The University Of Sheffield.

This is a repository copy of *Using big data to improve ecotype matching for Magnolias in urban forestry*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/155752/

Version: Accepted Version

Article:

Watkins, J.H.R., Cameron, R.W.F., Sjöman, H. et al. (1 more author) (2020) Using big data to improve ecotype matching for Magnolias in urban forestry. Urban Forestry & Urban Greening, 48. 126580. ISSN 1618-8667

https://doi.org/10.1016/j.ufug.2019.126580

Article available under the terms of the CC-BY-NC-ND licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).

Reuse
This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Using big data to improve ecotype matching for Magnolias in urban forestry

Summary

Trees play major roles in many aspects of urban life, supporting ecosystems, regulating temperature and soil hydrology, and even affecting human health. At the scale of the urban forest, the qualities of these individual trees become powerful tools for mitigating the effects of, and adapting to climate change and for this reason attempts to select the right tree for the right place has been a long-term research field. To date, most urban forestry practitioners rely upon specialist horticultural texts (the heuristic literature) to inform species selection whilst the majority of research is grounded in trait-based investigations into plant physiology (the experimental literature). However, both of these literature types have shortcomings: the experimental literature only addresses a small proportion of the plants that practitioners might be interested in whilst the data in the heuristic (obtained through practice) literature tends to be either too general or inconsistent. To overcome these problems we used big datasets of species distribution and climate (which we term the observational literature) in a case study genus to examine the climatic niches that species occupy in their natural range. We found that contrary to reports in the heuristic literature, *Magnolia* species vary significantly in their climatic adaptations, occupying specific niches that are constrained by trade-offs between water availability and energy. The results show that not only is ecotype matching between naturally-distributed populations and urban environments possible but that it may be more powerful and faster than traditional research. We anticipate that our findings could be used to rapidly screen the world's woody flora and rapidly communicate evidence to nurseries and plant specifiers. Furthermore this research improves the potential for urban forests to contribute to global environmental challenges such as species migration and ex-situ conservation.

Keywords

Big data; Biogeography; Ecotype matching; Predictive ecology; Urban trees.

Introduction

Through their provision of a complex suite of ecosystem services such as run-off water management, biodiversity habitat and cultural services, urban forests play a key role in mitigating some of the effects of a changing climate (Ordóñez Barona, 2015; Wilson, 2016; Acuto *et al.*, 2018). However, if urban forests are to be able to provide these benefits, their fitness needs to be improved so that they are able to deal with the many stresses that reduce urban forest growth and increase mortality risk (Bialecki, Fahey and Scharenbroch, 2018) and that are being exacerbated under climate change, such as prolonged or aseasonal drought, flooding or pathogens (Roloff, Korn and Ã, 2009; Allen, Breshears and McDowell, 2015; Fuller and Quine, 2016).

Building on earlier discourse (Santamour, 1990), urban forestry researchers and practitioners have emphasised the importance of species selection and diversification as a means to achieve this (Krajter Ostoić and Konijnendijk van den Bosch, 2015; Morgenroth *et al.*, 2016) with a number of recent publications providing guidance to aid decision making at the practice level (Vogt *et al.*, 2017; Barbrook *et al.*, 2018; Hirons and Sjoman, 2018). Whilst these publications are a significant development, they inevitably have to compromise between the detail with which they can present information and the range of species they are able to discuss, compounded by the practical limits of what genetic material nurseries have access to. Exacerbating these constraints, economic pressures on horticultural production lead to increasingly reduced genetic diversity amongst the trees available in nurseries, with many species represented by either a single clone or a small number of seed orchards. Some exceptions to this exist for species such as *Acer rubrum*, where there are multiple named clones, but many selections are based primarily on aesthetic criteria such as autumn colour potential and habit rather than fitness to environment. If specifiers want to truly diversify the gene pool of urban forests, new tools are required that can identify urban-fit ecotypes.

