TreePeople

Planting Resilience

Identifying Climate-Resilient Tree Species and Increasing Their Presence in Los Angeles' Urban Forest

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Table of Contents

Executive Summary

Climate change poses significant challenges for Los Angeles (L.A.), where increased heat and sustained drought will stress water sources and redefine urban landscapes. Trees are often the first line of defense against the effects of urban heat and air pollution in cities, making the tolerance of tree species to biotic stressors an important factor to consider for tree species selection. The City of L.A.'s Green New Deal sets out to expand the current tree canopy coverage to areas of greatest need to 50% by 2028, but this effort is limited in part by the lack of information on tree species that are well-adapted to historical and projected conditions of a changing climate.

The aims of this study are three-fold: 1) identify tree species that are resilient to climatic stressors and show promise for achieving tree canopy targets; 2) review the state of research on the various tree anatomical and physiological characteristics that enhance cooling benefits and reduce air pollution; and 3) evaluate the range of municipal- and state-level tree policies, market-based mechanisms, and approaches to building public awareness of climate-resilient trees that can influence future planting on public and private lands. Understanding the implications of this research for future planting initiatives will be critical, as will the dissemination of this information to key forestry practitioners.

IDENTIFYING CLIMATE-RESILIENT TREE SPECIES

This study used a three-step process to identify tree species for the L.A. County that are resilient to current and projected climate conditions, including drought, heat, and pest and disease outbreaks.

- **Identify promising species:** Potentially suitable tree species identified from existing research were consolidated into a tree species list, along with tree species recommended by horticultural experts, and approved street tree lists from municipalities within L.A. County, including the City of L.A., Santa Monica, and Pasadena.

- **Rate species according to selection criteria:** Tree species identified from the previous step were evaluated and rated according to four distinct criteria: drought tolerance, water demand, resistance to pests and diseases, and salinity tolerance.

- **Select finalists and document structural and functional characteristics:** Based on ranked criteria, the list of 115 taxa underwent a filtering process to derive a final list of trees for evaluation.

A total of 28 climate-resilient tree species for the L.A. region were identified as being drought-tolerant, resistant to major pests and disease threats, and requiring very low to low water usage including:

African Sumac
Rhus Lancea

Blue Oak
Quercus douglasii

Catalina Cherry
Prunus lyonii

Cajeput
Melaleuca Quinquenervia

Cedar of Lebanon
Cedrus Libani

Chitalpa
Chitalpa Tashkentensis

Coast Banksia
Banksia integrifolia

Emory Oak
Quercus emoryi

Flaxleaf Paperbark
Melaleuca Linariifolia

Honey Mesquite
Prosopis glandulosa

Island Oak
Quercus tomentella

Italian Stone Pine
Pinus Pinea

Lemon Bottle Brush
Callistemon citrinus

Maverick Mesquite
Prososis glandulosa

Netleaf Hackberry
Celtis reticulata

Osage Orange
Maclura pomifera

Peppermint Tree
Agonis Flexuosa

Prickly-leaved paperbark
Melaleuca styphelioides

Rose Gum
Angophora costata

Rosewood
Dalbergia sissoo

Silverleaf Oak
Quercus hypoleucoides

Soapbark Tree
Quillaja saponaria

Strawberry Tree
Arbutus uneda

Sweet Bay
Laurus Nobilis

Tecate Cypress
Mariosousa willardiana

Texas Ebony
Ebenopsis ebano

Weeping Bottle Brush
Callistemon viminalis

White Bottle Brush
Callistemon salignus

FUNCTIONAL TRAITS OF URBAN TREES

Tree characteristics that contribute to enhanced cooling benefits and air quality were evaluated from the literature.

- Characteristics that influence cooling from **reduced surface temperatures (shading)** include: 1) Round-shaped and horizontally-spreading tree canopies as opposed to pyramidal and columnal ones; 2) Dark green leaves of <0.15 mm thickness.

- Characteristics that influence **reductions in ambient air temperatures (transpiration)** include: 1) Annual tree growth (measured by DBH and height) and increases in leaf surface area; 2) Diffuse-porous tree species as opposed to ring-porous species; 3) Evergreen conifers have lower water demand relative to broadleaf deciduous tree species; and 4) Simple-shaped leaves, as opposed to needle or compound leaves.

- Characteristics that contribute to **air quality improvement** include: 1) Larger and denser canopies; 2) Larger leaves with rugged, waxy, and pubescent surfaces.

ASSESSING BARRIERS TO GROWING A CLIMATE-RESILIENT URBAN FOREST IN LOS ANGELES- STAKEHOLDER INTERVIEWS

Semi-structured virtual interviews were conducted with 17 key stakeholders from three groups of actors to identify public, private, and institutional barriers to expanding the presence of climate-resilient species in L.A.'s urban forest. Interviews covered involvement in urban forestry and planning for climate adaptation; challenges related to urban forestry governance; evaluations of current policies and tree ordinances; and perceptions of successful community engagement strategies. The following groups of actors were chosen to represent a wide range of professionals and organizations impacting the urban forest on public and private lands: 1) Policymakers from local government; 2) Municipal urban forestry staff; and 3) Non-profit organizations and community groups.

The following cross-cutting themes emerged as the primary barriers to growing climate-resilient species in the L.A.'s urban forest:

- Limited availability of high quality climate-resilient tree stock at commercial nurseries.
- Insufficient seed stock for meeting planting goals.
- Trees that die from lack of maintenance can reflect poorly on the local community and make residents distrustful and resistant to planting programs.
- The lack of adequate and sustainable funding hinders efforts to support a resilient urban forest.

- The geographic size of the L.A. region constrains the ability of municipal forestry agencies to assume the full responsibility of maintenance and establishment care.
- Financial, personnel, and curricular resources available for environmental education and sustainability inequitably distributed, making it more difficult for financially disadvantaged schools and districts to become more resilient.

RECOMMENDATIONS

Enhancing the resilience of L.A.'s urban forest to the emergent impacts of climate change will necessitate strategic cross-sector participation and collaboration between community, government, non-profit organizations, academic institutions, and private entities. To address the identified needs and obstacles, the following actions are recommended to growing a climate-resilient urban forest in the L.A. region:

- Encourage the use of climate-resilient tree species by private homeowners and on public lands.
- Connect and strengthen the capacity of smaller, local nurseries to grow climate-resilient tree stock.
- Prioritize street tree planting efforts in low-income, low-canopy, and disadvantaged communities.
- Increase funding for urban forestry.
- Devise and implement a coordinated public awareness campaign that utilizes multiple channels.
- Expand environmental education programs to support a baseline connection to trees.
- Build multi-generational coalitions.

List of Acronyms

BVOC	Biogenic Volatile Organic Compound
EE	Environmental Education
FD	Fusarium Dieback
ISHB	Invasive Shot Hole Borer
KSHB	Kuroshio Shot Hole Borer
LAI	Leaf Area Index
LSA	Leaf Surface Area
PM	Particulate Matter
PVM	Pest Vulnerability Matrix
SFT	Space-for-Time (Substitution)
TCC	Tree Canopy Cover
UF	Urban Forestry
UFD	City of Los Angeles Urban Forestry Division
UHI	Urban Heat Island
RAP	City of Los Angeles Department of Recreation and Parks
WUCOLS	Water Use Classification of Landscape Species
WUE	Water Use Efficiency

Introduction

Warmer and drier conditions from shifting climatic conditions, along with ongoing water management challenges in California, threaten the survival of many species within urban forests that are frequently identified as integral to mitigating the impacts of climate change. Abiotic factors, such as drought and heat stress from extreme weather events, as well as root damage from resulting soil compaction, impose additional stressors on tree species predisposed to disease and pests. In many instances, these impacts are already exceeding the designed capacity of city infrastructure to protect the health and safety of residents, businesses, and neighborhoods and, in turn, threatening the fiscal viability of cities and regions.

The greater Los Angeles (L.A.) metropolitan region contends with many of these challenges and offers the unique opportunity to study, evaluate, and adapt the urban forest towards the goal of ensuring future human and ecosystem health and wellbeing. Identifying a diverse mix of species well-adapted to the current and anticipated impacts of climate change is critical, as the combined effects of drought, pest and disease outbreaks, and municipal budget cuts precipitate rising rates of tree mortality. The U.S. Forest Service estimates that 33.5% of the total tree population in coastal Southern California is at risk of dying from one type of invasive beetle: the polyphagous shot hole borer (Sahagún, 2017). Threats to widespread tree mortality extend well beyond this pest.

If robust and extensive, an urban forest may confer valuable ecosystem services across a range of public health, social, and economic indicators. Increased exposure to nature in cities improves emotional state and cognitive functioning (Bratman et al., 2015; Ulrich, 1981). Healthy trees sequester carbon dioxide (CO2) in their biomass, increase property values, attenuate flooding, conserve energy used to heat and cool buildings, regulate air and water quality, provide habitat for diverse wildlife, and intercept rainfall to reduce stormwater runoff and erosion (McPherson and Simpson, 2002 and 2003; McPherson et al., 2008 and 2016; Xiao et al., 1998; Nowak et al., 2006; Pincetl et al., 2012). Trees can also reduce ambient air temperatures by as much as 9°F, and temperatures directly under trees can be 20 to 45°F cooler than air temperatures in surrounding unshaded areas (Sahagún, 2017). By diminishing urban heat island (UHI) effects, trees improve human thermal comfort and minimize the chance of heat-related morbidities by up to 25% (Brown et al., 2015; de Abreu-Harbich et al., 2015; Klemm et al.,2015).

There is a further impetus to strengthen the resilience of the urban forest: it is both fundamentally an issue of environmental justice and social equity. The geographies of urban heat risk in L.A. reflect long legacies of environmental racism, with communities of color, linguistically-isolated communities, and other marginalized populations bearing the disproportionate burdens of low tree canopy cover and attendant health risks from heat exposure (Danford et al., 2014; Watkins et al., 2016; Heynen et al., 2006; Schwarz et al., 2015). These spatial inequalities are rooted in historical policies and contemporary dynamics, with recent research, for instance, demonstrating the close correlation between redlined neighborhoods and contemporary UHI effects (Hoffman et al., 2020; Locke et al., 2021). L.A. is uniquely positioned as one of the first cities to make social equity the cornerstone of its urban forestry strategy. The city has pledged, by 2021, to add 90,000 trees to the existing stock of 1 million growing on public and quasi-public land and 9 million on private land, with the primary aim of increasing tree canopy coverage by up to 50% to benefit disadvantaged communities (Garcetti, 2019). The future success of these plantings depends in part on their ability to tolerate shifting climatic conditions, as well as the extent to which they reflect public preferences (Ordóñez, 2015).

Sustaining the health and stability of L.A.'s urban forest requires selecting for tree species that are well-suited to achieve high survival and growth rates in the face of projected climatic conditions

(McPherson, 2018). While previous research has considered various species selection processes of municipalities in Northern and Central California, there is a paucity of research on species that are well-suited to a range of current and projected climate regimes for the L.A. region (McPherson and Albers, 2014; McPherson et al., 2018; McPherson and Kotow, 2013). Furthermore, fast-track tree planting initiatives aimed at reducing UHIs and improving air quality may be constrained by the lack of knowledge about whether these benefits are species-specific and how to select the most suitable tree traits to achieve particular outcomes. Finally, adapting the urban forest for long-term resiliency requires leveraging effective strategies to build recognition and stimulate demand for climate-resilient trees, and more importantly, to promote a culture of stewardship in support of growing a healthy urban forest.

This study seeks to answer the following questions:

1. ***Which tree species are most suited to meeting tree canopy goals in L.A.?***

2. ***What role do characteristics such as physiology, leaf color, leaf and tree shape, canopy height, and density play in enhancing cooling impacts beyond providing shade?***

3. ***What existing policies, market-based approaches, and other approaches to increasing public awareness must be leveraged to foster a transition to a more stable and resilient urban forest?***

Part one examines the state of existing research on the tolerances of a wide range of tree species to climatic stressors such as drought, heat, and pest outbreaks and culminates in a shortlist of tree species that appear promising in terms of adaptation to historical and projected climatic conditions across the L.A. region. This research may inform future urban forestry planning and management efforts and support decision-making around species selection by municipal foresters, landscape professionals, and residents alike.

A detailed understanding of how the various regulating services of trees are conditioned by morphological and anatomical tree characteristics is helpful in guiding future management decisions. For instance, tree species with dense canopies and dark green leaves have been shown to provide more effective cooling benefits from shade (Rahman et al., 2002). To provide guidance for future tree selection and planning initiatives, the second part of this report reviews and synthesizes research on the various tree characteristics that enhance cooling benefits and reduce air pollution.

The final section of this report evaluates the suite of institutional and policy actions, market-based mechanisms, and approaches to building public recognition that can influence widespread demand for planting climate-resilient trees on public and private lands. These include modifying local and state jurisdictional policy through approved species lists; leveraging tree procurement strategies and scaling the capacity of existing nursery stocks; incentivizing planting climate-resilient trees at the local scale; and finally, but perhaps most importantly, improving strategies for engaging various publics in tree stewardship and disseminating information about climate-resilient trees in ways that are salient to the needs of local communities.

