. The municipal boundary includes both publicly and privately owned land. We used the municipal boundary to determine the percentage of overall canopy cover for the City by dividing the clipped 2006 and 2010 shapefiles, respectively, by the municipal area.

We performed further analyses to determine percent canopy cover on specific land use types, again using data developed by the City of Austin Watershed Protection and Development Review Department. We determined the geometry of the parcels using the City of Austin's 2003 Land Use Study, City of Austin base map, and county appraisal district GIS and CAD files. 2010 land use was determined using historical data from previous studies (especially 2003), county tax appraisal district information, and aerial photography. We calculated the percentage canopy cover for each land use within the City of Austin municipal boundary by dividing the area of canopy cover (2006 and 2010) on a specific land use type by the aggregate area of all parcels pertaining to that particular land use type.

The specific land uses selected for this study included: single family residence large lot, single family or duplex, multi-family, mobile home, office, commercial, industrial, civic, resource extraction, open space, transportation, streets and roads, undeveloped, utilities, and water, and are elaborated on in table 4.

Table 4: GIS land use data sources

2010 Land Use - *City of Austin*	**Definition** Source: City of Austin Neighborhood Planning Guide to Land Use Standards
Single Family Residence Large Lot	Single Family Residence Large Lot district is intended for a low-density single-family residential use on a lot that is a minimum of 10,000 square feet.
Single Family or Duplex	Single family detached, or two family

[1] The 'ETJ' refers to 'unincorporated land within five miles' of Austin's municipal boundary where the City has the capacity to influence development regulations that might affect 'quality of life,' and where 'Austin alone is authorized to annex land' (http://www.austintexas.gov/faq/extraterritorial-jurisdiction-etj-what-it).

	residential uses at typical urban and/or suburban densities.
Multi-Family	Higher-density housing with 3 or more units on one lot.
Mobile Home	Mobile Home Residence district is intended for a mobile home residence park and mobile home subdivision use.
Office	An area that provides for office uses as a transition from residential to commercial uses, or for large planned office areas. Permitted uses included business, professional, and financial offices as well as offices for individuals and non-profit organizations.
Commercial	Lots or parcels containing retail sales, services, hotel/motels and all recreational services that are predominantly privately owned and operated for profit (for example, theaters and bowling alleys). Included are private institutional uses (convalescent homes and rest homes in which medical or surgical services are not a main function of the institution), but not hospitals.
Industrial	Areas reserved for manufacturing and related uses that provide employment but are generally not compatible with other areas with lower intensity use. Industry includes general warehousing, research and development, and storage of hazardous materials.
Civic	Any site for public or semi-public facilities, including governmental offices, police and fire facilities, hospitals, and public and private schools. Includes major religious facilities and other religious activities that are of a different type and scale than surrounding uses.
Resource Extraction	Resource extraction use is the use of a site for on-site extraction of surface or sub-surface mineral products or natural resources. This use includes quarries, borrow pits, sand or gravel operations, oil or gas extraction, and mining operations.
Open Space	This category allows large public parks and

	recreation areas such as public and private golf courses, trails and easements, drainage-ways and detention basins, and any other public usage of large areas on permanent open land.
Transportation	Areas dedicated to vehicle, air, or rail transportation. These include existing and platted streets, planned and dedicated rights-of-way, and rail and rail facilities.
Streets and Roads	Unspecified
Undeveloped	Unspecified
Utilities	Land used or dedicated for public and private utilities, including pipelines, utility lines, water and wastewater facilities, substations, and telephone.
Water	Any public waters, including lakes, rivers, and creeks.

We also distinguished between canopy coverage on publicly and privately held land using groupings of the general land use types presented in table 4 above, with support from the geospatial data from the City of Austin's GIS database. For the purposes of this investigation, we designated publicly owned land to include City of Austin parks, City of Austin owned land parcels, and public right of ways, whereas we designated privately owned land as mobile homes, single family large lot, single family or duplex, multi-family, industrial, and resource extraction. We calculated combined canopy coverage for both public and privately owned land from 2006 and 2010 canopy coverage data within the City of Austin municipal boundary.

We also analyzed limited demographic data gathered from the American Community Survey 5-year census estimates. We clipped census block groups for Travis County to the Austin municipal limits. We then clipped canopy cover to census block groups, which we further grouped into the following median income buckets: less than $20,000, between $20,000 and $40,000, between $40,000 and $60,000, between $60,000 and $80,000, between $80,000 and $100,000, and over $100,000.

Findings

Through archival, interview, and geospatial research, we have collected data relating to Austin's urban forests. Our data describe the social and ecological importance of trees to Austin's identity. They describe the funding for Austin's urban forests, including funding provided by governmental and non-profit or private entities. They describe Austin's climate, and they describe how canopy cover differs across different land uses and over time. Demographic considerations are briefly discussed, as are the impacts of drought on the urban forest. Finally, we describe some of the long-term challenges facing Austin's urban forests. Our findings are presented below.

Urban Forests: Identity and Governance

The urban forest, and specific trees in particular, feed Austin's sense of identity as a green city in a semi-arid landscape. The Treaty Oak, a live oak said to mark the territorial boundary between European settlers and Native Americans in early Austin, was inducted into the American Forestry Association's Tree Hall of Fame in 1927. When the centuries-old tree was poisoned in 1989, over $100,000 was spent for its treatment and recovery, and the perpetrator was given a nine-year jail sentence (Giedraitis, 1989). Austin adopted a heritage tree ordinance in 2010 to prevent the removal of trees over 24 inches in diameter. The city's comprehensive plan "Imagine Austin" was adopted in 2012. Of eight overarching priorities in the plan, intended to guide all aspects of urban growth for the next 30 years, "green infrastructure to protect environmentally sensitive areas and integrate nature into the city" is number four. Aligned with this vision, Austin's urban forest master plan (UFMP) was formally adopted by the city in March 2014. The UFMP establishes a framework from which to manage the urban forest.

Private entities also work on issues directly and indirectly related to the urban forest. Dozens of non-profits, neighborhood associations, and tree-related foundations work in conjunction with, and sometimes in opposition to, municipal government to preserve and protect the urban forest. Austin Heritage Tree Foundation, for instance, picks up where city regulation leaves off, relocating threatened trees that the organization deems culturally significant, but that are too small to qualify for protection under city ordinance. The organization funds these relocations, which can cost tens of thousands of dollars, through private donations.

Austin's Urban Forest Management and Budget

Determining total expenditures on the urban forest is difficult, as some municipal departments with mandates largely unrelated to trees nevertheless perform activities that affect trees. Examples include the fire department's wildfire fuel reduction program, and public works right-of-way maintenance. Likewise, private organizations focused on environmental issues may impact the urban forest, but do not specifically delineate tree-related work in their budgets. Data compiled by Austin's arborist office estimate that the city spends over $34.4 million dollars on tree-related activities across 18 municipal departments or programs, the largest of which is the Parks and Recreation Department. The four largest non-profit organizations engaged in tree-related activities found in our investigations have a collective budget totaling over $2.1 million dollars, although as mentioned above, not all of this money goes directly to tree management.

While exact expenditure amounts were not discussed in the interviews, the interviewees drew ample attention to the variety of public, private, and nonprofit organizations that play a role in managing Austin's urban forest and the ecosystems of which that forest is a part. They stressed the collaborative effort necessary to effectively manage city trees and preserve the forest as a whole. Multiple city departments—including Parks and Recreation, Watershed Protection, Planning and Development Review, and Public Works—operate programs that affect trees. These public agencies do face financial and staffing constraints that limit their attention to the urban forest. For example, dwg. and Austin Parks Foundation President Daniel Woodroffe stated that "there is a bearing capacity as to what the Parks Department can do . . . they have a set budget that gets cut most years within the General Fund," and noted that the city's few foresters and arborists—though the best in their field—are saddled with management responsibilities that they cannot handle alone. Urban Forestry Board member Patrick Brewer voiced his concern that the city's forestry program manager, Angela Hanson, "doesn't have the staff and hasn't had enough support."

