Title (Data Paper)

The Global Urban Tree Inventory: A database of the diverse tree flora that inhabits the world's cities

Running Title: GUTI: A global database of urban tree species

Keywords: biodiversity, conservation, horticulture, urbanisation, urban forests, species richness

Abstract

Motivation

The Global Urban Tree Inventory (GUTI) is a compilation of datasets on tree species found in cities and towns throughout the world. GUTI data can be used to address a diverse range of theoretical and applied investigations related to species' biogeography and distribution, ecological and physiological tolerance to climatic, biophysical and environmental parameters, as well as plant conservation and invasion.

Main types of variables contained

GUTI contains current taxonomical data for 4,734 tree species planted in urban areas, their conservation status (*IUCN's Red List of Threatened Species*), and invasion potential (*Global Register of Introduced and Invasive Species*).

Spatial location and grain

473 urban areas in 73 countries across 5 continents. The urban areas spanned 21 of 29 Koppen-Geiger climatic zones, and all 19 FAO global ecofloristic zones.

Time period and grain

GUTI is based on the most recent collections of urban tree inventories and species lists compiled by local authorities or reported in the scientific literature. Most data have been collected or updated since 2010.

Major taxa and level of measurement

4,734 tree species (~8% of the global known arboreal flora). One tenth of these tree species face conservation risk in the wild, whereas 327 species are known to have invasion potential.

Software format

.xls file

1 | INTRODUCTION

Since the settlement of towns and cities, humans have planted and retained trees to beautify urban landscapes and provide essential resources such as food and timber. Urban areas now cover approximately 2% of the Earth's land surface and continue to rapidly expand (Grimm et al., 2008). Extensive trade and economic development have greatly facilitated the movement of plant species between countries and continents. Numerous tree species now thrive in urban areas far distant from their wild populations, climates and habitats of origin (Hulme, 2009; Van der Veken, Hermy, Vellend, Knapen, & Verheyen, 2008). This suggests that, notwithstanding some human intervention and management, many species might have climatic and realised niches much larger than previously thought (Kendal et al., 2018). This is important, as more precise estimates of species' niches could significantly affect projections of species' tolerance and adaptability to climate and environmental change. More comprehensive data on species can ultimately lead to improved species selection for urban forestry and greening applications (Watkins, Cameron, Sjöman, & Hitchmough, 2020).

Despite the value of including the urban occurrences of tree species in macroecological and biogeographic studies, no standardised global dataset is currently available. Here, we present the *Global Urban Tree Inventory* (GUTI), a database of the diverse planted tree flora inhabiting the world's cities and towns (Fig. 1). GUTI contains accepted taxonomic names, conservation status and invasion potential data for 4,734 tree species found in 473 urban areas globally. GUTI can be used to address a wide range of theoretical and applied questions related, for instance, to i) tree species distribution in climatic, environmental and/or geographic space, ii) variation and distribution of ecological, horticultural and aesthetic characteristics of tree species, iii) tolerance to climatic, biophysical and environmental parameters and stresses, iv) assessments of tree species conservation status and invasion potential, v) horticultural selection of climate-ready tree species for urban applications.

2 | METHODS

2.1 | Data acquisition and compilation

GUTI was compiled through an extensive search of published and unpublished tree inventories, online data portals and tree species lists contained in studies published in the scientific literature. Urban area refers to built-up areas of differing size and population, such as cities and towns. As the definition of "city", "town" and other urban areas varies across different countries, we generally refer to urban areas without making any distinction among different urban types. Urban tree data refer to tree species planted in the public realm (i.e., streetscapes, urban parks, public gardens, cemeteries, school grounds, etc.). Tree species planted on private land (e.g., residential gardens) or in remnant vegetation were not included in the present study due to the poor sampling of the tree flora therein.

First, we conducted an online search for urban tree inventories published in data portals and Geographic Information System (GIS) repositories through specific web queries translated from English in the respective native language/s (e.g., English: "*urban*" AND "*tree*" AND "*inventory*"; Spanish: "*arbolado*" AND "*urbano*", access dates Nov 2017 – Nov 2018). Where not immediately available for download, tree data were obtained by contacting the

respective data owner/s where possible (e.g., council departments in charge of urban tree maintenance, city GIS departments, etc.). Several municipalities provided raw tree inventory data under non-disclosure data sharing agreements to protect the location of trees of particular historical or heritage value, as well as rare species or species of botanical significance (data guardian: lead author). Urban tree inventories were initially processed in ArcGIS Desktop 10.5 (ESRI, Redlands, USA) and re-projected in EPSG:4326-WGS84.

