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Diversity and structure in California's urban forest: What over six million data points tell us about one of the world's largest urban forests

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ABSTRACT

Urban street trees provide many benefits to surrounding communities, but our ability to assess such benefits relies on the availability of high-quality urban tree data. While these data are numerous, they are not available in an easily accessible, centralized place. To fill this gap, we aggregated public and private data into a single, comprehensive inventory of urban trees in California called the California Urban Forest (CUF) Inventory. These data are offered to the public (aggregated to ZIP code) via an online data portal, which at the time of publication contained over 6.6 million urban tree records. In this study, we first describe the assembly and utility of the inventory. Then, we conduct the most comprehensive assessment of the diversity and structure of California's urban forest to date at statewide, regional, and local spatial scales. These analyses demonstrate that California's urban forests are highly diverse and among the most diverse urban forests in the world. We present a new and intuitive metric of species diversity, the top diversity or TD-50 index, which represents the cumulative number of species accounting for the top 50 % abundance of trees in an urban forest. We used species abundance data from 81 well-inventoried cities to demonstrate that the TD-50 index was a robust metric of diversity and a good predictor of comprehensive metrics like the Shannon Index. We also found that small-statured trees, such as crape myrtles (*Lagerstroemia* cv.) dominate California's urban forests. This aggregated inventory of one of the world's largest urban forests provides the data necessary to assess the structure, diversity, and value of California's urban forests at multiple spatial scales. The inventory's presentation to the public and the information that can be gained from its analysis can be a model for urban forest management worldwide.

1. Introduction

Urban trees are trees planted in towns and cities along streets, in yards, parks, gardens, and public spaces. The benefits of these trees to humans are well documented. Urban trees provide many ecosystem services and environmental benefits such as urban cooling and carbon sequestration while simultaneously reducing urban stormwater runoff and air pollution (Calfapietra et al., 2016; Hsieh et al., 2018; Livesley et al., 2016; Wang et al., 2021; Xiao and McPherson, 2016). Urban trees also dramatically increase the livability of a city, improve aesthetics, are associated with higher real estate value, and positively impact human health and well-being (Giacinto et al., 2021; Seo, 2020; Staats and Swain, 2020). Diverse urban forests can also function as wildlife habitat for a wide range of organisms (Firoj Jaman et al., 2021; Machar et al., 2022; Wood and Esaian, 2020). In California's urban forests, under which nearly 40 million people live and work, these services and benefits were valued at $8.3 billion annually in 2017 (McPherson et al., 2017).

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The extent to which urban forests can provide ecological, economic, or health benefits in urban environments depends on forest structure, diversity, and health (Livesley et al., 2016). For example, large tree canopies provide greater reductions in temperature and solar radiation than small canopies (Sanusi et al., 2016), and there is variability among tree species in their capacity to reduce stormwater runoff (Alves et al., 2018; Xiao and McPherson, 2016), uptake ozone from the atmosphere (Calfapietra et al., 2016), and sequester carbon (Boukili et al., 2017; McPherson et al., 2016b; Nowak and Crane, 2002). Moreover, the resiliency of urban forests in the face of climate change strongly depends on the species diversity of the urban forest because species vary in their vulnerability to increases in temperature and other stressors that are either directly or indirectly associated climate change (e.g., drought, pests, and diseases; McPherson et al., 2018). As such, assessing the structure and diversity of urban forests can provide insight into their function and resilience, while also helping to inform planning and management decisions.

Our ability to assess the current and future benefits of the urban forest relies on the availability of high-quality urban tree data. Previous studies that have assessed California's urban forests have obtained these data via several sources, including forest inventory analysis (or FIA plots) or through publicly available municipal inventories. In addition to these sources, urban tree data are also collected and stored by private arborist companies, many of which are contracted to conduct municipal inventories. This represents an extensive and previously inaccessible source of data. These disparate sources of data, however, and are not available in a centralized location making it challenging for researchers, urban foresters, or the public to access them.

To fill this gap, we have aggregated public and private data into a single, comprehensive inventory of urban trees in California and offer them to the public (aggregated to ZIP code) via The California Urban Forest (CUF) Inventory hosted at the Urban Forest Ecosystem Institute at Cal Poly, San Luis Obispo (https://datastudio.google.com/u/0/reporting/880d448d-de26–48d3-b563–0c6317e456e4/page/jWHKB). The majority of these data represent publicly managed street trees (at least 75 %). This inventory represents the largest inventory of individual trees in the United States and provides the data necessary to assess diversity and structure patterns across the state at multiple spatial scales. It also allows us to identify areas where urban forests may be especially vulnerable to stressors associated with climate change (Allen et al., 2010; McPherson et al., 2017), to monitor changes in the urban forest (McPherson et al., 2016a; McPherson and Kotow, 2013), and to more accurately estimate the ecosystem services and benefits provided to local communities by urban forests (Song et al., 2018).

In this study, we describe the process of assembling the CUF Inventory (which at the time of publication had over 6.6 million individual urban tree records), review the species-level attributes available through the data portal, and discuss how the inventory will benefit a wide range of users including urban forest managers, city planners, and scientific researchers. To demonstrate the utility of the inventory, we use these data to conduct the most comprehensive assessment of the diversity and structure of California's urban forests across multiple spatial scales to date. The goals of our assessments are described below.

1.1. Species diversity

Urban forest resiliency to biotic and abiotic stressors is linked to tree species diversity (Morgenroth et al., 2016); however, patterns of diversity, and thus vulnerabilities to stressors, can vary across spatial scales (Avolio et al., 2015; Galle et al., 2021; Ma et al., 2020). For example, an assessment of tree diversity across the 48 continental United States at multiple spatial scales revealed that, at the national scale, no one tree species dominated the urban forest by more than 10 %, a commonly used benchmark to assess over-reliance on a single species (Ma et al., 2020). However, at smaller regional and community levels, the most common species exceeded 10 % in various areas, revealing potential vulnerabilities at localized rather than national scales. Species diversity can also differ at hyperlocal, sub-city levels. Galle et al. (2021) found that among eight cities distributed globally, diversity was greater outside vs. inside city centers. These studies reveal that heterogeneity in the urban forest differs across spatial scales and highlights the need to conduct analyses across various scales to assess potential vulnerabilities at multiple spatial scales. Moreover, assessments of tree diversity at local scales can help identify community-specific vulnerabilities to various stressors, allowing managers to intervene and prevent the catastrophic loss of trees and associated ecosystem services.

There are several ways in which urban forest diversity is measured and monitored. The number of tree species in a given area, or species richness, is one commonly used metric (Galle et al., 2021; Gillespie et al., 2017). However, in natural ecosystems, it has been widely demonstrated that species richness depends on spatial extent (i.e., larger areas tend to have more species; Lomolino, 2000), making it difficult to compare richness across spatial scales. The extent to which this pattern holds true in human-constructed ecosystems like urban forests is understudied (but see Chang et al., 2021), and assessing this relationship is one of the goals of the current study. Species richness is also sensitive to sampling effort (Jin and Yang, 2020). Moreover, while two forests may have the same species richness, the relative abundances of each species (i.e., species evenness) may differ, which has important implications for forest resiliency (Raupp et al., 2006). Diversity indices such as the Shannon Index or Simpson's Index, are measures of diversity that consider the number of species present as well as their relative abundances, making them useful metrics with which to compare across spatial scales (Miller et al., 2015). Traditionally used by ecologists, these metrics have also been widely utilized to assess diversity in urban forests in the scientific literature (Avolio et al., 2015; Galle et al., 2021; Kendal et al., 2014). Despite their prevalence in the scientific literature, applied use of these indices by urban foresters is limited as they are difficult to interpret (they lack units) which makes them difficult to use as metrics to set diversity goals or benchmarks, a common component of management plans (Kendal et al., 2014).

Another common method to assess diversity and to set diversity goals or benchmarks is percent-based systems that use the relative abundance of species, genera, and/or families (Galle et al., 2021; Kendal et al., 2014). These benchmarks are based on the fact that related tree species tend to share similar susceptibilities to stressors, especially pests (Lynch et al., 2021). The most widely accepted benchmarks are those first proposed by Santamour (1990). He proposed the 10–20–30 rule which suggests that for maximum protection against pest outbreaks, urban forests should be comprised of no more than 10 % of any one species, no more than 20 % of any one genus, and no more than 30 % of any one family. Others have proposed even stricter or more specific benchmarks. For example, Ball et al. (2007) suggests no more than 10 % of any genus, especially those susceptible to potentially destructive pests (e.g., *Fraxinus* L. which is susceptible to the emerald ash borer). Previous research has demonstrated that adherence to such benchmarks often depends on spatial scale (Ma et al., 2020); at the city-level, urban forests are more likely to exceed species-level benchmarks relative to regional or national scales (Galle et al., 2021; Kendal et al., 2014). One limitation of using species, genus, and family abundances as benchmarks is that this method relies on three separate measures of forest diversity, making it difficult to draw meaningful comparisons or rankings of diversity across spatial scales.

California's urban forests are diverse, but whether and how patterns of diversity differ across state, regional, and local city scales has not been studied systematically (but see McPherson et al., 2017, 2016a). Here, we use the comprehensive inventory data provided by the CUF Inventory to fill this gap by assessing species richness, evenness, and diversity across these spatial scales, including among 81 well-inventoried cities (those with >20,000 tree records). This represents largest sample of California cities assessed to date. We also assess adherence to Santamour's 10–20–30 benchmarks at each scale.

Another goal this study was to use the CUF Inventory data to develop a new, single diversity metric that (1) is straight-forward to calculate and interpret, (2) can be easily implemented in urban forest management plans to set diversity goals, (3) is comparable across spatial extents, and (4) is correlated with diversity indices, like the Shannon Index, that incorporate both species richness and evenness. Here, we introduce a new and intuitive metric of urban forest diversity that meets these criteria, the top diversity index or TD-50 Index, which represents the cumulative number of tree species accounting for the top 50 % abundance of trees in an urban forest. We use the CUF Inventory data to evaluate whether the TD-50 index is a good predictor of diversity as measured by the Shannon Index among well-inventoried cities. To better understand the factors that drive urban forest diversity at local scales, we also use the city-based data to assess the relationship between city area and various diversity metrics.

1.2. Urban forest structure

Tree size, including tree height but especially tree diameter (e.g., diameter at breast height or DBH), is generally associated with tree age. Smaller trees are generally younger, although this relationship depends on species (McPherson et al., 2016b). The distribution of tree sizes in a region lends insight into the age structure of that urban forest and has important management implications. For example, a population with all large, senescent trees is expensive to maintain as they need frequent pruning to mitigate hazards and are at higher risk for failure so tree removals may have to be performed more frequently (Thompson and Reimer, 2018). While large, mature trees can provide many benefits to communities such as carbon storage, reduced stormwater runoff, and shade, having a large portion of mature trees in an urban forest can strain municipal budgets (McPherson et al., 2016a; McPherson and Kotow, 2013). In contrast, a variably-sized tree population allows for a more even distribution of maintenance costs over longer periods of time, and ensures juvenile trees are present in the population to replace dying trees and to counteract establishment-related mortality (McPherson et al., 2016a; McPherson and Kotow, 2013; Richards, 1983). Richards (1983) proposed several recommendations for street tree size diversity to ensure population stability. He suggested that street tree populations be un-even and dominated by juvenile trees with a target of 40 % of trees less than 20 cm in DBH, 30 % 20–40 cm, 20 % 40–60 cm, and 10 % larger than 60 cm in DBH. In this study, we use the CUF Inventory data to assess the size distribution of trees at state and regional scales to better understand the age class distribution of urban tree populations. We also examine the size distribution of the top 10 most abundant species in California, which lends insight into historical planting patterns in the state.