Given these constraints, the city works with nonprofit organizations that are devoted to improving the health of urban ecosystems and their living organisms. TreeFolks leads in this area, partly because its primary mission is to strengthen the urban forest, and its expert staff work directly with trees. Private partners, particularly individual volunteers and property owners, along with concerned businesses, also contribute, although their impacts tend to be smaller.

Environmental stewardship networks, formed by linkages between organizations that protect and promote the community's natural surroundings, are the final piece of the management puzzle. Both Greg Mast and Joanna Wolaver discussed how their organizations thrive on partnerships with other groups with overlapping goals and operating areas; Tree Folks has launched projects with the Texas A&M Forest Service and the National Arbor Day Foundation, among others, while Shoal Creek Conservancy counts among its partners Pease Park Conservancy, the Trail Foundation and TreeFolks. Greg Mast stated that "alone, TreeFolks would not exist, much less succeed."

Austin's Historical Precipitation and Temperature Data

Austin's precipitation and temperature have been relatively stable over the past half-century. According to information from the National Oceanic and Atmospheric Administration, charted in figure 1, precipitation over the past decade and a half has been trending downward; the city has experienced prolonged drought conditions. The average temperature in that time, however, has remained fairly steady.

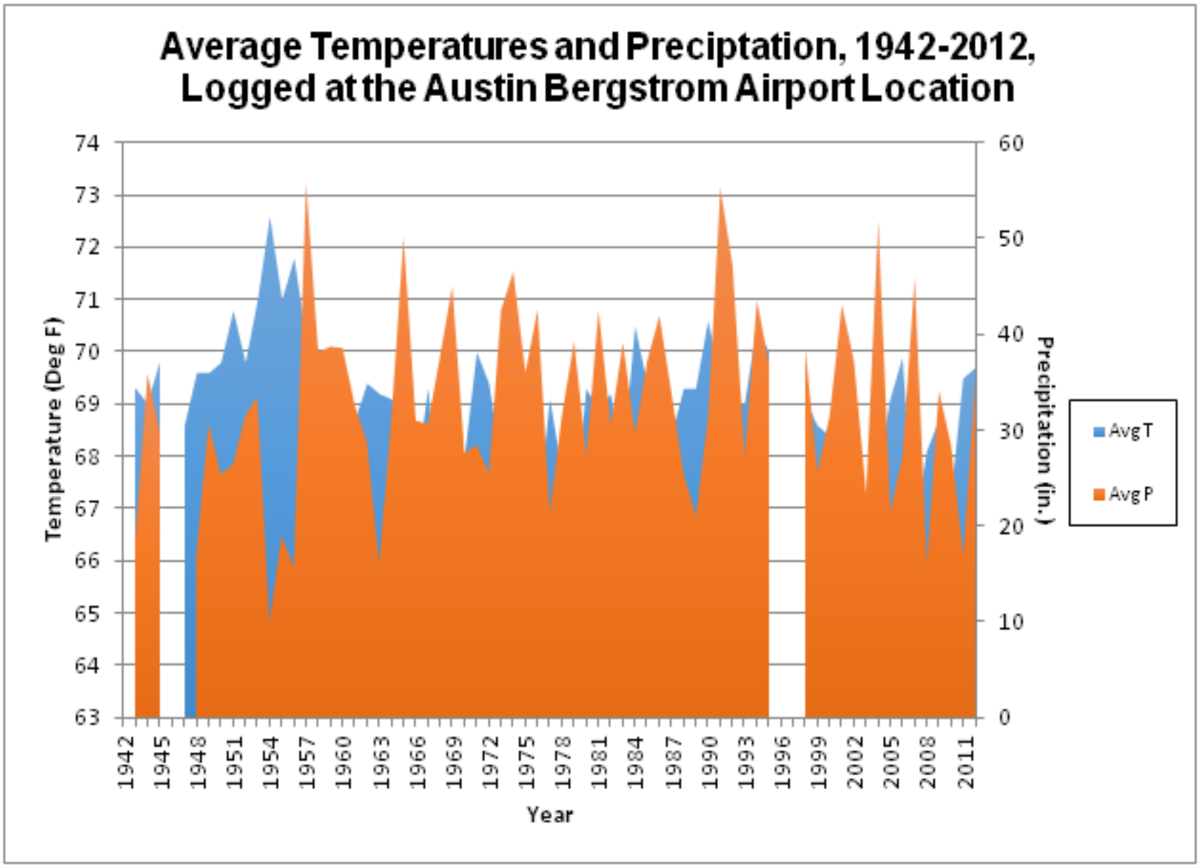

Figure 4- Historical averages for temperature and precipitation in the Austin area (NOAA).

Change Detection Mapping

The geospatial analyses we ran on Austin's urban forest revealed intriguing patterns related to canopy coverage, land use, and ownership within the municipality. Austin has a relatively high percentage of coverage for a city of its size and density, and demonstrated a general increase in coverage between 2006 and 2010. Our analyses indicated that in 2006, tree canopy cover totaled 56,074 acres, which equates to 33.5% of the total land area within the municipal boundary. In 2010, tree canopy cover totaled 61,706 acres, which equates to 36.9% of the total land area. These comparisons revealed a 10% increase in overall canopy coverage from 2006 to 2010. See figures 5 and 6 for canopy cover maps

The 2010 land use data, when mapped in conjunction with canopy coverage from both 2006 and 2010, revealed changes in distribution related to specific land use types. From 2006 to 2010, canopy coverage experienced the greatest increase on transportation (25.2%), open space (23.1%) and undeveloped land (25.9%). This may reflect the capacity and desire of the municipality to amplify tree plantings on publicly held land parcels within those land use types.