Second, we obtained data from unpublished urban tree inventories by contacting professional networks and professional societies of urban arborists, urban environmental managers, private contractors, companies and non-government organizations involved in urban greening and urban forestry globally (e.g., *Trees for the Cities*; *World Forum on Urban Forests*). Urban tree inventories are routinely collected and maintained by professional arborists and botanists with detailed horticultural knowledge of local tree species, hybrids and varieties cultivated and planted at a particular location. In this way, we assumed tree species identification, where available, to be reasonably accurate. A total of 334 urban tree inventories were collected globally (Supporting Information, Appendix 1 Fig S1.1; Appendix 3.1).

Once reasonable efforts to find urban tree inventories were exhausted, after one year of data collection (~1000 hours), we further surveyed the scientific literature containing urban tree species lists and published in English via *Web of Science* (i.e., "*urban*" AND "*tree*" AND "*species*" AND "country/city", accessed Nov 2018 - July 2019). During this search, we found several relevant publications in a country's native language containing urban tree species lists, which were included as part of this study. This allowed us to compile a further 139 urban tree species lists (Supporting Information, Appendix 3.2). Despite not containing the georeferenced positions of tree stems, these tree species lists allowed us to add species occurrence records for a considerable number of urban areas globally. This was particularly evident for urban areas in emerging and developing countries where resources to create georeferenced urban tree inventories are generally unavailable. For lists where tree stems were not georeferenced, we obtained geographic coordinates for either the specific location of the inventory (such as an urban park or garden) or, if this information was unavailable, the town hall or city centre.

Overall, tree species records were obtained for 473 urban areas in 73 countries located in all continents except Antarctica (Fig. 2). Urban areas occur in 21 out of 29 Koppen-Geiger climatic zones (46 urban areas in tropical climates (A); 49 in dry climates (B); 275 in temperate climates (C); 101 in continental climates (D); and 2 in polar climates (E)) (Peel, Finlayson, & McMahon, 2007). Urban areas investigated are located in all 19 FAO global ecofloristic zones (Ruesch & Gibbs, 2008).

2.2 | Tree record consolidation

A total of 12,929,959 raw "unclean" species records were collected from 473 urban areas. Data sources had disparate formats and structures, hence we performed an initial consolidation and harmonization of data manually as follows, as this process could not be automated.

First, a total of 35,141 unique species binomials (or common names where available) were extracted and manually checked by a single expert (AO). Second, this procedure allowed us to consolidate records and pre-process taxonomic information as follows: i) attribute the same species binomial to entries that had misspelled or incomplete but discernible species binomials, ii) remove author citations (where present) before further taxonomical validation (see section below), iii) attribute common names to species binomials, where possible (e.g., Chinkapin oak was attributed to *Quercus muehlenbergii*), iv) attribute cultivars, hybrids and subspecies to the relative species where possible (e.g., *Abies concolor 'Lowiana'* was coded as *Abies concolor* for further taxonomic validation, see below), and v) attribute non-available values (NAs) to records with no discernible species information (e.g., *Quercus sp.*). Ultimately, the data cleaning procedure allowed us to reduce the number of names by ~75% and decrease the number of unique names from 35,141 to 8,844 for further synonym reduction, life form and taxonomic validation.

2.3 | Life form and taxonomic validation

Because some of the 8,844 unique name entries belonged to species with growth forms other than trees (e.g., small shrubs), we cross-checked all name entries against the *GlobalTreeSearch* (GTS) database (version 1.2, DOI: 10.13140/RG.2.2.20454.11847). This database contains a list of 60,096 tree species currently recognized worldwide (Beech, Rivers, Oldfield, & Smith, 2017) and is available at https://tools.bgci.org/global_tree_search.php (accessed on 23.08.2018).

Taxonomic checks were performed by using the library *Taxonstand* in R version 3.4.1 (R Core Team 2017) as it is indexed to *The Plant List* (TPL) for its taxonomy backbone (http://www.theplantlist.org/). The taxonomy of the GTS database was initially checked against TPL to i) allow a common taxonomical benchmark to validate the taxonomy of the GUTI database, and ii) exclude species from GUTI that were not indicated as having a defined tree life form as recorded in the GTS database. The 8,844 unique species names from GUTI were also checked against TPL to attribute the most current and valid species binomial, hybridization status and author citation to each unique name entry (e.g., *Abelia koreana* was attributed to *Abelia biflora* Turcz.). The TPL-corrected GUTI species binomials were further intersected with the TPL-corrected GTS binomials to exclude species having life forms other than trees. Finally, the taxonomically-validated binomials for 4,734 tree species were re-attributed to each of the respective GUTI raw records (Supporting Information, Appendix 3.3).