2. Methods

2.1. Assembly of the California urban forest inventory

To assemble the CUF Inventory, we obtained as many inventories of California urban forests as possible. Much of our data was assembled from private arborist companies and municipal inventories. We obtained data from West Coast Arborists, Davey Tree Company, APlus Tree Care, and CAL FIRE. In addition, we reached out to many other municipalities throughout the state and asked them to share their data with us. The data we obtained was variable, but primarily consisted of public street tree records derived from municipal inventories conducted between 2012 and 2021. Data from each provider contained different information with variously named columns and were filtered to retain only the GPS point (collected with high-precision GPS units), species ID, tree diameter at breast height (DBH), and tree height. Tree DBH and height values were often not reported as exact values but were binned. Because bin boundaries were variable across inventories, we created six bins for DBH (at 15 cm each from 0 to 75 cm+) and five bins for tree height (at 5 m increments each from 0 to 20 m+). Trees were assigned to these bins using either the exact or binned values provided by the data source. If a given trees' bin range was outside of our bin boundary, we used the midpoint of the tree's original bin to re-assign it to one of our bins.

Our taxonomic knowledge of tree species is always evolving, and tree names often change. To integrate tree names across all inventories, we created a name resolution tool. For example, *Acacia greggii* A. Gray and *Senegalia greggii* (A. Gray) Britton & Rose are two names, or synonyms, for the same species, and should be treated as *Senegalia greggii*, the most current name for that species. The name resolution tool consisted of a spreadsheet that resolves misspellings, taxonomic changes, and removes records that are not trees (e.g., vacant space). Species names were aligned with those on SelecTree, an urban tree database and tree selection tool (https://selectree.calpoly.edu). Using these corrected names, the CUF Inventory was joined with a database of species attributes from SelecTree. Species attributes joined to the CUF Inventory included family, native range, foliage type, and water-use rating.

The CUF Inventory was uploaded to Google BigQuery and joined with BigQuery's publicly available shapefiles representing political boundaries to determine the county, city, and ZIP code, a postal code used by the United States Postal Service. We also joined each tree to one of six climate zones in California (Fig. 2). Climate zones used in this study were first delineated by McPherson et al. (2010) based on aggregated Sunset Climate Zones (Brenzel, 1997) and ecoregion boundaries defined by Bailey (2002) and Breckle (2002). These zones have been previously used to assess structure and diversity in California's urban forest on a regional scale, so use of these zones allows us to directly compare our results to previous studies (McPherson et al., 2017, 2016a, 2016b).

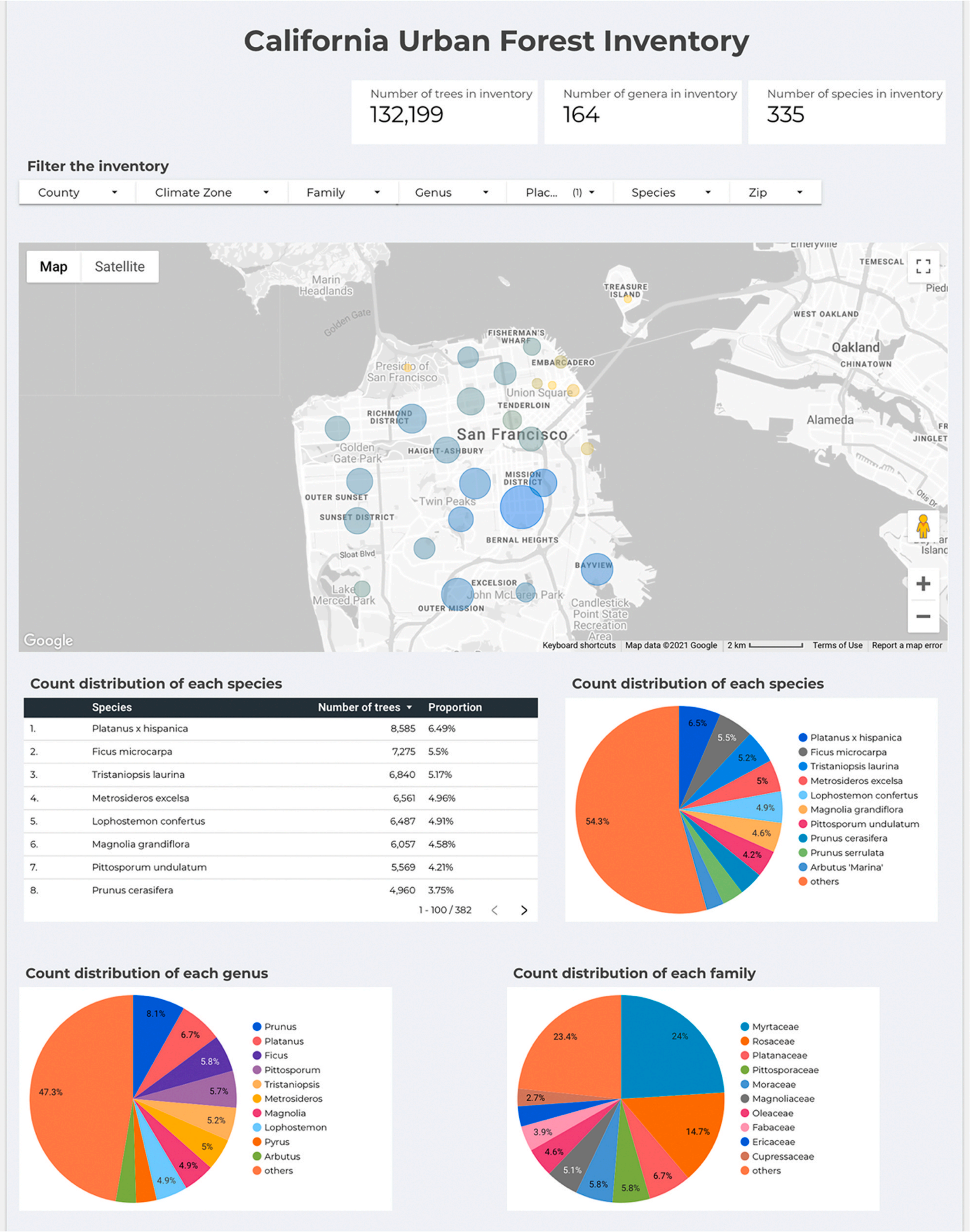
Before publication to the online data portal, we completed additional cleaning steps. First, we removed records of species represented by fewer than 100 individuals as these records may represent misidentifications or rare species represented in botanic gardens or arboreta (16,182 records representing about 0.2 % of all trees). Next, we removed any duplicate records by removing points within a 1.5-meter radius of another point of the same species. This criterion is likely to remove duplicate trees (i.e., the same tree surveyed on two different dates) rather than trees planted along streets in close proximity as the recommended planting space for a single tree ranges from 1 to 2 m (Gilman, 1997). These cleaning steps resulted in a final CUF Inventory of 6,661,473 urban tree records, a number that is growing as more inventory data is shared and incorporated into the Inventory. About 5.12 million (76 %) were obtained from complete municipal inventories and represent public street trees. The remaining records represent a combination of partial street tree inventories and private trees.

A geospatial database of these records were aggregated to ZIP code and offered to the public via an open data portal (https://datastudio.google.com/u/0/reporting/880d448d-de26–48d3-b563–0c6317e456e4/page/jWHKB) using the Google Data Studio platform (Fig. 1).

2.2. Assessing diversity and structure statewide and among climate zones

2.2.1. Diversity

We used the 6.6 million tree records to assess patterns of urban forest diversity and structure at three spatial extents in California: statewide, regionally among climate zones, and locally among well-inventoried cities. To assess tree diversity statewide, we calculated the relative abundance of the top ten most common species and determined the top 10 most speciose genera and families. We also determined the species richness (number of distinct species) as well as calculated the Shannon Index (H') and the Shannon Equitability Index (E_H) which is a measure of species evenness. The Shannon Index is a widely used metric of species diversity in forestry, including urban forestry, that accounts for both species richness and evenness (Blood et al., 2016; Cowett and Bassuk,



California Urban Forest Inventory

Number of trees in inventory
132,199

Number of genera in inventory
164

Number of species in inventory
335

Filter the inventory

County ▾ | Climate Zone ▾ | Family ▾ | Genus ▾ | Plac... (1) ▾ | Species ▾ | Zip ▾

Count distribution of each species

	Species	Number of trees ▾	Proportion
1.	Platanus x hispanica	8,585	6.49%
2.	Ficus microcarpa	7,275	5.5%
3.	Tristaniopsis laurina	6,840	5.17%
4.	Metrosideros excelsa	6,561	4.96%
5.	Lophostemon confertus	6,487	4.91%
6.	Magnolia grandiflora	6,057	4.58%
7.	Pittosporum undulatum	5,569	4.21%
8.	Prunus cerasifera	4,960	3.75%

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Count distribution of each species

Count distribution of each genus

Count distribution of each family

Fig. 1. A portion of the online data portal filtered to show urban tree records in the city of San Francisco only. Trees are aggregated to ZIP code and displayed on the map. Points are centered within ZIP code boundaries. Point colors represent number of distinct species (blue indicates more species) while point sizes represent number of tree records. Pie charts show the count distribution of each species, genus, and family as percentage of all trees in San Francisco. Tabular versions of summary tables and figures can be downloaded as CSVs. The portal can be accessed at https://datastudio.google.com/u/0/reporting/880d448d-de26–48d3-b563–0c6317e456e4/page/jWHKB.

2021; Kendal et al., 2014; Miller et al., 2015). It is calculated using the following equation:

$$H' = -\sum_{i=1}^{S} p_i \quad \ln p_i \tag{1}$$

where $_{pi}$ is the proportion of tree records of species *i* relative to the total number of records and S is the number of distinct species. We used the package *vegan* in the statistical software R to calculate the Shannon Index (Oksanen et al., 2020; R Core Team, 2020). Previous studies have found that typical Shannon Index values for urban forests range from 1.5 to 4.3 (Blood et al., 2016; Galle et al., 2021; Kendal et al., 2014). The Shannon Equitability Index ranges from 0 to 1 where 1 indicates complete evenness. It is calculated using the following equation:

$$E_H = \frac{H'}{ln(S)} \tag{2}$$

where *H'* is the Shannon Diversity Index and *S* is the number of species (i.e., species richness) in a given area (in this case statewide). We also calculated a new index that we call the top diversity index, or TD-50 index, which represents the cumulative number of species accounting for the top 50 % of trees at a given area.To calculate the TD-50 index, we determined the relative abundance (%) of each species in a given area (e.g., state, climate zone, or city), sorted species by abundance from highest to lowest, and then determined the cumulative number of species that account for the top 50 % of trees. We developed the TD-50 index as a new and intuitive metric of tree diversity in urban forests. Cities with low values of TD-50 have a low number of species making up half of their urban forest, whereas cities with high values have a more diverse urban forest. The fewer species comprising 50 % of trees, the more vulnerable an urban forest is to environmental change (Huff et al., 2020; Kendal et al., 2014; Raupp et al., 2006). A goal of this study was to test whether this metric is a good predictor of species diversity as measured by the Shannon Index (see Section 2.3).

To assess diversity among climate zones, we calculated the relative and cumulative abundance of the top ten most common species in each zone. We also calculated the relative abundance of the most common genus and family in each zone. Finally, we determined the total number of distinct species (species richness) and calculated the Shannon Index (*H'*), species evenness (E_H), and the TD-50 index in each zone.