Part 1: Climate-resilient Species for Los Angeles' Urban Forest

Average temperatures across the greater L.A. metropolitan region are predicted to warm by several degrees over the next three decades. Due to complex topographies and diverse regional landforms, these effects are not uniformly distributed, and temperature differences are perceptible at the local level. Inland areas separated from the Pacific Ocean by the Transverse Ranges, and places at higher elevations are likely to warm 20 to 50% more than their coastal and low-lying counterparts (Hall et al., 2012). For example, coastal neighborhoods of Venice and San Pedro are projected to witness average temperature increases of up to 3.8°F, whereas average temperatures of San Fernando are expected to rise 4.2°F (Hall et al., 2012). In addition to rising temperatures, meteorological models project a substantial decrease in average annual precipitation, representing losses ranging from 8% to 14.7% of the current precipitation (CalAdapt, 2014).

Extreme heat and drought threaten to exacerbate forest mortality throughout California (Allen et al., 2010; McDowell & Allen, 2015). From 2010 to 2017, severe drought was associated with the death of more than 129 million trees (USGCRP, 2018). Physiological changes such as early defoliation and reduced growth are visible for many of the commonly planted tree species, while others are failing to break dormancy in spring (Tadewaldt, 2013). This decline is spatially variable and species-specific, suggesting that the effects of climate change on urban tree populations might be strongly influenced by the interactions between local climate and local street tree composition.

Increasing urban temperatures may also foreshadow elevated incidences of pest outbreaks (Meineke, 2013). A fertile mix of urban and agricultural landscapes within the L.A. region creates ideal conditions for reproductive host species, pests, and symbiotic fungal diseases to infect tree populations over a large geographic area rapidly. Tree populations in the L.A. region are susceptible to a range of invasive pests, with an estimated 38% of the trees in the urban region at risk of infestation (Sahagún, 2017). Barring significant actions to mitigate these impacts, the approximate cost of removing and replacing these trees will be $15.9 billion with an annual accruement of $616.9 million over the next ten years (McPherson et al., 2017).

Transitioning to a more stable and resilient urban forest structure requires selecting tree species resilient to climate-related stressors such as heat, drought, and pests. The section below examines the state of the existing research on suitable tree species for the L.A. region, including their attributes and susceptibilities to different risks. A qualitative review of the literature will evaluate the various approaches that have been used to assess the adaptive capacities of trees to a range of climatic pressures, with a particular focus on the Climate Ready Trees study currently being undertaken by researchers from UC Davis and the U.S. Forest Service. This section will culminate in a synthesized list of climate-ready tree species that show promise for ensuring the long-term stability of L.A.'s urban forest. Understanding the implications of this research for future planting initiatives will be critical, as will the dissemination of this information to key forestry practitioners.

REVIEW OF EXISTING RESEARCH

Approaches to species selection. Species selection is informed by several crucial factors, including the proposed functions of the tree, its adaptation to the planting site conditions, and the degree of maintenance it will receive. Selecting the appropriate tree requires consideration of how numerous factors and the interactions between them may influence performance in the future. However, species-specific information on tolerances and susceptibilities is frequently incomplete, adding uncertainty to decision-making (Sjoman and Nielsen, 2010).

Concerns over global warming have led to a range of approaches used to evaluate and predict the suitability of landscape tree species to future climate scenarios and provide planting guidance for practitioners. Miller proposed a species selection model that included site (i.e., environmental and cultural constraints), social (i.e., aesthetics, functions, and disservices), and economic factors (i.e., costs to plant and maintain) (Miller, 1997). Asgarzadeh and colleagues extended this approach using horticultural experts to grade species for selection criteria and add relative weights to each (Asgarzadeh et al., 2014). Buley and Cregg devised an approach to urban tree selection with a focus on phenotypic plasticity—the ability of a species' morphology and physiology to respond to different environmental conditions—and suggested the increased use of plastic species such as *Acer, Gymnocladus, Nyssa, Platanus, Taxodium, and Ulmus* (Buley and Cregg, 2016). In California, a limited number of studies incorporate professional opinions on the adaptive capacity of trees to the state's four distinct landscape regions and consensus on the relative water requirements of common landscape species (Brenzel, 2007; Perry, 10; Costello and Jones, 2014). While these sources help assess the adaptation of tree species to shifting climatic conditions, they are inadequate substitutes for the systematic evaluation of tree performance.

Alternative approaches have been proposed for evaluating plant performance in the context of changing climate and predicting climate change effects on forest ecosystems. One method involves assessing trees' climate envelope—the set of climatic constraints on a species' distribution—by relating a group of climate variables and projected pest problems to make spatially explicit predictions of potential species distribution (Anacker et al., 2013). Climate envelopes have been used to assess the influence of climate change on the biology of pathogens and pests (Watling et al., 2014; Yang et al., 2009). However, climate envelopes for most non-native or introduced tree species are challenging to evaluate, particularly in the absence of accurate tree inventories. Other approaches involve more complex analyses that explicitly address management considerations, as well as social considerations and environmental constraints (Ordóñez and Duinker, 2014; Brandt et al., 2016).

Recent studies have adopted the space-for-time (SFT) substitution method commonly used in studies of plant succession to infer future adaptive capacities of different tree species from contemporary spatial patterns (Pickett, 1989). In brief, these assessments compare the performance of street tree species in representative cities to trees in corresponding cities with climates that are proximal to the conditions that the representative cities are predicted to reach by 2099 (McBride and Lacan, 2018). A recent landmark study consolidated results from SFT modeling with professional opinions by Bob Perry and WUCOLS (Perry, 2010; Costello and Jones, 2014) and found that as many as 55 of 140 common street tree species from representative cities across California were unsuitable for future climates due to their absence from corresponding cities (McBride and Lacan, 2018). Among this list, Broadleaf dicots dominated the list of ill-suited species, followed by conifers (including *Ginkgo biloba*), as well as three species of palms. Surprisingly, this study found species of *Acer and Platanus*—two of the genera suggested by Buley and Cregg for their plasticity—to be potentially unsuitable. However, only a limited range of species from these two species appeared on their list. SFT substitution suffers from inherent limitations, namely that it presumes that the absence of a species is attributed to its climatic incompatibility rather than to other causes (i.e., the aesthetic preference of residents of the local tree manager). Furthermore, results cannot affirm whether less-common species, absent from the study sample, will perform well in future climatic conditions, even though certain species may be well-adapted for warmer climates.

Climate Ready Trees. Currently, researchers from the University of California, Davis, are conducting a longitudinal study to evaluate the vulnerability of underutilized and promising tree species to climate change stressors in three of California's climate zones (McPherson et al., 2018). McPherson and others compiled tree inventory data from a sample of cities in each climate zone, and, with consultation by horticultural experts, narrowed in on 14 candidate tree species. These tree species were planted in the Inland Empire and Southern California's coastal climate zones for long-term monitoring and are shown in Figure 1.

While it may be too early to make definitive conclusions about species performance through maturity, a recent evaluation of species growth and survival two years after planting merit continued observation (McPherson et al., 2019). Overall, the study found that survival rates were higher in the Inland locations where growing conditions more closely matched the arid environments from which many of these species originated. Survival rates for the ten species planted at both climate zones were lowest for the Tecate cypress (78%) due to a root rot disease (*Phytophthora*) that caused twig dieback.

Survival Rates (2016-2018)	**Coastal**	**Inland**	**Both Sites**
Mulga *Acacia aneura*	**100%**	**92%**	**96%**
Brazilian Cedarwood *Cedrela fissilis*	**75%**	—	**75%**
Netleaf Hackberry *Celtis reticulata*	**100%**	**100%**	**100%**
Desert Willow *Chilopsis linearis* ‘Bubba’	—	**92%**	**92%**
Ghost Gum *Corymbia papuana*	**67%**	**100%**	**83%**
Rosewood *Dalbergia sissoo*	**83%**	**100%**	**92%**
Tecate Cypress *Hesperocyparis forbesii*	**42%**	**75%**	**78%**
Mariosousa willardiana *Palo Blanco*	**67%**	**100%**	**83%**
Palo Verde *Parkinsonia x ‘Desert Museum’*	—	**100%**	**100%**
Red Push Pistache *Acacia Pastacia ‘Red Push’*	**83%**	**100%**	**92%**
Maverick Mesquite *Prososis glandulosa x Maverick*	**100%**	**100%**	**100%**
Catalina Cherry *Prunus ilicifola spp. Lyonii*	**92%**	—	**92%**
Escarpment Live Oak *Quercus fusiformis*	**92%**	**58%**	**75%**
Island Oak *Quercus tomentella*	**92%**	**92%**	**92%**

Figure 1. Survival rates (%) for Climate Ready Trees in the Southern California Coastal and Inland climate zones. Adapted from “Climate-Ready Tree Study: Update for Southern California Communities” by G.E. McPherson, A.M. Berry, N.V. Doorn, J. Downer, J. Hartin, D. Haver, E. Teach, 2019, Western Arborist, Winter 2019: 12-18

Although Tecate cypress trees are performing poorly in Coastal sites, two other California natives, Catalina cherry (*Prunus ilicifolia* ssp. *Lyonii*) and island oak (*Quercus tomentella*), exhibited high survival rates. Species with high survival rates that require more frequent pruning include rosewood (*Dalbergia sissoo*), Maverick mesquite (*Prosopis glandulosa* ‘Maverick’), and netleaf hackberry (*Celtis reticulata*). While these species show promise to date, they warrant continued observation to gauge their adaptability, pest vulnerability, and pruning requirements as they reach maturity.

Criteria for Selecting Suitable Species

Species Diversity. Increasing species diversity is regarded as the primary means to buffer tree populations against catastrophic loss from pests and other threats (McPherson and Kotow, 2013). Guidelines—such as a widely used formula which stipulates no single species should account for more than 10% of the population, no genus more than 20%, and no family more than 30%—are frequently referenced to reduce the risk of catastrophic tree loss due to pests (Santamour, 1990).

However, a significant drawback of these diversity formulas is that they do not explicitly consider the susceptibility of individual tree species to specific insects and diseases (McBride and Lacan, 2018). This lack of differentiation leads to two potential problems: damage from pests that attack more than one tree species (multi-host generalists) and the similar-appearing damage caused by divergent pest species. Recent outbreaks by non-specialized pests such as the PSHB, the Emerald Ash Borer, Gypsy moth (*Lymantria dispar dispar*), and Verticillium wilt (*Verticillium* spp.), for instance, attest to the potential of a few aggressive pests to inflict significant economic and environmental harm to a wide range of landscape tree species.

Drought Tolerance. Prolonged periods of drought in California increase evaporative demand on urban trees and may exacerbate the incidence of tree failure and limb drop, making drought tolerance a crucial determinant of successful tree establishment. According to the Water Use Classification of Landscape Species (WUCOLS) plant database, which provides an assessment of irrigation water needs for over 3,500 taxa, 34 species require very low amounts of irrigation in standard South Coastal landscape settings, while 215 species were classified as requiring low water use (Costello and Jones, 2014). The database classifies 13 species with very low water use and 150 species with low water use for standard Inland Valley landscapes. A selection of commonly utilized landscape tree species from both water use categories is listed below in Figure 2. However, poorly drained soils in urbanized areas may limit the success of these species in the L.A. region. Further research is necessary to evaluate their tolerance to a variety of local soils and irrigation regimes.

McPherson et al. (2018) used a five-step filtering process to identify a number of underutilized drought-tolerant tree species from 8 municipal tree inventories. Tree species that are potentially suitable for the L.A. region include Shoestring acacia (*Acacia stenophylla*), Netleaf hackberry (*Celtis reticulata*), Rosewood (*Dalbergia sissoo*), and Texas ebony (*Ebenopsis ebano*), although the latter species may require too much maintenance to warrant large-scale use.

Figure 2. Drought Tolerant Species with Very Low - Low Water Use for South Coastal and Inland Valley Regions (Costello and Jones, 2014)

South Coastal Region

Very Low	Low			
Desert Willow *Chilopsis linearis*	**Mulga** *Acacia aneura*	**Tree Banksia** *Banksia integrifolia*	**Prickly-leaved Paperbark** *Melaleuca styphelioides*	**Torrey pine** *Pinus torreyana*
Dragon Tree *Dracaena draco*	**Knife Acacia** *Acacia cultriformia*	**Flame Tree** *Brachychiton acerifolius*	**Cajeput** *Melaleuca quinquenervia*	**Honey Mesquite** *Prosopis glandulosa*
Arizona Cypress *Hesperocyparis arizonica*	**Palo Blanco** *Acacia willardiana*	**Lemon Bottle Brush** *Callistemon citrinus*	**Glossy privet** *Ligustrum lucidum*	**Catalina Cherry** *Prunus ilicifolia lyonii*
Tecate Cypress *Hesperocyparis forbessi*	**Peppermint Tree** *Agonis flexuosa*	**White Bottle Brush** *Callistemon salignus*	**Olive** *Olea europaea*	**Island Oak** *Quercus tomentella*
Chinaberry *Melia azedarach*	**Tree of Heaven** *Ailanthus altissima*	**Weeping Bottle Brush** *Callistemon viminalis*	**Canary Island Pine** *Pinus Canariensis*	**Soapbark Tree** *Quillaja saponaria*
Desert Museum palo verde *Parkinsonia 'Desert Museum'*	**Silk Tree** *Albizia julibrissin*	**Chitalpa** *Chitalpa tashkentensis*	**Coulter Pine** *PInus coulteri*	**African sumac** *Rhus lancea*
Elephant Tree *Pacycormus discolor*	**Gum Myrtle** *Angophora Costata*	**Flaxleaf Paperbark** *Melaleuca linariifolia*	**Italian Stone Pine** *Pinus pinea*	**Tipu tree** *Tipuana tipu*
Holly leaf cherry *Prunus ilicifolia*	**Marina Arbutus** *Arbutus 'Marina'*	**Pink Melaleuca** *Melaleuca nesophila*		
Coast Live Oak *Quercus agrifolia*	**Strawberry Tree** *Arbutus unedo*			
Engelmann Oak *Quercus engelmannii*	**Common Manzanita** *Arctostaphylos manzanita*			
California Pepper Tree *Schinus molle*				

