GUBIC: the global urban biological invasions compendium for plants

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1 Abstract

1. Urban areas are foci for the introduction of non-native plant species, and they often act as launching sites for invasions into the wider environment. Although interest in biological invasions in urban areas is growing rapidly, and the extent and complexity of problems associated with invasions in these systems have increased, data on the composition and numbers of non-native plants in urbanized areas remain scattered and idiosyncratic.
2. We assembled data from multiple sources to create the Global Urban Biological Invasions Compendium (GUBIC) for vascular plants representing 553 urban centres from 61 countries across every continent except Antarctica.

3. The GUBIC repository includes 8,140 non-native plant species from 253 families. The number of urban centres in which these non-native species occurred had a log-normal distribution, with 65.2% of non-native species occurring in fewer than 10 urban centres.
4. *Wider implications and relevance*: The dataset has wider applications for urban ecology, invasion biology, macroecology, conservation, urban planning and sustainability. We hope this dataset will stimulate future research in invasion ecology related to the diversity and distributional patterns of non-native flora across urban centres worldwide. Further, this information should aid the early detection and risk assessment of potential invasive species, inform policy development, and assist in setting management priorities.

Keywords: Alien species, Biodiversity change, Biological invasions, Cities, Naturalized species, Non-native plants, Urbanization

2 Introduction

Urban areas, characterized by their high human population density and extensive landscape modification, present unique opportunities for the establishment and spread of non-native species. The convergence of global trade, transportation networks, modified microclimates, and human-mediated disturbances in urban areas facilitates the introduction and proliferation of non-native species (Gallardo et al. 2016; Potgieter et al. 2024). Urban plant invasions can have profound ecological, economic, and social impacts due to altered ecosystem services, impacts on human health, and costs incurred from management efforts (Potgieter et al. 2017; Heringer et al. 2024). However, there is a lack of foundational data on which species occur in urban centres globally. This data gap limits our ability to assess the potential threats non-native plants pose to urban ecosystems and the services they might provide (Milanović et al. 2020), with current knowledge remaining geographically heterogeneous and focused on only a few well-studied taxa (Vaz et al. 2018).

Frameworks for understanding and managing urban plant invasions are less frequently studied than in other habitats (but see Gaertner et al. 2016; Potgieter and Cadotte 2020). While existing frameworks integrate concepts from landscape ecology, population biology, and socioecological systems, they are limited in number and scope, highlighting the need for further development to facilitate a better understanding of the mechanisms that drive invasions in urban areas as well as options for managing them. Managers in urban areas face unique challenges due to the interplay between the built environment and complex socioeconomic factors which can significantly alter ecosystem conditions. However, these challenges have only recently been incorporated into models to predict urban invasion dynamics and impacts and identify appropriate management strategies (Gaertner et al. 2016; Potgieter et al. 2022).

Despite these advances, empirical studies on urban biological invasions remain limited, particularly in terms of taxonomic coverage and spatial scale (Cadotte et al. 2017). Most empirical studies have focused on the ecology of particular non-native species within small urban areas. This narrow focus limits the generalizability of findings across different organisms and urban contexts. Although numerous regional and city-specific inventories of non-native species exist, these are often from uncoordinated efforts carried out independently by research groups focusing on particular research questions. Therefore, these diverse resources lack of harmonization of collection methods, taxonomy, and sampling effort, making them challenging to be easily used. Moreover, because some of this work is developed in collaboration with city practitioners and managers, many are published in the grey literature and only available in non-English languages, limiting their accessibility. While these biological inventories are crucial to advancing our understanding of urban biological invasions at the city and regional levels, a comprehensive global dataset documenting the non-native flora in urban areas around the world is required to understand the role of urban areas in shaping the patterns of plant invasions and the underlying processes. Here, we unify this diverse body of knowledge and present a global repository of non-native flora in urban centres around the globe. This repository serves as a valuable resource for improving our understanding of urban non-native floras by providing essential data, fostering collaboration, informing management and policy, and facilitating coordinated global responses to the challenges they present.