2.2.2. Structure

To assess structure in California's urban forests, we evaluated tree size patterns (DBH and height) and the distribution of foliage types both statewide and among climate zones. Before assessing patterns in DBH, we removed records that likely represent errors in DBH measurement, either due to misreported units (e.g., inches vs. centimeters) or misidentifications. To do this, we retained records with a DBH larger than 130 cm only if it was one of the following species: deodar cedar (*Cedrus deodora* [Roxb.] G. Don), camphor tree (*Cinnamomum camphora*), blue gum (*Eucalyptus globulus* Labill.), northern California black walnut (*Juglans hindsii* Jepson ex R.E. Smith), Monterey cypress (*Hesperocyparis macrocarpa* Hartweg), giant sequoia (*Sequoiadendron giganteum* [Lindley] J. Buchholz), coast redwood (*Sequoia sempervirens* [D. Don] Endlicher), and California bay laurel (*Umbellularia californica* [Hooker & Arnott] Nuttall). These were the eight most frequent, large species in the CUF Inventory. This removed a total of 5995 tree records which represented about 0.09 % of inventory records. We calculated the relative abundance of individual trees in each of the six DBH size classes (0–15 cm, 16–30 cm, 31–45 cm, 46–60 cm, 61–75 cm, and 75 cm+) statewide and among climate zones and among the top ten most abundant species in California. We also calculated the relative abundance of trees in each of the five height classes (0–5 m, 6–10 m, 11–15 m, 16–20 m, and 20 m+) and in five foliage type categories (evergreen, deciduous, partly deciduous, coniferous, and palm) statewide and among climate zones.

2.3. Assessing diversity among California cities

Because the CUF Inventory only represents trees that have been inventoried, it does not contain all urban trees in an area; thus, we defined cities as being "well-inventoried" if they were represented by more than 20,000 tree records (n = 81 cities; Fig. 2A). This criterion ensures that cities are sufficiently sampled to accurately calculate the various diversity metrics of interest as some are sensitive to sampling effort (Chen et al., 2020; Jin and Yang, 2020). For each city, we determined the number of species, number of street trees, city area (km^2), city population (2020 census data), species per km^2 and street trees per person. We also calculated the relative abundance of the most common species, genus, and family. Finally, we calculated the Shannon Index (*H'*), species evenness (E_H), and the TD-50 index for each city.

We used city-based data to evaluate two potential predictors of species diversity as measured by the Shannon Index (*H'*): the TD-50 index and the relative abundance of the most common species. Kendal et al. (2014) previously demonstrated that the relative abundance of the most common species was a good predictor of *H'*, and although both the TD-50 index and the relative abundance of the most common species could be used as a more intuitive metrics of diversity than the Shannon Index, one of the goals of this study was to determine which might be a better predictor of *H'*. We compared the predictive capacities of these two metrics by constructing a linear regression model with each metric and *H'* using the *lm()* function in the statistical software R (R Core Team, 2020). All linear model assumptions were met.

We also used city-based data to evaluate the relationship between city area and species richness, species evenness (E_H), the Shannon Index (*H'*), and the TD-50 Index using the *lm()* function in R. To meet the assumptions of the linear model, we log-transformed city area.

3. Results

3.1. The California urban forest inventory

At the time of publication, the cleaned CUF Inventory available on the data portal contained 6,661,473 individual trees representing 497 species and 221 genera in 702 cities and 47 counties in California. The number of tree records per climate zone varied, ranging from 9435 in the Interior West to 2,458,564 in the Southern California Coast with every climate zone except Interior West having more than 50,000 records. Despite being the smallest zone by area, the Southern California Coast had the most tree records and the largest population (Table 1A; Fig. 2D.).

The portal offers tabular summaries and custom figures for various user-selected spatial extents (climate zone, county, city, or ZIP code) or taxonomic levels (family, genus, or species). Once the user applies their selected filters, the portal generates an interactive dot density map showing the spatial distribution of records where the dot color and size denote number of species and number of records, respectively, in each ZIP code. The portal also generates figures to summarize the relative abundance of each species, genus, family, and individual tree DBH measurements as well as the distribution of species' native ranges, foliage types, and water-use ratings (Fig. 1). Once generated, the portal allows users to download data summaries as CSVs.

3.2. Patterns of diversity and abundance

3.2.1. Statewide patterns of diversity and abundance

On a statewide scale, the top ten most common species (i.e., most abundant) ranged in abundance from 2.6 % to 6.3 %, and the cumulative abundance of the top ten species in California was 35.5 %. *Lagerstroemia* cultivated varieties (crape myrtles) were the most abundant species in California's urban forest followed by *Platanus* ×*hispanica* (London plane tree) Mill. ex Münchh., each comprising 6.3 % and 4.3 % of all inventory records, respectively (Fig. 3A, Table 2). Statewide, the Shannon

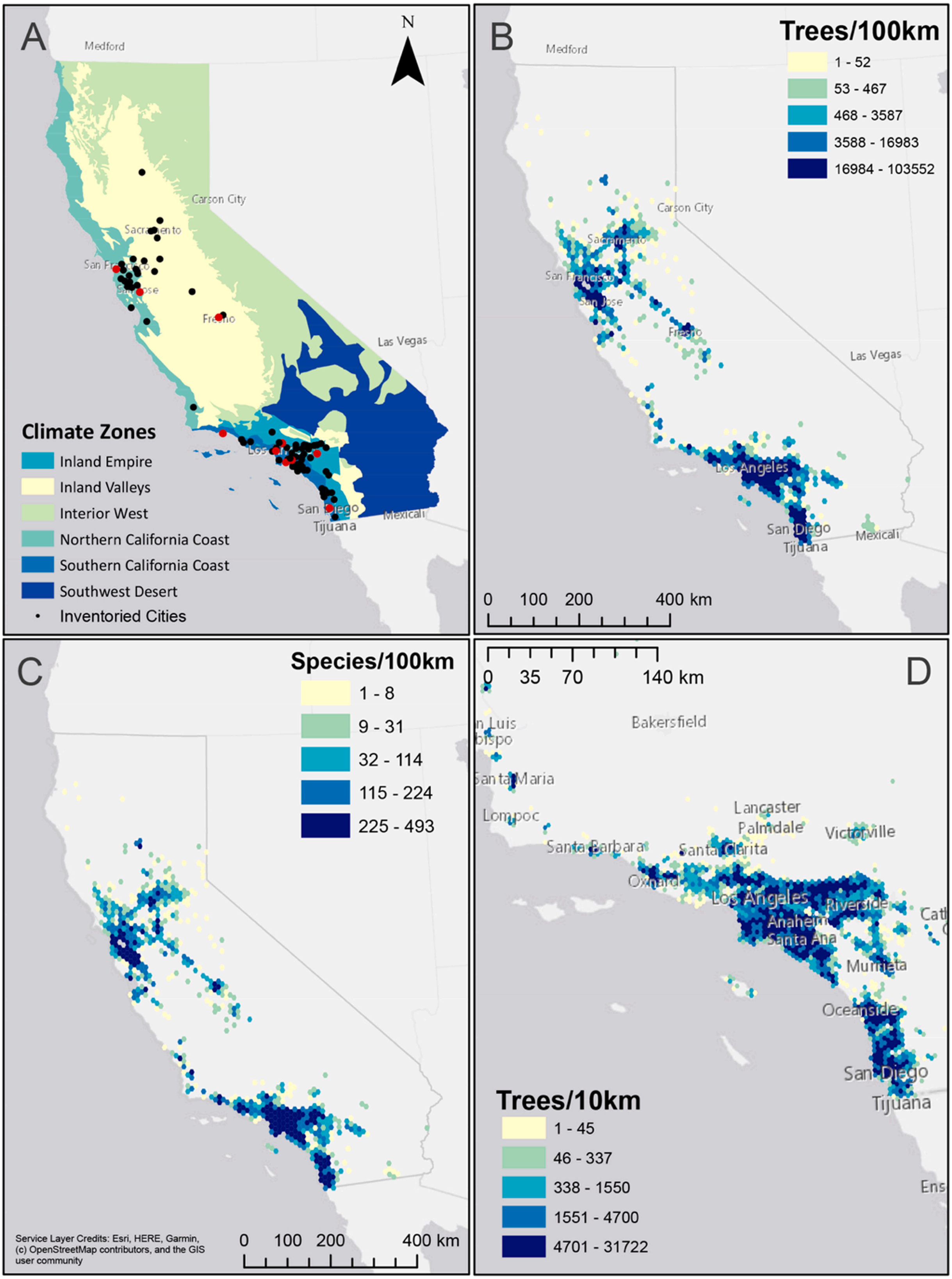

Fig. 2. Map displaying the California Urban Forest Inventory data in various ways. Panel A shows the boundaries of the six climate zones as well as the locations of the 83 well-inventoried cities (black points) and the top 10 most species-rich cities presented in Table 3 (red points). Panel B and C show the density of tree records and species, respectively. Panel D shows the density of tree records in Southern California.

Table 1
(A) Summary statistics statewide and among climate zones, and (B) relative abundance and identity of the most common species, genus, and family in each zone and statewide.

A.

Climate Zone	Number of Records	Zone Area (km^2)	Population (2020)	Number of Distinct Species	Number of Distinct Genera	Shannon Diversity Index (H')	Species Eveness (E_H)	TD-50 Index
Inland Empire	1,632,188	15,880.6	8416,313	475	211	4.30	0.70	14
Inland Valleys	1,081,748	142,156.3	9297,577	424	191	4.05	0.67	9
Interior West	9435	133,657.9	500,585	90	57	2.67	0.59	2
Northern California Coast	1,421,466	30,361.3	7732,571	470	206	4.48	0.73	16
Southern California Coast	2,458,564	9563.2	12,229,727	479	213	4.34	0.70	14
Southwest Desert	58,051	78,951.5	1361,450	215	124	3.68	0.69	8
California	6661,473	410,570.8	39,538,223	497	221	4.58	0.74	17

B

Climate Zone	**Most abundant species (relative abundance, %)**	**Most abundant genus (relative abudance, %)**	**Most abundant family (relative abundance, %)**
Inland Empire	*Lagerstroemia* cv. (8.9 %)	*Lagerstroemia* cv. (8.9 %)	Arecaceae (10.8 %)
Inland Valleys	*Pistacia chinensis* (8.8 %)	*Quercus* (11.9 %)	Fagaceae (12 %)
Interior West	*Pinus jeffreyi* (31.8 %)	*Pinus* (47.4 %)	Pinaceae (48.5 %)
Northern California Coast	*Platanus* ×*hispanica* (4.9 %)	*Platanus* (8.1 %)	Rosaceae (12.9 %)
Southern California Coast	*Syagrus romanzoffiana* (5.6 %)	*Pinus* (7.7 %)	Myrtaceae (15.8 %)
Southwest Desert	*Washingtonia robusta* (15.5 %)	*Washingtonia* (28.6 %)	Arecaceae (35.9 %)
California	*Lagerstroemia* cv. (6 %)	*Platanus* (6.6 %)	Myrtaceae (9.8 %)

Diversity Index and species evenness were 4.58 and 0.74, respectively. The TD-50 index was 17 species, indicating that 17 species accounted for the top 50 % abundance of urban trees in California (Table 1A).

The most abundant genus was *Platanus* L., which comprised 6.6 % of tree records, followed by *Quercus* L. (6.5 % of trees), and *Lagerstroemia* cv. (6.0 % of trees; Fig. 3B). The most abundant family in California's urban forest was the Myrtaceae (9.8 % of trees), followed by the Arecaceae (9.0 % of trees), and the Rosaceae (7.2 % of trees; Fig. 3C). The most abundant genera and families in California's urban forest were not the most speciose (i.e., not represented by the greatest number of distinct species). The most speciose genus in California was *Quercus* which was represented by a total of 25 distinct species, whereas *Platanus* species were the most abundant but were only represented by five species. The Fabaceae was the most speciose family in California, and was represented by 65 distinct species; however, individual trees in the Fabaceae family only accounted for 3.6 % of trees in California's urban forest and was not among the top 10 most abundant families.