A further taxonomic validation was performed on the 4,734 species binomials and their families by using the function *gnr_resolve* in the library *taxize* in order to calculate a matching score among taxonomical database listing each taxa (Supporting Information, Appendix 3.4). Tree species included in GUTI have a binomial name with broad taxonomic consensus (> 0.98%). Species authorities and infraspecific rank information has been omitted and this may introduce some uncertainty about taxonomic patterns.

2.4 | Global urban tree species occurrence, conservation and threat status

An occurrence matrix was produced by calculating whether each of the 4,734 tree species occurred in each of the 473 urban areas (1=presence; 0=absence). Species occurrence is defined as either at least one tree stem recorded in a tree inventory or as a record entry from a published tree species list. The number of urban areas hosting each tree species was summarized based on each species' occurrence records, totaling 43,560 occurrences (Supporting Information, Appendix 3.5).

Information on plant families was also obtained from TPL via the library *Taxonstand* in R version 3.4.1 (R Core Team 2017). Conservation status for 1,643 tree species (Supporting Information, Appendix 3.6) was obtained from the *International Union for Conservation of Nature*'s (IUCN) *Red List of Threatened Species* (Version 2017-3, http://www.iucnredlist.org, accessed on 15.07.2019).

The countries where recorded tree species are considered invasive or as having invasion potential (Supporting Information, Appendix 3.7) were obtained from the *Global Register of Introduced and Invasive Species* (GRIIS, Pagad, Genovesi, Carnevali, Schigel, and McGeoch (2018), http://www.griis.org, accessed on 15.07.2019). Information on native or exotic status at a location was not included due to the large number of taxa in GUTI and uncertainties over species' distributions.

2.5 | Tree flora sample completeness and bias

Estimates of statistical sample completeness and extrapolation of global tree species richness beyond the urban areas sampled were performed using *Hill numbers* (q = 0) implemented with the *iNEXT* library in R version 3.4.1 (Hsieh, Ma, & Chao, 2016; R Core Team, 2017). Extrapolations were performed by using 9,999 bootstrap interactions with a 250,000 units sample size and 0.95% confidence interval (Supporting Information, Appendix 2 Fig S2.1).

Representativeness of the sampled cities in global climate space was assessed by modelling the distribution of GUTI urban areas in relation to the percent area occupied by cities and towns among Koppen climate groups (i.e., A, B, C, D, E). Urban areas refer to the global urban footprint (Esch et al., 2018, GUF year 2015) provided by The German Aerospace Center (DLR, https://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-9628/16557_read-40454/, obtained on 04.04.2020.

2.6 | Data availability, access and use guidelines

GUTI is released under a *Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC)*. The current version (1.0) of the database is released in the Supplementary Information of this manuscript as well as published in an online permanent repository at: 10.6084/m9.figshare.12062634. New versions of the GUTI database will be created and released periodically as new urban tree species datasets become available globally and they will be made available via the online permanent repository. The Authors welcome data users to freely use the GUTI database non-commercially. As updates and studies derived from GUTI are ongoing, it is suggested that users contact the Authors to scope synergies, collaborations and avoid duplication of research efforts.

3 | DESCRIPTION OF DATA

The Global Urban Tree Inventory (GUTI) includes data for 4,734 tree species, representing 8% of all known tree species (60,096 species according to the *Global Tree Search* database, Beech et al. (2017)). Taxonomically, at least 68% of plant families that contain trees (i.e., 175 of 257 families), and 29% of known tree genera (1,272 of 4,335 genera), are represented in urban areas. Four families contribute 30% of tree species richness in the urban areas investigated (*Leguminosae* (518 spp.), *Myrtaceae* (394 spp.), *Arecaceae* (254 spp.) and *Rosaceae* (243 spp.)), although the majority of plant families identified are represented by less than 10 species (Supporting Information, Appendix 3.2).

All known species within seven plant families are planted within urban areas, however these families contain only one or two species (i.e., *Cercidiphyllaceae, Eupteleaceae, Strelitziaceae, Trochodendraceae, Eucommiaceae, Ginkgoaceae*, and *Sciadopityaceae*). Some larger families are also well-represented in urban areas, including *Pinaceae* (161 species representing 72% of species in this family), *Cupressaceae* (80 spp. or 59%), *Araucariaceae* (18 spp. or 49%) and *Betulaceae* (68 spp. or 43%). In contrast, the hyper-speciose *Rubiaceae* family (4719 total tree spp.) is represented by only 78 species.