Figure 5- 2006 canopy cover maps

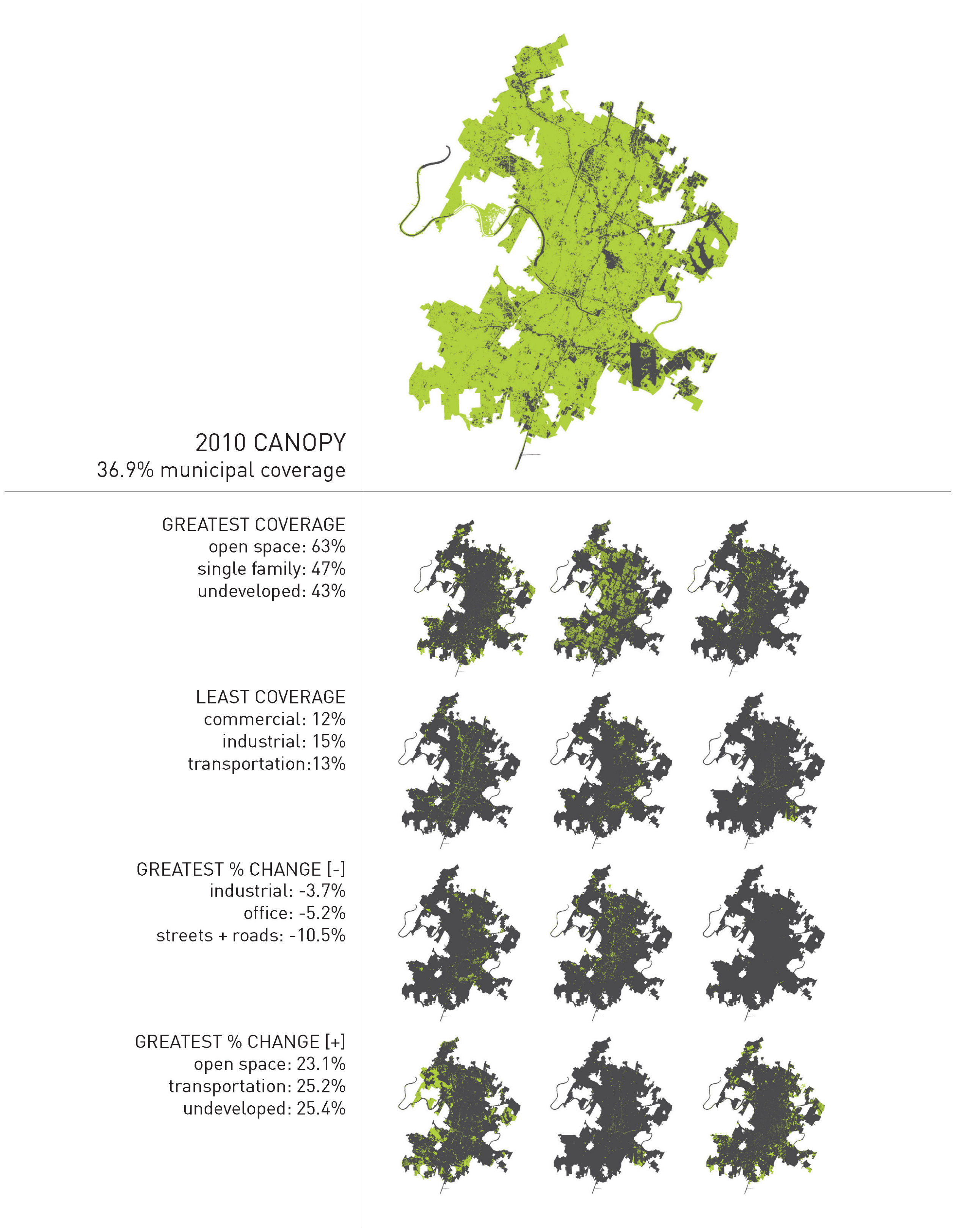

Figure 6- 2010 canopy cover

The land uses which experienced the greatest decrease in canopy coverage were streets and roads (-10.5%), office (-5.2%), and industrial (-3.7%), which may relate to the increased development of offices or industrial activities on those land use types. See figure 7 for proportions of canopy cover on different land uses in 2006 and 2010.

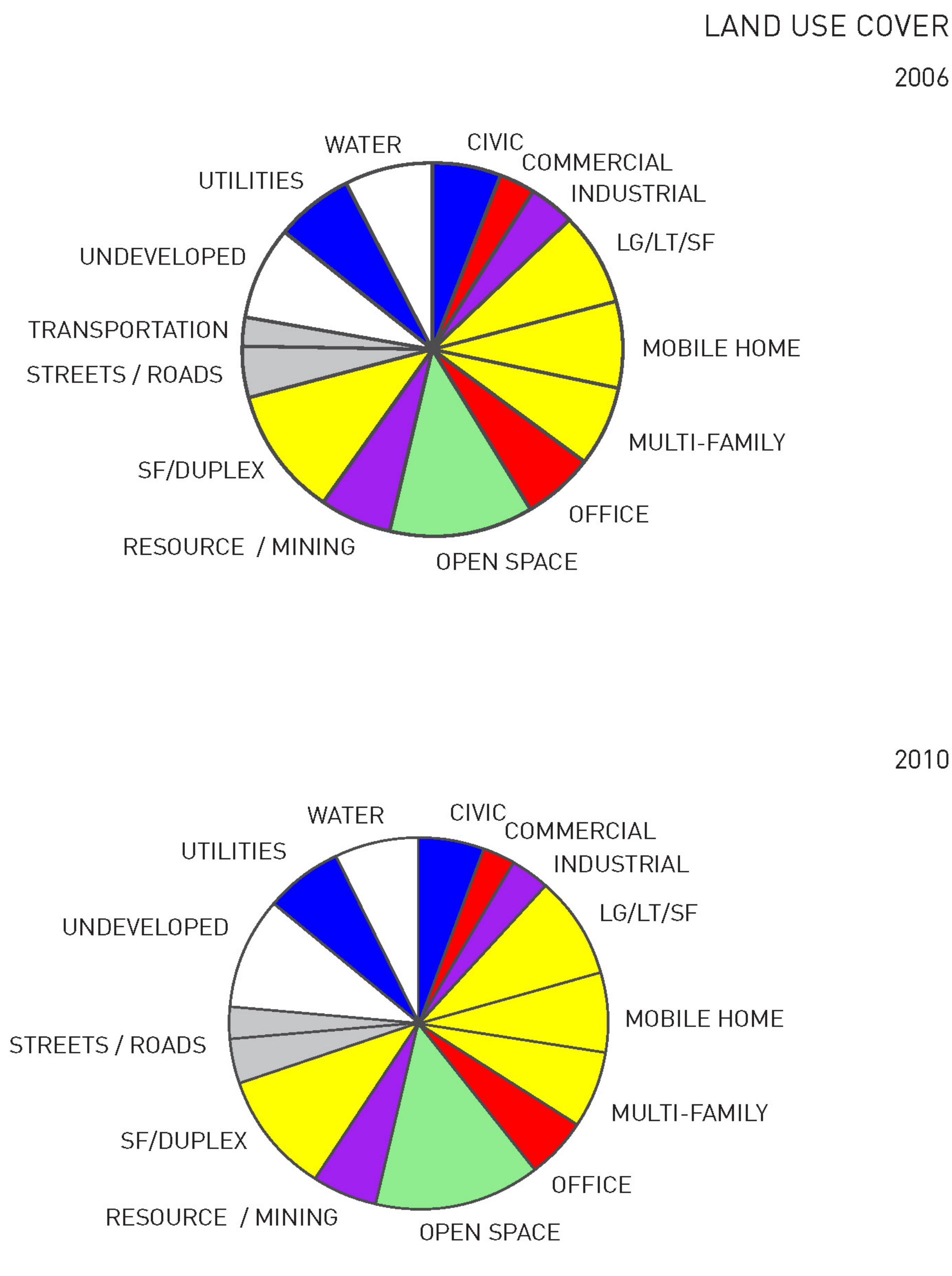

Figure 7- canopy cover on land use in 2006 and 2010.

We performed further analyses to determine the total canopy coverage on public and private land use types. Canopy coverage on public land, which includes City of Austin owned parcels, City of Austin parks, and public right of ways, totaled 20,136 acres, or 29.1% canopy coverage within the municipality. Canopy coverage on private land consists of mobile homes, single family large lot, single family or duplex, multi-family, industrial, and resource extraction, and accounts for 23,897 acres, or 39.9% canopy coverage. These figures draw attention to the sizable percentage of coverage on privately held land, and indicate a need to incorporate policies and practices tailored to the best management of existing trees with roots in the private realm. See Appendix C for a complete table of canopy cover data.

Current Urban Forest Species Inventory

No comprehensive tree inventory exists for Austin's urban forest. A 2008 survey examined the species composition, age, and condition of street trees and trees in parkland. The survey omitted trees on private land and trees in natural areas, greenbelts, and preserves--that is, it examined only a small fraction (and a specific kind of) trees growing within the city limits, and is not representative of the urban forest as a whole. Additionally, the Urban Forest Master Plan indicates that "non-native invasive trees . . . were not surveyed in 2008," meaning that at least some species that are actually present on the ground were not represented in the sample.

The 2008 survey, which sampled 14,925 trees, identified 166 different species growing on public land. The dominant species were Cedar Elm (*Ulmus crassifolia*, 15%), Southern Live Oak (*Quercus virginiana*, 12%) and Crape Myrtle (*Lagerstroemia indica*, 12%). 45% of these public trees were classified as "young trees," 47% were classified as "established trees," and 7% were classified as "mature trees." The characteristics of the dominant tree species are found in table 5.

Table 5: Dominant tree species in Austin

Species	% of Public Trees	Characteristics
Cedar Elm (*Ulmus crassifolia*)	15	Hardy drought-tolerant shade tree that can survive in compact soils and grow to over 90 feet in height. Moist soils and medium water use.
Southern Live Oak (*Quercus virginiana*)	12	A wide-spreading shade tree that grows to 80 feet in height. "Fairly drought-tolerant once established within its range" (Ladybird Johnson Wildflower Center, 2014). Susceptible to oak wilt. Medium water use.
Crape Myrtle (*Lagerstroemia indica*)	12	Quick-growing when young. Grows to 20 ft. Low to medium drought tolerance.

Hackberry (*Celtis laevigata*)	10	Can grow 60-80 feet in height. Frequently parasitized by misltletoe. High water use.
Pecan (*Carya illinoinensis*)	8	A large tree that can grow to 160 ft. Requires moist soils and has high water use.