Inland Valley Region

Very Low	Low			
Sweet Acacia *Acacia farnesiana*	**Palo Blanco** *Acacia willardiana*	**Weeping Bottle Brush** *Callistemon viminalis*	**Pink Melaleuca** *Melaleuca nesophila*	**Texas Red Oak** *Quercus texana*
Desert Sweet Acacia *Acacia farnesiana farnesiana*	**Peppermint Tree** *Agonis flexuosa*	**Chitalpa** *Chitalpa tashkentensis*	**Chinaberry** *Melia azedarach*	**African Sumac** *Rhus lancea*
Ribbonwood *Adenostoma sparsifolium*	**Tree of Heaven** *Ailanthus altissima*	**Ghost Gum** *Corymbia papuana*	**Desert Musuem Palo Verde** *Parkinsonia 'Desert Museum'*	
Big Berry Manzanita *Arctostaphylos glauca*	**Silk Tree** *Albizia julibrissin*	**Rosewood** *Dalbergia sissoo*	**Coulter Pine** *Pinus coulteri*	
Western Hackberry *Celtis reticulata*	**Gum Myrtle** *Angophora Costata*	**Dragon Tree** *Dracaena draco*	**Italian Stone Pine** *Pinus pinea*	
Tecate Cypress *Hesperocyparis forbessi*	**Strawberry Tree** *Arbutus unedo*	**Texas Ebony** *Ebenopsis ebano*	**Blue Oak** *Quercus douglassii*	
Guadalupe Island Cypress *Hesperocyparis guadalupensis*	**Common Manzanita** *Arctostaphylos manzanita*	**Coolibah** *Eucalyptus microtheca*	**Catalina Cherry** *Prunus illicifolia lyonii*	
Sonoran Palo Verde *Parkinsonia 'Sonorae'*	**Western Redbud** *Cercis occidentalis*	**Honey Locust** *Gleditsia triacanthos*	**Coast Live Oak** *Quercus agrifolia*	
Blue Palo Verde *Parkinsonia florida*	**Desert Willow** *Chilopsis linearis*	**Golden Rain Tree** *Koelreuteria paniculata*	**Engelmann Oak** *Quercus engelmannii*	
Holly Leaf Cherry *Prunus ilicifolia*	**Lemon Bottle Brush** *Callistemon citrinus*	**Sweet Bay** *Laurus nobilis*		
Interior Live Oak *Quercus wislizeni*	**White Bottle Brush** *Callistemon salignus*	**Flaxleaf Paperbark** *Melaleuca linariifolia*		

Salinity Tolerance. Water supply in the L.A. region is limited both quantitatively and qualitatively—a phenomenon expected to worsen in the future with extended periods of drought, urbanization, and water demand. To limit the strain on water supply during severe periods of drought, California plans to increase the amount of recycled water used for landscape irrigation from 1.2 billion m3 in 2020 to 1.6 billion m3 in 2030, respectively (California Department of Water Resources, 2016). During periods of drought, and as the distribution network for recycled water grows, urban trees are likely to be increasingly irrigated with recycled wastewater, making salinity tolerance an important factor in assessing a species' climate suitability. Due to water treatment processes, recycled water tends to have a higher salt content than potable water (Paranychianakis et al., 2004). High salinity can cause severe abiotic stress that impairs tree growth, development, and survival, by reducing water uptake (McPherson et al., 2018), with a recent study showing, for example, a 30-40% reduction in the height of Sequoia sempervirens grown in moderately saline soils (Nackley et al., 2015). One study measured the salt tolerance of landscape tree species and found that of the species sprinkler-irrigated with two salt (NaCl) concentrations, leaves of the Chinese Hackberry (*Celtis sinesis*), Silk Tree (*Albizia julibrissin*), Chinese Pistache (*Pistacia chinesis*), Gingko (*Gingko biloba*), and Liquidambar (*Liquidambar styraciflua*) exhibited severe damage through significant rates of leaf chlorosis and growth reduction (Wu et al., 2000), while Strawberry Tree (*Arbutus uneda*), Japanese Boxwood (*Buxus japonica*), Deodar Cedar (*Cedrus deodara*), and Coast Live Oak (*Quercus agrifolia*) showed moderate to high salt tolerance (Wu et al., 2001). While these results emphasize the importance of salt tolerance in species selection, future research is necessary to determine how this characteristic is modified by climate change, irrigation management, genetic variation among varieties, soil texture and structure, and soil fertility (Maas, 1990).

Pest and Disease Susceptibility. The effects of climate change are threatening to exacerbate the rate of pest outbreaks in urban tree communities in the L.A. region. The emergence of a few aggressive generalists, in particular, is of great concern for urban forest managers due to their ability to colonize a wide range of host tree species. The Granulate ambrosia beetle, for instance, has been shown to cause severe damage to Ficus, Golden Raintree (*Koelreuteria* sp.), Crape Myrtle, Sweetgum, Magnolia (*Magnolia* sp.), Oak, Chinese Elm, Plum (*Prunus cerasifera*), Cherry (*Prunus* sp.) and Redbud (*Cercis* sp.) (McPherson and Kotow, 2013). Other invasive ambrosia beetle borers, such as the PSHB and its close relative, the Kuroshio shot hole borer (KSHB), are known to transmit distinct breeds of phytopathogenic fungi to 64 species of reproductive host trees (Eskalen et al., 2013; Stouthamer et al., 2017; Husein, 2019). These beetles and their fungi mutualists, Fusarium euwallaceae and Fusarium kuroshium work in concert to cause severe damage to their hosts, with visible responses ranging from branch dieback to mortality. The most heavily-impacted hosts species that exhibit infestation rates exceeding 70% include Acacia (*Acacia* sp.), coral tree (*Erythrina caffra*), Chinese Flame tree (*Koelreuteria bipinnata*), Golden Raintree (*Koelreuteria paniculata*), Sweetgum (*Liquidambar styrachiflua*), Palo Verde (*Parkinsonia aculeate*), American Sycamore (*Platanus occidentalis*), California sycamore (*Platanus racemosa*), London Plane (*Platanus x hispanica*), and Willow (*Salix* sp.) (University of California Riverside Center for Invasive Species Prevention). Taken together, evidence from recent pest outbreaks corroborates previous research indicating that the level of damage inflicted upon trees has less to do with tree health than with pest biology and host availability

(Laćan and McBride, 2008).

A set of different pests might inflict similar-looking damage on multiple susceptible but unrelated tree taxa, such as the various species of aphids (*Aphis* spp., *Shivaphis* spp., *Macrosiphum* spp.) attacking, e.g., hackberry (*Celtis* spp.) and tulip trees (*Liriodendron tulipifera L.*). Similarly, a fungal disease known as anthracnose may be caused by several pathogens (Blanchard and Tattar, 1997). These pathogens produce very similar symptoms on distinct tree species and require similar environmental conditions for successful infection, often resulting in separate disease outbreaks appearing simultaneously on multiple tree species as if caused by a single pathogen.

METHODOLOGY

This study used a three-step process to identify tree species for the L.A. region that are resilient to current and projected climate conditions, including drought, heat, and pest and disease outbreaks. Borrowing from the discipline of systems ecology, resilience is defined as the capacity of a species to regain its fundamental structure, processes, and functioning when altered by stresses and disturbances (Holling, 1973; Gunderson, 2000; DeRose and Long, 2014; Newton and Cantarello, 2015; Lloret et al., 2011).

Step 1. Identify promising species

Potentially suitable tree species identified from the previous section were consolidated into a tree list, along with tree species recommended by horticultural experts, and approved street tree lists from municipalities within L.A. County, including the City of L.A., Santa Monica, and Pasadena. Duplicate species were removed, resulting in a final list of 115 distinct taxa.

Step 2. Rate species according to selection criteria

Tree species identified from Step 1 were evaluated and rated according to the following four criteria. Data used to assign ratings for each criterion were obtained from the SelecTree database, an online repository of tree species information managed by the Urban Forest Ecosystems Institute at California Polytechnic State University, San Luis Obispo unless otherwise specified (UFEI SelecTree).

Drought Tolerance. Warmer temperatures can increase evapotranspiration demand and drought stress, making drought tolerance a crucial characteristic to consider in species selection. Tree species were classified as 'Sensitive to Drought,' 'Moderately Drought Tolerant,' and 'Drought Tolerant.' While 'drought-tolerant' and 'drought-resistant' are often used interchangeably in the literature, drought tolerance refers to the ability of a species to continue functioning in spite of low water potential and soil desiccation, and drought resistance is the ability to survive for extended periods without water but unable to survive prolonged drought stress (Larcher, 2003; Tyree et al., 2003).

Water Demand. A general trade-off has been recognized between a species' ability to survive under low resource availability, and its capacity to exploit water resources when they are abundant (e.g., the trade off between slow-fast growth) (Reich, 2014). Nevertheless, in a drought-prone region where water supply and tree care are limited, selecting species with low water demand relative to their water needs is necessary to ensure long-term tree survival. WUCOLS was used to assign ratings of water use (Costello and Jones, 2014). WUCOLS classifies four classes of irrigation needs from 'Very Low' to 'High' based on experimental observations and expert horticultural field experience for over 3500 taxa in California landscapes. WUCOLS classifications for the Inland and Southern California coastal regions utilized this assessment.

Pest Resistance. Planting species with natural resistance to pests and disease may obviate the need for pesticide sprays, tree removal, and replacement. Species vulnerable to severe pest and disease threats—with a particular focus on those multi-host generalists (e.g., ISHB and beetle borers) and their fungal mutualists (e.g., FD)—were classified as 'Severe Risk.' Species vulnerable to specialist pests and diseases were classified as 'Moderate Risk.' Tree species without documented pest susceptibilities were classified as 'Low Risk."

Salinity Tolerance. Ratings in this category reflect soil salinity in the Inland and Southern California coastal regions. 'High' and 'Moderate' were used to qualify tolerances in this category. Trees with demonstrably high tolerance to saline site conditions were classified as 'High,' while trees with moderate salinity tolerance were classified as 'Moderate.'

Step 3. Select finalists and document structural and functional characteristics

Based on classifications from Step 2, the list of 115 taxa underwent a filtering process to derive a final list of trees for evaluation. In the first order of elimination, species classified as 'Sensitive to Drought' and 'Moderately Drought Tolerant' were excluded from consideration. Next, species with 'High' and 'Moderate' water demand were eliminated from the list. In the third order of elimination, species exhibiting 'Severe Risk' to pests were removed from the remaining list. For the last step of the elimination process, species with moderate salinity tolerance were removed from consideration.

RESULTS

Potentially Climate-resilient Tree Species for the Los Angeles Region

A total of 28 tree species were identified as being drought tolerant, requiring very low to low water usage, and demonstrating resistance to severe multi-host pests and disease threats. To encourage plant diversity, this list includes native and other suitable non-native species found in the L.A. region across a variety of microclimates. This list is not exhaustive and is offered instead as a baseline for species selection that foregrounds important criteria for planting decisions.

The 28 finalists are listed in Table 2. Information for each species includes general information on size, canopy characteristics, growth rate, capacity to provide cooling benefits through shade and transpiration, and susceptibility to minor pests and diseases. The suitability of each species to the environmental conditions of the planting site is paramount and warrants further consideration by municipal agencies and organizations overseeing future tree planting efforts.