3 Methods and Materials

To compile a list of non-native plant species in urban areas (see Section 3.1.2 for the methods used to delineate urban boundaries) globally, we combined multiple data sources. This approach allows for the application of standardized selection and inclusion criteria over multiple individual datasets, resulting in a harmonized and consistent dataset across urban areas and regions. We included only established non-native plant species, which are those with self-sustaining populations, also commonly referred to as naturalized (Richardson et al. 2000, Blackburn et al. 2011) (see 3.1.5).

3.1 Data acquisition and compilation

3.1.1 Data source 1: Global Urban Biological Invasions Consortium

An international workshop to address biological invasions in urban ecosystems was hosted by the Centre for Invasion Biology in Stellenbosch, South Africa, in November 2016 (Gaertner et al. 2017).

This workshop led to the creation of the Global Urban Biological Invasions Consortium which hosted a coordinating meeting in June 2019 that brought together more than 70 researchers from 14 countries from all continents except Antarctica. One of the prioritized activities was to compile lists of non-native plant species for urban areas. A working group "Synthesizing Global Urban Biological Invasion Knowledge" (sGUBIK, , funded by sDiv, the synthesis centre of iDiv, the German Centre for Integrative Biodiversity Research) was later established in September 2023 to synthesize these global data and examine the patterns and mechanisms driving non-native plant species' invasions in urban areas.

We compiled data using the following approaches. First, we sent a request to over 150 members of the Global Urban Biological Invasions Consortium in 2019 to upload datasets for any urban taxa to a SharePoint repository at the University of Toronto. The cut-off for the data request was December 2021. Second, we searched the published literature in English, Portuguese, and Spanish as well as the Dryad data repository (www.datadryad.org) between August 2019 and November 2019 for studies and datasets containing species lists for urban areas around the world, using keywords such as 'alien', 'animal', 'built-up', 'city', 'urban*', 'non-native', 'exotic', and 'plant'. These approaches yielded urban datasets that encompassed various taxa and spatial scales, incorporating demographic, environmental, and taxon-specific information. Additionally, we included the Urban Biodiversity Research Coordination Network (UrBioNet) dataset, a large multi-city compilation (Aronson et al. 2014), featuring 14,240 spontaneous plant species (i.e., not cultivated or planted), of which 4,241 are identified as non-native, derived from published surveys across 110 urban areas in five biogeographic regions.

To ensure consistency across the datasets, we standardized city and country names by resolving variations in spelling and correcting potential typographical errors. In instances where multiple urban centres within the same country shared the same name (e.g., Madison, Wisconsin vs. Madison, Indiana in the United States), we excluded these entries from the database if it was not possible to unambiguously determine the specific city to which the data pertained. Given that most data lacked spatially explicit coordinates, precise delineations of city boundaries were unavailable. As a result, datasets collected from data contributors, repositories or the literature were generally treated as representing areas surrounding the urban centres rather than being confined to specific urban boundaries.

3.1.2 Data source 2: Global Biodiversity Information Facility

Before extracting occurrence data for each urban area from the Global Biodiversity Information Facility (GBIF), we delineated the boundaries of urban areas. We used the global urban centres data provided by the Global Human Settlement Layer (GHSL, Pesaresi et al. 2019, https://ghsl.jrc.ec.europa.eu/ucdb2018Overview.php), which defines urban centres as contiguous 1 km^2 grid cells with a population density of at least 1,500 inhabitants per km^2 of permanent land (areas that are consistently above water and exclude bodies of water, such as oceans, seas, large rivers, and lakes) or with more than 50% built-up surface shared on permanent land, and with at least 50,000 inhabitants in the cluster with smoothed boundaries and small gaps (< 15 km^2) filled. Overall, there are 13,189 unique urban centres worldwide. Subsequently, smaller, nearby urban centres located within a 5 km radius of the larger urban centres were integrated into the larger one, as these proximally situated centres are close enough to be considered a single urban entity and often are considered part of the metropolitan area. We refrained from further merging smaller centres that, although within a 5 km radius of the previously merged smaller centres, were situated beyond the 5 km boundary from the larger urban centre. This process resulted in 11,621 unique urban centres globally.

