Urban Forestry & Urban Greening 29 (2018) 28–39

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Performance testing to identify climate-ready trees

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ARTICLE INFO

Keywords:
Adaptation
Climate change
Growth
Tree selection
Resilience
Urban forest

ABSTRACT

Urban forests produce ecosystem services that can benefit city dwellers, but are especially vulnerable to climate change stressors such as heat, drought, extreme winds and pests. Tree selection is an important decision point for managers wanting to transition to a more stable and resilient urban forest structure. This study describes a five-step process to identify and evaluate the performance of promising but infrequently used tree species. The approach is illustrated for the Central Valley of California, USA and has been implemented in the Inland Empire and Southern Coastal regions of California. Horticultural advisors nominated 134 taxon for consideration. A filtering process eliminated taxon that were relatively abundant in a compilation of 8 municipal tree inventories, then those with low adaptive capacity when scored on habitat suitability, physiology and biological interactions. In 2015, 144 trees were planted, with 2 trees of each of 12 species planted in 4 Sacramento parks and 4 replicates planted in the Davis, California reference site. This approach can serve as an international model for cities interested in climate adaptation through urban forestry.

1. Introduction

One of the most important urban forest climate adaption strategy is planting and stewardship of tree species well-suited to site growing conditions in the future as well as the present (Roloff et al., 2009; Yang, 2009). Having a diverse mix of species well-adapted to future conditions, what we call climate-ready trees, is critical to fostering a smooth transition to a more stable and resilient urban forest. This paper describes a five-step process to identify and evaluate the performance of promising tree species. It illustrates application of this approach in one California region. Because it will take decades to gradually shift the planting palette to climate-ready trees, the ultimate value of this research will be borne out in healthier and more resilient urban forests witnessed generations from now.

Trees in cities provide valuable ecosystem services that can improve quality of life, but also face a variety of stressors that can threaten these benefits. Stressors associated with climate change, such as drought, heat, pests and extreme weather events are already increasing mortality in forests (Allen et al., 2010). In cities, climate change can amplify the impacts of existing stressors such as inadequate soils, polluted air, contaminated runoff and mechanical damage from cars and vandals. Although researchers have predicted how forests respond to climate change (Allen et al., 2010; Iverson et al., 2008), patterns of disturbance to urban forests are largely unknown because their species composition is extremely diverse and largely non-native in origin (Tubby and Webber, 2010). Urban forests are especially vulnerable to climate change stressors because predominant species may rely on irrigation and other intensive management practices, and rates of climate change may be more rapid and extreme in cities than in rural areas (Van der Veken et al., 2008). Identifying and testing the resilience of tree species to climate change stressors is critical to the long-term stability of urban forests.

1.1. Tree performance testing

Long-term performance testing of tree species and cultivars is fundamental to successful tree establishment (Trowbridge and Bassuk, 2004). Nevertheless, limited testing of potential planting stock and lack of availability in local nurseries have long been challenges to urban forest diversification. Descriptions of site conditions and management activities can be used with multivariate statistics to explain their influence on growth and performance. Long-term studies of urban tree growth first began in the U.S. a half-century ago by arboreta, universities, and foundations. In the mid-1960s the Street Tree Evaluation Project began evaluating street tree species in five Ohio cities, as well as trees planted in research plots. The study includes 89 revisited sites and supplies valuable “then and now” information on survival and growth, as well as photographic records of visual impacts as trees mature

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https://doi.org/10.1016/j.ufug.2017.09.003
Received 15 November 2016; Received in revised form 17 March 2017; Accepted 5 September 2017

1618-8667/ Published by Elsevier GmbH.

(Sydnor et al., 2010).

In 1987 the Municipal Tree Restoration Program began testing trees planted under electric conductors to compare performance in 11 Pennsylvania communities (Gerhold, 2007). Twelve years of standardized performance data helped utilities select the most appropriate cultivars that did not exceed 8 m height to plant under conductors.

The National Elm Trial began in 2005 and has produced standardized information on the performance of 20 Dutch elm disease (*Ceratocystis ulmi*) resistant cultivars in 18 plots across the U.S. Reports from this research include information on survival and growth, as well as damage from pests, disease, abiotic disorders and pruning requirements (Griffin et al., 2017; McPherson et al., 2009). Results are helping managers determine which cultivars may perform best in their regions.

1.2. *Tree selection and anticipated performance*

Selecting the right tree requires consideration of how a myriad of factors may influence performance in the future. Species-specific information on tolerances and responses of trees is frequently incomplete, adding uncertainty to decision-making (Sjoman and Nielsen, 2010). Harris et al. (1999) noted that, "Selection is a compromise among proposed function of the plant, its adaptation to the site, and the amount of care it will receive." Miller (1997) 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). Asgarzadeh et al. (2014) extended this approach by using horticultural experts to grade species for each selection parameter and adding relative weights to selection parameters. Huber et al. (2015) developed an interactive computer tool that used vegetation data from the USDA Plant Database and a spatial database for Baltimore, Maryland that included site-specific environmental, situational and risk factors. Although greening programs strive to improve climate and quality of life through tree planting, there is a surprising disconnect when it comes to specifying trees with traits, such as low water use and large canopy size, that are most likely to achieve those goals (Pincetl et al., 2013).

Climate adaptation was recognized as a primary selection criteria for street and park trees by Sæbø et al. (2005), along with growth and pest resistance. Yang (2009) evaluated the potential effects of climate change on the biology of pests in Philadelphia, Pennsylvania, as well as the suitability of tree species to predicted climate at midcentury. Climate envelopes were derived from the dendrological literature for most species and incorporated temperature and precipitation. Although future climate was predicted to be less optimal for 10 species, overall it was likely to increase diversity. Species recommendations are difficult to make because large amounts of variability in response to stressors, such as extreme drought, reflects characteristics of the individual plants (e.g., age, size) and local site conditions (Fahey et al., 2013).

Roloff et al. (2009) focused on drought tolerance and cold hardiness as critical to future tree survival in a changing climate. Their analysis examined annual precipitation and minimum temperatures in the species' climate of origin to assure that it will be adapted to increased frequency and severity of drought, as well as late frosts. The conflicting assessment for honey locust (*Gleditsia triacanthos*) is instructive. Although honey locust's native habitat is moist bottomlands, it has proven to tolerate hot and dry situations. This contradiction highlights the importance of distinguishing between a tree species' optimum habitat of origin and its physiological plasticity, defined as the range of habitats to which it can adapt.

Lanza and Stone (2016) found that the projected northward migration of hardiness zones with climate change resulted in about a 6% average tree species loss across all cities. Interestingly, Atlanta and Washington D.C. lost the most species, while cities in the Southwest did not lose any tree species.

The System for Assessing Vulnerability of Species (SAVS) was developed as a tool for managers to identify the relative resilience of species to climate change (Bagne et al., 2011). The user scores level of resilience for habitat, physiology, phenology and biotic interactions, as well as an uncertainty score that reflects confidence in the predicted response. The SAVS framework was evaluated by Rowland et al. (2011), who noted that every assessment approach is limited by data and resource requirements, as well as sources of uncertainty that constrain their application. The SAVS approach is applied in this study for urban trees.