Figure 3. Climate Ready Trees for the Los Angeles Region

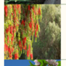
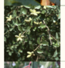
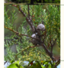
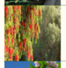
		Overall Mature Size	Height	Crown Spread	Canopy Form	Canopy Height	Growth Rate	Drought Tolerant	Shading Capacity	Water Demand	Pests and Diseases
	**Lemon Bottle Brush** *Callistemon citrinus*	Medium	20-25’	15’	Upright, Rounded, Spreading	Low	Moderate	Yes, once established	Dense	Low	Chlorosis
	**White Bottle Brush** *Callistemon salignus*	Medium	20-25’	10-15’	Rounded, Spreading or Weeping	Low	Moderate	Yes, once established	Moderate - Dense	Low	—
	**Weeping Bottle Brush** *Callistemon viminalis*	Small	25-35’	15’	Rounded, Spreading or Weeping	Low	Moderate	Yes, once established	Moderate - Dense	Low	Armillaria, Root Rot
	**Chitalpa** *Chitalpa Tashkentensis*	Medium	20-30’	20-30’	Rounded, Spreading, or Vase	Low	Moderate	Yes, once established	Moderate	Low	Aphids, Root Rot, Verticillium
	**Peppermint Tree** *Agonis Flexuosa*	Medium	20-30’	15-30’	Rounded, Spreading, or Vase	Low	Slow - Moderate	Yes, once established	Moderate	Low	Phytophthora and Root Rot
	**Sweet Bay** *Laurus Nobilis*	Medium	15-25’	15-20’	Upright, Conical, or Rounded	Low	Slow - Moderate	Yes, once established	Dense - Very Dense	Low	Psyllid, Scales, Phytophthora, Root Rot
	**Flaxleaf Paperbark** *Melaleuca Linariifolia*	Medium	15-20’	20-25’	Rounded	Low	Moderate	Yes, once established	Moderate - Dense	Low	Chlorosis, Phytophthora, Root Rot
	**Cajeput** *Melaleuca Quinquenervia*	Medium	25-35’	20’	Rounded, Oval		Fast	Yes, once established	Moderate - Dense	Low	Phytophthora, Root Rot
	**African Sumac** *Rhus Lancea*	Medium	20-30’	20-35’	Rounded, Spreading	Low	Moderate	Yes, once established	Moderate	Low	Root Rot, Verticillium
	**Blue Oak** *Quercus douglasii*	Large	50-65’	40-50’	Rounded, Spreading	High	Slow	Yes, once established	Moderate	Very Low	Caterpillars, Insect Galls, California Oak Moth, Gall Wasp, Scales, Crown Rot, Mistletoe, Armillaria, Powdery Mildew, Root Rot
	**Soapbark Tree** *Quillaja saponaria*	Medium	30-45’	15-22.5’	Columnar, Arching		Slow	Yes, once established		Low	Armillaria, Root Rot
	**Strawberry Tree** *Arbutus uneda*	Small	25-40’	25-40’	Rounded, Spreading, or Vase	Low	Slow - Moderate	Yes, once established	Dense	Low	Scales, Thrip, Anthracnose, Phytophthora, Root Rot, Rust
	**Italian Stone Pine** *Pinus Pinea*	Large	25-40’	40-60’	Conical, Rounded, or Spreading		Moderate	Yes, once established	Dense	Low	Aphids, Armillaria, Phytophthora, Root Rot, Pitch Canker
	**Cedar of Lebanon** *Cedrus Libani*	Large	80-100’	80-100’	Upright, Spreading, or Conical		Slow	Yes, once established	Dense	Low	Armillaria, Root Rot
	**Tecate Cypress** *Mariosousa willardiana*	Small	10-25’	20’	Upright, Columnar, or Rounded		Slow	Yes, once established	Dense	Very Low	Aphids, Insect Galls
	**Netleaf Hackberry** *Celtis reticulata*	Small	20-30’	25-30’	Rounded, Spreading, or Weeping	Low	Moderate	Yes, once established	Moderate	Low	—
	**Rosewood** *Dalbergia sissoo*	Large	45-60’	40’	Upright, Spreading		Moderate	Yes, once established	Low - Moderate	Low	—
	**Maverick Mesquite** *Prososis glandulosa*	Large	25-35’	30-35’	Rounded, Spreading		Fast	Yes, once established	Low - Moderate	Low	—
	**Catalina Cherry** *Prunus lyonii*	Medium	15-25’	15-20’	Upright, Rounded, or Spreading		Moderate	Yes, once established	Dense	Low	Root Rot, Rust, Verticillium, Virus
	**Island Oak** *Quercus tomentella*	Large	35–50’	25-30’	Upright, Rounded, or Spreading		Slow	Yes, once established	Dense	Low	Armillaria
	**Texas Ebony** *Ebenopsis ebano*	Small	30-40’	20-30’	Rounded, or Vase Shape		Slow - Moderate	Yes, once established	Moderate - Dense	Low	—
	**Emory Oak** *Quercus emoryi*	Large	30–50’	40’	Rounded		Slow	Yes, once established	Moderate	Low	Armillaria, Root Rot
	**Rose Gum** *Angophora costata*	Large	50-65’	30-50’	Upright, Concial, or Rounded	High	Fast	Yes, once established	Moderate	Low	Armillaria, Root Rot

Figure 3. Climate Ready Trees for the Los Angeles Region

		Overall Mature Size	Height	Crown Spread	Canopy Form	Canopy Height	Growth Rate	Drought Tolerant	Shading Capacity	Water Demand	Pests and Diseases
	**Silverleaf Oak** *Quercus hypoleucoides*		30-80’		Spreading, Rounded		Fast	Yes, once established		Low	Scales and Spider Mites, Spittlebugs, Armillaria, Drippy Oak, Root Rot
	**Coast Banksia** *Banksia integrifolia*	Medium	20-25’	10-15’	Rounded, Spreading or Weeping	Low	Moderate	Yes, once established		Low	—
	**Osage Orange** *Maclura pomifera*	Small	25-35’	15’	Rounded, Spreading or Weeping	Low	Moderate	Yes, once established		Low	Armillaria, Root Rot
	**Prickly-leaved paperbark** *Melaleuca styphelioides*	Medium	20-30’	20-30’	Rounded, Spreading, or Vase	Low	Moderate	Yes, once established		Low	Aphids, Root Rot, Verticillium
	**Honey Mesquite** *Prosopis glandulosa*	Medium	20-30’	15-30’	Rounded, Spreading, or Vase	Low	Slow - Moderate	Yes, once established		Low	Phytophthora and Root Rot

DISCUSSION

L.A.'s urban forest was established when irrigated water was more abundant (McPherson et al., 2018). In many cases, the most common species are native to temperate climates (e.g., *Fraxinus, Prunus, Liquidambar*) and not suited to withstand the anticipated pressures from climate change (McPherson et al., 2016). To increase the climate resilience of L.A.'s urban forest, managers can gradually shift the mix of species to reduce vulnerability and catastrophic loss of tree canopy. The close proximity of abiotic and biotic threats to the urban forest, including extreme heat, drought, pest outbreaks, and associated mortality events may initiate a rapid transition to a more resilient species composition and age structure.

Tree species selected in this study are native to a variety of hot and arid climates: desert (southwest USA), Mediterranean (Australia), temperate dry (Great Plains USA) and tropical dry climates (India). Given the broad geographic range of origins, however, there is a risk that species will be too well-adapted and become invasive, or poorly adapted in unanticipated ways and fail to establish. Future research is necessary to fully understand the suitability of each species to distinct urban sites, as well as the implications of each for management, maintenance, and biodiversity concerns.

Assuming a continued trend of disinvestment in tree maintenance and management stemming from insufficient municipal budgets, as well as future contestations over drought-induced water supply, this study employed a very conservative approach to species selection by excluding species with moderate water use and those with vulnerabilities to all invasive beetle borers. Many well-established trees in L.A.'s urban forest require moderate water use during the establishment phase, but are able to tolerate longer periods without watering after the establishment phase. In short, there may be many more species that are well-suited to current and projected climate regimes for the L.A. region that were not included in this study.

Tree selection is an important decision tool for managers aiming to enhance the resilience of their urban forests (Lacan and McBride, 2008). However, it represents one of many approaches that cities can take to incorporate UF into their climate mitigation and adaptation plans (Brandt et al., 2016; Ordonez et al., 2010). Other notable strategies being taken by cities to reduce the vulnerability of their urban forests include (Huber et al., 2015):

- Increasing seed diversity by piloting seed diversity projects that propagate locally native species (Toronto, CA).
- Contracting with nurseries to grow species that meet specified standards (New York City, NY).
- Emphasizing selection of drought- and saline-tolerant species (Palo Alto, CA)
- Including geographic diversity, along with species and age diversity, as strategies to increase the resilience of tree stands in the urban environment (Austin, TX).

This study faced a number of limitations that could be addressed by future research. First, it was challenging to obtain data on some of the vulnerability criteria, particularly for non-native trees from remote regions of the world. Lack of information on a species' range and growing conditions, physiological tolerances, invasiveness, and pest vulnerabilities contributed to heightened uncertainty in the assessment and selection processes. Moreover, this study does not account for spatially-variable climate projections and their impacts on candidate species, partly due to the fact climate modeling for urban environments is complicated by local UHI effects. To limit uncertainties, future research might incorporate how climate change exposures might influence the invasiveness and pest vulnerability of different species in the future.

This research may assist managers by providing information on tree species that appear promising in terms of adaptation to future climatic conditions, but are not locally grown and available. As high performing tree species enter the nursery trade, UF managers and decision makers can provide market signals by requesting them from commercial nurseries, and in turn, gradually shift public preference for climate resilient species. Most importantly, increasing the appetite for planting resilient tree species on both public and private lands will be paramount to improving urban forest resilience. Messaging on the importance of climate resilient species should adequately reflect their role in sustaining the critical regulating and provisioning services of trees that improve environmental quality, human health, and well-being in urban environments.

Part 2: Functional Traits of Urban Trees

Although urban tree advocates frequently cite the benefits of trees for mitigating the UHI effect and air pollution, there is a surprising disconnect when specifying trees with a combination of desirable and functional traits that are most likely to achieve those goals (Pincetl et al., 2013). The extent of regulating services provided by trees is contingent on a distinct set of tree morphological and physiological characteristics that vary with species, climate conditions, site parameters, and atmospheric factors (Rahman et al., 2018). Tree characteristics that contribute to enhanced cooling benefits and air quality, along with their implications for urban forestry management, are discussed in the section below.

TREE TRAITS FOR COOLING BENEFITS

Trees provide cooling benefits through two primary mechanisms: by blocking direct shortwave radiation from heating buildings and ground surfaces beneath the canopy (shading) and by decreasing regional air temperatures through the release of water vapor through stomata: tiny, closable, pore-like structures on the surfaces of leaves that regulate water movement between trees and the surrounding atmosphere (transpiration). Shaded surfaces may be 20-45°F cooler than peak temperatures of unshaded surfaces, while the impact of transpiration, alone or in combination with shading, can reduce ambient air temperatures by 2-9°F (Rahman et al., 2020; 2018).

A growing body of research has explored the potential of tree species characteristics for reducing urban heat. A systematic overview of species characteristics that enhance micro-climatic thermal regulation through cooling and transpiration, along with an understanding of the dependencies between site conditions and tree and leaf anatomical, physical, and morphological traits, may aid future decision making around tree selection and planting processes to optimize cooling benefits. A summary of different tree characteristics and their effects on shading and transpiration are listed in Figure 3 (Rahman et al., 2020).

	Crown Shape	Shade	Evapotranspiration
CONDITIONS	Climate	+++ *Mediterranean	+++ *Oceanic
	Surface	+++ *Asphalt	+ *Grass
ORIGIN	Cultivar		+++ *Cultivar
	Habitat	++ *Species-rich	+++ *Species-rich
LEAF TRAITS	Leaf thickness	++ *Thin	++ *Thin
	Leaf hairiness		+ *Some
	Leaf color	++ *Dark Green	++ *Dark Green
	Leaf shape	+ *Needle	+ *Simple
	Foliage density	+++ *High	
PHYSIOLOGY	Crown shape	++ *Pyramidal	
	Canopy height	++ *Small	+ *Tall
	Plant functional type	+ *Coniferous	
	Wood anatomy	+ *Non-porous	+++ *Diffuse porous

Figure 4. Summary of the findings on shading and transpiration air-cooling for species traits. Tree traits are listed in order of the magnitude of their effect on shading and transpriation, and are ranked from +++ (very high effect) to + (low effect). The most significant traits for each cooling benefit are indicated by *. Adapted from "Traits of trees for cooling urban heat islands: A meta-analysis," by M.A. Rahman, L.M.F. Stratopoulos, A. Moser-Reischl, T. Zölch, K.-H Häberle, T. Rötzer, H. Pretzsch, and S. Pauleit, 2020, Building and Environment, 170.

Shading Capacity

Leaf Area Index (Canopy Density). Tree canopies provide shade by intercepting direct shortwave radiation. Several studies have shown that deciduous species with broad, flat leaves can prevent up to 90% of shortwave radiation from reaching ground surfaces, particularly during hot summer months (Heisler, 1986; Zhang et al., 2013).

> **As measured by leaf area index, LAI$^{(m^2m^{-2})}$, the canopy density of a given crown is a critical factor in determining the extent of surface temperature reduction over paved surfaces.**

Tree species with a high LAI and dense canopies offer more shade and transpire more water than sparse canopies, resulting in cooler surface temperatures (Wujesa-Klause and Pfautsch, 2020). Research shows that every unit of LAI increase can reduce surface temperature by 1.2°C (Hardin and Jensen, 2007). However, the interactive effect of LAI and surface temperature is complex and is mediated by the soil moisture content of the growing site, which can vary with microclimate, water use efficiency (WUE), and LAI of plants in the surrounding system (Arx et al., 2013; Baldocchi et al., 2008).

Canopy Characteristics. A number of canopy characteristics—including tree height, the height of the crown base, and crown shape—may have significant effects on shade provision. Research shows that a tree's surface cooling potential decreases with tree height and height of the crown base (Helletsgruber et al., 2020; Rahman, 2020). The influence of tree height on surface cooling may be attributed to the fact that taller trees tend to have narrower canopies. In contrast, shorter trees generally have wider and denser canopies that cast shade on specific surface areas for extended periods (Rahman, 2020). Furthermore, taller trees can hold greater volumes of hot air masses beneath their canopies, which can increase ground heat flux.

Crown shape, which is parametrized by the absolute size, aspect ratio (height to width), and the shape of its contour, bears a strong influence on the distribution and extent of its shade. Crowns with different aspect ratios have inherently varying efficiencies of light interception. In lower latitudes, the shaded area of a narrow crown is smaller and more concentrated around the tree than the shaded area caused by a broad crown. Trees with more wide and dense crowns project a more effective shadow (Sanusi et al., 2017), and the path lengths from sunlight are shortest for flat, horizontally extended crowns (Kuuluvainen, 1992). Round-shaped and horizontally spreading tree canopies are more effective in surface cooling than pyramidal and columnal ones (Kuuluvainen, 1992). Specifically, in high latitudes, light penetrates from high solar inclination angles, and the path lengths of projected light beams increase with crown flatness. Beam path lengths are similar throughout the entire canopy for narrow, vertically extended crowns to maximize the direct light interception (Kuuluvainen, 1992).