While 241 genera have all their respective species planted in urban areas, approximately half of the genera recorded are represented by only a single species (675 genera). Many tree species planted in urban areas are drawn from a small selection of species-rich genera, including *Eucalyptus* (214 spp.), *Quercus* (114 spp.), *Ficus* (92 spp.), *Acacia* (74 spp.), *Pinus* (74 spp.), *Acer* (66 spp.), *Prunus* (57 spp.), *Sorbus* (54 spp.), *Magnolia* (48 spp.), *Salix* (45 spp.) and *Syzygium* (43 spp.). In contrast, the genus *Eugenia* is substantially underrepresented, with less than 2% of its 885 known tree species planted in urban areas.

Overall, 79 tree species are planted in more than 100 of the 473 urban areas, and 381 species in more than 30 (Supporting Information, Appendix 3.5). The most common species include *Ginkgo biloba*, the sole representative of family *Ginkgoaceae* (217 urban areas), and several species of *Acer* (*A. negundo* (207), *A. platanoides* (204), *A. rubrum* (197), and *A. saccharinum* (178)). By comparison, about half of the tree species recorded (n = 2191) are listed in only a single urban area. These under-planted species are potential candidates for expanding the diversity of urban forests in coming decades.

Of the 4,734 tree species recorded in urban areas globally, 34.7% (1,643 species) have been assessed by *IUCN* in its *Red List of Threatened Species*. Four species of the genus *Brugmansia* (*B. arborea, B. sanguinea, B. suaveolens, B. versicolor*) are considered "*extinct in the wild*" alongside *Franklinia alatamaha* and *Sophora toromiro,* although all are planted in some urban areas (Supporting Information, Appendix 3.6). Sixty-two urban tree species are considered "*critically endangered*" (including 20 from *Dipterocarpaceae* and 14 from *Arecaceae*); two of these species – *Fraxinus americana* and *Fraxinus pennsylvanica* – are extremely popular for urban arboriculture and are cultivated in at least 147 and 165 urban areas, respectively. Of the 122 "*endangered*" tree species, 37% belong to the *Pinaceae*, *Dipterocarpaceae* and *Arecaceae* families. At lower conservation risk, 179 tree species are listed as "*vulnerable*", 68 as "*near threatened*", 135 as "*lower risk*", and 984 as species of "*least concern*" (Supporting Information, Appendix 3.6). Among the species assessed for

their source of threat, 203 are threatened because of their declining wild populations (criterion A), 134 because of their limited native range size and geographic fragmentation (criterion B), whilst 44 have small or very small wild populations (criteria C and D).

Around 8% of tree species recorded in urban areas (n = 372), belonging to 209 genera and 68 families, are listed in the *Global Register of Introduced and Invasive Species* (Pagad et al., 2018) as having potential for biological invasion in at least one country (Supporting Information, Appendix 3.7). Of these, 21 species have been recorded as having invasion potential in 10 or more countries. Among these species, eight have been propagated and planted in more than 50 urban areas globally (*Acer negundo* = 209, *Ailanthus altissima* = 161, *Melia azedarach* = 147, *Casuarina equisetifolia* = 72, *Psidium guajava* = 63, *Acacia melanoxylon* = 56, *Casuarina cunninghamiana* = 56, and *Leucaena leucocephala* = 55). Perhaps not surprisingly, many tree species used in horticulture can be invasive as they are often selected for their general tolerance and fast growth rate, a common attribute of successful invaders (Leishman, Cooke, & Richardson, 2014).

Despite our statistical sample having a very high coverage (0.95 in a 0-1 range, Supporting Information, Appendix 2 Fig S2.1), the number of species recorded in the 473 urban areas included in this study is a conservative estimate of global urban tree species richness. Indeed, using *iNEXT's* asymptotic estimator (Hsieh et al., 2016), an extrapolation of species richness from our dataset estimates that 8,532 species ± 230 (s.e.m.) may be planted in the world's urban areas (Supporting Information, Appendix 2 Fig S2.1). This suggests that urban areas may contain up to ~14% of the known tree flora. Many of the tree species extrapolated to occur are likely to be present in only a single or a few urban areas globally, as our inventory records a high percentage of singletons (46%) and doubletons (13%). Further, the urban tree inventories and species lists we collated reported trees planted only on public land, not private land, urban reserves and remnants, and botanic gardens – the inclusion of trees from these additional areas will likely increase estimates of urban tree species richness (Bush et al., 2018; Ossola and Hopton, 2018; Threlfall et al., 2016). Nevertheless, it is clear that, over the last few centuries, humans have sustained or created a diverse tree flora in the world's urban areas (Gaertner et al., 2017).