1.3. *Climate change, urban forests and human health and well-being*

The types of effects climate change is having on urban forests differs geographically. For example, in large cities local urban heat island effects are playing a greater role in overall warming than greenhouse gas emissions (Stone, 2012). The coupling of urban warming from both these sources has cascading effects on tree health. For example, warmer temperatures can increase evapotranspiration demand and drought stress, predispose trees to pest attacks, and increase developmental rates and reduce winter mortality for many insects (Dale and Frank, 2014; Tubby and Webber, 2010). Warmer winter temperatures may increase the susceptibility of some species to late spring frosts (Miller-Rushing and Primack, 2008). Extreme weather events are likely to increase in the future, exposing trees to intense winds, rain, and hail, as well as flooding, storm surges and heavy snow and ice loads (Burley et al., 2008; Yang, 2009). Salinity from recycled irrigation water or coastal flooding can adversely affect soil health and tree growth. Hence, exposure to climate change disturbances are likely to exacerbate the stress already afflicting many urban trees. Species with narrow ranges of tolerance may be most adversely affected. Trees have little genetic capacity to adapt because of their long life span. Most cultivars have been bred for ornamental traits related to form, foliage, flower and fruit rather than tolerance of stresses caused by limited root space, poor soil, drought, pollutants and pests (Gerhold, 1985). As the role of urban forests expands to include enhancement of environmental quality, human health and well-being, trees may need to be bred to withstand stressors associated with climate change (Brummer et al., 2011; Kontogianni et al., 2011).

If urban forests are healthy and extensive, they can produce services that mitigate the impacts of climate change and improve well-being of city dwellers (Jim et al., 2015). Increasing doses of nature in cities have positive effects on an individual's emotional state and cognitive functioning (Bratman et al., 2015; Ulrich, 1981). Urban forests store carbon dioxide (CO_2) in their biomass, reduce energy used to heat and cool buildings and intercept rainfall to reduce stormwater runoff and protect water quality (McPherson and Simpson, 2003) (Xiao et al., 1998). By reducing urban heat islands, trees can improve human thermal comfort and reduce exposure to extreme weather events (Brown et al., 2015; de Abreu-Harbich et al., 2015; Klemm et al., 2015). However, a growing body of research indicates that there is substantial disparity among those who benefit from tree canopy cover based on socioeconomic characteristics (Danford et al., 2014; Watkins et al., 2016). For example, a number of studies have found positive relations between tree canopy and income (Heynen et al., 2006; Schwarz et al., 2015). These data suggest that communities of color and low income have disproportionate exposure to climate change risk factors (Shonkoff et al., 2011). Over the past several years California's Greenhouse Gas Reduction Fund has targeted $15 million annually for tree planting grants to benefit disadvantaged communities. The future success of these plantings depend in part on their vulnerability to climate change, as well as the extent to which they reflect the values of participating citizens (Ordóñez, 2015). Closing the social gap in ecosystem services delivered by urban forests will require that these plantings achieve high survival rates and vigorous growth in a changing climate.

There is impetus to develop an international network of tree performance evaluation sites for long-term monitoring (Vogt et al., 2015). Without such science-based data it may be difficult to identify the high-

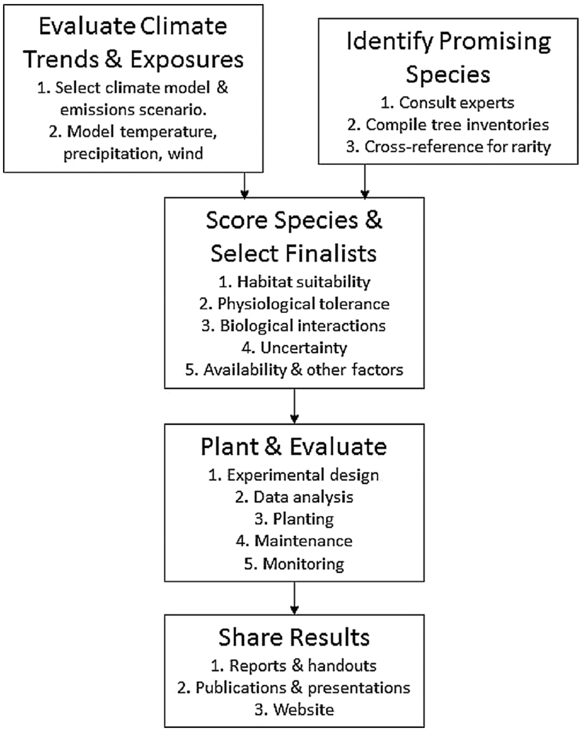

Fig. 1. A five-step process was used to identify and evaluate the vulnerability of promising tree species to climate change stressors.

performing species needed to stock more resilient urban forests of the future. This study describes a systematic process to evaluate the performance of promising tree species that can be applied internationally. It illustrates application of this process in the Central Valley of California. The knowledge gained from this research can have far-reaching effects on the long-term ability of urban forests to deliver the services increasingly demanded of them.

2. Methods

Our approach used a five-step process to identify and evaluate the vulnerability of tree species (Fig. 1). The approach and the definition of vulnerability were adapted from Glick et al. (2011). Vulnerability was defined as the degree to which a species is vulnerable to and unable to cope with adverse effects of climate change.

2.1. Step 1. Evaluate climate trends and exposures

The purpose of this step was to determine how much the climate may change and what problems this could pose for different species of trees. Exposure was defined as the likely climatic conditions that trees may experience in the future (Glick et al., 2011).

2.1.1. Select climate model and emissions scenario

We used the CalAdapt database to collect relevant climate change data for California's Inland Valleys climate zone (http://cal-adapt.org/). We selected the relatively conservative Parallel 1 climate model, and the relatively high A2 emissions scenario. The high emissions scenario was chosen because of the dramatic projections for fossil fuel consumption in the world's developing economies (Hayhoe et al., 2004) and the unlikelihood of policy mechanisms controlling greenhouse gas (GHG) emissions (Canadell et al., 2007; Raupach et al., 2007). Use of the conservative model with a high emissions scenario produces a moderate picture of future climate. Both the model and emissions scenario have high representation in the scientific literature and are considered robust in their estimations (Cayan et al., 2008; Moss et al., 2010). We chose to use projections extended to the end of the 21st century because of the potential longevity of trees planted early in the century.

2.1.2. Model effects on response variables

Three primary climatic response variables were selected to investigate because of their potential effects on tree health: temperature, precipitation and wind. The accuracy of projected changes in temperature are the least contested variable in most climate models (Vose et al., 2014). We examined projected changes in maximum, minimum and mean annual temperatures. Increases in summer air temperatures are of concern due to greater evapotransporation (ET) demands on trees at a time when water resources are often constrained due to drought. Drought stress can predispose trees to attacks from pests that further weaken their defenses. As the structural integrity of the trees deteriorate they become more likely to fail, posing greater liability to residents and property. However, warmer temperatures combined with elevated CO_2 concentrations can increase overall tree growth.