Leaf Characteristics. Leaf thickness and color can also have a significant influence on surface cooling. Species with thick leaves typically exhibit faster growth rates and are more light-demanding, although effects of leaf color on surface temperature reduction may be modulated by canopy density (Poorter, 2009). Tree species adapt to different sunlight regimes by producing leaves with varying degrees of reflectiveness. Darker-colored leaves absorb the most energy from sunlight, while light colored leaves reflect excess sunlight. In higher latitudes, where sunlight is limited, conifers with dark needles can absorb the most energy from available sunlight. By contrast, trees in low latitudes receive ample sunlight and possess light-colored leaves to prevent scorching by reflecting excess light. Dark green leaves of <0.15 mm thickness have been shown to deliver the most significant surface cooling benefit, although cooling may come at the cost of higher water consumption (Lin and Lin, 2010; Rahman et al., 2020).

Ambient Temperature Regulation (Evapotranspiration)

Several of biophysical and structural characteristics, such as tree growth, wood anatomy, functional tree type, and leaf traits, enable certain tree species to optimize water use efficiency (WUE), defined as the ratio of biomass produced from assimilated carbon to unit of water lost through transpiration (Briggs and Shantz, 1913). Other less directly observable characteristics, including leaf thickness, shape, color, and texture, also allow certain tree species to achieve growth despite challenges from climate stresses. These traits mediate evaporative demand and WUE, and could have significant implications for tree selection in L.A., where rising temperatures and diminishing rainfall may further limit the ability of trees to recharge atmospheric moisture, contribute to local rainfall, enhance soil infiltration, and regulate air temperatures.

Growth Rate. Annual tree growth (measured by DBH and height) and associated increases in leaf surface area (LSA) are principal determinants of evapotranspirative demand and consequent cooling effects, at least up to maturity (England and Attiwill, 2006). However, tree growth and evapotranspiration are also positively correlated to the moisture content of the growing site.

Wood Anatomy. Wood is the water-conducting tissue of a tree's vascular system, and its anatomical structure determines a species' ability to cope with the high evaporative demand imposed by heat, drought, and other climate stresses (Anderegg and Meinzer, 2016). Physiologically, drought stress can cause direct mortality of trees through the two interrelated mechanisms of carbon starvation and hydraulic failure (McDowell et al., 2008). Carbon starvation refers to the process of stomatal closure, which minimizes water loss to transpiration and limits the entry of CO2 necessary for photosynthesis. Subsequently, trees must rely on stored sugars and starches to survive and may die if these reserves are depleted before the drought ends. On the other hand, if a tree loses too much water too quickly, air bubbles may form. Hydraulic failure refers to the loss of vascular function when air bubbles form and spread throughout the sapwood, producing breaks in an otherwise continuous water column and preventing water from being transported from the roots to the leaves. This process—the result of cavitation, or the phase change of water from liquid to gas—is primarily dictated by wood anatomy.

Tree species have two distinct types of wood porosity, and differences in the size and distribution of pores lead to differences in the efficiency of water conduction (Wheeler et al. 1989) (see Figure 5). Ring-porous species exhibit higher WUE than diffuse-porous species, which typically have low WUE.

> **However, diffuse-porous tree species have been shown to transpire 2-3 times more than ring-porous species (Peters et al., 2010; Rahman et al., 2017, 2018; Bush et al., 2008), and consequently contribute to more cooling from transpiration.**

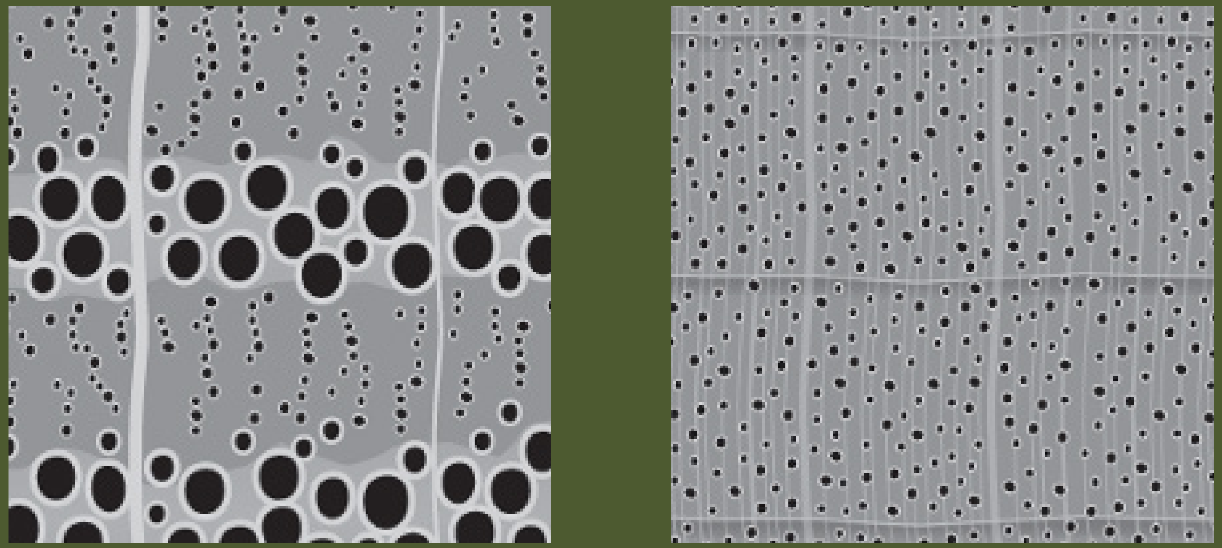
Ring-porous species typically have a bimodal distribution of wide early-season and narrow late-season vessels, making them more susceptible to cavitation (Rahman et al., 2020). Conversely, diffuse-porous species, which usually have more than double the density of vessels and slight variation in diameter in early versus latewood, are less sensitive to atmospheric drivers of transpiration (Oren and Pataki, 2001).

Plant Functional Type. In terrestrial ecology, plant functional types classify species with similar responses to the environment and with similar effects on ecosystem functioning. Trees are categorized into four functional types: broadleaf or conifer, and either deciduous or evergreen. With greater leaf thickness and LAI, Rahman and others found that small-sized evergreen coniferous species showed greater surface temperature reductions than deciduous or evergreen broad-leaved species (Rahman et al., 2020).

> **During dry summer months, many evergreen conifers have low water demand relative to broadleaf deciduous species, which require more water to drive photosynthesis (Peters et al., 2010).**

Despite these advantages, however, conifers are challenging to establish in public rights-of-way, as they typically require larger spaces to grow, and their growth form conflicts with overhead infrastructure.

Figure 5. *Wood, also known as secondary xylem, constitutes the water-conducting tissue of tree stems. In most angiosperm (flowering) trees, water conduction is achieved by vessels, which can join end-to-end with other vessels to produce longer conduits that form a complex wood tissue system. The size, number, and distribution of vessels affect the appearance and uniformity of hardness in a particular wood. Pores, or vessels, refer to the small circular holes visible on a cross-section of wood. Hardwoods are known as "porous woods," whereas softwoods, which are devoid of pores, are known as "non-porous woods."*



Ring Porous
In some species (e.g. oak and ash), the largest pores are in the earlywood while those in the latewood are more evenly distributed and uniform in size. These woods typically have distinct figures and patterns.

Diffuse Porous
In some species (e.g. maple, cherry and yellow poplar) the pores are distributed fairly evenly across the earlywood and latewood. Most domestic diffuse-porous woods have relatively small-diameter pores, but some tropical woods of this type (e.g. Rosewood) have rather large pores.

Leaf Traits. Leaves are the primary photosynthetic agents of trees, and a number of leaf morphological and physiological traits have been shown to moderate ambient air temperatures. Variations in leaf thickness, size, shape, color, and texture mediate the degree of thermal regulation influencing water loss and heat regulation (Stratópoulos et al., 2018).

Research shows that the size and shape of leaves also regulate the functions of leaf energy exchange, temperature, and photosynthesis. Variation in leaf size is generally understood as the trade-off between leaf size and the number of leaves produced, where leaf size is linearly negatively correlated with leafing intensity, and consequently, canopy density (Kleiman and Aarssen, 2007; Yang et al., 2008; Whitman and Aarssen, 2010). Generally, smaller leaves are advantageous in hot and arid conditions with high intensities of solar radiation, whereas large leaves have less efficient energy exchange capacity and are more suitable for cool and moist climates (Niinemets et al., 2006; Meier and Leuschner, 2008; Tozer et al., 2015). In terms of leaf shape, tree species with thicker or compound leaves exhibit higher rates of water loss than those with thin leaves and simple leaf shape (Lewis and Nobel, 1977).

> **In other words, tree species with simple-shaped leaves have been shown to exhibit higher cooling benefits from transpiration, compared to needle or compound leaves (Rahman et al., 2020).**

Leaf color moderates local heat absorption, and leaf reflectance is inversely correlated to the transpiration cooling (Lin and Lin, 2010). Light-colored leaves reflect excess sunlight, and consequently absorb less heat energy from the sun. By contrast, darker leaves absorb more light energy and in turn, more heat. Simply put, darker, thin-leaved species provided better transpiration cooling. Textural features of a leaf's boundary layer, which refers to the thin layer of unperturbed air over the leaf surface, also play an important role in regulating WUE and transpiration. For transpiration to occur, water vapor exiting the stomata must diffuse through this layer to reach the atmosphere, where it is subsequently carried off by air currents. Thicker boundary layers, therefore, result in slower rates of transpiration.

> **Waxy coatings and hairy leaf surfaces also slow the rate of transpiration by creating a thicker boundary layer and preventing excessive water loss (Rahman et al., 2020).**

Hairy (pubescent) leaves perform a variety of other functions, including light reflectance and protection from herbivores (Ehleringer and Mooney, 1978).

TREE TRAITS FOR AIR QUALITY

Trees may be effective at intercepting and removing atmospheric $PM_{2.5}$ and gaseous pollutants in urban areas, which are associated with a range of health complications, including cancer, respiratory and cardiovascular diseases, as well as neurological disorders (Gauderman et al., 2000, 2007; Blanusa et al., 2015; Habre et al., 2020). Particle capture occurs through two primary mechanisms: deposition on surfaces, and stomatal uptake (Grote et al., 2016). However, the magnitude of this benefit varies with species canopy structure (e.g. crown density, size and shape) and foliage characteristics (e.g. leaf shape, texture, and physiology).

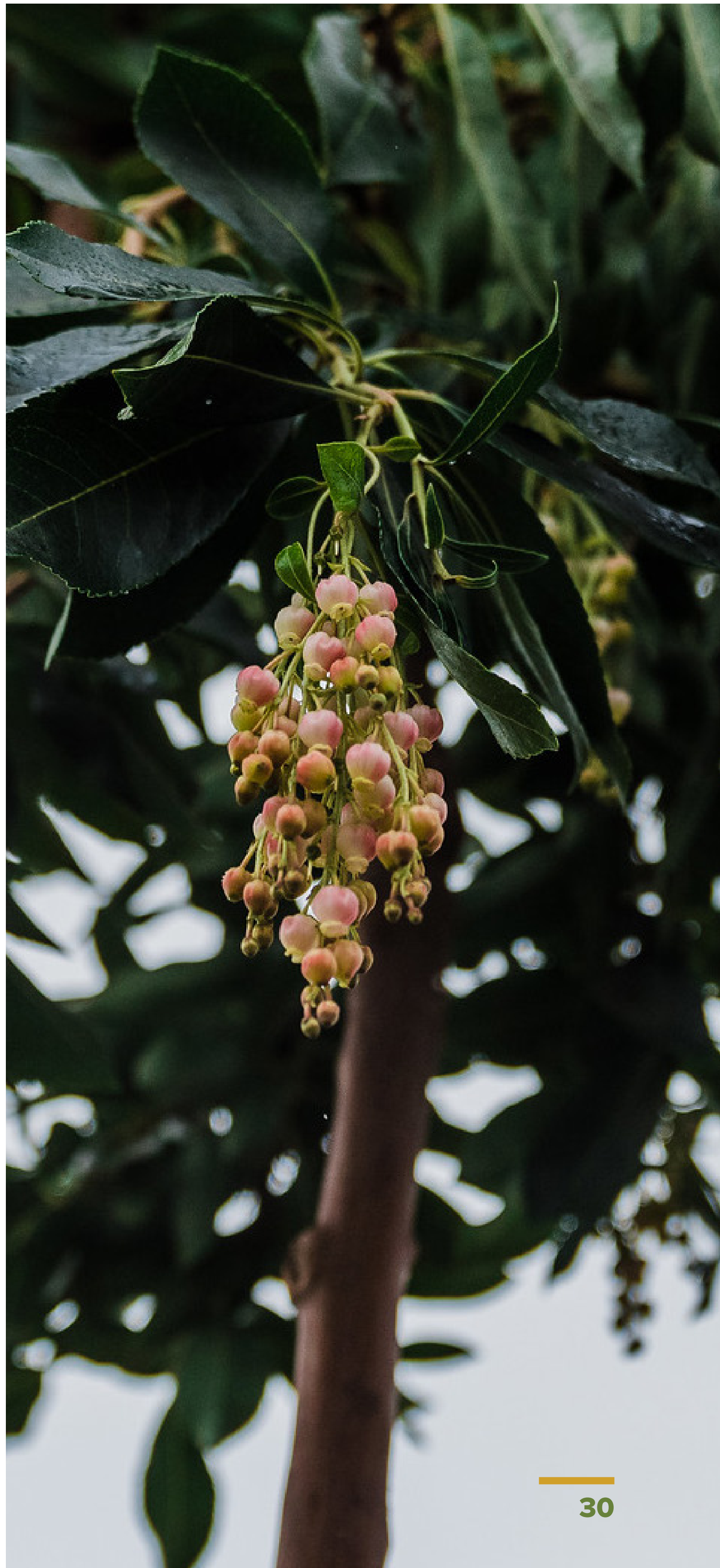
Larger and denser canopies are more effective at intercepting particles, although research is inconclusive on the complex feedbacks between canopy structure and local meteorological conditions (Amorim et al., 2013). Wind direction and urban form can dedicate the way pollutants are dispersed, suggesting the importance of local context in selecting species for mitigating air pollution (Aristodemou et al., 2018). Research also suggests that dense tree crowns can exacerbate PM concentrations in street canyons—abundant within urban environments—by reducing dispersion and atmospheric mixing (Gromke and Ruck, 2009; Hofman et al., 2013; Nowak et al., 2006).