Social & Equity Overview of Austin

Our research suggests a moderate positive correlation between income and canopy cover. The census block groups in which median household income was between zero and 20,000 had a canopy cover of 30% in 2006 and 33% in 2010, while the census block groups in which median household income was over $100,000 had a canopy cover of 47% in 2006 and 53% in 2010 (see Appendix C). The very high-income areas (median income greater than $100,000) not only had the highest overall percentage of canopy cover, but they also had the greatest increase in canopy cover between 2006 and 2010. That means that the wealthiest areas have the greatest access to the ecosystem services that trees provide. The lowest percent canopy cover was found in census block groups where median income was between $40,000 and $60,000 per year. While our data are fairly rough-grained, correlations between wealth and vegetation are borne out by the literature; Jenerette et al. (2011) found that not only did wealthier areas have higher vegetative cover, but also that disparities in green cover had gotten worse over time. See figure 8 for a graph of percent canopy cover by median income.

A number of factors may be responsible for the inequality between high income and low-income areas. Canopy cover on private land must be maintained by residents; trees require resource inputs, including water, which can be both expensive and a low priority. Wealthier residents may be able to afford more trees or larger trees, maintain those trees more effectively, and water those trees

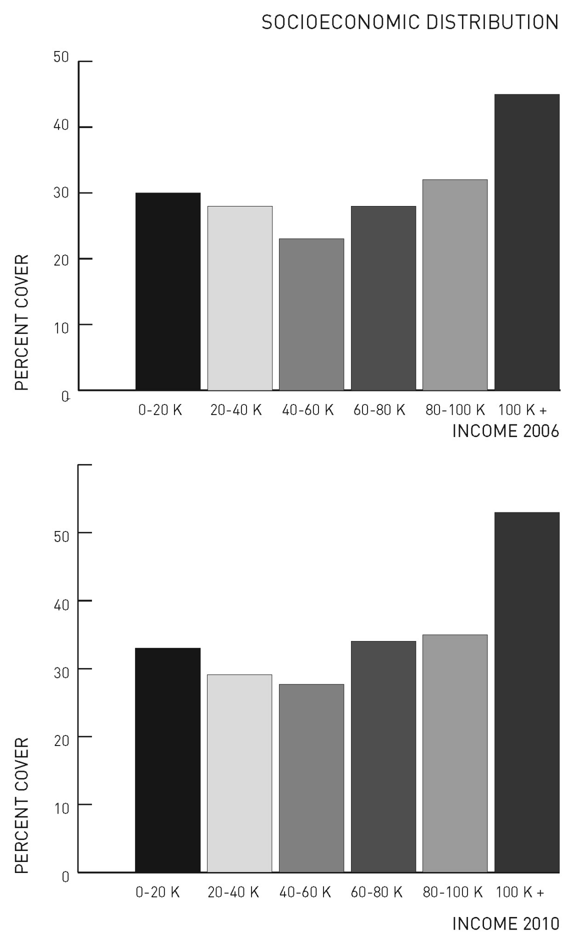

Figure 8- percent canopy cover by median income.

more often. A hotter, drier Texas is likely to drive further inequality as water prices increase under water scarcity conditions. Watering restrictions have already led some wealthy city residents to install wells, which allow them unrestricted watering even during severe droughts.

This sentiment regarding resource constraints was reflected during the discussion with Greg Mast of TreeFolks, who shared that "I have noticed, going through neighborhoods, that wealthier neighborhoods have more resources at their disposal to take proactive measurements, to take care of trees that they have; and they tend to have longer-lived species, more mature trees in better condition than the less affluent neighborhoods." Mast suggested that because trees are not a material necessity, they may receive lower priority in neighborhoods with less disposable income. Moreover, he described seeing a significant amount of poor pruning practices in less affluent areas, although this problem applies across the city. Poor pruning presumably leads to greater structural problems for affected trees, and in time will reduce canopy cover on poorly managed areas. However, as a general issue social equity (or inequity) did not feature prominently in the interviews; ecological and maintenance challenges tended to take priority.

The dip in canopy cover among middle-income residents ($20,000-$80,000) is interesting. A possible explanation is that residents in this income group are living in newer suburbs, where existing vegetation has been razed to make way for development. Trees in these circumstances are likely to be smaller, younger, and more susceptible to drought. Alternately, these income groups may be dominated by young professionals living in densely urban areas, like condos downtown. It would be interesting to examine finer-grained data to assess whether the shape of this curve would hold true in a larger data set.

Catalyzing the Conversation in Austin: the Drought & Climate Change (Urgency)

Drought has been a frequent occurrence in Texas in recent years. The state experienced a period of drought from 2007 to 2009 and then again from 2011 to the present day. Current conditions have often been compared to the "drought of record" that spanned from 1947 to 1957 and was the worst drought that Central Texas has faced since the beginning of the record in 1899.

Drought in Austin: Under a Data Lens

After a particularly wet 2007, Texas began to see much drier weather beginning in late 2010 (Buchele & Fehling, 2014)—weather so dry, in fact, that Lake Travis (which is a significant source of water for Austin), is currently only 36% full (River Report, 2014). In 2011 Texas experienced its driest year on record; the results were devastating. Millions of trees statewide succumbed to the drought conditions, and there was a 6.2% loss (over 300 million specimens) of tree inventory as a result (see figure 9). In Austin, by April of 2014, an estimated 10% of local trees had perished (KXAN, 2014). Drought-related mortalities included those attributed to wildfire, increases in parasitic populations, higher vulnerability to disease, and physiological stress. High levels of tree deaths like those in 2011 are very expensive—the dead trees must be removed quickly, as they pose safety hazards and power line threats, and they must also then be replaced. Additionally, the loss of shade trees, especially in the Texas summer heat, results in an increase in cooling power and, therefore, higher utility bills (Forsyth, 2012). And, without trees, property values drop, natural stormwater management weakens, and air pollution may increase in severity (Duncan, 2012).

Region	Live trees prior to the drought (million trees)	Drought-related mortality (million trees)	Drought-related mortality (percentage)
Southeast - East	597.1	7.5	1.3
Southeast - West	289.7	18.8	6.5
Northeast - East	356.0	13.9	3.9
Northeast - West	309.4	25.3	8.2
North	370.5	30.9	8.3
Brazos Valley	256.4	24.9	9.7
South	431.2	31.7	7.4
Central	1,540.0	102.3	6.6
Panhandle	556.3	33.1	6.0
Trans-Pecos	163.4	12.2	7.5
Total	**4,869.9**	**300.6**	**6.2**

Figure 9- Tree loss in Texas, resulting from the 2011 drought (Texas A&M Forest Service, 2012)

The rather drastic changes in precipitation we have seen are more than just ephemeral conditions; they are the result of climate change, which is predicted to alter the climate of the state over the course of the next few decades. The region is expected to develop much more arid conditions, with an increase in average annual temperatures of up to 4.2°C by the end of the century and a very likely decrease in precipitation (Jiang & Yang, 2012). Such events will likely prompt a change in the area's ecology, and the state must prepare to shape its urban forestry, landscape design, and overall resiliency plans in accordance with these projections. Austin, in particular, should look to novel, drought-resistant vegetation that will thrive in a xeric setting, much like the vegetation described in the California Statewide Adaptation Strategy for Reforestation, Urban Forestry, and Forestland Conservation (California Natural Resources Agency, n.d.).

While Austin's Urban Forest Master Plan indicates an awareness of the need for more progressive species selection, specific trees and plants are not explored in the document (Urban Forest Master Plan, 2014). According to findings from TreeFolks, a range of native Central Texas trees would be very appropriate for the changing Texas climate, because of their low water requirements, high propensity for shading, adaptability/drought resistance, and moderate to rapid growth speeds (TreeFolks, n.d.). Additionally, future programs that integrate wastewater recycling into landscape watering plans could be quite beneficial with regards to tree prosperity. For example, treated water from car washing facilities could be reused in additional watering cycles for urban trees (Barry, n.d.).

Drought in Austin: Under a Media Lens

There were 275 media articles found from the Austin American Statesman and Austin-area nonprofit organizations from the past five years in which the recent periods of drought in Texas were either the main topic or prominently discussed. Out of all the years analyzed, 2011 and 2012 had the highest frequency of media articles regarding the drought (79 in 2011 and 78 in 2012).