If minimum temperatures increase, the growing season could be extended and trees could experience increased ET stress. Tree species that require a minimum number of chilling hours to reach dormancy and set fruit (e.g., stone fruits) may no longer bear fruit if chilling thresholds are not met (Luedeling et al., 2009). Alternatively, increased minimum temperatures may create new opportunities for migration of species that were formerly marginally hardy. We use the 2012 USDA Hardiness Zone Map to translate how projected changes in average annual minimum temperatures can influence the range where trees can grow (http://www.planthardiness.ars.usda.gov/). This map is the standard by which arborists in the U.S. determine which trees can survive cold damage at a location. Changes in mean temperatures indicate overall changes in the temperature environment of urban trees.

Precipitation intensity and patterns are expected to shift as a result of climate change, though regional predictions of what the changes will be are more variable than for temperature change (Vose et al., 2014). Although the adverse effects of changes in precipitation on tree health can be mitigated through irrigation, restrictions that began during the drought from 2010 to 16 resulted in water deficits for many trees during summer months (Fear, Feb. 27, 2016).

Modeling the effects of climate change on wind are least certain. Extreme precipitation events could lead to soil inundation. When combined with increases in wind speed, more wind thrown trees could result (Moore, 2014). Wind is also of concern in the potential drier, summer months, due to the possibility for increase fuels and fire threats to communities in the urban-wildland interface.

2.2. Step 2. Identify promising species

The purpose of this step was to develop a short list of trees that may be well-suited to future climate exposure and are not presently abundant in cities. Species recommended by horticultural advisors were cross-referenced with a compilation of regional street tree inventories to eliminate overly abundant species. In Step 3 this short list underwent a secondary filtering process to derive the final list of trees for evaluation.

A list of 20 professional horticulturalists, growers and academics familiar with city trees in Central Valley communities was developed. This study was described in a letter sent to each advisor, and each person was asked to identify 12 species for inclusion in the evaluation. Several selection criteria were mentioned in the letter.

- stock must be available for planting during 2015
- provide shade in street and park locations with minimal irrigation after establishment
- attractive, require minimum maintenance once established and not pose hazards to people
- currently present in Central Valley cities, but in small numbers and

not well-tested
- not currently present but proven successful in regions with somewhat different climate, rainfall and soils
- not currently present but proven successful in regions with somewhat similar climate, rainfall and soils
- not currently present but proven successful in regions with a somewhat warmer winter climate and likely to be hardy in Central Valley cities as the climate warms

A follow-up letter was sent to non-respondents after two weeks. Recommended species were compiled into a single list noting the number of times a species received nomination.

Cross-reference with compiled tree inventories. Street tree inventories from 8 communities in the Central Valley were compiled and sorted by species and abundance. The final list contained 296,958 inventoried trees comprising 447 taxon. To determine if a species was relatively rare we established an arbitrary threshold wherein if the species accounted for less than 0.01% of the total population it was considered rare. Nominated species that were not rare were removed from further consideration.

2.3. Step 3. Score species and select finalists

The purpose of this step was to derive a final list of 12 species for field testing. Each species that was nominated and found to be relatively rare was evaluated on three vulnerability criteria following the SAVS framework: habitat suitability, physiology and biological interactions. These criteria reflect each species' adaptive capacity, defined as its potential to ameliorate exposure to climate change stressors. Each species received a rating of −1, 0, or 1 (sensitive, neutral, insensitive) for each criterion based on its adaptive capacity, as reported in the literature. Scores were summed and each species was placed into one of five vulnerability classes (low, low-moderate, moderate, moderate-high, high). Once the highest scoring species were identified their availability for planting was confirmed. Species that could not be obtained for spring planting were replaced with the next highest scoring candidate. The indicators for each criterion follow. Data used to assign scores to each species were from the SelecTree database (https://selectree.calpoly.edu/) unless otherwise noted.

2.3.1. Habitat suitability – soil moisture, texture and pH, sunlight exposure

Given the heterogeneous nature of soil in urban environments associated with site age, human impact, and land use (Greinert, 2015), trees that can tolerate a wide range of soil moistures in their native habitat are preferred to those that require specific soil moisture to thrive. Moreover, as California landscapes transition from mesic to xeric, species with wide tolerances to soil moisture levels are at an advantage because the likelihood of survival is enhanced for species tolerant of ample irrigation in turf as well as minimal irrigation in xeriscapes. Species tolerant to moist and dry soils received +1, those tolerant to only moist or dry received a −1.

Specific effects of climate change on soil interactions are not well understood. Some researchers believe that increased atmospheric CO_2 could increase vegetative growth, which would lead to an increase in soil organic matter content (Davidson and Janssens, 2006). Kirschbaum (1995) suggested that increased temperatures will drive microbial activity, hastening the decomposition of soil organic matter and decreasing organic carbon content in soils. Given the heterogeneous nature of urban soils and this uncertainty, tree species that exhibit tolerance to all soil texture types (i.e., clay, loam, sand) and pH ranges (i.e., acidic to alkaline) received +1, while those restricted to a single texture or pH level received −1.

Continuous tree mortality and planting, as well as building demolition and construction, results in changing sunlight exposure for trees. Trees known to tolerate a wide range of sunlight exposures, from sun to shade received +1, while those restricted to a single exposure level received −1.

2.3.2. Physiology – drought, wind, salt tolerance and hardiness

Trees that can tolerate drought were preferred to those that cannot because climate models predict that drought and heat waves will increase evaporative demand. The Water Use Classification of Landscape Species (WUCOLS) database was used to assign ratings (Costello and Jones, 2014). WUCOLS classifies irrigation needs from high to very low based on experimental observations and expert horticulturalist field experience for over 3500 taxa in California landscapes. Data specific to the Central Valley region were used in this study. Species rated with low and very low water needs received +1, those with high water needs received a −1.

Climate modeling predicts that climate change will bring more frequent extreme weather events, meaning that the high winds and heavy rains associated with these events could induce tree failures (Dominguez et al., 2012). Prolonged periods of drought that are predicted for California could exacerbate incidence of tree failure and limb drop. Species rated with strong branch attachments (i.e., able to withstand high wind speeds) received +1, and those classified with weak attachments received −1.

In 2009, 825 million m^3 of recycled water was used in California, with the amount used for landscape irrigation (24%) second to agricultural irrigation (37%) (California Department of Water Resources, 2016). California plans to increase this amount to 1.2 and 1.6 billion m^3 in 2020 and 2030, respectively. Cities are likely to use recycled water to irrigate urban trees during periods of drought, making salinity tolerance an important metric in evaluating a species' future fitness. Recycled water is higher in salinity than potable water because treatment processes often add salt to the source water (Paranychianakis et al., 2004). High salinity creates hostile growing conditions by reducing water uptake. For example, Nackley et al. (2015) found a reduction in relative height of 30–40% in *Sequoia sempervirens* 'Aptos Blue' grown in moderately saline soils. Species rated as tolerant and highly tolerant received +1, and those regarded as being salt sensitive received −1 (Wu and Dodge, 2005).