Our analysis of the representativeness of the urban areas included in GUTI suggests that urban areas in continental climates, and particularly in Eastern Europe, might be slightly under-represented as compared to urban areas in temperate climates (Fig. 2). Despite this, the number of urban areas in GUTI had a significant linear relationship ($R^2 = 0.81$) with the percent of global urban footprint contained in each Koppen climate group, thus suggesting that overall the urban areas sampled were evenly distributed in the global climatic space.

While urbanisation is often cited as a driving force for species' extinctions (McKinney, 2008), our dataset shows that the world's urban areas host a diverse tree flora. Incorporating our urban global tree data in future studies, together with existing datasets on species occurrences (e.g., Global Biodiversity Information Facility (GBIF), Atlas of Living Australia (ALA), iNaturalist, etc.) and their ecological and environmental traits (TRY Plant Trait Database, Botanical Information and Ecology Network (BIEN), etc.), will help to better understand species' tolerance and plasticity to climatic and environmental change and the potential of urban floras for plant conservation globally (Fig.3). Ultimately, GUTI can

provide an important benchmark to better quantify and optimise the ecosystem services that a diverse tree flora can provide to the world's cities.

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DATA ACCESSIBILITY STATEMENT

The authors declare that all the consolidated and validated data supporting the findings of this study are available within the paper as Supporting Information. The current version of the GUTI dataset (Appendix 3) is also stored on a permanent repository (10.6084/m9.figshare.12062634).