The media has portrayed the 2007 to 2009 drought and the current drought in a variety of ways. The overarching theme in the media articles we compiled was how the recent periods of drought affect water consumption. Lake levels in Austin's main water reservoirs, household watering restrictions, water conservation efforts, and new water projects to meet growing demand for dwindling water resources figured prominently in these articles. Another key theme in the media articles was how periods of drought affect the agriculture sector of Texas' economy. A third key theme was how drought conditions precipitate fire events, and the damage these events can have in terms of life and property across the state. The 2011 fires in Bastrop were discussed significantly in these articles. Other themes across the articles include how periods of drought impact recreation and businesses associated with recreation, wildlife, and infrastructure.

While trees were a relatively minor theme across the articles, how the drought has negatively impacted trees in Texas was discussed. A few articles highlighted the "Thirst" art installation above Lady Bird Lake memorializing the 300 million trees that had been lost at that point due to the current drought. Other articles discussed how drought-stressed trees are likely to cause property damage. Still others outlined how the drought has negatively impacted trees on private and public spaces such as Zilker Park in Austin, Texas. A potential reason for why discussion of drought's impact on trees was limited in the media articles we found is Austin residents may be more concerned with the immediate impacts of drought on water resources and the state's economy.

The current drought has had a number of repercussions for Austin specifically. Austin is a growing city; persistent drought has implications for the city's water supply, and how many more Austin residents the city's water resources can serve. Furthermore, the current drought has increased the urgency surrounding the management of Austin's urban forest. The drought has highlighted the importance of the city's care for existing drought-stressed trees. Moreover, the drought has implications for efforts to increase canopy cover on private land. Water restrictions have frequently been put in place to conserve water in times of drought. Although Austin residents may be amenable to planting trees on their property, those trees won't survive without water.

Long-term Challenges for Urban Forest Health

Rising cultural awareness of the value of green infrastructure, the impacts of climate change, and the drought and wildfires of 2011 in Texas have worked together to catalyze action around forest management in the Austin region, at least in terms of financial investment. Within the city government, money allocated to tree-related services has generally increased over the past decade, including an increase in the parks department's maintenance budget from $7.5 million to $12.8 million. Between 2005 and 2013, the forestry department's budget increased from less than $1 million to over $2.7 million. Since 2006 the city has created and funded an Oak Wilt response plan, and since 2011 it has created and funded a wildfire fuel reduction program.

In the private sector, the majority of organizations examined had increases in their budgets between 2010 and 2011. Whether this increase is due to an improved economy or an increase in population is unclear, but most of the nonprofits experienced budget decreases from 2009 to 2010. This may suggest that public concern over the forest was elevated in the wake of multiple large-scale wildfires in and around Austin and extreme drought experienced in the summer of 2011. Whether this increase will be sustained in the absence of extreme weather events remains to be seen.

Public vs. Private Management

The city government is the single most important entity affecting urban forest management in Austin, with a tree-related budget approximately eight times higher than the largest tree-related non-profit in our investigation. Additionally, the government's ability to impose tree ordinances on private interests puts it in a unique position of influence. However, the role of private management of urban forests should not be understated. When volunteer hours are taken into account, non-profits' and citizen groups' financial contribution become more substantial. The city beautification and environmental group Keep Austin Beautiful, for instance, logs over 8,000 volunteer hours on its annual Clean Sweep Saturday alone. Additionally, the budgets of private groups seem to be increasing more rapidly than municipal budgets. Most groups surveyed increased their budgets at least 15% from 2010 to 2011, with the largest increase of over 400% by Town Lake Trails. However, such spikes in resources may be a reaction to the extreme weather and forest mortality of 2011. Following non-profit budgets in subsequent years should give a better indication of whether private groups will be in a position to significantly increase their investment in the urban forest.

Discussion

Based on our findings, we've identified several challenges for the planning and management of Austin's urban forest. These challenges include a changing climate, urban development, climate uncertainty, increasing management costs, and poor public knowledge of tree maintenance. This section discusses these challenges in greater detail.

Ecological Viability

Climate change is predicted to alter the fundamental climatology of the state over the course of the next few decades. Austin will likely become much more arid, experiencing more frequent and longer lasting periods of drought. At the same time, population growth in the city will continue to put increased pressure on already tight water resources. Right now, for example, Lake Travis is below 40% capacity. During another intense drought like that of 2011, it is likely that plant care would be allotted less or even no resources for watering. City-imposed watering restrictions significantly impact the care of trees on private land, which comprise the majority of Austin's canopy cover. Patrick Brewer expressed this concern during his interview, stating that "we just didn't have the capacity to intervene" during the drought in 2011 and that trees are still dying from its lasting effects. According to Brewer, "if we had another drought like 2011 in 2014, I'm not sure what we'd do. I mean, we would probably have to stop watering plants altogether."

A key challenge for the City of Austin, therefore, is to use good planning and management to help mitigate these difficulties. Incorporating novel, drought-resistant species into the urban forest inventory, using innovative methods such as wastewater recycling for tree watering, and educating residents on the impacts watering restrictions will have on their ability to plant and maintain trees, are all ways the city can take changing climate conditions into account. Additionally, yet another challenge is the amount of ecological nuance that must go into the City's planning efforts. Austin is a place with highly variable soil composition, so species selection must be site-specific—for anything from rural to urban landscapes, and from Hill Country to Blackland Prairie.

Built Environment

A predominant challenge facing the city's urban forest resources is how to balance green infrastructure, such as street trees, with the grey infrastructure that is increasing as a result of local development pressures. Because Austin is one of the fastest growing urban areas in the country, city officials (and often developers) must reconcile the economic and ecological interests of the city and its landscape. Developers are tasked with constructing residential and commercial spaces to accommodate the people and businesses that are moving to the area and expanding the economic base of the city. At the same time, developers must leave sufficient plantable space for trees and other vegetation to grow healthily when possible, so that key ecological functions of the landscape can be maintained. The built/natural interface of green and grey infrastructure must be carefully managed to maximize benefits.

Our research suggests that the city's planting regulations may not go far enough to create feasible conditions for tree survival. Daniel Woodroffe of dwg. expressed concern about the size of pits in which street trees are planted, and the spacing between those pits and nearby structures. He asks: "How plausible is it to expect a tree to grow to 200 years if we're building ten feet behind the curb and the tree is in a five by five planter, it's seven feet from the face of the building, and you've got to maintain an 18-foot clearance" for larger vehicles on the street. Is the buffer between business and residential establishments and the trees around them adequate for the critical root zone? Does the size of the city's tree pits provide enough room for root growth? Additionally, the sheer area of pavement and reflective surfaces of buildings in the urban environment increases heat stress on trees and places greater strain on their survival.

Margaret Valenti in PDRD introduced a different facet of the problem of population pressure and increasing activity within Austin, discussing how the city's burgeoning food truck culture has consequences for trees. She described how food trucks park beneath trees because trees provide shade and a "pleasant outdoor environment" for customers to enjoy meals and socialize. However, these food trucks, their customers and often those customers' parked cars are compacting these trees' critical root zones from above. The city lacks regulations that prevent food truck owners from taking this action.

A city's ability to maintain robust urban forests is restricted by the soil and root zone compaction caused by grey infrastructure (such as roads and buildings), and the reduction of plantable space and removal of trees that results from new residential and commercial development. Maintaining canopy cover under these conditions can require unorthodox or expensive solutions, such as relocating trees from a construction site to other appropriate areas, or designing buildings around existing trees to preserve their habitat. However, these solutions may still leave trees in less favorable conditions than they enjoyed before—because the new structures compress their growth and make it tougher for them to survive. Patrick Brewer of Bartlett Tree Experts mentioned how developers spent roughly $300,000 to successfully move a tree for a project on Shoal Creek. Relocation is costly and still potentially damaging to the health of a tree.