Tolerance for cold temperatures limits the distribution of tropical tree species in California. We used the USDA hardiness zones, which are in 10° F (5.6 °C) increments based on average annual minimum temperatures, to determine if the species was suited for the region's climate now and in 2090 given climate change projected by the Cal-Adapt tool (Daly et al., 2012; Koy et al., 2011). Species hardy now and in the future received +1, those not hardy now but hardy in future received 0, and species not hardy now or in the future received −1.

2.3.3. Biological interactions – invasiveness and pest threats

Invasive species are undesirable given their ability to displace native species and reduce biodiversity in the urban forest. A database created by the California Invasive Plant Council (Cal-IPC) was used to assess invasiveness (California Invasive Plant Council, 2016). Cal-IPC scores plants on whether they exhibit high, moderate, or limited invasiveness. Species that are not invasive or native to California received +1 and those deemed invasive with moderate or severe ecological impacts were given −1.

Planting species that have natural resistance to pests and disease may result in savings for costs of pesticide sprays, tree removal and replacement. Pesticides could also have adverse effects on the health of urban dwellers. A Pest Vulnerability Matrix (PVM) first developed by Lacan and McBride (2008) for Northern California and extended to Southern California by McPherson and Kotow (2013) assesses the susceptibility of 174 tree species to 122 pests and diseases. Species with minor pest and disease threats scored +1, while those with severe pest and disease threats scored −1.

Climate change may create new habitat for pests, some of which may not have existed previously in the region. Because the PVM addresses emerging pests and diseases, it was used for ranking species. A species received a +1 if the PVM showed it had very few emerging pest threats, and it received a −1 if it had emerging pest threats regarded as severe.

2.3.4. Uncertainty

It was difficult to score some species because data were lacking. Also, some of the strongest climate change effects have yet to manifest (e.g., emerging pest threats) so the effects are unknown for many species. Following the SAVS framework, uncertainty was quantified as the percentage of criterion scored where either the direction of change could not be predicted because of lack of information or the predicted response was comprised of both negative and positive aspects.

2.3.5. Availability and other considerations

Scores were totaled for each species and species were sorted. Availability of nursery stock and the cost for freight was assessed for each of the highest ranking species. Another consideration that influenced selection was the desire to promote taxonomic and physiognomic diversity in the final list of species to test. At least two species with small, medium and large mature sizes were desired. The number of species from the highest scoring genera were limited to no more than two, and preferably only one.

2.4. Step 4. Plant and evaluate in experimental plots

The purpose of this step was to establish a methodology that would result in collection and dissemination of meaningful data over the 20-year study duration.

2.4.1. Experimental design

Twelve species of trees were randomly planted in a reference site and each of 4 parks, where the entire reference site and each park are blocks in randomized complete block design (RCBD). Four replicates were planted in the reference site (4 replicates x 12 species, 48 trees), a UC Cooperative Extension (UCCE) Field Station plot in Davis, with all trees receiving the same irrigation, pruning and other maintenance activities. An additional 96 trees were planted in 4 parks (2 replicates per park, 24 trees per park) where growing conditions and maintenance activities were more variable between parks. Overall, this is a balanced design because each of the 12 species was planted in equal number at a given site. All trees are evaluated annually for the first five years after planting, and biannually thereafter. The trees are expected to remain in the ground for at least 20 years.

2.4.2. Data analysis

The analysis of the data will be a repeated measures ANOVA. These models can be generalized (as unbalanced mixed models) in case there are missing values in the data, or to accommodate a more complex correlation structure (such as spatial power or first degree autoregressive) than is used in a traditional repeated measures analysis. Analysis of the data were limited because this study is only in the second year. Tree dimensional data were plotted to visually compare initial differences in growth.

2.4.3. Planting

Trees were received for planting in February 2015 from three nurseries and planted during February and March. Sizes ranged from bareroot to 24” box. Planting sites were randomly assigned to each species and marked with paint on the ground a few days prior to planting. The Sacramento Tree Foundation coordinated local volunteers in planting three parks, while staff with City of Sacramento Urban Forestry Division and UC Davis Ground Department planted trees in the remaining park and reference site. Trees were watered and staked at the time of planting. Mulch was applied at the reference site, but not at the park sites until 2016.

Trees that died within the first few weeks after planting, due to substandard stock or transplanting stress, were replaced during the second year of the project. Trees that died for other reasons were removed and not replaced.

2.4.4. Maintenance

Our approach to maintenance was to apply a consistent level of maintenance to trees in the reference plot (i.e., UCCE field station) and to record and compare differences across species, such as amount of pruning, staking and pest control required. In the case of pruning, we did minimal pruning to discern the underlying branching pattern of these species. By applying a minimal and uniform level of maintenance we can assess the amount of resources required to establish and maintain each tree species in good to excellent condition throughout the 20-year period.

Trees planted in the parks were treated by park staff similar to other trees in the parks. The level of care varied from park to park and year to year based on the individuals involved and financial resources available. Hence, park trees were subject to lower levels of maintenance than trees in the reference plots, and their growth will likely be highly variable, reflecting the response of each species to the specific stressors and maintenance activities it received. Park personnel were periodically interviewed to discern the level of care provided to the trees.

2.4.5. Monitoring

Protocols for collecting size and health data on each tree, collecting and processing soil samples and measuring irrigation water use were developed and applied to each site (see Supplementary Data). Meteorological data were downloaded from California Irrigation Management Information System (CIMIS) stations closest to the park and reference plots at UC Davis and Sacramento. These data were used to identify the climatic conditions influencing growth and included:

- Monthly and annual precipitation
- Annual minimum air temperature
- Average, maximum and minimum monthly air temperatures
- Monthly reference ET (ET_o, environmental demand for evapotranspiration) for the year

2.4.6. Performance ratings

The relative amount of pruning level required for each species was evaluated as the average score for the sum of two criteria: growth (1 = rapid, 3 = slow) and structure (1 = worst, 3 = best). Structure included central leader development, branch size relative to the trunk and branch attachment characteristics. Subjective performance ratings (1–5) (1 = poor and 5 = excellent) were collected for each species every year. Scoring incorporated observations of survival, growth rate, crown vigor, branching patterns, pruning requirements, aesthetics and insect and disease damage. Project scientists and cooperators independently scored each species after measuring trees at each reference and park site.

2.5. Step 5. Share results to effect change

Effective communication of performance evaluation results requires targeting messages to those responsible for growing, retailing, specifying and purchasing trees. This step is critical to shifting the tree palette to more climate-ready species. We adopted strategies from Trowbridge and Bassuk (2004) and others (Miller, 1997) to identify key audiences and develop outreach strategies and materials that target each audience.

2.6. Central Valley case study

2.6.1. Step 1. Evaluate climate trends and exposures

California’s Central Valley extends north-south approximately 720 km (Fig. 2). It is 60–100 km wide, lying between the Sierra Nevada

Fig. 2. Projected climate change impacts on temperature and precipitation are presented for the Central Valley cities shown in this map of California.

to the east and Coastal mountain range to the west. The Mediterranean climate is characterized by mild, wet winters and warm, dry summers. Productive soils support an agricultural economy that produces over one-half of the United States' fruits, vegetables and nuts. The 6.5 million residents account for about 15% of the state's population.