The majority of gaseous and particle deposition occurs at the leaf surface.

> **Larger leaves with rugged, waxy, and pubescent surfaces have a greater influence on particle deposition than small and smooth leaves.**

Pollutant uptake by leaves—other than those that merely bind to or are dispersed at the boundary layer—occurs through the stomata. Stomatal uptake is contingent upon photosynthetic activity and leaf water potential, which are determined by environmental variables. For instance, a study by Fares and others (2014) showed that stomatal uptake in a Mediterranean evergreen forest was considerably higher in spring, when water supply and vapor pressure were greater than during summer.

Although urban trees are increasingly regarded as being effective for reducing ambient PM concentrations, their ability to reduce atmospheric PM is fiercely debated (Maher et al., 2013). Empirical evidence of PM reduction by trees, particularly at the local scale, islimited (Fowler et al., 2004). More notably, trees may actually contribute negatively to air quality by emitting primary organic particles known as biogenic volatile organic compounds (BVOCs) (Churkina et al. 2015). These effects can produce ground-level ozone, secondary organic aerosols, and PM in urban environments (Niinemets and Monson, 2013). As urban trees respond to the anticipated effects of climate change, including rising temperatures, greater urban pollution, and atmospheric carbon dioxide (CO2) concentrations, their associated BVOC emissions may intensify substantially (Calfapietra et al. 2013b).



Part 3: Towards a Climate-resilient Urban Forest

The final section of this report evaluates the suite of institutional and policy actions, market-based mechanisms, and approaches to building public recognition that can influence widespread demand for planting climate-resilient trees on public and private lands. These include modifying local and state jurisdictional policy through approved species lists; leveraging tree procurement strategies and scaling the capacity of existing nursery stocks; and finally, but perhaps most importantly, improving strategies for engaging various publics in tree stewardship and disseminating information about non-traditional climate-resilient trees in ways that are the most salient to the needs of local communities. In the following section, we outline some pertinent findings of these studies, unresolved questions and debates, and discuss the attendant barriers and opportunities for growing the presence of climate-resilient tree species in L.A.'s urban forest.

REVIEW OF EXISTING RESEARCH

A limited body of research has explored three critical mechanisms that have significant implications for the distribution of climate-resilient trees across public and private lands: modifying local and state jurisdictional policies through approved tree species planting lists; ensuring regional availability of nursery tree stock; and increasing public awareness of non-traditional tree species.

Amending Approved Street Tree Species Lists. Trees planted on public and private lands must be selected from a list of pre-approved tree species, which are determined by municipal tree ordinances. These lists are created to publicly identify and endorse certain tree species tolerant of common biotic and abiotic stresses using information gathered from experience and historical records. The convergence of species on approved lists with those that are planted in public spaces illustrates the practical approach that municipalities adopt toward species selection and suggest that approved species lists are valuable predictive estimates of the tree species that cities will require for future planting (Pincetl, 2010a; Burcham and Lyons, 2013). However, research on the most effective procedures for revising and adapting approved tree species lists is sparse. Future research is necessary to evaluate how these lists might be designed with the flexibility to incorporate new findings and respond to the changing needs for species selection and urban forest management, and how decision-making processes may include different forms of input in the species inclusion criteria.

Tree Acquisition and Procurement. Nursery supply contributes significantly to urban forest population dynamics. As nurseries provide the majority of cultivated private and public street trees in cities, harnessing the landscape tree supply chain is an critical first step towards ensuring the availability of tree stock (Pincetl et al., 2013). Within existing greenhouses, seedbeds, and other infrastructure, nurseries have the potential to increase seedling production by 34% nationwide (American Forests, 2021). However, the ability to scale up production to increase healthy tree stock is contingent upon supply chain dynamics, operational practices, the length of production cycles, and other factors.

Nurseries propagate, grow, and distribute trees used for planting. Over the past few decades, the commercial nursery industry has been segmented into various components, including seedling production, whip production, wholesale producers, and brokers (Sydnor et al., 2010). Municipal tree procurement is primarily negotiated through direct trade with wholesale nurseries. However, trees may also be purchased from intermediaries, such as re-wholesalers or brokers, who can access a more extensive network of buyers and sellers (Burcham and Lyons, 2013). Collectively, these varied transactions comprise the latter stages of the supply chain delivering landscape trees to end consumers. At the same time, propagators and liner nurseries (e.g., primary growers) contribute to the earlier stages of this process by germinating and growing trees from seed. One of the casualties of a segmented supply chain, however, is a line of severed communication between segments, particularly seed growers overseeing the seed production and end-users, such as municipal arborists (Sydnor et al., 2010).

Operational processes of the nursery tree trade may also impact the hardiness and longevity of trees once they are planted. Nursery production methods have been shown to modify tree root morphology and architecture, with adverse outcomes for tree growth, survival, stability, and capacity to withstand drought stress several years after planting (Gilman, 2001; Gilman and Harchick, 2008; Gilman et al., 2003; Hewitt and Watson, 2009). Formative pruning, or the process of shaping a tree during the first few years of growth to establish tree shape, is often carried out by nurseries; improper pruning practices may similarly alter tree structure and weaken branch attachment, particularly when branches grow relatively large compared to the dominant trunk (Gilman, 2003).

Commercial nurseries are also wary of the attendant economic risks of building additional greenhouses and buying land and equipment to accommodate more production. Seedlings require two years to grow, and the production lead time for a shade tree—from the time it takes a germinated seed to grow into a finished, landscape-sized tree—ranges between 2-5 years (Warren, 1990). This unusually prolonged production cycle makes it challenging for nurseries to forecast demand and respond to sudden or short-term market changes. To limit the likelihood of throwing out seedlings if buyers do not materialize, nurseries typically favor growing species with established demand, making it particularly challenging for end consumers to procure non-standard species without widespread recognition (D'Amato et al., 2002; Gainer, 2000; Vallet, 2001).

To address these limitations and ensure sufficient tree stocks, municipalities may assert greater control over the landscape tree market through several mechanisms. Direct procurement from primary growers and contract growing emerge as promising approaches to acquiring large quantities of tree stock (Burcham and Lyons, 2013). Harnessing the upstream segments of the supply chain affords municipal foresters the ability to influence planning decisions and production techniques at these earlier stages and tailor growth outcomes according to their preferences. Additionally, allocating dedicated funds towards expanding the capacity of existing nurseries (e.g., adding new greenhouses) or starting up brand new nurseries (e.g., purchasing land) may provide nurseries with long-term market demand signals that enable them to take on debt to scale up capacity (American Forests, 2021). To stimulate private demand for particular species, incentive programs—such as the use of a voucher system established in conjunction with local nurseries (issued by government to private property owners)—may allow municipal agencies to streamline the species control process, allowing municipalities to incentivize only those tree species which have the most significant environmental impact (Thompson, 2017). The use of vouchers has also been shown to enable municipal control of the cost of tree planting and target specific populations or neighborhoods (Ibid). However, research is generally limited on how the dynamic interaction between nurseries and municipalities can be effectively structured to reduce market uncertainty and maximize utility for all participants.

Communicating to the Public about Climate-resilient Tree Species.

Despite their potential benefits, newly planted climate-resilient trees are vulnerable in urban environments due to human and environmental factors, and strategies for canopy expansion are unlikely to succeed without increasing public awareness about this specific group of trees. An approach to communicating with the public about these species that incorporates a mix of strategies, including media campaigns, formal and informal educational programming, incentives for tree planting and proper care, and the dissemination of information through websites and local organizations, is vital to developing widespread support for planting and managing climate-resilient trees (Young, 2011; APA, 2009).

Popular media plays a vital role in shaping public perception by increasing awareness of a topic and influencing opinions and perceived realities, particularly concerning environmental threats (such as exposure to extreme heat, pest infestation, and tree death). Media campaigns can conceivably influence management decisions by residents and directly change public opinion on urban trees, which can, in turn, exert pressure on local policy actors (Burke, 1999). Radio and social media campaigns can broadcast information to reach a wider audience than other mediums and are accessible to people who are otherwise isolated by geography, language, or poverty (Ibid). While many studies have addressed this mode of communicating science, there are there are limited assessments of the effectiveness of the information residents receive about the role of urban forests in strengthening community resilience to climate change (Clarke et al., 2020; Conway and Jalali, 2017), and a paucity of research into what content should be communicated to the public to promote species adoption and adequate tree care (Clarke et al., 2020).

While expanding TTC with climate-resilient tree species requires substantial outreach to the public (Clarke et al., 2020), merely presenting people with information from experts may not equate to behavior change (Lakoff, 2010). Instead, the general public often interprets information based on framings of a particular phenomenon (Ibid). Contemporary news media is predominantly driven by events and capitalizes on intense event portrayals that convey feelings of "doom and gloom" (Pezzullo and Cox, 2018). Climate stressors such as pest invasions and tree die offs can be regarded as examples of doom and gloom events, facilitating media narratives of dead trees. To spur positive outcomes of tree planting and stewardship, it is important to evaluate and tailor media representations accordingly (Lyytimäki, 2014). Although the loss of urban trees to drought and pests is inherently harmful in terms of the ecological and economic consequences, dramatic representations of gloomy events may discourage or overwhelm the public in their response if their efforts around tree management and advocacy are perceived to be unavailing. More research is necessary to improve the understanding of language framings that effectively influence public opinion and motivate public action in urban forestry management and climate adaptation strategies.

Attempts to encourage private adoption of climate-resilient trees may also engender mistrust and tension between the experts and the general public if the public perceives that their opinions are not valued in the decision-making process (Clarke et al., 2020). Although experts are often regarded as trusted sources of information, environmental issues like species selection and proper management strategies require public participation to support long-term tree survival. Therefore, promoting climate-resilient trees and urban forest management may present an opportunity to engage the public in environmental discourse rather than employing the traditional top-down model of knowledge sharing.

Environmental Education. Educational programs in informal settings can be efficient tools for the general public to establish affective links with climate-resilient trees in the urban environment and promote them to non-specialist publics. Proactive guided tours of nurseries and botanical gardens that incorporate lessons in botany with mindfulness activities have been shown to enhance public awareness about trees in urban spaces (Lopes et al., 2019). Outdoor learning activities that focus on particular tree species, and incorporate hands-on activities to direct attention towards their natural, scientific, historical, cultural, and aesthetic attributes, can achieve dynamic and cooperative learning experiences. Passive observation and active exploration contribute to building positive memories of trees and certain notions about them. These strategies also contribute to improving values and attitudes and to developing environmental responsibility within a social context. As Fančovičová and Prokop (2011) have shown, these strategies may positively influence participants' attitudes toward and knowledge of trees and represent suitable alternatives to conventional biology courses in more formal learning environments. This idea is further corroborated by Lohr and Pearson-Mims (2005), who showed that positive perceptions and actions towards trees in adulthood are directly influenced by active and passive interactions with plants during early childhood development. Children are more likely to respect trees if they plant and care for them while observing them as they grow and bloom (Viana, 1999). Activities that engage participants to interact directly with trees have been recommended in several studies (e.g., Drissner et al. 2010; Nadelson 2013; Sanders, 2007).

Nursery Workshops and Messaging Strategies. Nurseries and garden centers are also well-poised to promote public awareness about climate-resilient trees. Workshops addressing factors to consider during the species selection process may help alter demand toward resilient species well-adapted to local climatic and environmental constraints (Conway and Vander Vecht, 2015). Many nurseries already offer workshops to attract customers and provide educational programming to promote certain tree species (Conway and Vander Vecht, 2015). Additionally, nurseries can create demand for climate-resilient tree species with messaging and marketing strategies to enhance awareness about unconventional species and provide relevant information about site suitability and specific traits that align with consumer preferences (Sjöman and Nielsen, 2010; Avolio et al., 2018). Underlying all of these approaches is the need for clear and accessible information about tree species, in addition to detailed information on ways to plant and maintain them (Sjoman & Nielsen, 2010). Researchers, municipal authorities, and plant nurseries can collaborate to inform future landscaping decisions by bridging the information gap between tree traits and their attendant services (e.g., provision of shade, temperature regulation, and beauty) and disservices (e.g., maintenance requirements, water use, potential infrastructure conflicts) (Roman et al., 2021).

METHODOLOGY

In this study, semi-structured interviews were conducted to identify public, private, and institutional barriers to expanding the presence of climate-resilient species in L.A.'s urban forest. Three groups of actors were chosen to represent a wide range of professionals and organizations impacting the urban forest on public and private lands, including policymakers from municipal, state, and federal government, municipal UF staff, and representatives from non-profit organizations. Private landowners were excluded from this analysis due to time constraints and sampling limitations. However, individuals selected for interviews interface with landowners in various ways to communicate general information about trees and provide specific planting services and were therefore regarded as appropriate proxies for assessing public opinion.