Appropriate species selection can sometimes help balance the needs of green and grey infrastructure. As Margaret Valenti noted, if trees are to be planted under a power line, then smaller understory trees are preferable to tall-growing trees, because small trees will not grow into power lines and incur additional expenses for Austin Energy to trim them. Conflicts between green and grey infrastructure manifest themselves in various ways across Austin, and it takes a variety of solutions to mitigate the negative impacts of these conflicts on the urban forest.

Climate Uncertainty

Recent IPCC reports suggest that the impacts of climate change will be even more intense than that organization had previously predicted. To compound this problem, the greenhouse gas mitigation efforts necessary to prevent or reduce temperature rise appear nearly impossible, primarily because they call for either widespread investment in prohibitively expensive carbon capture and storage (CCS) technology, or a rapid and also-expensive move toward renewables and energy storage technologies (or both). The chances of dramatic temperature increases are therefore quite high. As a result, Texas stands to undergo a fundamental climate shift—how large a shift, however, is unknown. Additionally, many aspects of climate science, such as precipitation forecasting, are associated with huge uncertainty. For instance, some predictions have Austin's climate getting wetter rather than drier. And any shift in climate could have unpredictable spin-off effects on soil composition and distribution, the presence (or loss) of disease and pests, and even plants' genetic makeup.

The uncertainty surrounding climate science and climate forecasting puts planners in a difficult position, forcing them to plan for a future when little to no certainty about what that future will look like exists. This complicates the city's urban forest planning efforts. As Daniel Woodroffe with dwg. said, "a robust infrastructure is so important." Robustness and resiliency *are* critically important, precisely because of the uncertainty surrounding the impact of climate change on the Austin area.

Managerial Feasibility

Although total funding for forest management in Austin is increasing, the costs of forest management can also be expected to increase in light of the decreased forest health and increased tree mortality that is already occurring. As climate change intensifies and costs increase, satisfactory forest management may run up against economic constraints. It is also worth noting that natural disasters such as those experienced in the region in 2011 do not always translate into increased across-the-board support for forest management. The Bastrop chapter of the Native Plant Society of Texas, for instance, shut down in 2011 as many residents left Bastrop in the wake of devastating wildfires. And the coordinator of the Barton Creek Greenbelt Guardians reported that the wildfires negatively affected its organization, stating in an email:

> "NO, the 2011 drought and fire season did not increase our financial donations—in fact, the concerns about a perceived increased potential for fires due to . . . the increased amount of deadwood (for slash management on the greenbelt we organize the cut-up trunks and branches into stacked windrows), was to prohibit us from doing invasives removal, even though we had a large grant to do so. Our volunteer hours remained approximately the same, we just had to redirect the tasks we did."

These experiences stand in contrast to those of the majority of tree-related organizations, which received increased support in 2011, but they serve as a reminder that public support for urban forests stems from individuals' perceptions about forests' costs and benefits.

Advocates for the urban forest sometimes justify maintenance expenses by presenting estimates of the savings forests provide in ecosystem services. When asked how they calculate such dollar value amounts, all of the advocates in both municipal and non-profit positions in Austin referred to i-Tree, the software tool developed by the U.S. Forest Service to help urban planners and engineers design landscapes for optimum social value. The i-Tree software takes aspects of a planner's design into account when calculating tree value, but ultimately its estimates are based on average ecosystem service outputs from forests in parts of the country outside the southwest. While having a scientifically rigorous estimate of ecosystem services is certainly a positive advancement in forest management and urban planning, this generic average may or may not accurately reflect the reality of such services in the Austin context. As such, it introduces uncertainty into economic-based decisions about forest management.

Community Education

One themed that emerged clearly in our interviews was education: the importance of teaching people the proper planting and maintenance techniques for trees in the urban environment. Greg Mast of TreeFolks emphasized the strategy of "right tree, right place" when discussing the best approach for a managerially feasible urban forest; planners and volunteers must know which species are appropriate for specific ecological conditions—soil quality, water access, proximity to built infrastructure—in a particular location. This returns to the question of what species mix will best ensure a responsive and resilient urban forest system that can withstand health threats in a changing, less hospitable future climate. Several interviewees discussed how poor pruning practices, such as topping trees, can stunt those trees' growth.

Several organizations in the environmental stewardship fold have educational initiatives intended to educate city residents who lack expertise in tree care. TreeFolks combines volunteer planting events with educational outreach activities such as tree ID hikes, classes, and workshops, including its urban forest steward section. Meanwhile, the city's Community Tree Program interfaces with residents in target neighborhoods and distributes instructional material that details the growing conditions of individual trees. For example, watering requirements are listed on the adoption papers given to every resident who receives a tree through the Community Tree Program. Residents must be made aware of the best time of year to plant trees (in the fall), as well as how to properly prune trees on their property. While greater citizen participation in urban forest stewardship is to be welcomed, volunteers and private property owners must know how to foster healthy tree growth.

Interviewees also expressed the sentiment that education must extend to tree care professionals and perhaps even the city officials responsible for urban forest planning. Greg Mast noted that TreeFolks tries to educate "volunteers, homeowners, professional tree workers, arborists about proper tree care . . . with guidelines of where and how to plant the trees." Even professionals may need continuing education as local conditions change. Some environmental groups take direction from others. For her part, Joanna Wolaver explained that when addressing tree-related issues in the Shoal Creek watershed, she will "look to direction from the Urban Forestry Department and TreeFolks . . . that are foresters and ecologists, for giving us advice." Thus, education on maintenance and preservation flows from experts in the field to the individuals tasked with caring for a tree.

The importance of education revolves not only around how to properly manage a tree once it is planted, but also how to help the public understand the true value of trees and all the benefits they provide including mitigating the urban heat island effect and increasing property values. Daniel Woodroffe explained that people place a subconscious value on trees—they like trees and enjoy engaging in activities around trees—but their valuation of trees remains abstract. Until people realize the exact benefits (including economic benefits) of trees, as well as trees' importance to both humans and natural ecosystems, people will continue to undervalue trees and be less willing to invest effort in their maintenance and protection. Accurately quantifying the real value of trees in the Austin context, and educating the public about that value, will help encourage community members to support the urban forest. Patrick Brewer may have best summed up the vital nature of education in saying, "Knowledge is power, and if people know what the right thing is to do, they're more likely to do it."

Recommendations

Based on our report findings, our team has a series of recommendations for how Austin can better manage and develop its urban forest in light of the changing climate and growing built environment.

Better Management of Existing Urban Forest

We recommend that Austin prioritize the maintenance of the existing urban forest over the expansion of the urban forest.

As reflected in the geospatial analyses and interview findings, Austin is fortunate to have an existing urban forest that is extensive in both its coverage and distribution. As Austin considers the future of its urban forest in an era of rapid development, it must balance expanding the urban forest (in terms of both acreage and percent cover), and properly managing existing forest stands.

As noted by Eric Courchesne, various entities such as Austin's Urban Forestry department or City Parks Department have the opportunity to expand the benefits conferred by Austin's existing urban forest through improved tree care measures that target long-term performance. Unfortunately, budgetary constraints and the preferential allocation of funds to land acquisition and development can direct city dollars away from 'best management' practices for existing trees.

When the city prioritizes expansion over maintenance, it can negatively affect trees' long-term health and viability. While Austin has extensive canopy cover, aspects of that cover are not optimal. There are concerns about the homogeneity of Austin's current urban forest—a healthy forest should have a mix of tree species, and also a mix of trees of different ages, from saplings to heritage trees. There are additional concerns about the ongoing viability of Austin's urban forest in the face of changing climate conditions.

As such, best management practices must seek to secure the future viability of existing resources before it allocates funds towards the expansion of those resources. We believe that diversifying the species composition and age structure of Austin's existing forest stands is more important than the sheer extension of 'roots in the ground' canopy cover acreage. Our findings suggest that investing in maintenance will greatly benefit the long-term ecological viability and managerial feasibility of Austin's urban forest.

Local Policies

We recommend that Austin include trees on private lands in its urban forestry policymaking and planning.

Austin's existing Urban Forest Master Plan only addresses trees on public lands. These are only a fraction of the trees in Austin; residential areas in particular host a significant portion of the city's canopy cover. Because so many trees grow on private land, and because of the ecologic importance of canopy connectivity, the city should consider implementing policies to protect trees on private land. The city has an existing heritage tree ordinance, but it could do more to protect trees of all sizes. Legal tools available to the city include tree removal permits, requirements for landscaping plans, and ordinances to protect trees during construction.