Criteria for a case study genus

This study uses a single genus as a case study to investigate the literature for the efficacy of selecting novel ecotypes, firstly reviewing existing species selection literature, then developing a methodology for assessing new sources of information. The criteria for a suitable candidate genus should reflect the nature of the challenge: it should not be widely planted in urban forests, nor widely discussed in urban forestry literature, and ideally it should display some degree of natural variation. *Magnolia* is a flagship genus (Cires *et al.*, 2013) that fits these criteria, with high ornamental value and perceived low tolerance of stress or disturbance. The literature of *Magnolia* tends to focus on horticultural or cultural aspects (Bunting 2016, Callaway 1994, Gardiner 2000), genetics and phylogeny (Muranishi *et al.*, 2013; Budd, Zimmer and Freeland, 2015), and conservation (Cicuzza, Newton and Oldfield, 2007; Rivers *et al.*, 2016), with relatively few studies into their functional traits (Cires *et al.*, 2013) or the extent to which species within the genus are able to withstand stresses (Sjöman, Hirons and Bassuk, 2018). Nevertheless, *Magnolia* might contain effective selections for urban forestry given its reported intra-specific variation (Azuma, Toyota and Asakawa, 2001; Azuma *et al.*, 2011) and the wide range of environmental conditions to which it has adapted (Azuma *et al.*, 2001). In spite of its reputation for being intolerant of climatic extremes and poor quality soils, its ornamental qualities are highly valued and could be important in encouraging people to accept urban forests as an acceptable landscape type for dense cities (Hitchmough and Bonugli, 1997; Hoyle, Hitchmough and Jorgensen, 2017).

The existing species selection literature

A preliminary review identified two broad categories of literature that could be used in species selection: the experimental and heuristic literature (see Table 1). The experimental literature is rooted in functional ecology, tends to be published in peer-reviewed journals, and typically studies either morphological or physiological traits in controlled studies. By contrast, the heuristic literature (by which we mean work that is based upon the accumulated knowledge of those working in practice in horticulture or urban forestry (Ippoliti, 2015; Vogel and Henstra, 2015)) describes experiences of growing a wide range of species and observing their characteristics over a long period of time. The heuristic literature tends to be published in the form of horticultural monographs, nursery catalogues or growers' manuals and provides information about whole-plant characteristics such as overall size or growing conditions, or particular ornamental qualities such as leaf or flowering characteristics. Both literature types have specific objectives and are aimed at different audiences: the experimental literature, for example, uses technical language, is highly focussed in its study area and is mostly used by researchers to address macro ecological questions; on the other hand, the heuristic literature presents a wide range of information that is aimed at the horticultural and professional landscape sectors. The heuristic literature differs philosophically from the experimental in that observations are made without the capacity to know what the responses would be if a different set of conditions or treatments were involved. In practice, urban foresters tend to rely upon a range of sources, with some publications such as professional journals or industry-endorsed guidance (Hirons and Sjoman, 2018) straddling the boundaries of these broad categories.

Table 1: A typological classification of the existing urban forestry species selection literature

Literature typology	**Publications**	**Target audience**	**Data**
Experimental	Trait literature[1]	Functional ecologists, dendrologists, botanists	Functional traits (e.g. SLA, SSD, Plant height) or functional type
Heuristic	Nursery catalogues[2]	Gardeners, landscape architects, landscape contractors, urban foresters	Plant size, floral or leaf aesthetics, resource requirement (eg water, light), soil conditions
Heuristic	Encyclopaedia[3]	Gardeners, landscape architects, urban foresters	Plant size, floral or leaf aesthetics, resource requirement (eg water, light), soil conditions
Heuristic	Horticultural monographs[4]	Gardeners, landscape architects, botanic gardens and arboretums	Plant size, floral or leaf aesthetics, resource requirement (eg water, light), soil conditions
Heuristic	Industry guidance[5]	Landscape architects, landscape contractors, urban foresters	Plant size, floral or leaf aesthetics, resource requirement (eg water, light), soil conditions, management requirements

[1] For example, (Kattge *et al.*, 2011; Sjöman, Hirons and Bassuk, 2018).
[2] For example, Glover 2016, or catalogues from UK nurseries such Burncoose and Coblands.
[3] For example, Hillier Manual of Trees and Shrubs (8th ed), Dirr (2011) or Gardiner (2012).
[4] For example, Bunting (2016), Callaway (1994), Gardiner (2000), Treseder (1978).
[5] For example, Samson et al (2017) Hirons and Sjoman (2018), UK National Plant Specification.