The current pattern of annual precipitation decreases along a north-south gradient from Redding (65.3 mm) to Bakersfield (12.3 mm) (Table 1). The climate model projections follow this trend. By 2090 average annual rainfall is projected to increase 8.0 mm (12.2%) in Redding to 1.35 mm (6.3%) in Fresno. Precipitation in Bakersfield is expected to decrease 0.66 mm (5.4%).

According to the CalAdapt modeling scenario, average maximum temperatures are expected to increase over 80 years along the north-south gradient, from 1.57 °C (4.2%) in Redding to 3.23 °C (8.5%) in Bakersfield (Fig. 3). Local urban heat islands could exacerbate this warming (Stone, 2012). Anticipated changes in average annual temperatures are less dramatic, 2.3 °C to 2.4 °C or 12.7%–14.3% of current averages (Table 1).

Table 1
Climate model projections for 2010 and 2019 for five Central Valley cities along a north-south gradient.

	Redding	Sacramento	Merced	Fresno	Bakersfield
Population	91,119	475,516	80,793	505,882	358,597
Elevation (m)	151	9	52	94	123
Avg. Ann. Precip. 2010 (mm)	65.27	37.04	26.29	21.50	12.27
Avg. Ann. Precip. 2090 (mm)	73.23	40.77	27.70	22.85	11.61
Avg. Ann. Temp. 2010 (°C)	16.89	16.43	16.42	17.25	18.92
Avg. Ann. Temp. 2090 (°C)	19.32	18.77	18.73	19.60	21.33
Avg. Ann. Min. Temp. 2010–19 (°C)	1.15	2.61	0.90	1.45	2.38
USDA Hardiness Zone (2010–2019)	10A	10B	10A	10A	10B
Avg. Ann. Min. Temp. 2080–89 (°C)	4.77	5.80	3.84	4.43	5.29
USDA Hardiness Zone (2080–2089)	11A	11A	10B	11A	11A

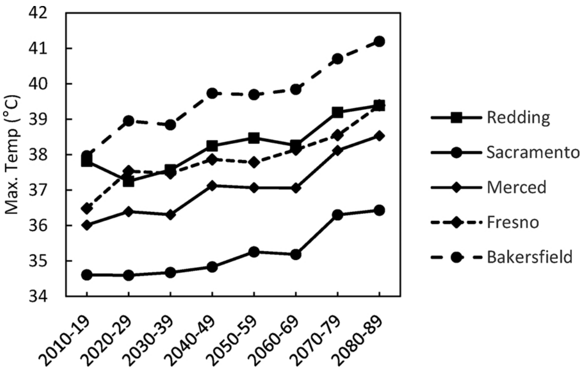

Fig. 3. Average maximum temperatures are projected to increase 1.6–3.2 °C by 2090.

Climate change modeling projects that the change in average annual minimum temperatures will be greatest in Redding (3.6 °C) and least in Bakersfield (2.9 °C) (Table 1). These warmer minimum temperatures correspond to an increase in each city's USDA Hardiness Zone of one-half (e.g., 10 B–11 A) to one full zone (i.e., 10 A–11 A).

2.6.2. Step 2. Identify promising species

Horticultural advisors nominated 134 taxa for consideration. Compiled inventories from eight Central Valley cities contained 296,958 trees belonging to 447 taxa. Surprisingly, there were 208 taxa that contained less than 30 trees (0.01% of all trees) and deemed relatively rare. After cross-referencing the 134 nominated trees with the list of relatively rare species, 52 taxa were found to be common and eliminated from the list of promising species to evaluate. The list of 82

Table 2
Numbers and percentages of taxon in each vulnerability class.

Vulnerability class	Number taxon	% total taxon
Low (5–8)	16	21.9
Mod-Low (2–4)	34	46.6
Moderate (0–1)	12	16.4
Mod-High (−1)	9	12.3
High (−2)	2	2.7

trees was further reduced because it contained oaks that were being tested in another study (e.g., *Quercus englemanii, garryana, oblongifolia*), species known to have rootstock and graft incompatibility problems (i.e., *Prosopis alba* 'Colorado', *Quercus frainetto*), species known to require ample irrigation (*Acmena smithii*) and species known to be previously tested in the region (i.e., *Quercus fusiformis*).

2.6.3. Step 3. Score species and select finalists

The remaining 73 taxon were scored and ranked. Scores ranged from −2 to 8. Species were placed into one of five vulnerability classes based on their score (Table 2). The distribution of taxon was skewed towards lower vulnerability classes because the advisors were asked to nominate trees likely to be drought tolerant and widely adapted. The uncertainty percentages ranged from 0% to 80%. Out of the 73 taxa assessed, 41.1% had 0% uncertainty and 87.7% had less than 33% uncertainty.

The 12 finalists were selected from the 32 taxa that scored 3 or higher (Table 3). Selection of the final list of 12 was based on availability, as well as the desire to obtain a diversity of mature sizes and taxon. The *Acacia* genus was the only genus in the final list with more than one species. Five of the finalists were small-stature (< 8 m tall), four medium (8–15 m tall) and three large (> 15 m tall). The following descriptions of each finalist provide its geographic origin, general information on size and culture, as well as potential management concerns.