Better coordination between practitioners

We recommend that the City of Austin improve cooperation and coordination between the many departments involved in urban forestry.

Austin has no city-wide urban forestry best management practices. Data from interviews with practitioners identified gaps between defined best management practices among Austin's urban forest managers, planners and designers. These gaps in coordination and communication can lead to the creation of forest designs that are difficult to manage and maintain, particularly when considering resource constraints like water availability. Poor coordination between the many departments with a stake in Austin's forests affects not only short-term management efficacy, but also the future viability of urban forests as green infrastructure. We recommend that the city engage in direct policy action to better coordinate management practices across urban forest practitioners, through improved communication of goals and procedures, to ensure quality care for urban trees at each level.

City Planning

We recommend that the city consider social equity issues when implementing tree planting and tree protection policies and programs.

There is a visible difference in percent canopy cover east and west of I-35; these areas differ socioeconomically and demographically, at least in part because of historical, institutionalized racial segregation (though ecological differences in east and west Austin may also contribute to canopy differences). If the city is promoting the services that urban forests provide, it should further research correlations between income and consider implementing policies to address disparities in service provision between high and low-income areas.

Species Selection

We recommend that Austin plant tree species appropriate to spatial constraints and climate conditions, especially drought, and that it not limit itself exclusively to native species.

When considering the design of Austin's urban forest, there are critical issues to take into account concerning both the functional and experiential qualities of stand arrangements. In terms of structure, composition, and desired benefits, what species are selected and where they are placed will have a measurable impact on both the managerial feasibility and ecological viability of Austin's urban forest.

Interviewees expressed concern about the spatial requirements for tree health (Daniel Woodroffe), the threat of disease and invasives, and funding to carry out both planting efforts and maintenance over time. These findings suggest that in places where the city has jurisdictional authority, minimum requirements must be established to protect trees' critical root zones, encourage the selection of contextually appropriate species, and develop implementable plans for long-term tree care.

As part of this strategy, the City of Austin's species selection must reflect anticipated changes in climate, and the expected persistence of drought conditions. Table 6 lists certain native species that may be good candidates for new plantings. We have selected these species based on low water requirements, drought resiliency, speed of growth (as mature trees require less water), and amount of canopy provided. As growing conditions continue to evolve due to climate change, certain non-native tree species can perform similarly, if not better than natives, in terms of climatic tolerance, growth, benefits to humans, and drought tolerance.

Table 6. Native central Texas tree species with high resiliency

Tree Name	Height	Spread	Water Requirements	Benefits
Anacacho Orchid	15'	10'	Low to Medium	· Moderate growth speed · Requires very little water
Bald Cyprus	50' +	25' – 50'	Low	· Adaptive to new conditions · Moderate growth speed · Good shading
Bur Oak	50' +	50' +	Very Low	· Rapid growth speed · Good shading

				• Requires very little water
Chinkapin Oak	50' +	25' – 50'	Low	• Good for limestone soils in Austin area • Good shading • Moderate growth speed
Eastern Red Cedar	45'	25'	Low	• Rapid growth speed • Decent shading • Adaptable
Gum Bumelia	45'	50'	Low to Medium	• Good shading • Moderate growth speed • Very adaptable and drought resistant
Mesquite	25' – 35'	25' – 35'	Low	• Decent shading • Very drought tolerant
Texas Mountain Laurel	15' – 20'	12' – 15'	Very Low	• Very drought tolerant

Future Research Questions

How do extreme weather events related to climate change affect public perceptions of and support for urban forest management?

Our research has found volatility in the year-to-year funding for tree-related nonprofits and private organizations as compared with the municipal budget for trees. Further research is required to see if such volatility is related to changes in perceived threats or benefits of the forests as they relate to water consumption, fire danger, or drought stress.

How accurately are the ecosystems services provided by Austin's urban forest being measured?

Currently the city of Austin's assessment of such services relies on the i-Tree tool, which estimates the benefits of trees using samples of trees located outside of Austin (and in climates very different from Austin). Further research to determine Austin-specific estimates may provide a more reliable measure of the costs and benefits of Austin's urban forest.

Do water limitations impose a cap on the quantity and quality of urban forest that Austin can sustain?

Trees require resource inputs; in Austin's hot, dry climate, a significant input is water. Doing a mass balance of the urban forest's water requirements (water in and water out), and then comparing that mass balance to water availability under a few different climate scenarios, could provide insight into this question.

One question this study raises is: are trees the best alternative for providing ecosystem services to Austin? Could services like carbon storage, stormwater reduction, and heat island mitigation be effectively provided by other kinds of vegetation? Specifically, could these services be provided by vegetation that is better adapted to Austin's current and future climate?

Acknowledgments

Special thanks to all the interviewees: Angela Hanson, Greg Mast, Daniel Woodroffe, Eric Courchesne, Jim Carse, Margaret Valenti, Joanna Wolaver, Matt Hollon, Zach Baumer, Keith Mars, Dave Nowak, and Patrick Brewer. Thanks also to Dr. Kerry Cook and William Boettner for their entertaining insight. Thanks to Dr. Sarah Dooling for her overarching guidance and support, and to Kate Vickery for keeping us on track.

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Appendix A: Core Interview Questions

1. Please describe to me the role of your (agency, firm, nursery, etc.) in relation to urban trees and urban forests in the greater Austin metropolitan region. Please describe to me your role. What various aspects of urban forests does your work focus on?
2. How do you define what an urban forest is?
3. From your perspective, what aspects of a tree's ecology are important for the persistence of a tree in the Austin region?
4. What time frame do you typically think about when (regulating, designing, advocating)?
5. From your perspective, what makes a tree feasible to manage?
    a. Does your perspective about feasibility change if you extend the time frame (from short to long)? If so, can you please tell me how.
6. From your perspective, what makes an ecologically viable tree for the greater Austin region?
    a. Does your perspective about ecological viability change if you extend the time frame (from short to long)? If so, can you please tell me how.
7. What challenges do you see facing (design, regulation, advocacy for) urban forests now?
    a. In the short-term?
    b. In the long-term?
    c. How do you think these challenges might change over time?
8. What are the key ecological reasons for these challenges?
9. What are the key social or economic reasons for these challenges?
10. What are strategies might alleviate or address these challenges immediately?
    a. In the short-term?
    b. In the long-term?
    c. Are there specific opportunities that don't exist now, but that you think might exist in the future?

Appendix B: Interview Code List and Code Definitions

Codes	Code Definitions
Balancing Green & Grey Infrastructure	Different from urbanization in that it focuses on how you balance the space for trees (and other green infrastructure) amidst the specific built structures that are already there or are being built. How do you accommodate trees in the built environment?
Citizen Participation	Volunteering, getting citizens excited about trees and environmental preservation through community organizing, or concerned citizens taking their own initiative. Different from education, which focuses on citizens learning rather than participating. Can also describe good private management of trees (like a resident who takes good care of trees in her yard).
Community Livability	Trees can make one's urban surroundings more enjoyable.
Coordination	Because it's a challenge, this means lack of coordination between the people and entities responsible for the urban forest. It can also refer to the challenge of allocating resources efficiently to receive the greatest benefit from the entire urban forest.
Departmental Collaboration	Think of this as the "Opportunity" that supplements the code "Challenges > Social >Managerial > Coordination," which signifies a lack of coordinating functions between municipal agencies.
Development Pressure	Austin is growing fast, and the need to accommodate incoming residents' balances against interest in preserving the ecosystem. This code looks at development from a financial perspective: developers stand to gain, the city will promote business, new residents will move in and earn a living, all at the expense of trees.
Disease/Pests	For example: oak wilt, Dutch elm disease, emerald ash borer.
Drought	Water scarcity is threatening the urban forest. Related to climate change.
Ecological Variability	Describes variation of ecosystems in Austin (escarpment vs. prairie) and how this differentially impacts soil, water, and tree growing conditions across the city. Can also include different land uses, or different levels of urbanization at various sites, which affects how well trees can grow.
Environmental Stewardship Networks	Partnerships between public, private, and nonprofit organizations, or functions performed and investments made by one of these organizational types that indirectly supports the functions of another organization. Focuses more on social/community advocacy.
Financial Constraints	No further specification.
Forms of Green Infrastructure	Trees/urban forests are an important component of the green initiatives implemented in urban areas.
Future Climate Uncertainty	No further specification.
Heat Stress	Viability of particular types of trees in hot climates.
Incentives & Regulations	No further specification.
Information Constraints	Different from knowledge constraints in that it does not apply to tree care, but rather to the types of tree data that managers collect to help them plan for urban forest preservation. There are limits to the data they collect.
Invasive Species	Discusses how invasive species can take root and choke out the native trees around them.