Alternative data sources: the observational literature

In contrast to the experimental and heuristic literatures which describe plant performance or traits, a third literature source exists that could be used by urban foresters to understand the naturally occurring niches that plants occupy. Using the type of data used in biogeographical studies (Table 2) would require a fundamentally different approach to species selection, requiring urban foresters to understand and harness evolutionary adaptations, target specific populations or ecotypes and then match these to specific designed environments. Such an approach would enable a far greater degree of precision and confidence in designing urban forests to meet specific challenges.

Table 2: Proposed additions to urban forestry species selection literature

Literature typology	Publications	Target audience	Data
Observational	Plant identification and distribution resources[6]	Taxonomists, conservationists and horticulturists	Natural distribution of species or individuals, habitat in fundamental or realised niche
Observational	Climate[7]	Climate scientists, biogeographers, ecologists, planners	Mean monthly rainfall, mean monthly temperature

We use the term 'observational literature' to describe the vast records of observations of plant occurrences and climate set out in Table 2. The observational literature category includes all records of the natural distribution of species, whether the results of fieldwork, plant collecting or exploration and is usually held in herbaria or databases (such as GBIF), whilst climate records can be accessed through resources such as WorldClim. Comprising millions of data points, this information is often termed 'big data' (Hallgren *et al.*, 2016; Serra-Diaz *et al.*, 2017; Allen *et al.*, 2018; Pelletier *et al.*, 2018), and is increasingly used as a powerful resource for describing species distribution and environmental adaptation (Booth, 2018; Wang *et al.*, 2018).

[6] For example, GBIF (https://www.gbif.org), Global Plants (https://plants.jstor.org)
[7] For example, Global Climate Data (http://www.worldclim.org) or The World Bank Climate Change Knowledge Portal (http://sdwebx.worldbank.org/climateportal/)

These records are not without their idiosyncrasies: records have been accumulated over the past four hundred years and whilst these records have often been reviewed regularly by botanists working in herbaria, they can reveal bias or patchiness in their coverage of a species distribution, level of detail, or nomenclature. As such, these records are often difficult to interpret, contextualise or physically access, requiring archival research in herbaria and whilst major efforts are being taken to digitise these records and share via online repositories, a large proportion of the world's 380m herbarium vouchers remain un-digitised (James *et al.*, 2018). Similar factors affect climatic data (particularly rainfall and temperature) that have been recorded around the world over the past 150 years. As a result, despite the sophisticated interpolation of climate data and rapidly evolving techniques for recording information, models do not yet offer a consistently accurate record of climate across multiple scales of resolution, posing problems for identifying climate niches in mountainous areas where aspect and elevation complicate interpolation.

In spite of these shortcomings, the theoretical basis for bringing observational literature sources together is robust: the effects of water and energy relations upon plant distributions has been well established through indices of potential evapotranspiration, moisture indices and warmth index (Yim and Kira, 1975; Kreft and Jetz, 2007; Wright *et al.*, 2017), and as such the biological and climate data that is available online remains a substantial resource. If we are able to treat these resources in a probabilistic manner using biogeographical conceptual frameworks and techniques, it should be possible to identify not only variation in bioclimatic niches across which *Magnolia* is distributed but also population-level intra-specific variation, and thus providing the basis for improved matching between ecotype and urban site into which it might be planted.

In this paper we identify a new literature source and develop a methodology for handling the enormous and widely distributed data sets that it contains, allowing us to address three long-standing challenges in the management strand of urban forestry (Morgenroth *et al.*, 2016): what is the most effective source of information for species selection? Is it possible to access information about superior trees at the level of the ecotype, rather than species? And finally, if these literature sources are sufficiently powerful to identify likely superior ecotypes, how accessible are they to urban foresters? Together, these research questions allow us to rapidly screen genetic diversity within species to identify sub-specific populations suitable for urban forestry under climate change.

Materials and Methods

To address these challenges, we developed a novel research approach involving a sequence of steps to classify and analyse two classic literature sources and a new source of species selection literature. To answer the three research questions identified above, we carried out the following steps:

a) We described the scope of each literature type, recording the number of species discussed and the number of records for each species within each source,

b) We assessed the level of precision to which traits, resource use or climate niche were described (i.e. genus, inter-specific, or intra-specific), and

c) We assessed the efficacy of each literature type in identifying potential match between resource requirement, traits or climate niche and possible designed urban sites.

.