Most urban trees planted in California were not native to the state of California but rather native to Asia (29 %), Australia (14 %), or Central and South America (13.3 %), cumulatively representing 56.2 % of trees in California. About 10 % of trees representing 36 species were native to California (Fig. 3D).

3.2.2. Diversity and abundance patterns among climate zones

Despite being the smallest zone by area, the Southern California Coast had the highest species richness (479 species) of all climate zones, with 96 % of the 497 distinct species in California growing in that zone. The Northern and Southern California Coast were the first and second most diverse climate zones, respectively, as measured by the Shannon Index (Northern California Coast: 4.48, Southern California Coast: 4.34, $\overline{x}$=3.92), by the TD-50 index (Northern California Coast: 16, Southern California Coast: 14; $\overline{x}$=10.5), and by species evenness or EH (Northern California Coast: 0.73, Southern California Coast: 0.7, $\overline{x}$=0.68; Table 1A). The most diverse climate zones tended to be those with large, densely populated urban areas. All zones with a population greater than 7 million people had Shannon Diversity indices greater than 4, a species evenness of greater than 0.65, and a TD-50 index of 9 or more species. (Table 1A).

All climate zones differed in their most abundant species, and no single species was shared in the top 10 most common species of all zones. The Inland Empire was the climate only zone in which the most abundant species was consistent with California statewide (*Lagerstroemia* varieties); however, *Lagerstroemia* cv. were the second or third most common species in the Inland Valleys and the Northern and Southern California Coast (Table 2). Palms were the first and second most the abundant species in both the Southern California Coast (queen palm, *Syagrus romanzoffiana* [Cham.] Glassman and *Washingtonia robusta* H. Wendland) and the Southwest Desert (fan palms, *Washingtonia* spp.). The Interior West was the only zone dominated by a coniferous species (Jeffrey pine, *Pinus jeffreyi* Greville & Balfour; Table 2). Cumulative abundance of the top ten most common species among all climate zones ranged from 39.2 % in the Southern California Coast to 80.3 % in the Southwest Desert (Table 2). Among climate zones, the most abundant genus ranged from 8.1 % (*Pinus* in the Southern California Coast) to 47.4 % (*Pinus* in the Interior West). The most abundant family ranged from 12 % (Fagaceae in the Inland Valleys) to 48.5 % (Pinaceae in the Interior West; Table 1B).

3.2.3. Diversity among well-inventoried cities

A total of 81 cities were considered well-inventoried and collectively represented 4,586,506 tree records (69 % of the CUF Inventory; Fig. 2A). These cities were highly urbanized areas and were home to 18,905,658 Californians (48 % of the state's population; Table S1). The number of street tree records per city ranged from 20,872–401,823 ($\overline{x}$=56,623

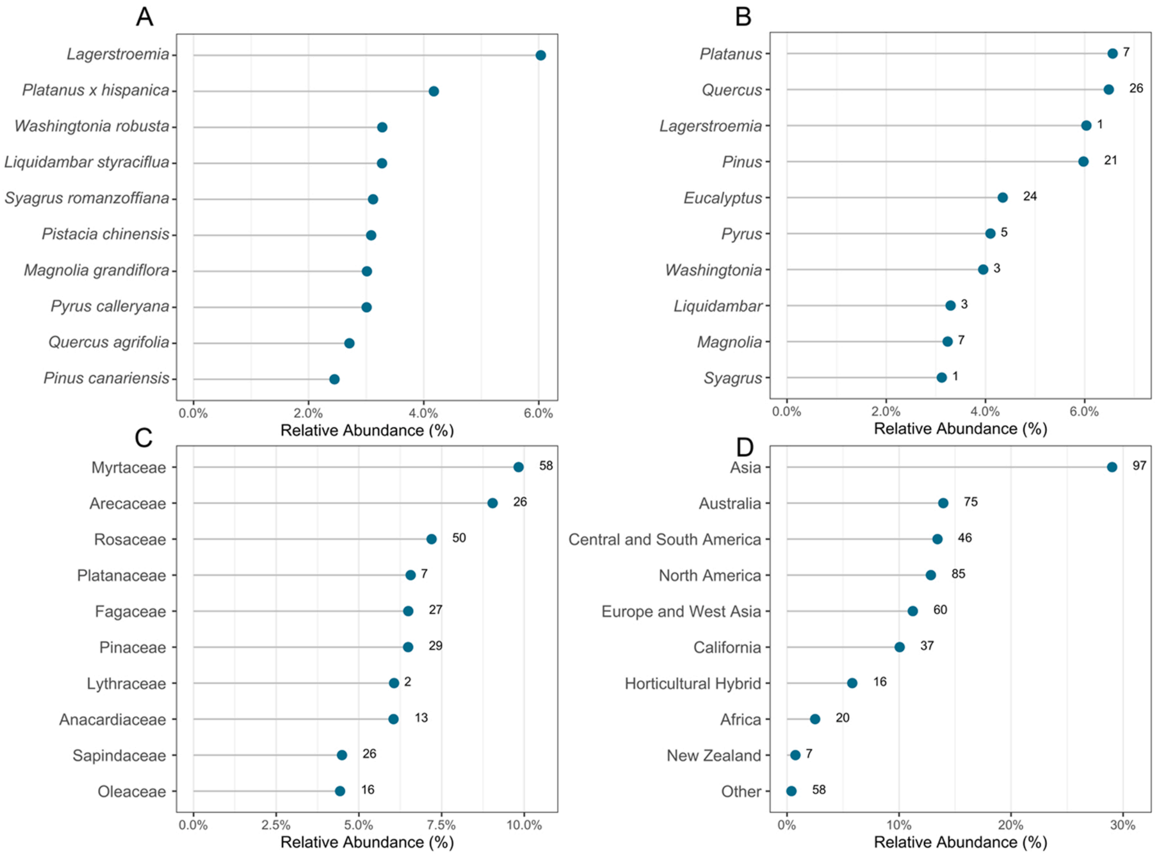

Fig. 3. Relative abundance of the top ten most common species (A), genera (B), families (C), and native ranges (D) of urban trees in California. Trees with a native range scored as "other" in panel D represent species with ranges broader than a single country or continent (e.g., pantropical). Numbers at the end of each line in B-D denote number of species in each group.

trees; SD=63,281 trees). Urban forest species diversity and richness varied markedly among these cities. The number of species present (i.e., species richness) ranged from 137 to 398 species ($\bar{x}$=234 species; SD=53 species), species evenness (E_H) ranged from 0.34 to 0.70 ($\bar{x}$=0.71; SD=0.03), the Shannon Index ranged from 3.31 to 4.41 ($\bar{x}$=3.89; SD=0.25), and the TD-50 Index ranged from 4 to 17 species ($\bar{x}$=9 species; SD=3 species; Fig. 4A-D, Table S1).

Relative abundances of various taxonomic groups also varied among cities. The relative abundance of the most common species ranged from 5.8 % to 21 % ($\bar{x}$=10.7 %, SD=3.1 %), the most common genus ranged from 5.9 % to 33 % ($\bar{x}$=13.2 %, SD=4.8 %), and the most common family ranged from 9.3 % to 39.5 % ($\bar{x}$=18 %, SD=5.4 %; Fig. 4E-G, Table S1). *Lagerstroemia* cv. was the most frequent most abundant species among cities; it was the most abundant species in 15 of the 81 cities. *Platanus* ×*hispanica* was the second most frequent most abundant species (12 cities). This is consistent with state-wide patterns of species abundance; *Lagerstroemia* cv. and *Platanus* ×*hispanica* were also the top two most abundant species in California's urban forest (Fig. 3A; Table 2).

Among well-inventoried cities, the number of street trees per person ranged from one tree per 12 people in Los Angeles to 3.2 trees per person in Laguna Woods, and the mean number of trees per person was 0.4 or about one tree for every two people among all cities (SD=0.35 trees/person). The density of species richness in well-inventoried cities (number of species per km^2) ranged from 29 species/km^2 in Laguna Woods to 0.33 species/km^2 in Los Angeles.

We present the top ten most species-rich cities (those with the greatest number of distinct species) in Table 3 (see Table S1 for all cities). Los Angeles was most species-rich city with an urban forest comprised of 398 distinct species, indicating that 80 % of all species in California's urban forest were grown in Los Angeles. It was also the largest city by area (1213 km^2). Although Los Angeles was the most species-rich city, it was not the most diverse city as measured by either the Shannon Index (highest *H'*: San Mateo and Santa Cruz at 4.41) or the TD-50 index (highest TD-50 index: San Mateo and Ventura with 17 species each; Table 3, Table S1).

The TD-50 Index and relative abundance of the most common species both predict diversity as measured by the Shannon Index; however, the TD-50 Index is a stronger predictor of the Shannon Index than the relative abundance of the most common species. Among cities, the TD-50 Index explained about 83 % of the variance in Shannon Index ($F_{1,79}$ =398, $P < 0.001$, R^2 =0.83; Fig. 5) while the relative abundance of the most common species explained 38 % of the variance in the Shannon Index ($F_{1,79}$ =50.6, $P < 0.001$, R^2 =0.38).

Species richness and species evenness (E_H) were both associated with city area. Larger cities had higher species richness ($F_{1,79}$ =27.2, $P < 0.0001$, R^2 =0.25) and lower species evenness ($F_{1,79}$ =9.1, $P = 0.0035$, R^2 =0.092; Fig. 6). Neither the Shannon Index ($F_{1,79}$ =0.12, $P = 0.72$, R2 =−0.01) nor the TD-50 Index ($F_{1,79}$ =0.15, $P = 0.69$, R2 =−0.01) were associated with city area (Fig. 6).

3.3. Patterns of urban forest structure statewide and among climate zones

3.3.1. Trunk size (DBH)

About 6.4 million of the 6.6 million records in the CUF Inventory were measured for DBH (97% of all records) and were included as part of the trunk size analyses presented here. On a statewide scale, the most abundant sized trunk was 16–30 cm in DBH with 32.5 % of urban trees in this range. Collectively, 57 % of trees in California were less than 30 cm and 91 % were less than 60 cm in DBH (Fig. 7A). The most abundant trunk size varied among climate zones and not all zones were

Table 2
Relative abundance of the top 10 most common among climate zones and statewide.