Knowledge Constraints	Refers to limited skills/expertise in how to plant and care for trees. If caretakers do not know proper tree care techniques, or the proper tree to choose in a location, the tree stands a lower chance of survival. Also related to improper planting or maintenance strategies.
Municipal Regulations	In addition to public regulations, this also includes public agendas or programs that affect the urban forest. It also reflects conflicting needs (regulations designed for one good purpose, such as water use restrictions, end up hurting trees (which have their own good purpose.)
Novel Solutions	Includes specific responses to drought and water issues, development pressures, the need for more green infrastructure, solving capacity constraints for managers. Can involve new public policy as well. Or perhaps any other interesting opportunities you can't fit into another category.
Personnel Constraints	Focuses on the number of people dedicated to tree management, not their level of knowledge (that part falls under "knowledge constraints").
Planting & Maintenance Strategies	Ability to plant trees in suitable areas, proper maintenance with pruning, mulching, watering practices etc. Utilizing best time of year to plant trees. Careful species selection based on the ecological viability of different species in a particular location (not based on social preferences).
Preservation & Viability	This code includes maintaining trees with an eye to long term health, and making long term management plans. In other words, managing trees to ensure urban forest resiliency.
Program Constraints	Public and nonprofit tree programs engage in a limited range of activities. Use this code whenever someone references those limitations.
Programs	Considers tree planting and care programs in which a public agency is involved.
Public Perception	Whether people are favorable or unfavorable to having trees around them or their property. Also includes people's perception of certain types of trees, and preferences for particular species. Can also reflect conflicting needs from an individual perspective: for example, does someone want solar panels on their property more than they want trees? Because they may not be able to have both, trees may get left out of the equation.
Public vs. Private Ownership	No further specification.
Public-Private Partnerships	This code focuses specifically on partnerships between businesses/individual property owners that do not have environmental purposes, and public/nonprofit organizations with environmental functions.
Public & Professional Education	Education initiatives targeted at ordinary citizens, or professionals. Can be offered by any organization. Can also describe the need for education in certain respects.
Quantifying Tree Values	Quantifying urban forest value, or at least taking more full account of the benefits it offers the surrounding environment.
Resource Management	No further specification.
Root Zone & Growth Space	Also includes root health.
Social Equity	No further specification.
Soil Quality/Space	No further specification.
System Responsiveness & Resiliency	Includes regional level species selection that can best protect the entire ecosystem against future losses, based on the conditions we have now and may have in the future. This code focuses more on the trees themselves, or the concept of resiliency; whereas the "preservation" code focuses more on human management strategies to achieve resiliency.

Time Frames	No further specification.
Tree Benefits	Trees provide numerous benefits to the surrounding environment.
Tree Canopy Cover	Whenever someone mentioned "canopy" specifically.
Tree Drawbacks	The negative aspects of trees: allergies, fallen limbs, etc.
Tree Longevity	Related to resilience; trees should be planted to last.
Tree Species	Use this every time you see a specific species mentioned.
Urban Densification	This is the process of urbanization: what happens to trees as more houses are built, as more urban infill projects get underway, as the space for trees to operate is squeezed.
Urban Forest Composition	Do we want a monoculture or biodiversity in the urban forest species selection? Do we want a native or novel ecosystem? Questions such as these that focus on people's preferences. Also consider, do we want younger or more mature trees (on average) in the urban forest?
Value Perception	No further specification.
Water Access/Management	Includes drought tolerance solutions, stormwater control, flooding problems, etc.
Weather Events	Significant weather events that cause damage to trees and ecological systems.

Appendix C: Raw canopy cover data

Canopy Cover						
2010 Canopy Cover (acres)	61706.58564		CoA parcels overall area including ETJ (acres)	47634.189238	Note: this includes areas outside of our CoA municipal boundaries that we used for the 33% cover	% Change (2006-2010) Canopy Cover
2006 Canopy Cover (acres)	56074.053552		2006 tree canopy cover (acres)	20721.659202	0.43501651930016	
City of Austin area (acres)	167240.08		2010 tree canopy cover (acres)	25814.763013	0.54193770117549	
2010 Percent Canopy Cover	0.36897008					10.0448100110742
2006 Percent Canopy Cover	0.33529076015749					
Percent Change (2006-2010) %	0.03367931984250					
2006 Canopy Cover Parcels (clipped to municipal boundary)	16230.598148		Area of COA parcels excluding ETJ (within municipal boundary)	29275.698756	0.55440514958412	
2010 Canopy Cover Parcels (clipped to municipal boundary)	16157.748251				0.55191674110557	

LAND USE	Total area (acres)	2006 Canopy Cover (acres)	2006 Canopy Cover %	2010 Canopy Cover (acres)	2010 Canopy Cover %	Percent Change (2006-2010) %
Civic 600	8,634	2,153	0.25	2,201	0.25	2.23793061812101
Commercial 300	7,764	1,005	0.13	903	0.12	-10.1413764553687
Industrial 500	6,407	1,011	0.16	974	0.15	-3.66355404763789
Large lot single family 160	1,678	576	0.34	673	0.40	16.7410006767191
Mobile Homes 113	1,107	344	0.31	348	0.31	1.28838050892195
Multi-Family 200	9704	2850	0.29	2802	0.29	-1.6842105263158
Office 400	5500	1398.38	0.25	1325	0.24	-5.24750067935756
Open Space 700	33274	17033.23	0.51	20972	0.63	23.1240346076464
Resource Extraction (Mining) 560	461	118	0.26	109	0.24	-7.6271186440678
Single Family 100 OR Duplex 150	40451	18485.71	0.46	18992	0.47	2.73881825474922
Streets and Roads 860	102	19	0.19	17	0.17	-10.5263157894737
Transportation 800	4650	488	0.10	611	0.13	25.2049180327869
Undeveloped 900	23838	8215.33	0.34	10305	0.43	25.4362271509483
Utilities 870	1259	339	0.27	372	0.30	9.73451327433629
Water 940	199	62	0.31	61	0.31	-1.61290322580646

Socioeconomics + Demographics

Median income in past 12 months	Area (US acres)	2006 Canopy Area (acres)	2006 Canopy Cover %	2010 Canopy Cover (acres)	2010 Canopy Cover %	Change (2006-2010)
0-20,000	4065	1222	0.30061500615006	1324	0.32570725707257	0.02509225092250
20,000-40,000	25115	7046	0.28054947242683	7256	0.28891100935695	0.00836153693012
40,000-60,000	34370	8105	0.23581611870817	9540	0.27756764620308	0.04175152749490
60,000-80,000	35997	10579	0.29388560157790	12351	0.34311192599383	0.04922632441592
80,000-100,000	17123	5554	0.32435904923202	6025	0.35186591134731	0.02750686211528
100,000+	51975	24605	0.47340067340067	27309	0.52542568542568	0.05202501202501

Ownership	Acres (US acres)	Canopy area (US acres)	Canopy Cover %	Canopy area (US acres)	Canopy Cover %	Change (2006-2010)
Public Land, City of Austin (parcels, parks, public right of way)	69192.7	16599.65	0.23990464311986	20136.4	0.29101913930226	0.05111449618240
Private Land (mobile home, single family (160), single family (100), multi-family, industrial, resource)	59807.448031	23384.590445	0.39099796454914	23897.75045	0.39957816688003	0.00858020233088