Identifying sources for each literature typology

Urban forestry literature is highly diverse, with specification sources and practices varying widely between practitioners. A preliminary literature review was carried out, identifying three broad sources of literature: the experimental literature, heuristic literature, and observational literature (Tables 1 and 2). Literature searches were tailored for each literature type. For the experimental literature, searches were carried out on Scopus, Web of Science and Google Scholar using terms including '*Magnolia'*, species names (eg '*acuminata', 'biondii', 'campbellii*' etc,.), plant organs (e.g., 'leaf', 'stem', 'root') and traits, including spelling variations and abbreviations (e.g. 'SLA' and 'Specific Leaf Area', 'SSD' and 'Specific Stem Density' / 'Wood Density'), complemented by searches in trait databases (TRY, Bien R). *Magnolia* species were searched for in the heuristic literature in 12 texts that are frequently used by landscape architects and urban foresters to account for the varying approaches that urban foresters take to species selection and their own interests or specialisms. Some well-established sources of heuristic literature were not eligible for this study due to opaque evaluation or inconsistent data collection techniques (e.g. the Royal Horticultural Society's AGM scheme). Within the observational literature, climate data was searched using the University of East Anglia's world climate model (accessed at http://sdwebx.worldbank.org/climateportal/), whilst plant records were searched using the online repositories GBIF, Global Plants and the Chinese Online Herbarium, and supplemented by archival searches in herbaria at Oxford University, the Royal Botanic Gardens Edinburgh and Kew (RBGE, RBGK). During these searches we followed the convention established by the IUCN Red List (Rivers *et al.*, 2016) of lumping subspecies and varieties into species accounts as a means of standardising the analysis across different literature sources, with the exception of *M. sieboldii* where practitioners habitually maintain the distinction between *M. sieboldii* and its subspecies *M. sieboldii subsp. sinensis*.

Gathering and tabulating data

Within the heuristic literature, information relating to requirements of water and light were considered more precise than descriptions of hardiness as hardiness is often context-dependent and thus difficult to interpret consistently. These descriptions were recorded as categorical variables followed by a review of the vocabulary used in the publication so that numeric values on a scale of 1-5 could be applied to the categorical variables for resource requirement (1 = low resource requirement, 5 = high resource requirement), similar to the systems used by Ellenberg (1974) or (Bassuk *et al.*, 2009). For example, Hillier Manual of Trees and Shrubs (Armitage, Edwards, & Lancaster (eds), 2014) uses the terms “Good in dry soils,” “Well-drained,” “Moist,” “Plenty of moisture,” and “Wet” to describe optimal growing conditions. These terms were recorded, ordered, and assigned numeric values to reflect this order; in this way, “Good in dry soils” was assigned ‘1’ and “Wet” was assigned ‘5’.

Within the experimental data, the well-established plant economics spectrum identifies key traits that explain plant metabolism and tolerance of stress, such as specific leaf area and plant height (Wright *et al.*, 2004; Díaz *et al.*, 2016). Data for key traits that play recognised roles in plant functioning (Pierce *et al.*, 2017) were gathered and recorded, and filtered for data that recorded growth under normal or control conditions (i.e. data from experimental studies where variables such as drought or soil salinity were studied were excluded). Data was then formatted to SI units to allow comparison.

Within the observational literature, only records of verified observations were included in the study, as reports that describe distribution ranges (such as "between 1800m – 2400m in Sichuan, Henan and Hubei") were considered too vague for inclusion. After positively identifying a plant record, the location of the observation was recorded using Google Maps and decimal coordinates were derived. The decimal coordinates were then used to identify the location with the University of East Anglia's climate model (http://sdwebx.worldbank.org/climateportal/) and mean monthly rainfall and temperature were recorded. Whilst Potential Evapotranspiration (PET) is commonly used in ecotype matching and biogeographical modelling (Haxeltine and Prentice, 1996), we considered that plotting water-energy relations found at each site (sensu Aguilar-Romero et al. (2017)) would allow for a study design that was more sensitive to the relatively small number of population records and potentially have greater explanatory power than a single variable that integrated both water and temperature. To represent energy relations, Warmth Index was considered more sensitive than Mean Annual Temperature (Woodward, Lomas and Kelly, 2004) as this variable accounts for the intensity of energy during growing season, and excludes cold season temperatures which can have a distorting effect on an annual mean. On this basis, we summed the mean monthly rainfall to calculate the annual rainfall and used the mean monthly temperature to calculate Warmth Index using the formula developed by Yim and Kira (1975):

$$WI = \sum (Tm-5), \text{ when } Tm > 5^{o}C$$

(Tm: Monthly Mean Temperature)