- Mulga (*Acacia aneura*) – Mulga is native to arid Western Australia and tolerates hot and dry conditions. It can grow in sandy, loam, or clay soil types. This versatile and hardy tree produces ascending thornless branches and grows 5–6 m in height. The leaves are evergreen and the tree has yellow, showy flowers in the spring. Can it thrive in the Valley's heavy clay soils?
- Shoestring acacia (*Acacia stenophylla*) – This evergreen thornless acacia from Australia grows rapidly into an arresting specimen. The canopy is open with weeping, linear leaves. Shoestring acacia reaches a height of 7–10 m. Fragrant and showy yellow flowers grow in clusters from fall to spring. The tree is drought tolerant and prefers well-drained soil. How long will it require staking and will it sprout from the roots?
- Netleaf hackberry (*Celtis reticulata*) – The netleaf hackberry is native to riparian areas in the Southwest but drought tolerant. A deciduous tree, it reaches heights of 9–11 m with a spreading or weeping canopy. The ovate leaves are medium green and turn yellow in the fall. The flowers mature into red drupes that attract birds. Will the netleaf hackberry require continuous pruning to form an upright tree?
- Desert willow (*Chilopsis linearis* 'Bubba') – The desert willow is native to California and the Southwest. It is a small flowering desert tree that can reach a height of 5–6 m. The cultivar Bubba is upright in form and has profuse, long-lasting blooms. Leaves are linear blue green and turn golden in the fall. The showy flowers are pink and white. Will the desert willow thrive in a variety of soil types and will fruit pods persist throughout winter?
- Ghost gum (*Corymbia papuana*) – The ghost gum is native to Australia and reaches 20 m in height. The trunk is smooth and snow white. It has gray green evergreen leaves that are tinged purple by frost. White flowers bloom in the summer. It tolerates drought but can be used in well-irrigated landscapes. Will it survive the Central Valley's occasional sub-freezing temperatures?
- Rosewood (*Dalbergia sissoo*) – The rosewood is native to Northern India and its evergreen foliage can be damaged by frost. The tree recovers quickly in the spring. It reaches a height of 10–15 m with a 12 m crown spread. Rosewood tolerates periods of drought and can grow in sandy, clay, and loam soil types. Will this species thrive too well, becoming invasive?
- Texas ebony (*Ebenopsis ebano*) – The Texas ebony is native to Texas and Northern Mexico, where it is evergreen. It tolerates modest frost but goes deciduous. The tree can reach a height of 10 m, but is slow growing. Once established, it is very drought tolerant. It has a distinctive branching pattern, thorns, and fragrant yellow flowers that mature into large woody pods. Will Texas ebony require too much training to warrant large-scale use?
- White Shield osage orange (*Maclura pomifera* 'White Shield') – Osage orange is native to the western Great Plains. It grows quickly to a height of 10–15 m. The deciduous foliage is glossy green. The White Shield cultivar is thornless and fruitless. Will this cultivar be tough enough to handle a wide range of soil types and irrigation amounts?
- Desert Museum palo verde (*Parkinsonia* x 'Desert Museum') – The Desert Museum is a palo verde hybrid that exhibit qualities of the blue, foothills, and Mexican palo verdes. The tree has a strong upright branching structure and rapid growth, reaching a height of 6–8 m. This hybrid is thornless and has little litter. Will the roots of this attractive tree extend deep enough in clay soils to support its ample crown when strong north winds sweep the Valley?
- Canby's oak (*Quercus canbyi*) – The Canby oak is native to northern Mexico and Texas. It grows rapidly with an upright habit to reach 12–18 m. The thick leathery leaves are semi-evergreen and resemble red oak. Acorns are small and narrow. This deep rooted oak is heat tolerant. Will the foliage persist throughout winter and will acorns pose a litter problem?
- Emerald Sunshine elm (*Ulmus propinqua*) – The Emerald Sunshine elm is a deciduous tree that reaches 12 m in height with an 8 m spread. It has a vase shaped growth habit. Emerald Sunshine is tolerant of hot and windy conditions. Will this hybrid be truly pest and disease resistant?

2.6.4. Step 4. Plant and evaluate in experimental plots

The 144 trees were obtained from three nurseries and planted during February and March 2015. The four park sites were identified with help from the City of Sacramento Parks and Public Works Departments. Soil sampling and irrigation monitoring results indicated that each park presented different challenges to tree survival and growth (Table 4).

2.7. CIMIS data

Data from the CIMIS station closest to the reference site collected during 2015 indicated that transplants were not exposed to extremely low air temperatures that could test their hardiness. The lowest hourly temperature was −2.3 °C on December 27. During this time temperatures were below 0 °C for eight hours. Over the past 25 years the average minimum annual temperature at the Davis site was −3.1 °C. During 2015 annual precipitation (180.5 mm) was less than the historic normal (466.5 mm) and ET_o was slightly higher than normal (1,496.7 versus 1,440.3 mm).

2.8. Tree survival and growth

Tree mortality research shows that tree losses are highest during the establishment stage when they are most vulnerable (Roman et al., 2014). Hence, there is something to learn from tree performance during this critical period. Recognizing that what we learn during tree

Table 3
The 32 species that scored 3 or higher are listed with highest scores first. Scores for each of the 10 vulnerability indices are shown, where N/A indicates insufficient information to score. Names of the 12 finalists are in bold.

Species	Common Name	Soil Texture and pH	Soil Moisture	Sunlight Exposure	Drought Tol.	Salt Tol.	Wind Tol.	Cold Hardiness	Invasiveness	Major or Minor Pests and Diseases	Emerging Pests and Diseases	Total Score	Uncertainty	Availability & Notes
Prosopis glandulosa 'Maverick'	Honey Mesquite	1	1	0	1	1	1	1	1	0	1	8	0%	3 nomin.
Prosopis x 'Phoenix'	Phoenix Mesquite	1	1	0	1	1	1	1	1	0	1	8	0%	improved cultivar
Chilopsis linearis	Desert Willow	0	1	0	1	1	1	1	1	0	1	7	0%	7 nomin.
Gymnocladus diocia	Kentucky Coffeetree	1	1	1	0	−1	1	1	1	1	1	7	0%	mod. water use
Maclura pomifera cv.	Osage Orange	1	1	0	1	1	1	1	1	NA	NA	7	20%	thornless, fruitless
Prosopis juliflora	Mesquite	1	1	0	1	1	0	1	1	0	1	7	0%	variable form
Acacia aneura	Mulga	1	1	0	1	NA	0	1	1	0	1	6	10%	2 nomin.
Acacia pendula	Weeping Myall	1	1	0	1	1	−1	1	1	0	1	6	0%	desert SW cities
Acacia stenophylla	Shoestring Acacia	1	1	0	1	NA	0	1	1	0	1	6	10%	desert SW cities
Hesperocyparis macnabiana	McNab Cypress	1	1	−1	1	NA	1	1	1	0	1	6	10%	not available
Pittosporum angustifolium	Willow-leaved Pittosporum	1	1	0	0	1	0	1	1	0	1	6	0%	mod. water use
Caesalpinia cacalaco	Cascalote	0	1	1	1	1	−1	1	1	0	0	5	0%	not available
Eucalyptus spathulata	Swamp Mallet	1	1	0	1	1	0	1	0	−1	0	4	0%	not available
Parkinsonia praecox	Palo Brea	0	1	−1	1	1	0	1	1	NA	NA	4	20%	desert SW cities
Parkinsonia x 'Desert Museum'	Desert Muesum Palo Verde	0	1	−1	1	NA	0	1	1	0	1	4	10%	improved cultivar
Parrotia persica	Persian Ironwood	0	1	0	0	1	0	1	1	NA	NA	4	20%	mod. water use
Pinus roxburghii	Chir Pine	0	1	0	0	1	0	1	1	NA	NA	4	20%	mod. water use
Pinus torreyana	Torrey Pine	1	0	0	0	−1	1	1	1	0	1	4	0%	mod. water use
Pistacia integerrima	Kakar Singhi	1	1	0	0	−1	1	1	1	−1	1	4	0%	not available
Quercus canbyi	Sierra Oak	1	1	0	1	0	1	1	1	−1	−1	4	0%	desert SW cities
Quillaja saponaria	Soapbark	0	1	NA	1	NA	NA	1	1	NA	NA	4	50%	not available
Ulmus propinqua	Emerald Sunsine Elm	NA	1	0	1	NA	1	1	1	0	−1	4	20%	2 nomin.
Ulmus wilsoniana	Prospector Elm	NA	1	0	1	NA	1	1	1	0	−1	4	20%	3 nomin.
Celtis reticulata	Netleaf Hackberry	0	1	1	1	NA	0	1	1	−1	−1	3	10%	not available
Corylus colurna	Turkish Hazel	1	0	0	0	−1	1	1	1	NA	NA	3	20%	not available
Dalbergia sisso	Indian Rosewood	0	0	0	1	−1	NA	0	1	1	1	3	10%	desert SW cities
Ebenopsis ebano	Texas Ebony	1	0	−1	1	0	1	0	1	NA	NA	3	20%	desert SW cities
Eucalyptus microtheca	Coolibah	1	1	0	1	0	0	1	0	−1	0	3	0%	desert SW cities
Corymbia papuana	Ghost Gum	0	1	0	1	1	0	1	0	−1	0	3	0%	not available
Olneya tesota	Ironwood	0	1	−1	1	−1	1	1	1	NA	NA	3	20%	2 nomin.
Pterocarya stenoptera	Chinese Wingnut	0	1	−1	NA	NA	1	1	1	NA	NA	3	40%	not available
Vauquelinia californica	Arizona Rosewood	0	1	0	1	−1	NA	1	1	NA	NA	3	30%	desert SW cities

Table 4
Descriptions of each experimental site.