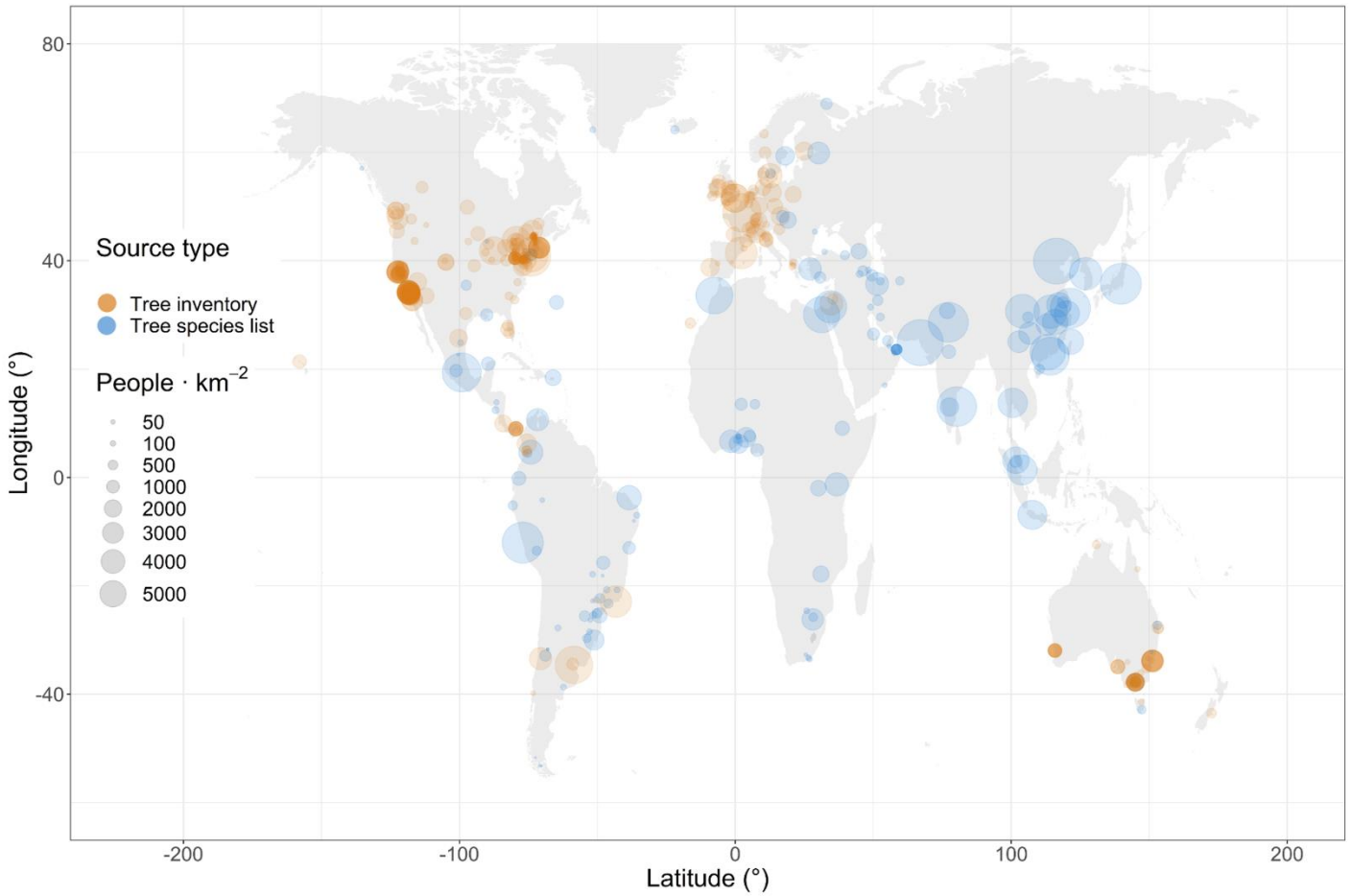


Fig. 1 | Location of urban areas investigated globally. Tree species occurrence data for 473 urban areas in 73 countries was obtained from municipal tree inventories (orange dots) and tree species lists (blue dots) published in the scientific literature. Human population densities (circle size) are those reported in the Gridded