Data analysis

Microsoft Excel (v15.26) was used to tabulate the data and RStudio (v1.1.383) was used to manipulate data and carry out statistical analysis. To calculate the number of species discussed in each literature type, records were tabulated, ranking species from high to low (see Table 3) within each literature type (experimental, heuristic and observational). At this point in became clear that there were insufficient experimental data to identify interspecific differences and this literature source was excluded from further studies.

A key cultural perception is that *Magnolia* are generally intolerant of climatic extremes and poor-quality soils, with little variation reported within the genus (Samson *et al.*, 2017). To investigate this, the second step tested the data in the heuristic and observational literatures for normality using the Shapiro-Wilks W test (H_0 = sample distribution is not different from normal distribution), and calculating means for each species' reported resource requirement or the availability of resources in their natural distribution.

Following the results of the Shapiro-Wilks W test, non-parametric analysis of variance was carried out using the Kruskall-Wallis rank sum test to determine whether the means for each species resource requirement or resource availability were significantly different, allowing us to assess the level of inter-specific variation reported in each literature. Due to their different objectives, the heuristic and observational literature reported plant water-energy balances in subtly different ways, resulting in different analyses: in the heuristic literature, preferred provision of water and light were plotted against each other (Figure 5) and using the observational literature, Annual Rainfall (mm) was plotted against Warmth Index (WI) in Figure 6, in effect creating basic Species Distribution Models (SDM). Regression lines and 95% confidence intervals were plotted and the degree of inter-specific variation in each literature type was recorded as R^2, slope and intercept. At this point it became clear that the heuristic literature did not identify significant variation at the inter-specific level and was excluded from further analysis. The last step in answering our second question (the level of precision that the literature describes genetic variation) was to assess whether the observational literature was capable of identifying intra-specific variation: the same process was repeated for each species, plotting Annual Rainfall against Warmth Index and recording R^2, slope and intercept of the regression.

To answer the third question (whether the literature might be able to describe fit between a ecotype and an urban environment under climate change), hypotheses for rear and leading edge populations (Hampe and Petit, 2005) were identified using the SDMs for *Magnolia* species that showed significant regression, and these populations were plotted against selected urban environments in

Northern Europe to identify potential matches between naturally distributed *Magnolia* populations and current urban climates.

Results

Range of species recorded in each literature type

Significant differences between the scope of each literature were identified and are summarised in Table 3: the heuristic literature discussed most of the temperate *Magnolia* species, suggesting a thorough treatment of the genus. Within this literature, most of the sources tended to provide generic descriptions of species' preferred growing conditions and detailed information about horticultural qualities such as flower size or colour. On the other hand, the experimental literature was relatively narrow in terms of the species discussed and uneven in the level of detail to which they were discussed: the large majority of trait data were calculated in controlled studies in north American universities, with especially high numbers of replicates in the studies of *M. fraseri, M. grandiflora* and *M. virginiana*.

Figure 1. Locations of 247 Magnolia populations recorded in observational literature

The observational literature was the most extensive both in terms of species discussed but also in terms of the level of detail provided, with 247 records identified (Fig 1). It was found that the observational literature was limited for some taxa, perhaps due to their limited species distribution (e.g. *M. dawsoniana*), recording bias or geopolitical factors that might affect botanical exploration. Nevertheless, the studies reported represent a small fraction of the records available within herbaria, suggesting that it might be possible to develop a stronger and more robust database of occurrences.