Inland Empire	Relative Abundance (%)	Northern California Coast	Relative Abundance (%)
Lagerstroemia cv.	9.10 %	*Platanus ×hispanica*	7.04 %
Washingtonia robusta	4.46 %	*Lagerstroemia* cv.	5.08 %
Platanus ×hispanica	4.16 %	*Pyrus calleryana*	4.92 %
Liquidambar styraciflua	3.89 %	*Liquidambar styraciflua*	4.50 %
Syagrus romanzoffiana	3.39 %	*Sequoia sempervirens*	4.49 %
Quercus agrifolia	3.21 %	*Pistacia chinensis*	4.25 %
Pinus canariensis	3.19 %	*Quercus agrifolia*	4.21 %
Magnolia grandiflora	3.10 %	*Magnolia grandiflora*	3.15 %
Cinnamomum camphora	2.78 %	*Prunus cerasifera*	2.78 %
Schinus molle	2.36 %	*Fraxinus angustifolia*	1.62 %
Total	39.6 %	**Total**	42.4 %
Inland Valleys	**Relative Abundance (%)**	**Southern California Coast**	**Relative Abundance (%)**
Pistacia chinensis	9.14 %	*Syagrus romanzoffiana*	5.81 %
Lagerstroemia cv.	8.41 %	*Washingtonia robusta*	4.98 %
Platanus ×hispanica	7.72 %	*Lagerstroemia* cv.	4.21 %
Pyrus calleryana	5.79 %	*Lophostemon confertus*	4.13 %
Sequoia sempervirens	5.51 %	*Magnolia grandiflora*	3.78 %
Quercus lobata	4.03 %	*Pinus canariensis*	3.65 %
Celtis sinensis	2.65 %	*Cupaniopsis anacardioides*	3.59 %
Liquidambar styraciflua	2.63 %	*Jacaranda mimosifolia*	3.58 %
Acer rubrum	2.30 %	*Liquidambar styraciflua*	2.88 %
Zelkova serrata	2.26 %	Platanus *×hispanica*	2.58 %
Total	50.4 %	**Total**	39.2 %
Interior West	**Relative Abundance (%)**	**Southwest Desert**	**Relative Abundance (%)**
Pinus jeffreyi	33.17 %	*Washingtonia robusta*	16.23 %
Calocedrus decurrens	12.90 %	*Washingtonia filifera*	12.58 %
Pinus eldarica	7.98 %	*Phoenix dactylifera*	5.14 %
Fraxinus velutina	7.41 %	*Parkinsonia florida*	3.31 %
Quercus kelloggii	4.37 %	*Pinus eldarica*	3.05 %
Quercus chrysolepis	4.06 %	*Olea europaea*	2.86 %
Pinus ponderosa	3.52 %	*Searsia lancea*	2.84 %
Hesperocyparis arizonica	2.66 %	*Brachychiton populneus*	2.73 %
Populus trichocarpa	2.35 %	*Fraxinus velutina*	2.39 %
Platanus ×hispanica	1.82 %	*Lagerstroemia cv.*	2.37 %
Total	80.3 %	**Total**	53.5 %
California	**Relative Abundance (%)**		
Lagerstroemia cv.	6.27 %		
Platanus ×hispanica	4.34 %		
Washingtonia robusta	3.41 %		
Liquidambar styraciflua	3.40 %		
Syagrus romanzoffiana	3.24 %		
Pistacia chinensis	3.21 %		
Magnolia grandiflora	3.13 %		
Pyrus calleryana	3.13 %		
Quercus agrifolia	2.82 %		
Pinus canariensis	2.55 %		
Total	35.5 %		

consistent with statewide patterns (Fig. 7A). For example, trees in the Southwest Desert and Interior West were generally larger than trees in California collectively. The most abundant trunk size in both these zones was 31–45 cm. Trees in the Inland Valleys were generally smaller than trees statewide where the most abundant trunk size was 0–15 cm.

We also assessed trunk size distribution among the top 10 most common species statewide which collectively represented 2.2 million tree records (33 % of the CUF Inventory). None of the ten species were dominated by trees larger than 45 cm in DBH, but the distribution of trunk sizes among the remaining DBH classes varied among species (Fig. 8). For example, *Lagerstroemia* cv. were dominated by small trees with 60 % of trees 0–15 cm in DBH (230,191 trees total). In contrast, both *Liquidambar styraciflua* L. (American sweet gum) and *Pinus canariensis* C. Sm. ex D.C. (Canary Island pine) were dominated by moderately sized trees (31–45 cm DBH; *L. styraciflua*: 30 %; *P. canariensis*: 30 %), with few young, small trees present in the urban forest (0–15 cm DBH: *L. styraciflua*: 12 %, *P. canariensis*: 8%). Southern magnolias (*Magnolia grandiflora* L.) were present at relatively equal abundances among 0–15 (25 %), 16–30 (30 %), and 31–45 (28 %) cm DBH classes (Fig. 8).

3.3.2. Tree height

About 4.9 million of the 6.6 million records in the CUF Inventory were measured for height (74 % of all records). Statewide, most trees were between 6 and 10 m tall (40 %), and 87 % were under 15 m (Fig. 7B). Among all climate zones, the distribution of tree heights was similar to statewide patterns. All zones were dominated by trees between 6 and 10 m tall. The Interior West had the highest proportion of trees over 15 m, with 32% of trees in the 16–20 m bin (Fig. 7B).

3.3.3. Foliage type

About 6.4 million records in the CUF Inventory were scored for foliage type (97 % of all records), representing 497 species. The remaining records were those trees only identified to genus where species in the genus exhibit different foliage types (e.g., *Quercus*). Statewide, California was dominated by deciduous and evergreen trees, collectively representing 71 % of trees (deciduous: 39 %, evergreen: 33 %; Fig. 9). Of the remaining trees, about 11 % were conifers, 9 % were palms, and 8 % were considered partly deciduous.

The most abundant foliage type varied among climate zones with only the Inland Empire exhibiting a similar distribution of foliage types as California. The Inland Valleys and Northern California Coast were dominated by deciduous species (71 % and 50 %, respectively), while the Southern California Coast was dominated by evergreen species (41 %). The Interior West was dominated by conifers (64 %), and the Southwest Desert was dominated by palms (38 %; Fig. 9).

4. Discussion

At the time this study was conducted, the CUF Inventory contained about 6.6 million tree records and was the most comprehensive inventory of California's urban trees. About 5.12 million of these records were obtained from complete municipal inventories and represent public street trees. In 2016, McPherson et al. (2016a) estimated that

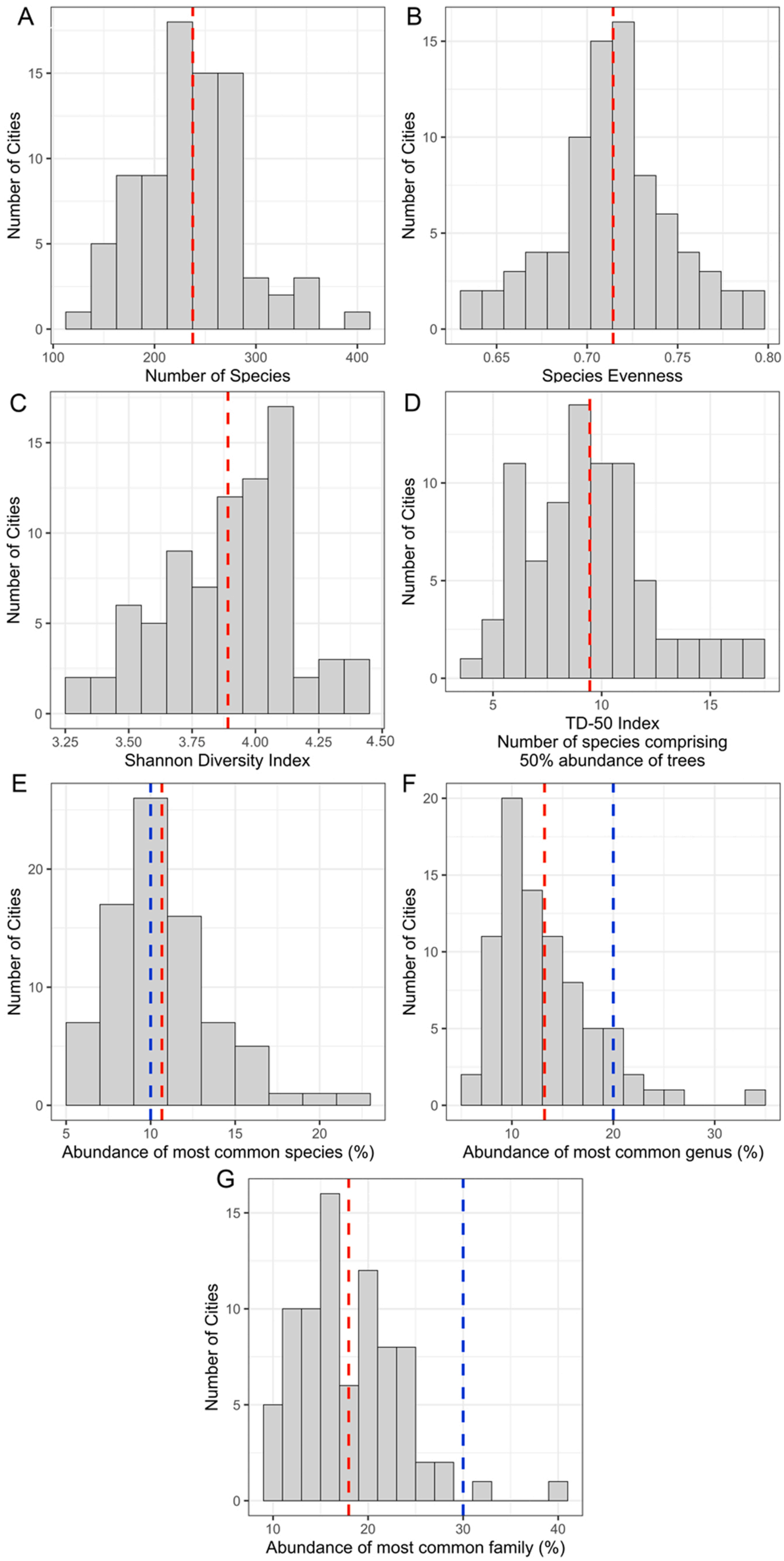

Fig. 4. Histograms showing the distribution among well-inventoried cities (those with >20,000 tree records; n = 81) of (A) species richness or the total number of distinct species present, (B) species evenness or E_H, (C) the Shannon Diversity Index or *H'*, (D) the top diversity index or TD-50 index, which represents the number of species accounting for the top 50 % of trees in a given city's urban forest, and (E) the relative abundance of the most common species, (F) genus, and (G) family in each city. The vertical red dotted line denotes the average among all well-inventoried cities. The vertical dotted blue lines on panels E-G denote the 10–20–30 diversity benchmark for the relative abundance of the most common species, genus, and family, respectively.

Table 3

Summary statistics (A) and relative abundances of the most common species, genera, and families (B) for the top 10 most species-rich cities of the well-inventoried cities identified in this study. See Table S1 for summary statistics for all 83 well-inventoried cities.

A.

City	Number of species	TD-50 Index	Shannon Index	Species Evenness (E_H)	Number of street tree records	Area (km^2)	Population (2020 Census)	Species per km^2	Street trees per person
Los Angeles	398	11	4.20	0.70	309,150	1214	3,910,013	0.33	0.08
San Jose	361	11	4.10	0.70	325,539	459	1024,933	0.79	0.32
Riverside	359	11	4.08	0.69	139,000	210	306,828	1.71	0.45
San Diego	356	10	3.92	0.67	401,823	843	1,415,547	0.42	0.28
Oakland	337	10	4.23	0.73	71,730	145	440,637	2.33	0.16
San Francisco	336	11	4.11	0.71	128,204	121	873,965	2.77	0.15
Long Beach	306	10	4.00	0.70	120,263	131	471,343	2.33	0.26
Santa Barbara	305	10	4.09	0.72	33,984	51	100,838	6.04	0.34
Anaheim	302	12	4.09	0.72	70,521	130	339,327	2.32	0.21
Irvine	286	11	4.06	0.72	90,116	170	318,414	1.68	0.28

B.