Population of the World vers. 4.11 dataset estimated for 2015 (gpw_v4_population_density_rev10_2015_15_min, Center for International Earth Science Information Network - CIESIN - Columbia University. 2018. Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H49C6VHW, accessed on 15.07.2019).

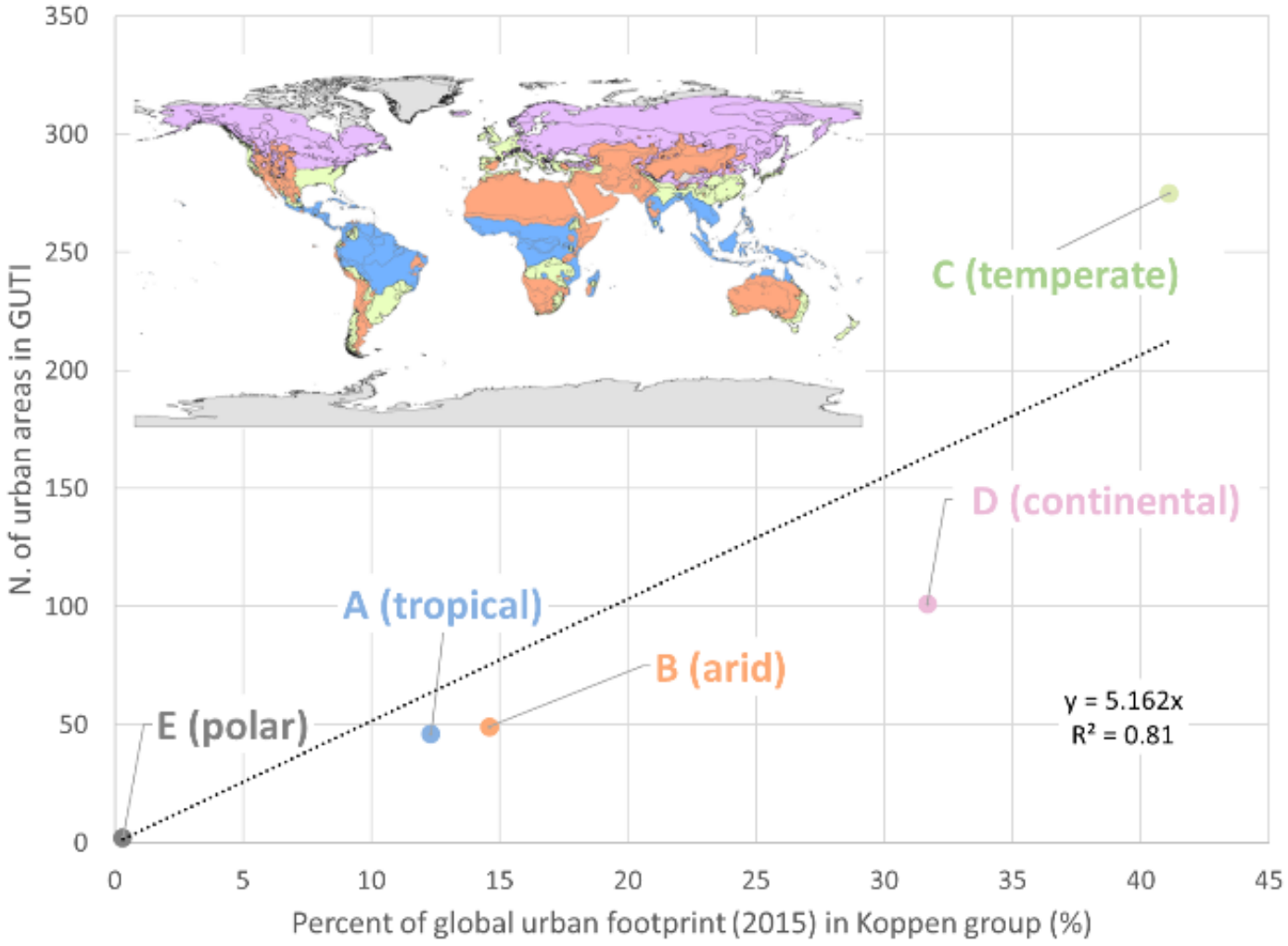
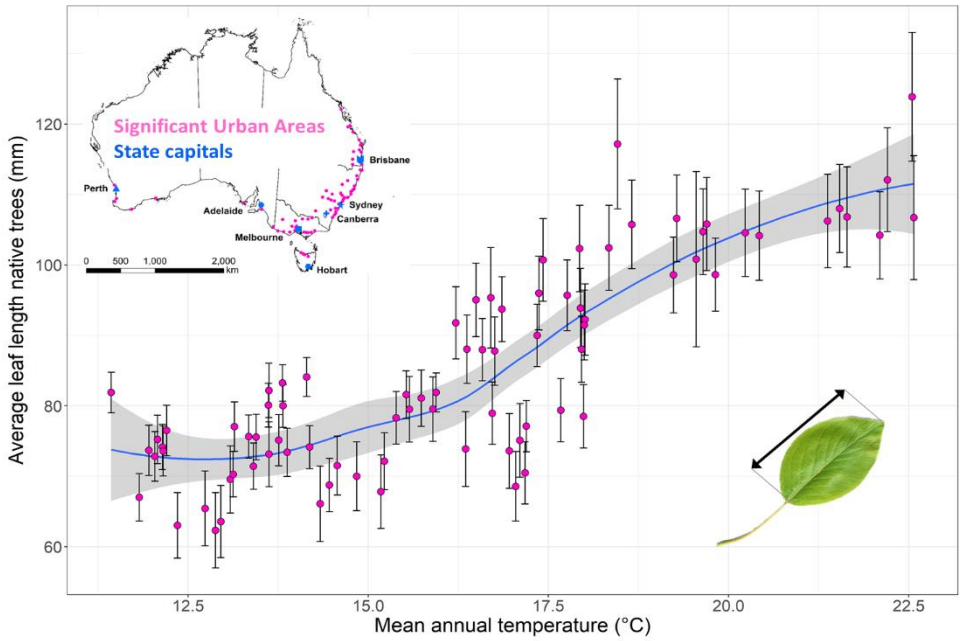