In August 2023, we queried GBIF and downloaded plant occurrence records from each urban centre to compile the flora of these urban areas (see Table S1 for the DOIs of downloaded datasets). The initial download comprised over 500 million records. We cleaned the GBIF data of each of the urban centres by removing records with common issues such as erroneous coordinates using R package 'CoordinateCleaner' (Zizka et al. 2019). We also removed all records with identification above species level, fossil specimens, preserved specimens, living specimens, and those with locality uncertainty greater than 30 km or within a 500 m vicinity of biodiversity institutions, botanic gardens, zoos, museums, GBIF headquarters, etc.

3.1.3 Quality control and merging of data

Before merging data from sources 1 and 2, we conducted preliminary filtering of these datasets. For each urban centre with GBIF data, we used the number of observations of each species as a proxy for the abundance of that species. We calculated observed species richness and estimated species richness using the Chao1 equation, which incorporates singletons and doubletons (i.e., species observed only once or twice):

$$\text{Estimated richness} = \text{Observed richness} + S^2/(2D) \qquad \text{(Eqn. 1)}$$

where S represents the number of singletons and D is the number of doubletons (Hsieh and Chao 2016). We also determined the sample coverage percentage, a measure of sample completeness, based on the rarefied estimate of the total number of individuals in each urban centre using the R package 'iNEXT' for rarefaction (Chao et al. 2014; Hsieh and Chao 2024).

We considered an urban centre to have robust GBIF data if: 1) it had over 1,000 observed plant species; 2) the community sample coverage was > 90%; and 3) the observed species richness was greater than 75% of the estimated species richness. We used these criteria to balance the number of retained urban centres and data quality. For data source 1, if an urban centre had more than 300 plant species, we retained it and further integrated it with data source 2 (GBIF data) of that urban centre regardless of the GBIF data quality. If an urban centre had fewer than 300 species from the data source 1 and did not have adequate GBIF data coverage, we removed that urban centre from our database. If an urban centre had fewer than 300 species from data source 1 but had adequate GBIF data coverage (i.e., met the above three criteria), we retained both data sources for that urban centre. We removed those urban centres with only GBIF data that did not meet the three criteria above (see Fig. 1 for a schematic workflow). The final database included 553 urban centres (Fig. 2). For each of these urban centres, we derived a list of established non-native plant species using the merged data sources.

3.1.4 Standardize species names

We standardized species and family names against the World Checklist of Vascular Plants (WCVP, Govaerts et al. 2024) for the merged database using the R package rWCVP (version 1.0.3, Brown et al. 2023). We selected WCVP as it represents one of the most comprehensive and up-to-date taxonomic resources available (Grenié et al. 2022). WCVP also serves as the taxonomic backbone for the most recent version of the Global Naturalized Alien Flora (GloNAF), which was updated following van Kleunen et al. (2019). GloNAF was used to determine whether a species is non-native in a particular region where an urban centre was located (see section 3.1.5 below). Note that species with “unplaced names” or has not match from WCVP were excluded from the final dataset (https://powo.science.kew.org/about-wcvp#unplacednames), reflecting the challenges in our current taxonomic knowledge of plants worldwide. We also merged subspecies or varieties to the main species and only kept binomial species names in the final database.

3.1.5 Cross-validation to determine the status of species

To distinguish between established (naturalized) and native or casual species (i.e. those that might flourish and even reproduce occasionally in an area but which do not form self-replacing populations; Richardson et al. 2000) located in a specific urban centre, we used the GloNAF database as it provides the most updated information of naturalized plant species across the world. For each urban centre, we used the delineated boundaries provided by the GHSL. For each species listed within an urban centre, we classified the species as non-native to that urban centre if its polygon intersected with the species’ naturalized or invasive range. We also cross-referenced all species with local checklists of non-native plant species validated by experts (Kalusová et al. 2024). Therefore, for those urban centres (mostly in Europe), the lists of naturalized species were slightly different from those based on GloNAF alone.