City	**Most abundant species (relative abundance, %)**	**Most abundant genus (relative abudance, %)**	**Most abundant family (relative abundance, %)**
Los Angeles	*Washingtonia robusta* (7.7 %)	*Washingtonia* (8.4 %)	Arecaceae (16.31 %)
San Jose	*Pistacia chinensis* (8.4 %)	Platanus (10.04 %)	Rosaceae (11.62 %)
Riverside	*Washingtonia robusta* (12.6 %)	*Washingtonia* (17.26 %)	Arecaceae (24.94 %)
San Diego	*Syagrus romanzoffiana* (11.3 %)	*Eucalyptus* (14.06 %)	Myrtaceae (23.89 %)
Oakland	*Platanus* ×*hispanica* (9.1 %)	*Platanus* (10.37 %)	Rosaceae (16.82 %)
San Francisco	*Platanus* ×*hispanica* (6.7 %)	*Prunus* (8.4 %)	Myrtaceae (24.76 %)
Long Beach	*Jacaranda mimosifolia* (6.4 %)	*Washingtonia* (6.37 %)	Arecaceae (15.96 %)
Santa Barbara	*Quercus agrifolia* (12.6 %)	*Quercus* (14.55 %)	Arecaceae (21.43 %)
Anaheim	*Magnolia grandiflora* (7.5%)	*Pinus* (8.33 %)	Arecaceae (15.29 %)
Irvine	*Pinus halepensis* (7.3%)	*Pinus* (22.22 %)	Pinaceae (22.3 %)

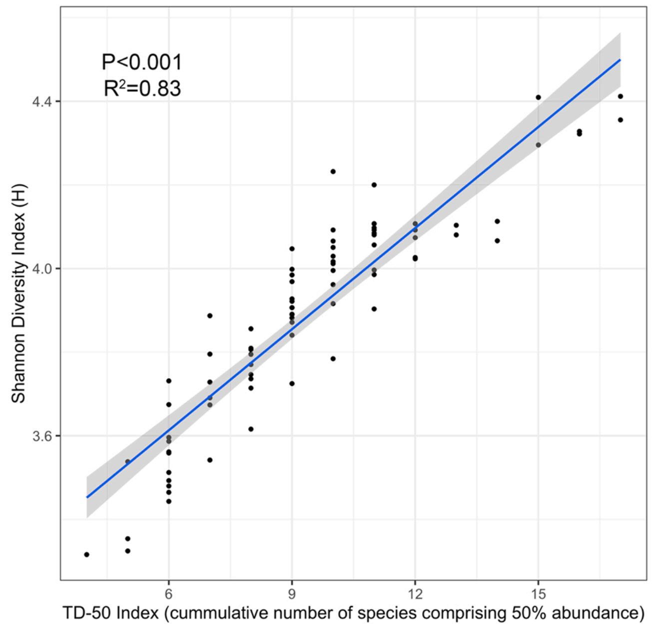

Fig. 5. The correlation between the Shannon Diversity Index and the top diversity index or TD-50 index, which represents the number of species accounting for the top 50 % of trees in a given city's urban forest. Each point represents the diversity values for a well-inventoried city (n = 81).

there are about 9.1 million street trees in California, and assuming that this estimate is still valid, the CUF Inventory conservatively represented 56 % of street trees in California. Among well-inventoried cities (those with >20,000 tree records), we estimated that the mean number of street trees per capita was about 0.4 or about one tree for every two people, which is higher than previous statewide estimates of 0.26 (one tree for every four people) reported by McPherson et al. (2016a).

Here, we discuss several of the many ways in which the CUF Inventory will benefit a wide range of users. To demonstrate how these data can be used to learn more about California's urban forest, we present the most comprehensive assessment of the diversity and structure of California's street trees at state, regional, and local scales and discuss a new metric of urban forest diversity, the TD-50 index. We also present the first assessment of the relationships between species diversity and city area in California, which helps us better understand the drivers of species diversity at local scales.

4.1. The California urban forest inventory will benefit many users

Urban forests provide a multitude of benefits to surrounding communities, and data obtained from the CUF Inventory can be used as inputs to software programs capable of quantifying the monetary value of such benefits (McPherson et al., 2017, 2016a). The software program i-Tree Eco is one such tool. To evaluate benefits, i-Tree requires at minimum the species identity and DBH of all trees in the given area of interest, both of which can be obtained from the CUF Inventory. By combining inventory data with air pollution and meteorological data, i-Tree can model and quantify the many benefits provided by urban forests to communities, including carbon storage and sequestration, avoided stormwater runoff, oxygen production, and pollution removal (i-Tree Eco User's Manual v6.0, 2021). Evaluating the net benefits of urban forests can help municipalities or non-profits advocate for maintaining urban forests and can also help urban and community forestry programs justify investment or improvement costs (Song et al., 2018).

The CUF Inventory can also be used to evaluate urban forest vulnerability to pests or other stressors. Species differ with respect to their pest or disease vulnerability; thus, planting species with different susceptibilities could mitigate the potential loss of trees to any one threat. Knowing the relative abundance of species in an urban forest will help managers make more informed species selections for new plantings. Tree selection guides like SelecTree (https://selectree.calpoly.edu) provide species-specific pest and disease vulnerability information that can help managers make such decisions. Managers can also use data from the CUF Inventory as inputs to i-Tree Eco which uses species identity to assess forest susceptibility to 36 pests and diseases and calculates the potential damage and value lost from outbreaks. The CUF Inventory combined with tools like SelecTree and i-Tree eco provide managers with powerful tools to set species planting priorities and foster resiliency in their urban forests.

Finally, the CUF Inventory can be used to address important socioeconomic or sociodemographic questions. For example, diversity or structural characteristics of urban forests affect health outcomes (Giacinto et al., 2021) and may affect other benefits such as urban cooling. The CUF Inventory can also be used to assess whether benefits from urban forest diversity are equitably distributed among groups. Previous work has found that canopy cover and tree density, and thus the benefits they provide, are inequitably distributed among socioeconomic groups (Avolio et al., 2015; Clarke et al., 2013; Mills et al., 2016). We also know that ecosystem services provided to communities by urban forests, as well as a forest's vulnerability to disturbance (e.g., pest outbreaks), depends in part on species composition and diversity (McPherson et al., 2016a; Rahman et al., 2019; Wang et al., 2021). If urban forest composition or diversity varies among socioeconomic groups, then these groups may receive different benefits from urban forests as well as different risk of tree loss to pest outbreaks (Avolio et al., 2015; Clarke et al., 2013). The CUF Inventory provides the data necessary to evaluate differences in urban forest species diversity and composition among communities at both large and small spatial scales, which can inform policy and management decisions.

4.2. California's urban forest is highly diverse, especially in coastal urbanized areas

California's urban forests are highly diverse relative to other urban forests nationally and globally. At all spatial scales, California's urban forest had greater diversity as measured by the Shannon Index (statewide: 4.58; climate zones: 3.92; well-inventoried cities: 3.89) than the value reported for the United States on a national scale (3.125) by Ma et al. (2020). Diversity in California was also higher relative to the Western United States region (3.533), which Ma et al. (2020) reported as the most diverse region in the United States. In another study, a global analysis of urban forests among 108 cities showed that their Shannon Indices ranged from about 1.5–4.3 (Kendal et al., 2014). In California, Shannon Indices among well-inventoried cities ranged from 3.31 to 4.41, while Shannon Indices among the top 10 most species rich cities were above 3.92. These results demonstrate that urban forests in California, especially among coastal cities, are among the most diverse in the world. Moreover, diversity in California's urban forests is comparable to some of the world's most diverse and productive natural ecosystems, tropical rainforests, which exhibit Shannon Indices from 4 up to 5.5 (Djuikouo et al., 2010; Féret and Asner, 2014; Ifo et al., 2016; Laidlaw et al., 2007).

At a broad spatial scale, differences in urban tree species compositions are driven in part by differences in climate, predominately by the capacity for species to withstand freezing temperatures (Jenerette et al., 2016; Kendal et al., 2012; Nitoslawski et al., 2016). Mild climates in California, especially coastally, allow for the inclusion of frost-tender species in the urban tree palette, which boosts species diversity in these areas (Clarke et al., 2013). Moreover, California is a relatively large state that spans close to ten degrees of latitude and thus spans many temperature regimes. Different temperature regimes favor different species, which also contributes to high levels of diversity in California. For example, deciduous species were favored in the Inland Valleys where seasonal temperatures fluctuations are more pronounced

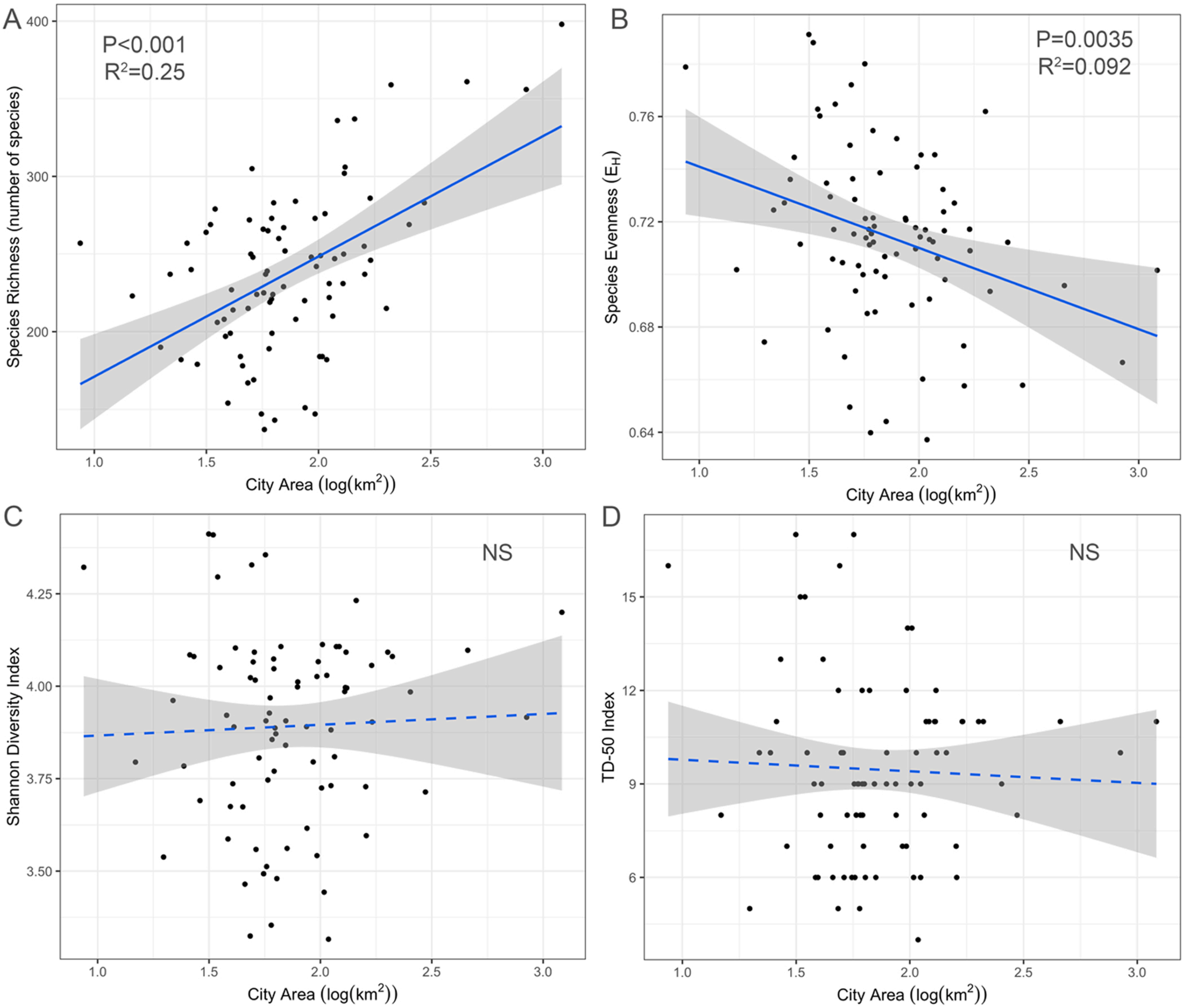

Fig. 6. Correlations between city area (km^2) and various diversity metrics including (A) species richness or the number of species, (B) species evenness or EH, (C) Shannon Diversity Index or H', and the TD-50 Index. City area was log-transformed to meet linear regression model assumptions.

while evergreen species were favored in the Southern California Coast where fluctuations in temperature are milder (Fig. 9). However, climate change, particularly changes to precipitation regimes and its cascading effects on municipal water budgets, may make high water-use species an impractical choice for new plantings (Pincetl et al., 2013; Roloff et al., 2009). More work is needed to identify climate-ready tree species so that diversity, and the benefits of urban forests, can be maintained as the climate changes in California (McPherson et al., 2018; Ordóñez and Duinker, 2014).