The first two sets of actors—policymakers and municipal UF staff—are directly involved in devising and implementing tree-related policies and forestry goals, many of which are spread across multiple area codes and administered by different bureaus. Local policymakers affect broad policy direction for managing the urban forest and contend with competing policy priorities to balance numerous community objectives. In this way, they offer a unique vantage point to consider possible policy mechanisms and barriers to achieving a resilient forest structure. UF staff are responsible for establishing planting plans and procuring tree stock and are well-poised to offer crucial insights into associated obstacles. While street and other city-owned trees represent 9% of the urban forest, they constitute the most accessible trees to urban residents. Therefore, they represent a significant part of the forest in shaping residents' experiences and preferences.

The third group—local non-profit organizations and advocacy groups—interface with the public, either at the city or neighborhood scale, to increase public awareness around the benefits of urban trees and engage constituents in actions related to UF. These organizations are also responsible for overseeing a large share of tree planting activities, potentially affecting species composition and resident preferences in the long term.

Of these three groups, I interviewed a total of 17 subjects: the chief UF coordinator (Los Angeles Department of Public Works); one representative from Council District 5; three arborists (Recreation and Parks Forestry Division and UFD); one urban forester; three city planners (DCP), two environmental specialists from the LA Sanitation and Environment (City of L.A.); two members from non-profit organizations; two community forestry council committee members from the California Urban Forests Council (CaUFC) and the City of L.A.'s Community Forest Advisory Committee (CFAC); and a research scientist from the USDA Forest Service (See Appendix B for the complete list of interviewees and respective affiliations). This composition came from using snowball sampling. All participants provided informed consent to participate as confidential subjects and to be audio recorded. Interview length averaged 40 minutes to an hour and covered involvement in UF and planning for climate adaptation; challenges related to UF governance; evaluations of current policies and tree ordinances; and perceptions of successful community engagement strategies. Recordings were transcribed in full, and findings from these interviews were used to inform policy recommendations for representatives from key UF sectors.

RESULTS AND DISCUSSION

The following themes emerged from numerous sources as the primary barriers and opportunities to growing climate-resilient species in the urban forest.

1. There are significant challenges related to the current tree supply process.

The current procurement process of street trees has resulted in strong working relationships between commercial nurseries and the L.A. Conservation Corps (LACC), the non-profit organization tasked with overseeing procurement and inspection of nursery stock for the City of L.A.'s Department of Public Works. Within these relationships, however, municipal foresters cited several challenges commonly encountered during tree procurement, including the limited availability of climate-resilient tree stock at commercial nurseries, in addition to obtaining trees of high enough quality that are well-adjusted to the different microclimates in the L.A. region.

Foresters and LACC staff noted that the limited availability of certain tree species at a given size hinders attempts to match trees with appropriate planting site characteristics and complicates efforts to improve urban forest structure and composition over time. Supply shortfalls usually result in changes or variations to planting designs and can cause less suitable species to be installed at a particular site. Having a limited number of species available at regional nurseries can delay planting schedules and result in a less diverse and stable urban forest, higher costs per tree, and the inability to plant non-standard species.

In addition to the small consumer segment occupied by municipal tree procurement, the prolonged tree production cycle partially explains the extent to which nurseries can adjust available supply to accommodate shifts in demand (Warren, 1990). Foresters suggested that the landscape tree market offers little incentives for nurseries to focus on the needs of a relatively small consumer segment, despite making requests on a biweekly basis to nurseries to increase the availability of certain species. Some participants also voiced frustration with a lack of commonly accepted tree quality grades and standards defining tree health, root structure, and canopy architecture, contributing to challenges in obtaining a constant source of high-quality trees. Tree quality can be inconsistent among the nurseries or species. One participant noted:

> **"Sometimes we'll want to plant a wider variety of trees, but many won't be available, so we'll have to substitute them with other species. If they are available, they're of poor quality with defects and damage....The unfortunate thing that I've been having to do lately is when I do these inspections, I won't even assign certain species that are on the species lists because I know they're not going to be available anywhere."**

While LACC staff have come up with techniques to improve the overall quality through additional treatment before tree planting, these treatments take up additional time and effort, which could otherwise be diverted to increasing the number of street trees planted or to other areas like public engagement and publicity to raise public awareness. Poor quality trees also pose issues for subsequent maintenance.

LACC staff also noted the problem related to obtaining trees originating from much drier and sunnier climates, resulting in highly stressed trees that are not acclimatized to L.A. microclimates and variable site conditions across urban landscapes. Trees growing in nurseries are usually well taken care of with the necessary growing requirements. However, when non-native trees are planted in highly constrained urban environments, these trees may face difficulty adapting to the new site conditions, leading to higher mortality rates and requiring subsequent replacement.

2. The supply of diverse and climate-resilient seed stock may be insufficient to meet planting goals.

A significant constraint to ramping up the production of non-standard tree species was attributed to the lack of diverse and climate-resilient seeds. Nurseries cannot respond to increasing demands for climate-resilient trees if seed stock of the appropriate species of adequate quality and genetic variability is not available. Supplies of low-elevation seed sources in California are running low as demand skyrockets due to wildfires consuming what seed source remains (American Forests, 2021). Limited seed inventory constrains the ability of nurseries to respond to increased demand with the seed stock of the appropriate species, genetics, and quality.

An additional concern cited by a local nursery manager was the lack of seed collectors and growers to process seeds for storage and production (Kat Superfisky). Seed inventories vary regionally and depend on the quality and capacity of seed storage, access to storage facilities, adequacy of funding to support storage and infrastructure, and assurance that demand for a particular species is sustainable. Smaller nurseries operated by federal parks groups and private non-profit organizations run most of the seed banking infrastructure for species in the L.A. region. However, these seed collectors typically focus solely on propagating and cultivating native plants from throughout California and within the California Floristic Province, which may create significant bottlenecks for obtaining climate-resilient seeds of non-native species.

3. Tree mortality from insufficient maintenance represents both a sunk management cost and a reflection of neglect in disinvested communities.

Newly planted trees will not provide the long-term environmental benefits sought by planting programs without adequate maintenance throughout the establishment phase. While there may be a brief period of aesthetic appeal from newly planted trees, once the trees are dead, they represent a sunk management cost and contribute to landscape disorder (Nguyen et al., 2017). The death of newly planted trees due to insufficient maintenance can, therefore, be viewed as a consequence of decision-making that does not support the resources, staffing, and stewardship networks required for tree canopy expansion (Breger et al., 2019). Trees that die from lack of maintenance can reflect poorly on the local community and make residents distrustful and resistant to planting programs (Carmichael and McDonough 2019), compounding the negative impacts of tree death. As one interview from a non-profit planting organization noted:

> ***"If [community residents] see you come in and plant trees, and then a year later, they're all dead, it's almost better if you had not done anything at all because dead trees cast in stark terms how neglected certain neighborhoods are."***

Chronic disinvestment in UF extending from the 2007-2009 financial recession has severely limited the City of L.A.'s UFD and RAP ability to perform the requisite tree maintenance activities. Many interviewees acknowledged that insufficient citywide maintenance creates an ambiguity around whose responsibility it is to water and care for trees in public parkways, which contributes to resident distrust of government agencies and well-meaning non-profit organizations. With limited funding towards tree care and a suggested 'establishment period' for new street trees of five years or more, plans for canopy expansion will need to leverage sustainable funding streams to ensure adequate maintenance.

4. The lack of adequate and sustainable funding hinders efforts to support a resilient urban forest.

Nearly all interviewees cited the need for increased funding at all levels—from federal agencies to philanthropic foundations to municipalities. If community forests are to provide the infrastructure support needed to create sustainable and resilient communities, then forests need to be adequately maintained, canopies need to be expanded, and emerging uses and functions for these forests need to be understood and utilized. Funding for urban forestry has been cut significantly since 2008, and many interviewees noted that federal funding for urban forestry had not increased substantially in the past decade. If this community asset is to fulfill its potential, more funding is strongly needed, both from federal sources and more public-private partnerships. Thought leaders noted the need to look to new funding sources for UCF, look to public-private partnerships for new opportunities, and connect the benefits and requirements of a resilient urban forest with non-traditional sources of UF funding. For example, one interviewee from the mayor's office noted that policies around carbon in California had become a significant source of financing for UF agencies and organizations.

5. Engaging communities in the care and maintenance of newly planted trees across the region necessitates a multi-pronged approach.

Along with significant budgetary shortfalls, the geographic breadth of the L.A. region remains an important constraint for municipal forestry agencies in assuming the full responsibility of maintenance and establishment care. To this end, engaging community-based ambassadors and youth groups to raise awareness about climate-resilient tree species and advocate for ongoing tree maintenance are essential to ensuring the success of planting initiatives. These limitations also underscore the need to develop systematic neighborhood-based maintenance and care plans co-produced with those directly involved in tree stewardship within their communities. Plans should incorporate mechanisms that will enable municipal decision-makers to support communities with the financial and logistical assistance required to plant and maintain trees in public right-of-ways. Similarly, plans should require accountability and delegate responsibilities of enforcement, which are fundamental to the long-term health of the tree canopy.

The short lifespan of an urban tree means that most trees will grow and survive with two or more generations of people. Several UF managers noted the importance of long-term planning to ensure that a tree will grow and age successfully in step with adjacent residents. At the same time, a tree planted today must withstand decades of hotter and drier climate conditions. In this way, enlisting younger members to engage members of their community in tree stewardship may be a practical approach to ensuring the survival of newly planted trees.

Several interviewees suggested the importance of leveraging other novel approaches, some of which already may currently be underway, to expand outreach to communities across the region. These approaches include instating a youth-led resident forester program that builds upon the examples of several related programs which are prevalent in several U.S. cities, such as the Green Street Steward Program in Portland or the Tree Ambassador Program in Seattle. One important consideration will be aligning the purpose of these programs with the overall urban tree canopy goals. For instance, in areas with limited tree canopy, a multi-generational program might create green jobs for expanding canopy or guiding tree walks in their neighborhoods. In contrast, areas with higher rates of tree canopy may engage urban tree corps in learning from and providing maintenance alongside certified arborists. The types of programs that can expand public awareness and further tree planting and maintenance goals will likely determine the form that a multi-generational program will assume.

6. The need for culturally relevant environmental education is vital to the success of tree planting initiatives.

Successfully implementing solutions to combat the effects of climate change—including planting and caring for climate-resilient tree species—requires fostering environmental literacy in ways that spur interest, understanding, and critical thinking about environmental issues from a young age. Positive outcomes of environmental education (EE) include achievement motivation; awareness of social and environmental activism; critical thinking, problem-solving, and decision-making skills; civic engagement; positive environmental attitudes, behaviors, interests, and values; student-parent environmental communication; and systems reasoning (Ladwig, 2010).

Unfortunately, only 13% of public schools in California have successfully integrated EE into their curricula, according to a 2014 study published by the Californians Dedicated to Education Foundation. Within the LAUSD school system, many K-12 students lack consistent access to adequately supported, high-quality learning experiences in and beyond the classroom that cultivate environmental literacy. While some students regularly participate in systematic, ongoing EE experiences, many more receive only a limited introduction to environmental curricula, and some have no access at all. Financial, personnel, and curricular resources available for EE and sustainability are inequitably distributed, making it more difficult for financially disadvantaged schools and districts to participate in environmental science and increase climate literacy. These disparities highlight a pernicious and significant problem that students and educators face in equal measure—the lack of EE available to the public (Cohen and Reilly, 2013).

Interviewees noted that LAUSD educators practicing EE recognize that the context in which they are working requires embracing diversity, yet their values, lack of preparedness, and inadequate support underscore the difficulties of adapting EE to multiculturally diverse classrooms. Within the critical discourse, there have been calls for EE to more fully incorporate a multicultural dimension (Gigliotti, 1990, Running Grass, 1994) by respecting and elevating alternate ways of knowing and seeing the world. However, Agyeman (2003) suggests that little has been done to generate specific genres to understand, characterize, and support diversity within mainstream EE. Furthermore, EE is often regarded as being a curriculum for the privileged and affluent (Running Grass, 1995). Historically, cultural perspectives have been excluded or marginalized, and understandings of the environmental challenges and attendant solutions are formed by the perceptions of the dominant group (Martin, 2007; Taylor, 1996). Urban issues commonly experienced by people of color and linguistically isolated communities, such as persistent poverty, poor health, polluted environments, and lack of access to green open spaces, are framed as social rather than environmental problems (Running Grass, 1994). As one interviewee stated,

> ***"[Many of [our] youth grow up in areas [without] trees, so culturally relevant environmental education is really important. It has to be rooted in their experiences, and incorporate stories and experiences of trees from their cultures and communities."***

Perhaps part of facilitating a culturally-sensitive EE is to build teacher capacity to co-create curriculum on urban trees that foregrounds family and community inclusion in curriculum development (Running Grass, 1995). To foster curriculum co-creation, teachers could position themselves as collaborative action researchers (Stringer, Christensen, & Baldwin, 2010) who collect information on the linguistic, cultural, religious, and ethnic conceptions of trees and climate challenges, from both inside and outside the classroom, incorporating common themes in classroom activities and redesigning curriculum relevant to their students. When children's lived experiences with trees are brought into the classroom, it signifies that their experiences and opinions are important and valued, building their self-efficacy. As teachers encourage children to share and discuss their lived experiences with trees, children can actively become engaged in environment curriculum development in meaningful and relevant ways.

7. Messaging about the benefits of a resilient urban forest to mitigating is not reflecting the particular needs and concerns of local communities.