4 General Patterns

We present a global urban non-native flora for 553 cities from 61 countries across every continent with permanent human settlements (Fig. 2). These data are, however, biased towards European and North American urban centres, which together account for 80.8% of all non-native species, and 82.2% of all records within our database across the world, respectively. Our global repository includes 8,140 established non-native plant species from 253 families (Fig. 3). Most families contain few species, with 73 families each containing 20 or more non-native species (Fig. 3). Asteraceae, Poaceae, Fabaceae, and Rosaceae contain about one-third of all species (n = 2,641; Table 1). The most widespread non-native plant species can be found in Table 1; the top 20 cities and countries with the greatest number of non-native plant species in our database can be found in Table 2. A rarefaction of species occurrences across urban centres (Fig. 4) shows that we are approaching an asymptote with our sample of 553 urban centres. However, the sampling curve also suggests that more urban floral sampling is needed, especially from regions with sparse data (e.g., South Asia, northern South America).

5 Usage Notes

In forming a dataset of this magnitude, we made several simplifying decisions and recognize that limitations are inevitable. Some issues to be cognizant of for analysis and interpretation include:

1 Our definition of urbanized areas delineated contiguous areas. Because of this definition, some urbanized areas span multiple regions or municipalities and form contiguous land areas. In these cases, the urbanized region is referred to as the largest administrative centre; for example, Guangzhou, China includes Foshan. In some cases, contiguous urbanized areas span larger administrative areas and even countries. For example, Detroit, Michigan, USA, not only includes neighbouring cities in Michigan, like Dearborn, but also the Canadian city of Windsor.

2 While most recorded species in our dataset can be confirmed as established, the status of some species could not be definitively verified with our methodology. Additionally, the dataset might include non-established non-native plant species or intentionally cultivated individuals that were not fully distinguishable from naturally occurring records. As a result, the data should be interpreted cautiously, particularly when comparing non-native species richness at broader spatial scales, such as across countries, rather than at the city level. Species in our dataset with widespread occurrences across multiple urban centres are likely to be established, whereas

species recorded in only one urban centre might require further scrutiny. We recommend that users consider including these singleton records in sensitivity analyses to assess the robustness of their results. Therefore, the numbers of non-native species reported here (e.g., Table 2) are in some cases higher than those reported for individual countries in recent studies (Pyšek et al. 2017, Kalusová et al. 2023).

3 The combination of these many individual datasets means that our list is subject to numerous methodological differences, from lists being built from herbarium specimens to those observed during direct sampling. Because our goal is to compile a non-native flora of urban centres, these limitations do not significantly affect our dataset.

4 The data extracted from GBIF include geographically biased and incomplete sampling, and species counts derived from these data should not be considered exhaustive despite our strict criteria listed above. For example, many urban centres in China included fewer than 100 non-native species in our database (Fig. 2, 5A), which are likely underestimates. Analyses of richness and diversity should include rarefaction or some other way of accounting for unequal sampling as the number of non-native species increased with the number of observations (Fig. 5B). Notably, many urban centres from the Global South (e.g., India; Fig. 2) were absent from our database due to the paucity of available data.

5 Conclusion

The database presented here represents a unique and valuable resource for addressing a wide range of basic and applied ecological questions, particularly those related to biological invasions. This resource can support hypothesis testing at the macro- and global scale (e.g., biotic resistance, or invasion debt). It can also be used to model non-native plant species invasions, underscoring its utility not only in scientific research but also in conservation planning and practice. Lastly, it has the potential to guide more informed decision-making in biodiversity conservation, ecosystem restoration, environmental sustainability, and invasive species management across diverse ecological, biogeographical, and urban contexts.

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7 Author contributions

The Global Urban Biological Invasions Consortium, led by MWC and including all co-authors, conceived the initial idea, which was further developed by the sGUBIK working group (DL, LJP, MFA, IA, BB, MC, LCG, SK, IK, ACLM, ZL, FMC, PP, DMR, LBT, RDZ, MWC). LJP led the data collection effort, gathering information from the literature and contributors, who were invited to join as co-authors if they provided additional contributions to the manuscript. DL led the data compilation from GBIF. The sGUBIK team supported data integration and standardization. LJP and DL drafted the manuscript, with all co-authors contributing to its editing and revision.

8 Conflicts of Interest

The authors declare no conflicts of interest.

9 Data Availability Statement

Data are available at https://doi.org/10.5281/zenodo.14559925.