In California cities, species richness and evenness were dependent on spatial extent (Fig. 6A-B). Cities with the highest species richness and lowest species evenness also tended to be cities that were large by area. This also helps explain why even though Los Angeles, the largest city by area in our dataset, had the highest species richness, it did not have the highest species diversity as measured by the Shannon Index because species evenness in Los Angeles was low relative to other cities (Fig. 6, Table 3). The positive relationship between species richness and city area demonstrated in this study is similar to the species-area relationship (SAR), one of the most widely demonstrated qualitative patterns in natural ecosystems (Lomolino, 2000), whereby larger areas tend to have higher species richness. In this current study, we show that this pattern also occurs in urban forests, a mostly human-constructed ecosystem (Fig. 6A). Our results suggest that at smaller spatial scales (i.e., among cities), area is one driver of species richness in urban landscapes, a pattern which has also been demonstrated in urban parks (Chang et al., 2021). In addition to area, Avolio et al. (2015) found that socio-economic status of community residents may also drive species richness at smaller spatial scales in California. In this study, we found that species evenness was also dependent on city area (Fig. 6B); however, the Shannon and TD-50 Index were independent of area, making these better metrics to compare species diversity across varying spatial extents.

The stability of urban forests is linked to species diversity. High species diversity lowers the risk of tree mortality and urban canopy loss from any one threat such as storms, pests, or climate change (Huff et al., 2020; Nitschke et al., 2017; Paquette et al., 2021; Raupp et al., 2006). Resistance or resilience of urban forests to change plays an important role in maintaining the benefits of trees to surrounding communities (Nitoslawski et al., 2016; Paquette et al., 2021). Ideally, urban forests contain many different species, and their abundances are relatively evenly distributed with no one species dominating the population. Although the Shannon Index provides a single, comprehensive metric

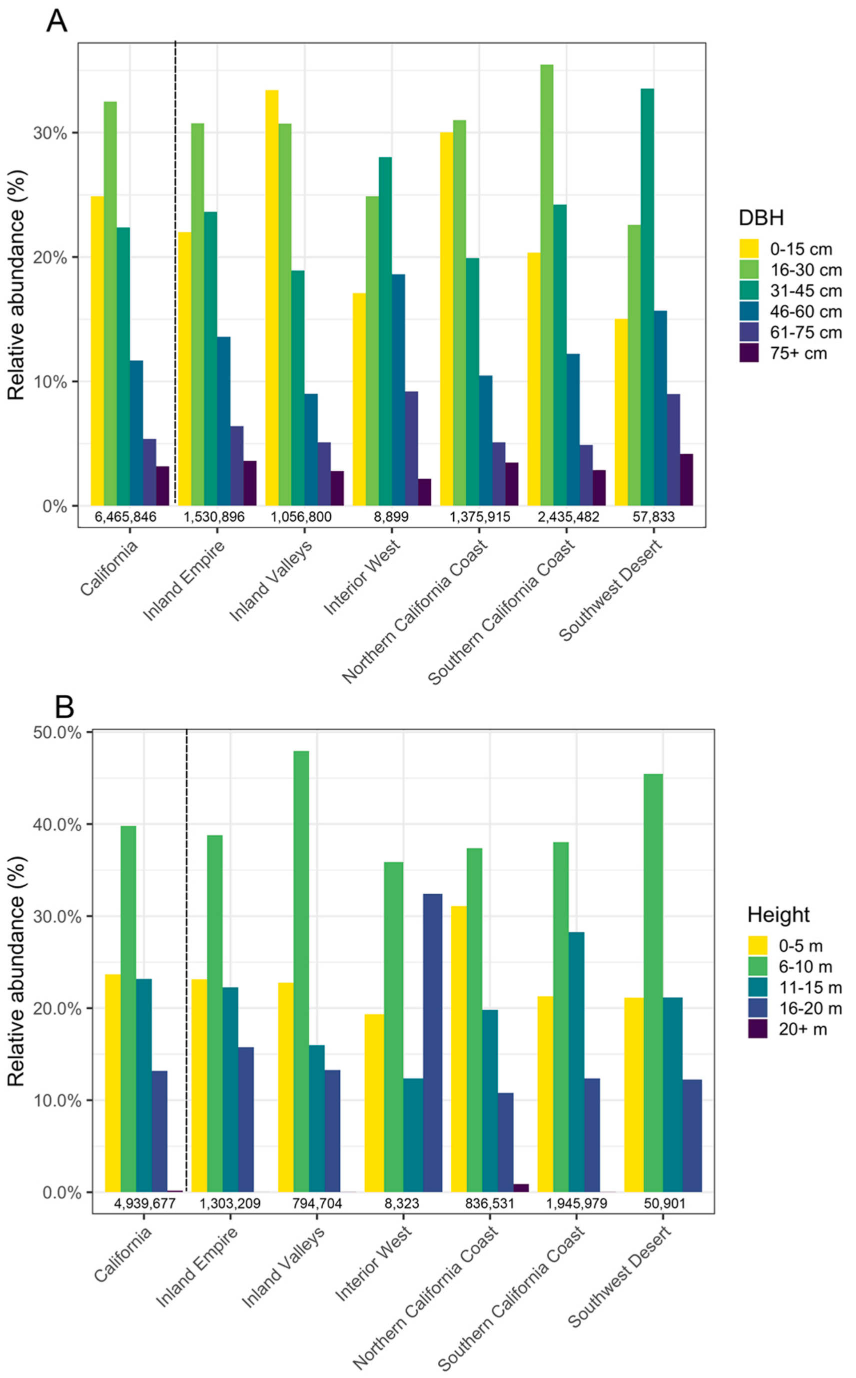

Fig. 7. Distribution of street tree DBHs (A) and heights (B) statewide and among all climate zones. Numbers below each cluster of bars represent the number of trees scored for each trait in that climate zone. The vertical dashed line separates statewide and climate zone results.

with to measure and compare diversity, it is not a practical metric for setting diversity goals or benchmarks in urban forest management plans. Thus, various diversity targets and guidelines have been introduced with the aim of helping urban forest managers maintain species diversity. Santamour's 10–20–30 rule is a widely accepted set of benchmarks; however, there is little evidence that many cities meet these targets simultaneously (Kendal et al., 2014).

Urban forests in California exceed Santamour's benchmarks more commonly at smaller rather than larger spatial scales. Statewide, the relative abundance of the most common species, genus, and families were lower than the benchmarks set by Santamour (Fig. 3A–C). Only two of the six climate zones exceeded the benchmarks (Interior West and Southwest Desert); however, these zones also had the fewest tree records, thus these patterns could change as sampling increases in these areas (Table 1B). Among well-inventoried cities, no city exceeded all three of Santamour's proposed benchmarks simultaneously; however, 39 cities exceeded at least one benchmark (Fig. 4E–G, Table S1). In Poway, for example, the relative abundance of trees in the genus Eucalyptus and in the family Myrtaceae each exceed 30 %, but the most common species (*Eucalyptus rudis* Endl.), did not exceed 10 %. In a study of 667 cities in the United States, Ma et al. (2020) similarly found that diversity benchmarks were more commonly exceeded at regional and local scales rather than at the national scale. These results together suggest that urban forests tend to be more heterogenous at large scales

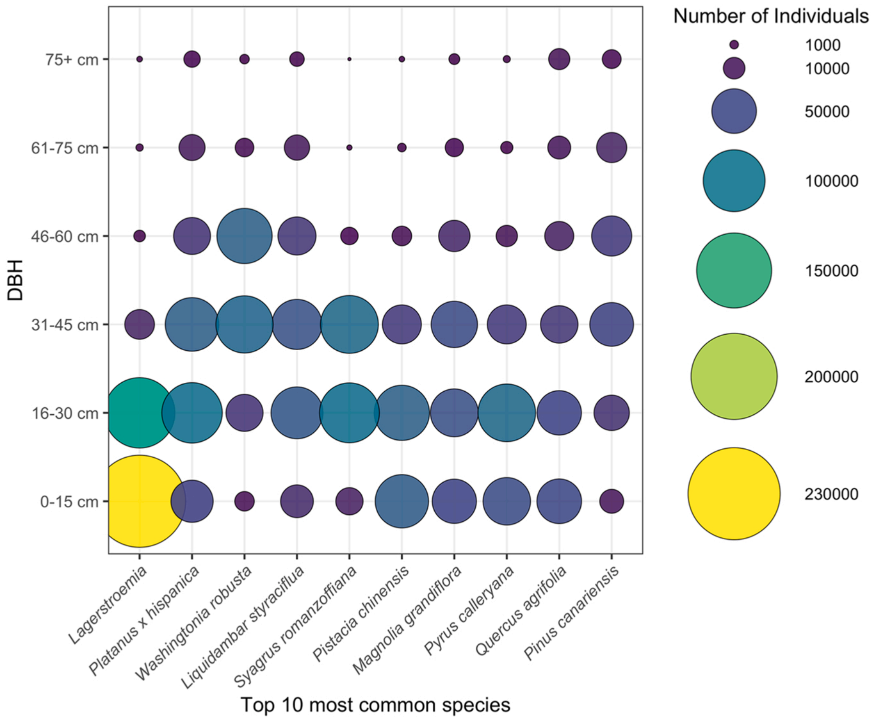

Fig. 8. The DBH distribution among individuals of the top 10 most common species statewide.

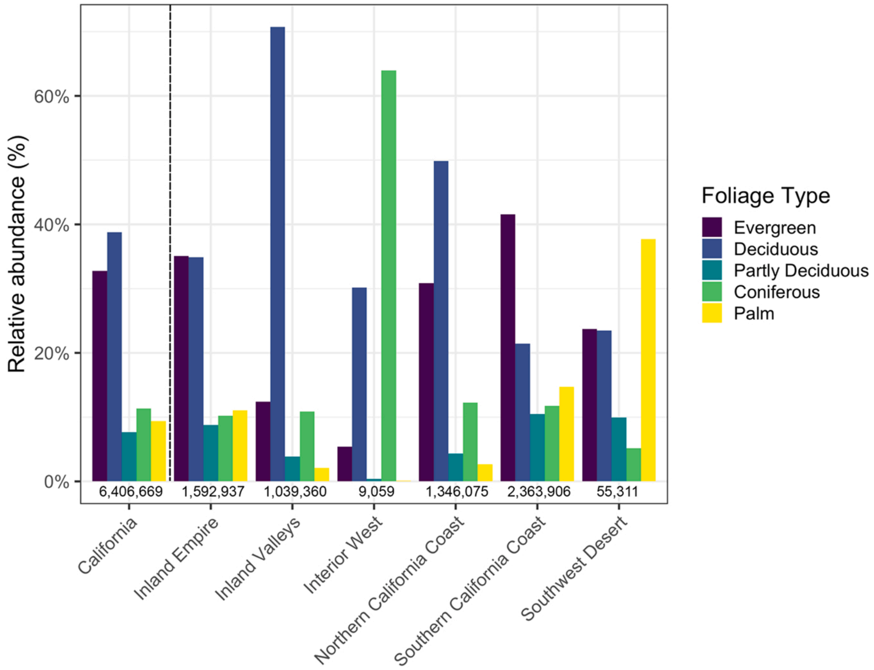

Fig. 9. The distribution of foliage types statewide and among climate zones. Numbers below each cluster of bars represent the number of trees scored for each trait in that climate zone. The vertical dashed line separates statewide and climate zone results.

than small scales, and highlight the need to study species diversity and abundance at multiple spatial scales to assess variation in forest resiliency across such scales.