Name/Location	Terrain	Use	Soils	Irrigation
Laguna Creek Park/South Sacramento	Flat turf, some areas shaded by a grove of mature trees	heavy recreational use, some vandalism	clay loam, neutral pH (6.72)	sprinklers 3 days a week for 20 min for April–September, 20 min 2 days a week for October, average annual rate 48 cm per year
Regency Park/North Sacramento	west-facing slope, fescue grass	little foot traffic	loam, neutral pH (7.10), only 2.26 ppm of nitrate available	sprinklers on two valves, for March-September, 15 trees on the north side for 25 min 3 days a week, 9 trees on south side for 20 min 2 days a week, average annual 58 cm per year
Fisherman's Lake/North Sacramento	East-facing slope to water, bare soil	foot path gets moderate use	clay loam, neutral pH (7.39)	sprinklers on three valves, for April-October, all trees for 6 min 2 days a week, 11 trees for 25 min 2 days a week, 7 trees on for 25 min 1 day a week, average annual 24 cm per year
Kohl's Bike Path/North Sacramento	West-facing slope in a swale, grass and weeds	bike path at top of swale gets heavy use	clay loam, neutral pH (6.97)	drip 2 days a week for 15 min for March-October, average annual rate 7340 cm per year
UC Davis Reference Plot/2 km west of campus	Flat field site, trees on 8 m centers, 4 rows of 12 trees with border rows	No users	loam, neutral pH (6.81)	drip 3 days a week for 420 min for March-September, 2 days a week for October-November, average annual rate 408,857 cm per year

establishment is a small part of the full story on tree performance, we present preliminary findings on survival, growth and management needs.

Four bareroot Emerald Sunshine elm trees died within the first few weeks after planting, likely due to drying of the roots prior to planting. These trees were replaced in spring 2016 with 15-gal stock. Other losses counted towards mortality in our experimental design. After two years of monitoring, three trees died and were removed (2.1%). All three (rosewood, ghost gum, Texas ebony) were in Regency Park, where growing conditions are most challenging due to the slope, fescue grass and use of string pruners that stripped bark from trees.

Early differences in growth rates provide an initial indication of establishment success. Species exhibiting the most robust dbh growth were Maverick mesquite, Canby's oak and shoestring acacia (Fig. 4). Differences in growth of trees of the same species in the park and reference sites could indicate their ability to exploit rich growing conditions, as well as thrive in impoverished sites and tolerate substandard maintenance practices. Maverick mesquite was excelling in both the park and reference sites.

Subjective performance ratings were recorded and tallied for each species after the second year of monitoring (Table 5). Canby's oak received an excellent overall performance rating, while Texas ebony received the lowest rating. Other species judged to be performing very well at this time were the mulga, desert willow and ghost gum. Canby's oak was deemed to require the least pruning, followed by Emerald Sunshine elm and White Shield osage orange. Netleaf hackberry and Maverick mesquite were judged to require the most pruning.

2.8.1. *Step 5. Share results to effect change*

The research team has established a website (http://climateready-trees.ucdavis.edu/) and posts regular performance updates. Research results have been presented at local and regional conferences sponsored by the urban forest community (i.e., Western Chapter International Society of Arboriculture, California Urban Forest Council, California ReLeaf) and in trade magazines (i.e., *Western Arborist*). The research team has reached out to growers and landscape architects through presentations to local advisory committees, such as the Sacramento Tree Foundation's Technical Advisory Committee. This group periodically updates the list of trees approved for planting in the regional Greenprint effort to plant 5 million trees, and includes representatives from local nurseries, design firms and cities. Preliminary results have been shared with arborists and landscape contractors through presentations and handouts distributed at University of California Cooperative Extension (UCCE) workshops and field days. Researchers are delivering findings to home gardeners through UCCE's Grow With Us and Master Gardener programs. Our knowledge concerning the types of sites where each species performs best, its functional value (e.g., shade, wildlife), vulnerabilities to pests, traits of concern (e.g., invasive, tender) and management requirements are expected to change as more is learned over the 20-year evaluation period.

3. Discussion

The approach described and applied in this study contains features of other tree performance trials, but differs in several significant ways. For example, like the National Elm Trials (NET) trees were planted in well maintained reference plots. Similar to the Street Tree Evaluation Program (STEP) and Municipal Tree Restoration Program (MTRP) trees were planted in typical growing sites, here parks instead of streets. This study differs from previous trials by containing both reference and park plots to provide more robust data for statistical analyses. This study's experimental design, with 12 replicates of each species growing in a variety of sites, is more rigorous than previous studies. It has potential to produce solid scientific information on tree performance at a manageable cost.

Previous trials have had a relatively narrow focus compared to this

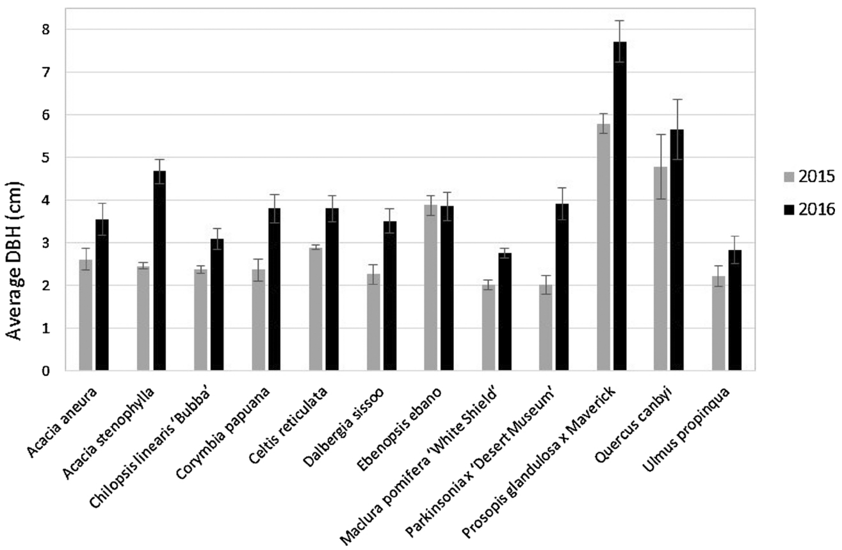

Fig. 4. Average dbh (cm) with standard errors, measured approximately one and two years after planting, for approximately 8 trees of each species planted in Sacramento parks and 4 of each planted in the UC Davis reference site.