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11 Figures

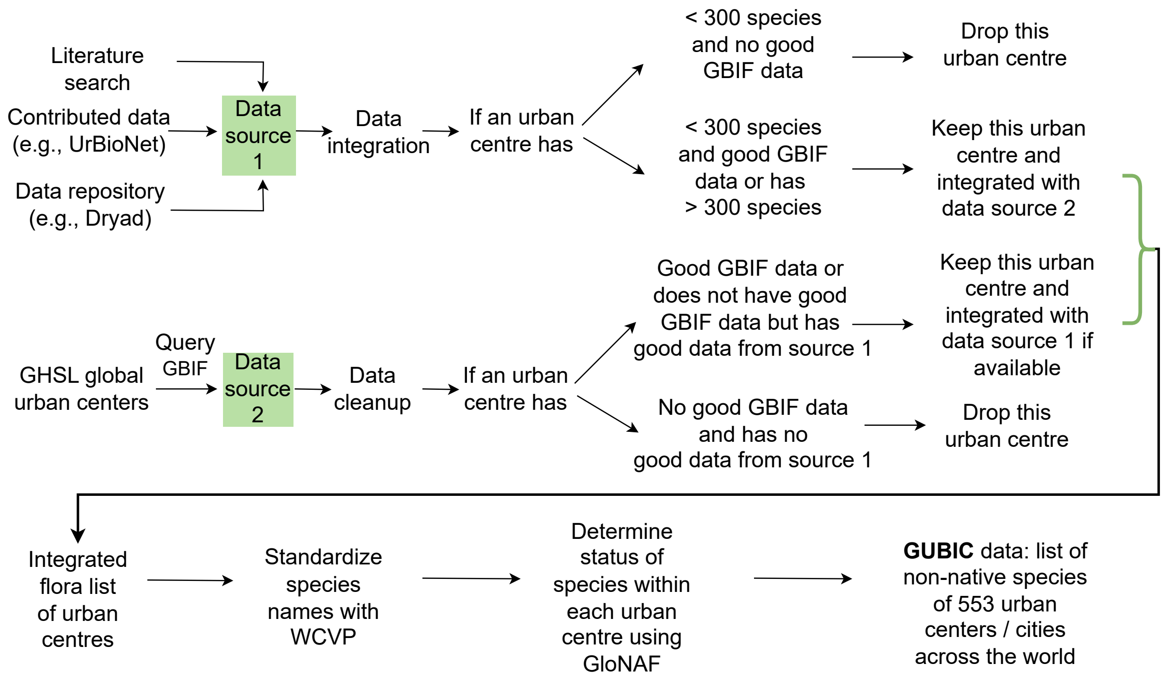

Figure 1. Schematic figure showing the workflow of the compilation of the Global Urban Biological Invasions Compendium database. UrBioNet: The Urban Biodiversity Research Coordination Network. GHSL: The Global Human Settlement Layer. GBIF: the Global Biodiversity Information Facility. WCVP: The World Checklist of Vascular Plants. GloNAF: Global Naturalized Alien Flora.