Fig. 2 | Relationship between percent of global urban footprint contained in each Koppen group (A, B, C, D, E in colors) and respective number of urban areas in GUTI. The global urban footprint (GUF) refers to the year 2015 (Esch et al., 2018) and was obtained from The German Aerospace Center (DLR) on 04.04.2020. The equation represents the linear regression model (dotted line).

A



B

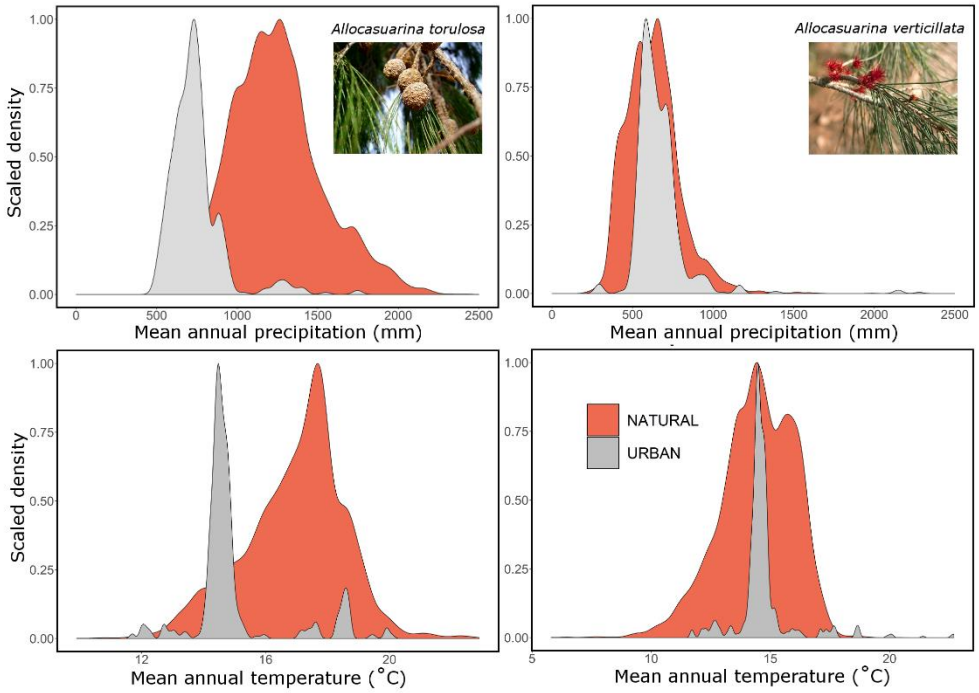


Fig. 3 | Examples of application of the GUTI dataset. A, trait distribution of average leaf length of the 176 common urban tree species native to Australia found to have suitable climate habitat across the 82 most populated Significant Urban Areas (SUAs, in pink) across the continent (drawn from bioclimatic modelling data from Burley et al. (2019) and leaf trait data from ABRS, 2020; Cooper & Cooper, 2004; de Salas MF, 2009; Maslin, 2012; NT Government, 2014; RBGSYD, 2000; SHSA, 2014 and Wheeler et al., 2002. Bars are standard errors of mean.

B, example of precipitation and temperature niches for *Allocasuarina torulosa* and *Allocasuarina verticillata*, two congeneric trees species native to Australia but widely planted in cities and towns globally (drawn from Burley et al., 2019). *A. torulosa* has urban (GUTI) precipitation and temperature niches (grey) significantly different from those calculated from the species' natural occurrences (i.e., GBIF/ALA, in coral). Conversely, *A. verticillata* has an urban climate niche largely enclosed in its natural niche. Images are from Wikimedia Commons and freely available in the public domain.

Supporting Information

Figure S1.1 | Summary schematic of the structure and content of the GUTI database. Key figures are reported on urban tree species, their conservation and invasion potential status, as well as geography and climate of the 473 urban areas considered in GUTI.

Figure S2.1 | Global urban tree species richness. a, Tree species interpolation (solid line), extrapolation (dashed line) and confidence intervals (highlighted area) based on the 43,560 samples (i.e., tree species occurrences) recorded in 473 urban areas globally and calculated based on iNEXT (Hsieh et al., 2016). **b**, Sample coverage based on the 43,560 samples.

Supporting Information, Appendix 3.1. List of the 473 urban areas and countries investigated in the study ranked by continent, country and city/town. Tree data sources are classified in inventories or published studies based on the provenance of tree species records. Latitude and longitude refer to the centre of each urban area. Climate zones refer to Koppen's classification (Peel et al., 2007). Mean Annual Temperature (MAT, ˚C) and Mean Annual Precipitation (MAP, mm) are the *Bioclim* variables wc2.0_bio_10m_01 and wc2.0_bio_10m_012 derived from *WorldClim2.0* (https://www.worldclim.org/bioclim, accessed on 15.07.2019). The global *FAO Ecofloristic Zones* encompassing each urban area are those reported in Ruesch & Gibbs, 2008 (*Global ecofloristic zones mapped by the United Nations Food and Agricultural Organization*, https://databasin.org/datasets/dc4f6efd1fa84ea99df61ae9c5b3b763, accessed on 15.07.2019). Human population densities are those reported in the *Gridded Population of the World vers. 4.11* dataset estimated for 2015 (gpw_v4_population_density_rev10_2015_15_min, *Center for International Earth Science Information Network - CIESIN - Columbia University*. 2018. Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H49C6VHW, accessed on 15.07.2019).

Supporting Information, Appendix 3.2. List of the 4,734 tree species found in 473 urban areas globally. Taxonomy is based on *The Plant List* (http://www.theplantlist.org/).

Supporting Information, Appendix 3.3. Taxonomic match between GUTI species binomials and those returned by the function *gnr_resolve* in the R library *taxize*.

Supporting Information, Appendix 3.4. Taxonomic match between GUTI families and those returned by the function *gnr_resolve* in the R library *taxize*.

Supporting Information, Appendix 3.5. Species occurrence matrix for the 473 urban areas investigated (1=presence; 0=absence). Species are ranked based on the decreasing number of urban areas hosting each tree species, summarised as the sum of each species' occurrence (i.e., presence) records.

Supporting Information, Appendix 3.6. Conservation status of 1,643 tree species as indicated by the *International Union for Conservation of Nature's (IUCN) Red List of Threatened Species* (Version 2017-3, http://www.iucnredlist.org, accessed on 15.07.2019).

Supporting Information, Appendix 3.7. Tree species invasive status by country as listed in the *Global Register of Introduced and Invasive Species* (GRIIS, http://www.griis.org, accessed on 15.07.2019).