While a resilient urban tree canopy confers many benefits, perhaps most salient in an urban context is its role in improving public health across a range of indicators (Dudek, 2018). For several decades, researchers, practitioners, and advocates have redoubled their efforts to promote UF to various publics by directly correlating trees to positive public health outcomes. As extreme heat and the effects of climate change take on mounting importance in the coming years—particularly in low-income neighborhoods that are vulnerable to the worst of their impacts—UF managers and decision-makers will need to assess the extent to which earlier messaging has been effective. If public funding continues to follow the trend of decline, some argue that budget priorities do not adequately reflect the receptivity of these earlier messages. A few interviewees indicated that messaging is not reaching the appropriate people, likely referring to those directly engaged in decision-making. Others noted that while the public health benefits of trees are indubitably important, other priorities, such as infrastructure conflicts and the costs of maintenance deter disinvested communities from embracing trees as nature-based solutions.

Perhaps then, the messaging should raise awareness that the benefits trees provide outweigh the costs of maintaining them, and square trees as the first line of defense against extreme heat with the multiplicative benefits that can be realized from incorporating them into capital projects. As one interviewee from Climate Resolve, noted:

> ***"There is very much a connection between trees and the benefits that they provide to health, but overall, within our communities, it's about heat, and heat stroke, and honestly, the deaths that come with extreme heat."***

A city with compelling climate goals should regard trees not merely as an environmental priority but as a strategic investment in public health (Garcetti, 2019; Nature Conservancy, 2016). If trees are managed as essential infrastructure—much like the city's expansive network of street lamps, which have a dedicated budget for installation, maintenance, and replacement—they might be more effectively coupled with other infrastructure programs to ensure adequate management.

Recommendations

Based on this study and conversations among UF staff who participated in the research, the following practices are recommended to enhance the successful establishment of climate-resilient trees:

1. Harness Supply of Climate-resilient Trees

Encourage the use of climate-resilient tree species by private homeowners and on public lands.

- Create public demand for climate-resilient trees by giving out free trees or issuing tree purchase vouchers for private property owners to incentivize nurseries to stock non-standard tree species.
- Work with local retail and large commercial nurseries to increase the supply of climate-resilient species appropriate for urban spaces.
- Replant dying or standing trees with climate-resilient tree species.
- Update the municipal approved street tree planting lists, and support adoption of ordinances that encourage or require the use of appropriate climate-resilient species
- Support data collection and tracking of canopy loss to invasive pests and diseases, such as the ISHB and FD.

Connect and strengthen the capacity of smaller, local nurseries to grow climate-resilient tree stock.

- Engage extension foresters and summer fellows in a regionally distributed network of tree seed collectors to collect climate-resilient seeds and coordinate collection opportunities and funding.
- Build on existing partnerships with smaller nurseries operated by federal parks groups and private non-profit organizations to grow and expand programs centering on native tree species that are climate-resilient; convene stakeholders in UF, including representatives from municipal agencies, landscape architects, developers, and non-profit organizations to support local production of climate-resilient tree stock.
- Assist communities in developing their nurseries of non-native biodiverse trees; this might be accomplished through partnerships with LAUSD schools, botanic gardens, and parks.
- Work with UC Cooperative Extension and agricultural-facing academic institutions to assist in constructing nurseries to cultivate native- and non-native tree species that are climate-resilient.
- Garner public support to secure more funding to support the Commonwealth Nursery, with areas dedicated explicitly to propagating and growing climate-resilient tree species to increase nursery stock availability, ensure a reliable supply of high-quality trees of desired species, eliminate transplanting shock from trees grown in other climates, and provide opportunities for local green jobs and educational opportunities.

2. Implement Institutional Strategies

Prioritize street tree planting efforts in low-income, low canopy neighborhoods.

- Prioritize tree planting in historically disinvested areas where available sites are predominantly small to distribute TCC equitably.
- Expand planting sites with concrete cuts and bump-outs; increase planting on private property may be the only way to meet canopy goals in some neighborhoods.
- Devise measures of tree health after the establishment period to track the success of planting initiatives.
- Integrate the lived experiences of community members in areas where trees are planted, thereby ensuring that the benefits of planting initiatives are coupled with other benefits that are the most salient to adjacent communities.

Increasing funding for urban forestry.

- Use funding to guide and reward the selection of climate-resilient tree species and proper maintenance.

- Increase public awareness about the benefits of climate-resilient tree species and the needs of UF more broadly, so they are more likely to support increased funding for UF at the local, state, and federal level *(Related to #3 as well)*
- Leverage sustainable funding streams for tree maintenance from public and private institutions.
- Develop and leverage innovative sources of funding for UF from private foundations, carbon sequestration legislation, utility businesses, etc., focusing on funding opportunities that have overlap with UF

3. Raise Awareness and Connect with Communities

Devise and implement a coordinated public awareness campaign that utilizes multiple channels.

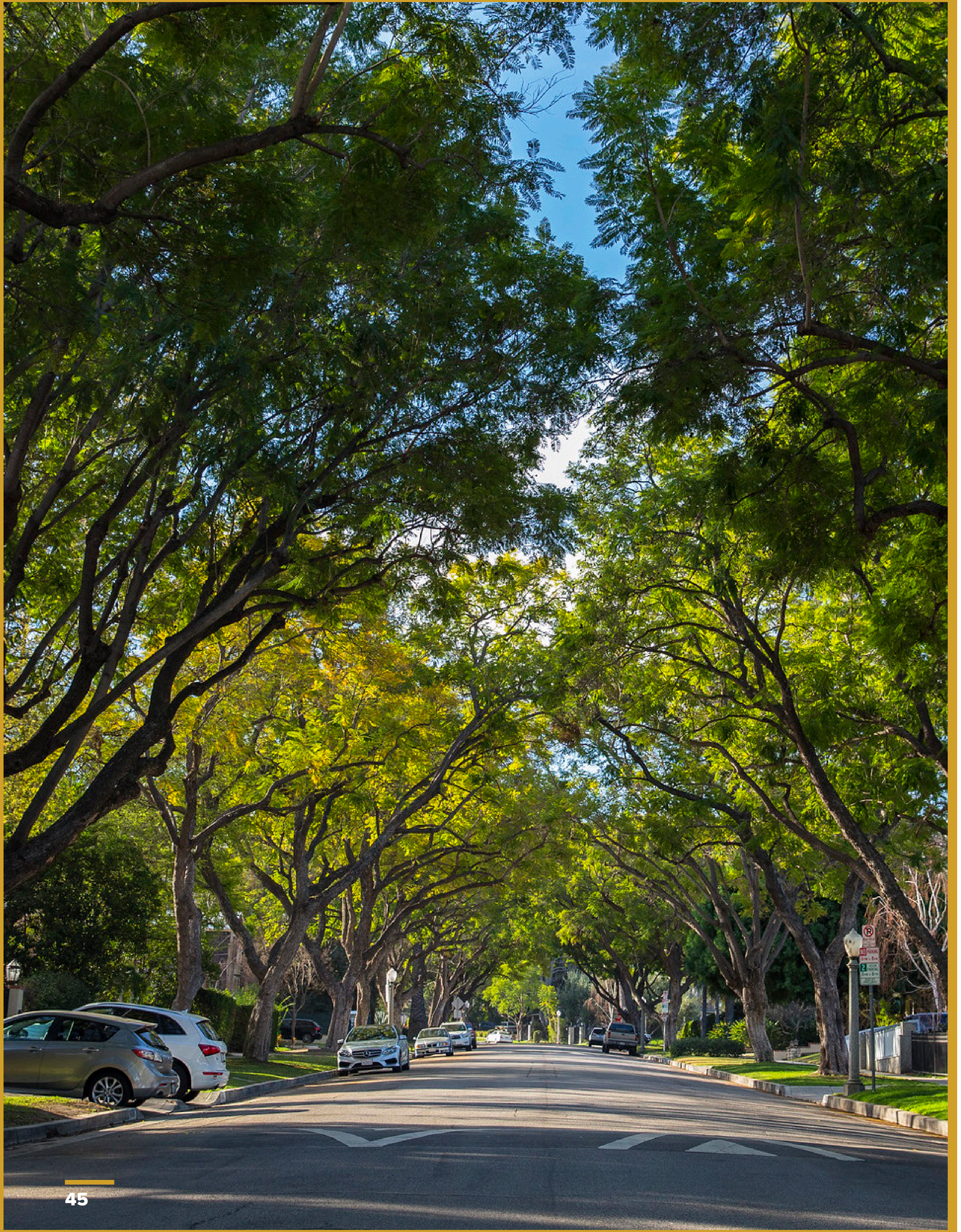
- Develop a coordinated strategy to create a regional public awareness/education campaign, using radio, social media, TV, and marketing to significantly increase awareness of climate-resilient tree species. Utilize well-known public relations entities to develop this or engage the US Forest Service public relations staff members.
- Use multiple avenues to highlight the importance of climate-resilient trees and the urban forest, focusing on radio and social media to reach a broad audience quickly.
- Develop a page on the CityPlants website that showcases climate-resilient tree species and includes pertinent information about each species, where to find them, and how to plant and care for them appropriately.
- Explicitly tie climate-resilient trees to mitigating extreme heat and enhancing public health outcomes for future generations. Focus on how a resilient urban forest creates climate resilience, an important message for creating public awareness.
- Translate critical pamphlets and resources to other languages to be accessible to a wide range of audiences.
- Increase public awareness around the biophysical needs of trees, geared towards planners, landscape architects, and developers, such as affording sufficient growing space, healthy soil, and efficient watering and maintenance for urban trees
- Focus outreach by theme, population, and community needs to increase the efficiency of communication.
- Create a public awareness campaign about climate-resilient tree species that is specific to policymakers to impart the importance of UF as a climate adaptation strategy. Create model ordinances or model legislation to promote climate-resilient species and share it with local, state, and federal elected officials.

Expand environmental education programs to support a baseline connection to trees.

- Collaborate with LAUSD school district administrators and teachers to develop culturally relevant EE programs supporting a baseline connection to trees rooted in different aspects of students' lived experiences.
- Develop education programs about trees and climate change for children where they live and learn, focusing on urban ecosystems, issues related to climate change, and EE opportunities within their communities.
- Plant climate-resilient tree species at schools as demonstration sites, outdoor classroom laboratories for EE, and as a vector for teaching about trees and urban ecology.
- Design outreach programs for teachers, and public works managers, to help them understand the importance of a resilient urban forest.
- Foster learning and research opportunities from elementary to graduate school level, focusing specifically on college-level areas within urban planning, landscape architecture, and public works fields to ensure UF literacy.

Build multi-generational coalitions.

- For future plantings, consider community collaborations and youth jobs programs that promote maintenance and stewardship (Roman et al., 2015).
- Create a youth-centered Urban Tree Corps of Tree Ambassadors, representative of their communities.
- Enlist youth groups and councils to raise awareness of climate-resilient trees using multiple avenues, including door-to-door campaigns.
- Enlist Tree Ambassadors to develop engaging, positive tours to engage communities with climate-resilient trees in their neighborhoods and lead Tree Walks as a public event.
- Create a youth-led engagement program to raise awareness, tying engagement with education and workforce development to open new career opportunities.



Conclusion

L.A. is home to the most extensive urban forest in the nation (Rachel Malarich).
If properly implemented, comprehensive urban forestry planning can mitigate the effects of climate change and set a national standard for climate adaptation. To ensure more resilient, and greener futures for all Angelenos, however, stakeholders from state and municipal agencies, non-profit organizations, youth and neighborhood councils, nurseries, and urban forestry advocacy groups must come together to drive transformational shifts in policy priorities and practices aimed at improving the health and resiliency of the urban forest. Because it will take decades to gradually shift the urban forest composition to climate-resilient trees, the ultimate value of this research may be borne out in a more sustainable and resilient urban forest witnessed generations from now.

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Appendices

A: Interview Questions

1. In what ways do you work with trees or work on issues related to urban forestry?

2. As urban forest managers, do you consider the characteristics of the species being planted so that the species mix (now and into the future) optimizes urban cooling potential? If not, what other characteristics do you consider?

3. What are the most important factors to consider when selecting tree species? Of the list of factors, what would you prioritize as the top three most important and the bottom three least important?

4. Can you walk me through the current species selection process? What are the most important factors that impact the location for planting trees in your jurisdiction?

5. Which species are performing well? Which species are performing poorly? What are some important takeaway lessons that can help inform future species selection processes?

POLICIES AND OPPORTUNITIES

6. What do you perceive as the barriers to planting and management of climate appropriate tree species?

7. How can the City of Los Angeles help advance these goals, and how might it provide more support (e.g. incentives, policies, public awareness, etc.)?

CURRENT TREE SOURCING AND PLANTING

8. How many trees does your department plant per year? Which are the top 5 most common species planted?

9. What is the process of ordering trees? From where does your department source its trees from?

10. Can you consistently buy enough shade trees to meet planting needs? Have you consistently sourced shade trees with adequate quality characteristics?

B: List of Respondent Entities

Los Angeles Department of Public Works, City of Los Angeles Department of Recreation and Parks, City Plants, Los Angeles Department of Water and Power, City of Los Angeles Department of City Planning, City of Los Angeles Bureau of Sanitation & Environment, City of Los Angeles Bureau of Street Services (StreetsLA), TreePeople, Los Angeles Conservation Corps, Northeast Trees, Council District 15, Council District 3, City of Los Angeles Theodore Payne Foundation, Grown in LA, U.S. Forest Service, Climate Resolve, California Urban Forest Council, California ReLeaf, San Marcos Growers, Boething Treeland, AY Nursery, Devil Mountain Nursery, Norman's Nursery

TreePeople

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