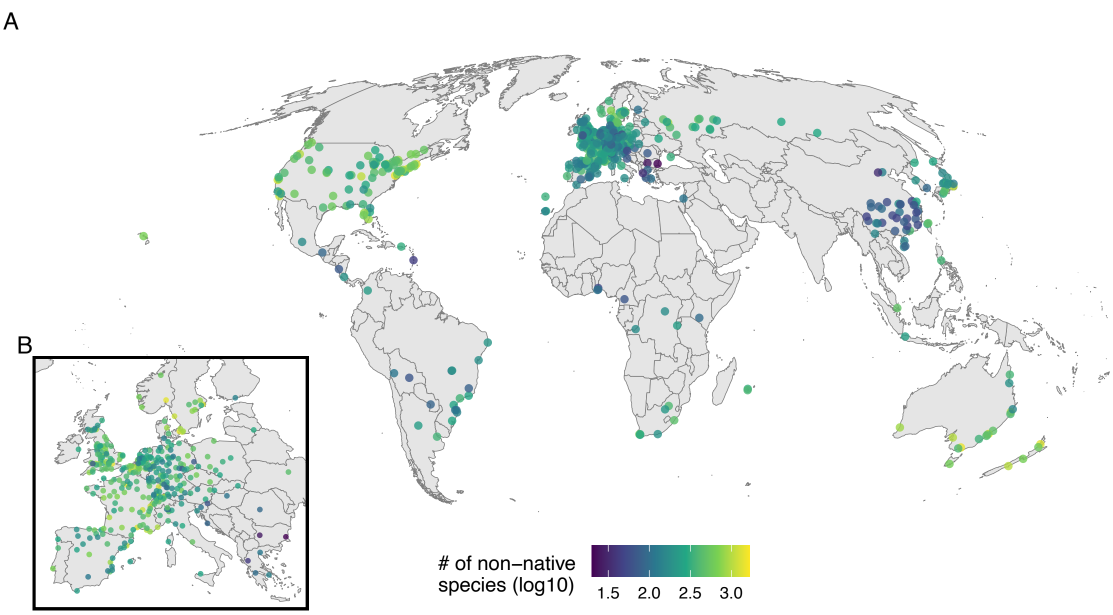

Figure 2. Geographic distribution of urban centres across the world (panel A; *n* = 553) and Europe (panel B) and the number of established non-native plant species they contain (coloured points).

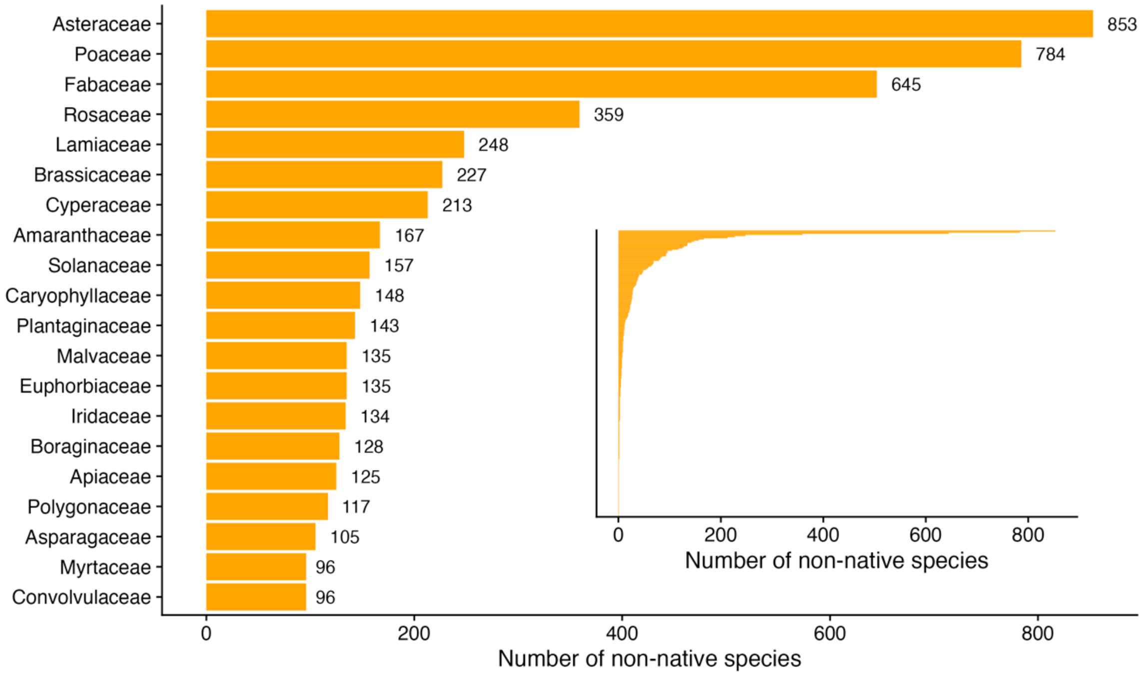

Figure 3. The distribution of family sizes for the 253 established non-native plant families in the dataset. The main plot contains the top 20 families which together account for 61.6% of all plant species in our dataset. The embedded plot presents the distribution of the number of non-native plant species across all families.