4.3. *The TD-50 index is a good measure of species diversity in municipal urban forests*

Assessing species diversity is an important component of managing resilient urban forests. Current guidelines, such as 10/20/30 rule, are simple to calculate and intuitive to understand, but are only moderately good proxies for more comprehensive measures of diversity, such as the Shannon Index, that incorporate measures of species richness and evenness. For example, Kendal et al. (2014) explored species diversity and relative abundance in 151 urban forest inventories from cities around the world and found that the relative abundance of the most common species was moderately associated with the Shannon Index (R^2

=0.66). In their study, they found that the more abundant the most common species was in an urban forest, the lower the Shannon Diversity Index of that forest. In the current study, we demonstrated that the number of species comprising the top 50 % of trees in an urban forest (i.e., the TD-50 index) was a better predictor of species diversity as measured by the Shannon Index than the relative abundance of the most common species. This is likely because the TD-50 index better incorporates species evenness (i.e., the relative abundance of several species in contrast to just a single species).

The TD-50 index meets all criteria we set for developing a new metric of urban forest diversity. The index is strongly associated with the Shannon Index (Fig. 5), it is easy to calculate, and it has straightforward units (number of species) that make it simple metric to interpret and to use to compare diversity between forests or points in time. Finally, among cities, the TD-50 index was not associated with city area, meaning that it can be used to compare diversity across varying spatial extents (Fig. 6D). Municipalities and urban forest managers have reported that maintaining or increasing diversity is a core objective in managing urban forests (Thompson and Reimer, 2018), and the TD-50 index is a good metric to help attain those targets. For example, municipalities could include increasing the TD-50 index as an explicit goal in management plans. A good goal would be to aim for a TD-50 index between 8 and 10 species comprising 50 % of trees in an urban forest, which would correspond to relatively high diversity and even distribution of the most abundant species. One strategy to increase the TD-50 index in California cities would be to expand the approved species list as previous work has found a strong association between the number of species in an urban forest and the number species on the approved planting list (Muller and Bornstein, 2010). Muller and Bornstein (2010) found that cities with larger approved planting lists tended to have more species in their urban forests, and targeted planting of suitable but underrepresented species would increase the TD-50 index of urban forests. Urban forest managers would of course need to consider whether or not these species are in the same genus as closely related species can share susceptibility to pests (Lynch et al., 2021; Raupp et al., 2006). The TD-50 index could also be integrated into inventory management software which would allow mangers to easily track changes in diversity.

The mean TD-50 index was lower among cities than statewide, again suggesting that diversity is higher at larger scales relative to smaller scales in California (Fig. 4D, Table 1A). Muller and Bornstein (2010), detected similar patterns of species diversity using municipal inventories from 18 cities in California. They found that 9 species accounted for 50 % of trees among half of these cities. In an early assessment of street tree diversity in California, Lesser (1996) found that 15 species accounted for the top 50 % of trees in Southern California, which is similar to the statewide TD-50 index value of 17 species estimated in the current study. The similarities between our current study and previous studies discussed here suggest that the TD-50 index is a robust metric of diversity across various sampling efforts. Even with much smaller sample of municipal inventories, both Muller and Bornstein (2010) and Lesser (1996) were able to detect similar patterns of relative species abundance as those we detected here with a larger sample representing 81 cities and 4.6 million tree records.

4.4. Small trees and palms were common in California's urban forest

The extent to which urban trees can provide ecosystem benefits to surrounding communities depends, in part, on their size and functional traits like foliage type (Livesley et al., 2016; Nytch et al., 2019; Sjöman et al., 2016). In the current study, we found that crape myrtles (*Lagerstroemia* varieties and hybrids) were the most abundant species in California's urban forest, comprising 6.3 % of street trees (Fig. 2A, Table 2). This result is not surprising considering that *Lagerstroemia* cv. were cited as the most commonly planted street trees by 300 municipal urban and community forestry programs in California surveyed in 2017 (Thompson and Reimer, 2018). Among these municipalities, urban forestry managers report a lack of public growing space as the main factor influencing species selection for new street tree plantings, which drives dependence on small-statured trees such as *Lagerstroemia* cv. Moreover, because of these space limitations, urban forestry programs also report planting fewer large shade trees than in previous decades, which in the future may limit the cooling benefits and urban heat island mitigation provided by large-canopied trees to surrounding communities (Ballinas and Barradas, 2016; Hsieh et al., 2018).

In contrast to the current study, the most recent previous study of street tree diversity in California by McPherson et al. (2016a) found that the London plane tree (*Platanus* ×*hispanica*) was the most abundant species, comprising 10.5 % of trees in a dataset representing street tree inventories from 49 cities in California (929,823 street trees total). In our study, we found that the London plane tree was the second most abundant species, comprising 4.3 % of street trees in California. Despite differing slightly in the identity of the ten most abundant species in California, both studies found that the top ten species collectively accounted for similar proportions of street trees statewide (current study: 37.1 %; McPherson et al., 2016a: 46.2 %).

Differences in estimates of species' abundances between McPherson et al. (2016a) and the current study likely reflects underlying differences between the datasets used to conduct the analyses rather than changes in species' abundances through time (i.e., from 2016 to 2021). Our 6.6 million tree inventory captures a larger sample of street trees across more cities in California.

The current study and previous work (McPherson et al., 2017, 2016a) found that palms (species in the Arecaceae family) were a relatively common component of California's urban forest at multiple spatial scales. Collectively, these studies found that the palms were among the most abundant genera (*Phoenix* L., *Syagrus,* and *Washingtonia*) and species (*Washingtonia robusta* and *Syagrus romanzoffiana*) statewide (Fig. 3B-C). The palm family (Arecaceae) was also the 2nd most abundant and the 6th most speciose family in California, comprising 9 % of all trees and 27 species in the urban forest (Figs. 3 and 8, Table 2). These studies also found that palms were dominant in the Southwest Desert climate zone (Fig. 9). The palm family as also the most abundant family in 17 of the 81 well-inventoried cities. Despite their relative abundance in California, palms remain a controversial component of the urban forest as they store less carbon and provide less shade relative to their soft- or hardwood counterparts (Aguaron and McPherson, 2012; Horn et al., 2015); however, palms do contribute rainfall interception (they are in-leaf during California's winter rainy season rather than deciduous) and to the aesthetic value and sense of place in Southern California (Farmer, 2013; Pataki et al., 2013; Roman et al., 2018).

4.5. California is dominated by street trees less than 45 centimeters in diameter and between 6 and 10 m tall

Although the DBH bins used in this study did not perfectly align with those proposed by Richards (1983), we were able to interpret the DBH patterns considering his recommendations. Statewide, the distribution of small trees matched Richard's recommendations fairly well, but large, mature trees were slightly underrepresented. About 57 % of trees were under 30 cm in DBH; however, only about 8 % of trees were mature, large trees (60 cm +) compared to Richard's recommendation of 10 %. The proportion of small trees in California will likely increase in the future because of the increasing dependence on small-statured trees (e.g., *Lagerstroemia* cv.) due to concerns regarding limited planting space (Thompson and Reimer, 2018). *Lagerstroemia* cv.*,* the most abundant street trees in California's urban forest, are rarely capable achieving DBHs greater than 40 cm. In the current study, we found that 99 % of all *Lagerstroemia* individuals were less than 45 cm in DBH (Fig. 8). The abundance of small trees is not unique to urban forests in California. Among eight cities in the Southern United States, Blood et al. (2016) found that urban forests and parks were both dominated by small trees under 15 cm with few large trees present in the population. Similarly, urban forests in Lhasa, China and Lisbon, Portugal were dominated by young, small trees with 40 % of trees under 15 cm in diameter (Soares et al., 2011; Yang et al., 2012).

Size distribution of individuals within a single species can lend insight into historical planting patterns. In California, populations of both *Liquidambar styraciflua* and *Pinus canariensis* are dominated by relatively mature trees (31–45 cm DBH) with far fewer young individuals in the population (Fig. 8). This pattern suggests that these species are no longer being planted regularly as young trees. This may indicate fading popularity of these species as street trees or a trend toward planting smaller-statured street trees. Large shade trees have been declining in popularity as species' selection is constrained by overhead and planting space, which makes planting large trees challenging (Thompson and Reimer, 2018).

Large-statured trees provide many benefits to surrounding communities that will be vital as the climate continues to change; however, they are challenging and expensive to maintain. In California specifically, the mean municipal urban forestry budget has been declining since 1988 (Thompson and Reimer, 2018), and maintenance costs account for a large portion of these budgets. For example, pruning costs for established trees was the largest cost category in urban forestry budgets in Modesto and Santa Monica, California, accounting for half of total expenditures (McPherson and Simpson, 2002). This makes it challenging for urban foresters to balance the increased benefits of planting large-statured shade trees with the increased costs of maintaining them in the future. Declining budgets combined with reduced planting space has driven urban foresters to shift planting preferences from large-statured shade trees to reliance on small-statured trees such as *Lagerstroemia* cv. – a pattern which was reflected in the results presented in the current study. Ensuring funding through either general funds or public grant programs, such as CAL FIRE or U.S. Forest Service grants, will be vital to maintaining a functioning and resilient urban forest so that they can continue to provide many benefits to surrounding communities.

5. Conclusion

This study presents the most comprehensive database and analysis of California's urban forest to date. Through the analyses of these data, we found that California's urban forests were highly diverse and among the most diverse urban forests globally, especially in coastal, urbanized areas. We developed a new and intuitive metric of species diversity, the TD-50 index, which will be a useful metric for setting and attaining diversity targets. We also found that small-statured trees, such as *Lagerstroemia* cv., were abundant in California, a pattern which likely reflects declining planting space and budgets for urban forestry programs. The data contained in the California Urban Forest Inventory are vital to assessing the structure, diversity, and value of urban forests at multiple spatial scales in California, which in turn can be used to make recommendations for improvement as well as advocate for the benefits of urban forests. This aggregated inventory of one of the world's largest urban forests, its presentation to the public, and the information that can be gained from its analysis can be a model for urban forest management worldwide.

CRediT authorship contribution statement

Natalie L.R. Love: Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Viet Nguyen:** Methodology, Data curation, Software. **Camille Pawlak:** Methodology, Data curation, Visualization. **Andrew Pineda:** Resources, Data curation. **Jeff L. Reimer:** Conceptualization, Software, Resources. **Jennifer M. Yost:** Conceptualization, Methodology, Resources, Supervision, Project administration, Funding acquisition. **Jonathan D. Ventura:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **G. Andrew Fricker:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **Jacqueline M. Doremus:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **Taylor Crow:** Conceptualization, Methodology, Formal analysis. **Matt K. Ritter:** Conceptualization, Methodology, Resources, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

For CUF Inventory data inquiries at spatial scales finer than ZIP code, please contact the corresponding author, Natalie L.R. Love, at nllove@calpoly.edu.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127679.

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