Table 5
Initial overall performance ratings (1 = poor and 5 = excellent) and relative pruning requirements (1 = most and 3 = least) for each species approximately one year after planting. These ratings are the averages of subjective scores submitted by members of the research team.

Species	Overall	Prune Req.
Quercus canbyi	4.0	2.8
Acacia aneura	3.7	1.8
Chilopsis linearis 'Bubba'	3.7	2.3
Corymbia papuana	3.7	2.3
Dalbergia sissoo	3.3	1.8
Acacia stenophylla	3.0	2.3
Ulmus propinqua	2.7	2.5
Maclura pomifera 'White Shield'	2.3	2.5
Celtis reticulata	2.0	1.3
Parkinsonia x 'Desert Museum'	2.0	1.5
Prosopis glandulosa x Maverick	2.0	1.3
Ebenopsis ebano	0.7	1.8

study. NET focused on elm cultivars, while STEP and MTRP focused on street trees, with the latter using small-stature trees under utility lines. This study contained trees representing a variety of species, sizes and landscape uses. Results from this study should be of interest to a wider range of users than the previous trials cited here.

This approach followed work by Asgarzadeh et al. (2014) that used horticultural experts to score each species. However, we used experts to identify the most promising climate-ready species. Instead of relying on the experts to grade each species we used objective information from the literature. We did not apply weights to selection parameters, but this could have been part of our scoring process. One limitation we faced in this study was obtaining a complete list of candidate species from horticultural experts. A significant amount of follow-up was required in this study to solicit the 134 nominations.

In traditional forests, assisted migration is one climate adaptation strategy to increase resilience (McLachlan et al., 2007). However, assisted migration is fraught with controversy and uncertainty over issues such as provenance of seed/plant sources and unintended consequences to native plant communities. Many urban areas already contain ornamental plantings native to more southerly latitudes (Woodall et al., 2010). Global trade in ornamental plants results in their movement into environments very different than their native habitat, and is widely accepted because the composition of urban forests is already cosmopolitan. It is much less expensive and much faster to import species for testing than for nurseries to select, breed and market new climate-ready species, which can take a decade or more. In our trial the finalists were native to a variety of hot and dry climates: desert (southwest USA), Mediterranean (Australia), temperate dry (Great Plains USA) and tropical dry climates (India). With this wide diversity there is risk that species will be too well adapted and become invasive, or poorly adapted in unforeseen ways and fail. Intensive monitoring will be needed over the 20-year period to fully understand the suitability of each species.

Tree selection is an important leverage point for managers striving to reduce the future vulnerability of their urban forests (Lacan and McBride, 2008). We recognize that our approach is one of many that cities can take to incorporate urban forestry into their climate mitigation and adaptation plans (Brandt et al., 2016; Ordonez et al., 2010). Some of the other innovative strategies being taken by cities to enhance the resilience of their urban forests include (Huber et al., 2015):

- Creating new plant-growing lists with selections that can thrive in warmer conditions (Chicago, IL)
- Piloting seed diversity projects that propagate locally native species to increase genetic diversity (Toronto, CA)
- Contracting with nurseries to grow species that meet specified standards (New York City, NY)
- Emphasizing selection of drought and recycled water-tolerant species (Palo Alto, CA)
- Including geographic diversity, along with species and age diversity, as strategies to increase resilience (Austin, TX).

Our study differs from these in that incorporates responses to climate change in multiple directions, not a single direction such as drought tolerance. Also, it can be readily adapted and applied globally.

This study faced a number of limitations that could be overcome by others and with new research. We found that it was difficult to obtain data on some of the vulnerability indices, especially for trees from remote regions of the world. Lack of information on a species' native habitat, physiological tolerances, invasiveness and pest vulnerability increased uncertainty. A global database on ornamental tree species could be very valuable in this regard.

Our approach allows only one response for each of the ten indices. Providing more flexibility could result in a better scoring system. Moreover, it does not spatially model climate projections and their impacts on the ranges of candidate species. In part, this is because climate modeling for urban environments is complicated by finer-scale heat island effects.

Many urban tree species are non-native and there was much uncertainty regarding their true range and habitat. Another related limitation was the difficulty of incorporating how climate change exposures might influence the invasiveness and pest vulnerability of different species in the future. New research could generate information to reduce these uncertainties.

4. Conclusions

California's urban forests were established when irrigation water was plentiful. In many cases the predominant species are native to temperate climates (e.g., *Fraxinus, Prunus, Liquidambar*) and not drought tolerant or climate-ready (McPherson et al., 2016). To increase the climate resilience of their urban forests, managers can gradually shift the mix of species to reduce vulnerability and catastrophic loss of tree canopy. Extreme weather events, like California's drought and associated mortality pulses can accelerate the transition to a more resilient species composition and age structure.

This research may assist managers by providing field-based information on the performance of tree species that appear promising in terms of adaptation to future climatic conditions, but are not locally grown and available. As high performing species enter the trade through local nurseries, managers can use them to gradually shift the species composition and increase urban forest resilience. A more resilient urban forest consisting of climate-ready species is likely to produce more ecosystem services that can improve environmental quality and human health and well-being, compared to a less resilient forest.

There are other important uses for this research. For example, this study can tell us at the species level, how site conditions (i.e., soil, water, light, microclimate), management practices and climate influence growth and survival. Data on the maintenance requirements of each species over the 20-year timespan, such as pruning frequency, can help designers and managers avoid unnecessary costs when the wrong tree is put in the wrong place. By understanding these limitations it may be possible to avoid future problems such as tenderness to cold, invasiveness, shallow rooting, weak branch attachments, sensitivity to salinity, graft incompatibility and other root problems.

The approach used here is relatively straightforward and pragmatic. It combines climate change science with urban horticulture in a five-step process that can be easily applied in other urban environments. In 2016 the approach was replicated in Southern California's Inland Empire and Coastal climate zones, with several new species planted for testing in each zone. It can serve as an international model for cities interested in climate adaptation through urban forestry.

Acknowledgements

Funding for this project was provided to the University of California, Davis by The Britton Fund, International Society of Arboriculture, Western Chapter, USDA Forest Service, Pacific Southwest Research Station and City Plants Los Angeles. We are deeply indebted to our horticultural advisors and all of our partners who provided trees and helped to plant, maintain and measure the trees in three California regions. These cooperators include Erika Teach (U.S. Forest Service, PSW) and Qingfu Xiao (UC Davis). Our Southern California trials included colleagues with the University of California Cooperative Extension, Janet Hartin (San Bernardino, Los Angeles and Riverside Counties), Jim Downer (Ventura County) and Darren Haver (South Coast Research & Extension Center, Irvine). Trees were generously provided for testing by Mountain States Wholesale Nursery, Boething Treeland and J. Frank Schmidt & Sons. The Sacramento Tree Foundation assisted with planting and stewardship and the City of Sacramento, Departments of Public Works and Parks and, UC Davis Grounds Department identified sites, installed irrigation and maintained the trees. In the Southern California trials the Los Angeles Beautification Team, City Plants, and Los Angeles City Recreation and Parks Department assisted with planting and stewardship. Without the contributions of these and other cooperators this study would not have been possible.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2017.09.003.

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