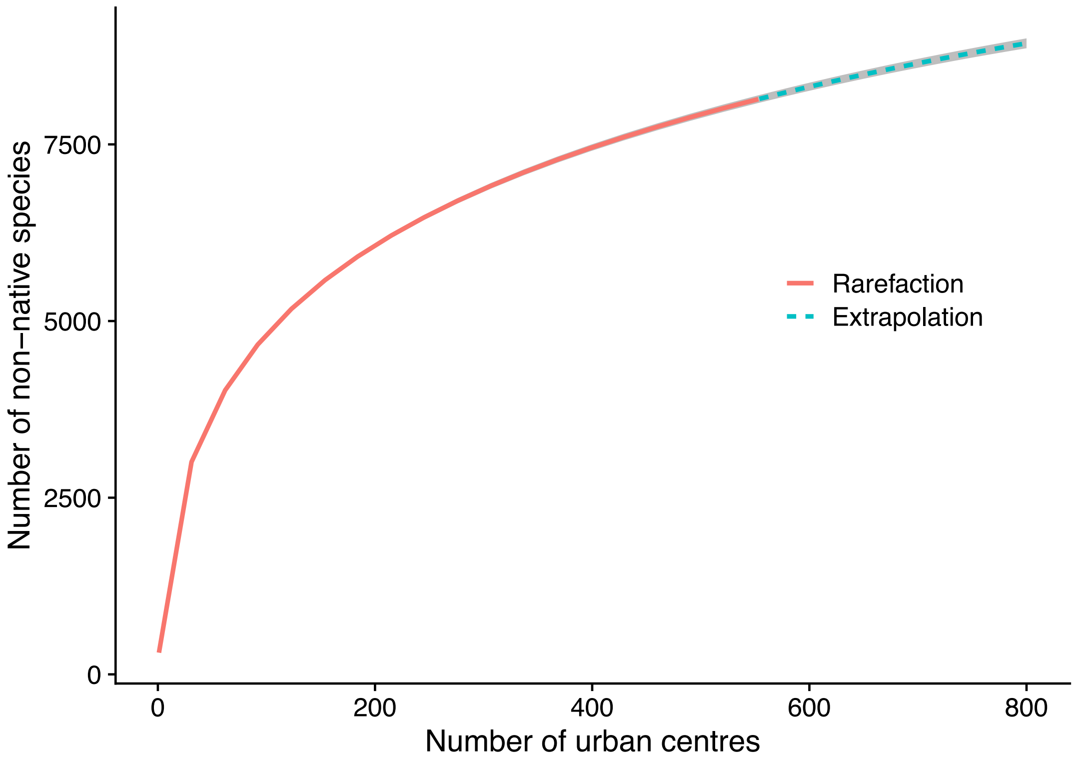

Figure 4. Rarefaction curve of the number of non-native plant species in 553 urban centres.

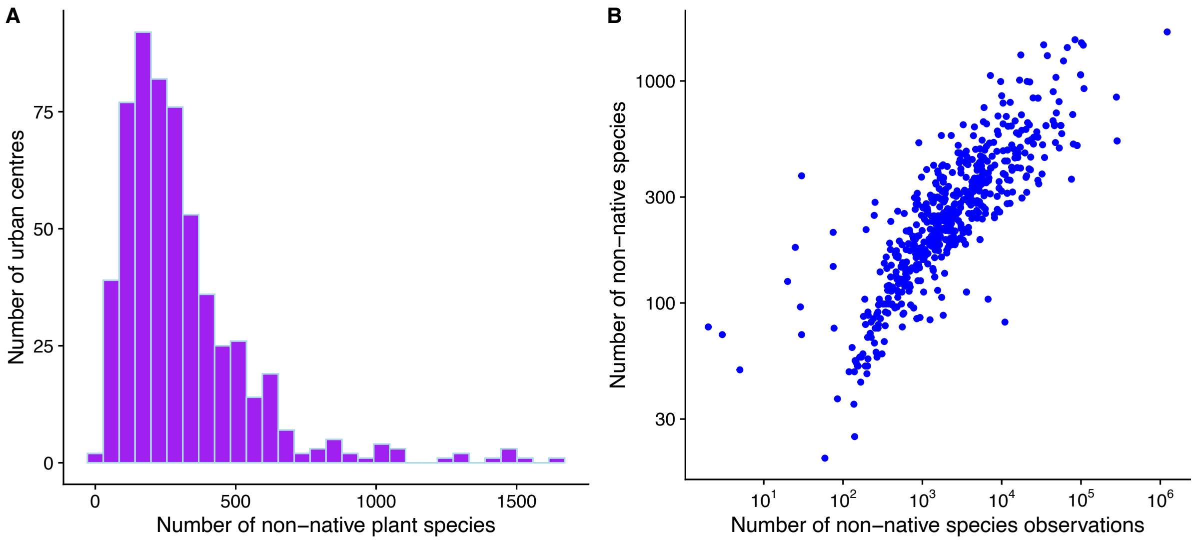

Figure 5. A) Distribution of the number of non-native plant species in urban centres (*n* = 553) across 61 countries and B) the relationship between the number of non-native plant species and the number of non-native species occurrence records in that dataset.

12 Tables

Table 1. The most widespread (top 30) established non-native plant species in urban centres (n = 553) across the world. Note that this list was derived from different sampling efforts and has a bias in favour of non-native species in European and North American urban centres.

Scientific name	Family	Number of urban centres	Number of countries	Number of GBIF records
Erigeron canadensis	Asteraceae	469	47	64 760
Veronica persica	Plantaginaceae	451	41	41 176
Oxalis corniculata	Oxalidaceae	434	48	23 721
Datura stramonium	Solanaceae	410	46	12 531
Robinia pseudoacacia	Fabaceae	404	41	44 657
Syringa vulgaris	Oleaceae	393	29	21 767
Amaranthus retroflexus	Amaranthaceae	381	41	8 602
Galinsoga quadriradiata	Asteraceae	376	40	18 509
Ailanthus altissima	Simaroubaceae	369	35	50 732
Medicago sativa	Fabaceae	369	39	24 969
Prunus cerasifera	Rosaceae	369	26	26 924
Aesculus hippocastanum	Sapindaceae	367	24	35 349
Reynoutria japonica	Polygonaceae	367	29	88 542
Cymbalaria muralis	Plantaginaceae	366	33	31 151
Matricaria discoidea	Asteraceae	363	33	26 254
Melissa officinalis	Lamiaceae	359	25	20 768
Buddleja davidii	Scrophulariaceae	356	33	45 122
Lunaria annua	Brassicaceae	340	19	12 135
Galinsoga parviflora	Asteraceae	337	43	7 306
Rosa rugosa	Rosaceae	334	22	18 499
Vinca major	Apocynaceae	326	23	11 597
Helianthus tuberosus	Asteraceae	320	34	4 244
Tanacetum parthenium	Asteraceae	320	27	9 527
Lepidium draba	Brassicaceae	315	29	14 831
Acer negundo	Sapindaceae	313	36	17 459
Lysimachia punctata	Primulaceae	312	15	10 279
Brassica napus	Brassicaceae	307	25	5 376
Impatiens glandulifera	Balsaminaceae	301	25	35 332
Lepidium didymum	Brassicaceae	301	31	13 459
Prunus laurocerasus	Rosaceae	298	22	48 188

Table 2. The top 20 urban centres (left) and the top 20 countries (right) with the greatest number of non-native plant species. Note that these lists are skewed towards European and North American urban centres (see Fig. 2). The numbers presented for some countries (e.g., France) also included non-native plant species from their overseas urban centres.

Urban centre	Number of established non-native species
New York	1 663
Los Angeles	1 534
Sydney	1 486
Philadelphia	1 455
Melbourne	1 450
Washington D.C.	1 414
Auckland	1 310
Boston	1 300
San Jose (USA)	1 231
Tijuana	1 066
St. Louis	1 058
Tokyo	1 038
London (UK)	1 014
Christchurch	1 009
Adelaide	995
Brisbane	994
Portland (OR, USA)	990
Moscow	924
Chicago	895
Perth	858

Country	Number of established non-native species
United States of America	4 409
Australia	2 596
France	2 187
New Zealand	1 561
Canada	1 476
Russia	1 251
Japan	1 154
Mexico	1 142
Germany	1 123
United Kingdom	986
Switzerland	966
South Africa	947
Spain	916
Belgium	906
Netherlands	860
Sweden	832
Denmark	800
Norway	792
Portugal	596
Brazil	588

13 Appendix

Table S1. Global Biodiversity Information Facility (GBIF) data used to derive the Global Urban Biological Invasions Compendium database. All data were accessed in August, 2023.

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