Table 3.Number of times a species is reported in each literature type

Species	Heuristic literature	Experimental literature	Observational literature
M. acuminata (L.) L	11	5	18
M. biondii Pamp.	6	-	14
M. campbellii Hook. F. & Thomson	11	-	7
M. dawsoniana Rehder & E. H. Wilson	7	-	9
M. denudata Desr,	11	3	9
M. fraseri Walter	-	6	17
M. globosa Hook. F. & Thomson	-	-	8
M. grandiflora L.	13	11	7
M. kobus DC	12	2	16
M. liliiflora Desr.	11	1	6
M. macrophylla Michx.	17	2	16
M. obovata Thunb.	7	4	9
M. officinalis Rehder & E. H. Wilson	7	1	12
M. rostrata W.W.Sm.	4	-	11
M. salicifolia (Siebold & Zucc.) Maxim.	8	2	12
M. sargentiana Rehder & E. H. Wilson	8	-	15
M. sieboldii K. Kobch	18	2	15
M. sprengeri Pamp.	7	-	13
M. stellata (Siebold & Zucc.) Maxim.	12	2	6
M. tripetala (L.) L.	9	4	12
M. virginiana L.	19	6	12
M. wilsonii (Finet & Gagnep.) Rehder	10	-	10

Differences between data formats in each literature

Table 4 illustrates the challenges of using the heuristic literature, with criteria for plant behaviour varying greatly between (or sometimes within) sources. This is complicated by the literary style or vocabulary that the sources use, often giving the impression of 'Cinderella' species that require difficult-to-achieve conditions of fertile, moist, well-drained soils, and making it difficult to consistently compare identify distinctive features or nuances of species between sources. Nevertheless, the use of the 1-5 scale allowed this vocabulary to be compared effectively across sources and analysed in later stages.

Table 4. Resource requirements of the eight most commonly-described Magnolia species in the heuristic literature

Species name	Description
M. acuminata	"Responds to rich living, good drainage and plenty of moisture" Hillier Manual of Trees and Shrubs (8th ed)
M. campbellii	"Quite happy in full sun where moisture and humidity levels are high" Gardiner (2000)
M. denudata	"Prefers moist soils" Callaway (1994) "Needs well-drained soils' Bunting (2016)
M. grandiflora	"Does not like dry soils" Gardiner (2000) "Needs fertile, moist, well-drained soil" Burncoose (2018)
M. kobus	"Adaptable to many conditions" Callaway (1994)
M. liliiflora	"Prefers well-drained soils" Brickell (2003)
M. stellata	"Tolerates shade although it is more vigorous and blooms more profusely in sunny locations" Callway (1994)
M. virginiana var. *australis*	"Needs medium to wet soils" Missouri Botanic Garden

The values found in the experimental literature (Table 5) demonstrate that whilst these studies discuss aspects of plant morphology or physiology that are essential for plant functioning and explain aspects of stress tolerance or competitive ability, there is not yet sufficient data to generate meaningful findings to guide urban forestry species selection or to ordinate species within functional schemes in the manner of Reich (2014) or Grime and Pierce (2012). For this reason, the experimental literature was not evaluated further in this study.

Table 5. Mean trait values reported within the experimental literature

Taxa	Plant height (m)	Leaf area (mm)	Leaf dry matter content (%)	Specific leaf area (mm^2/ mg^{-1})	Specific Stem Density (g/cm^3)	Leaf turgor loss point ($\Delta\Psi\pi100$ (MPA))
M. acuminata	27.6	-	-	-	-	0.40
M. denudata	29.3	-	17.32	29.27	0.43	-
M. fraseri	21.5	-	-	22.70	0.40	-
M. grandiflora	14.1	9185	-	9.72	0.44	-
M. kobus	17.8	-	-	-	-	0.26
M. liliiflora	4.0	-	-	-	-	-
M. macrophylla	23.5	-	-	-	-	-
M. obovata	27.7	-	-	12.38	-	-
M. officinalis	20.0	-	-	-	-	-

M. salicifolia	-	-	-	32.82	-	0.35
M. sieboldii	8.0	-	-	-	-	0.39
M. stellata	6.2	-	-	-	-	-
M. tripetala	13.9	-	-	-	-	0.47
M. virginiana	10.0	6912	-	10.28	0.42	-

Whilst the heuristic literature describes the preferred or acceptable conditions for plant growth in horticultural environments, the observational literature reports the actual conditions experienced by trees in their natural ranges, showing that there are both greater inter-specific and intra- specific differences in the Warmth Index than the Annual Rainfall experienced by *Magnolia* populations. Figs 2a & b illustrate these differences (including London as a benchmark for comparison), showing that most *Magnolia* populations are likely to grow in conditions that are slightly warmer and generally with much higher water availability than European urban environments,

Figure 2a. Warmth Index experienced by wild-growing Magnolia species, as reported in the observational literature

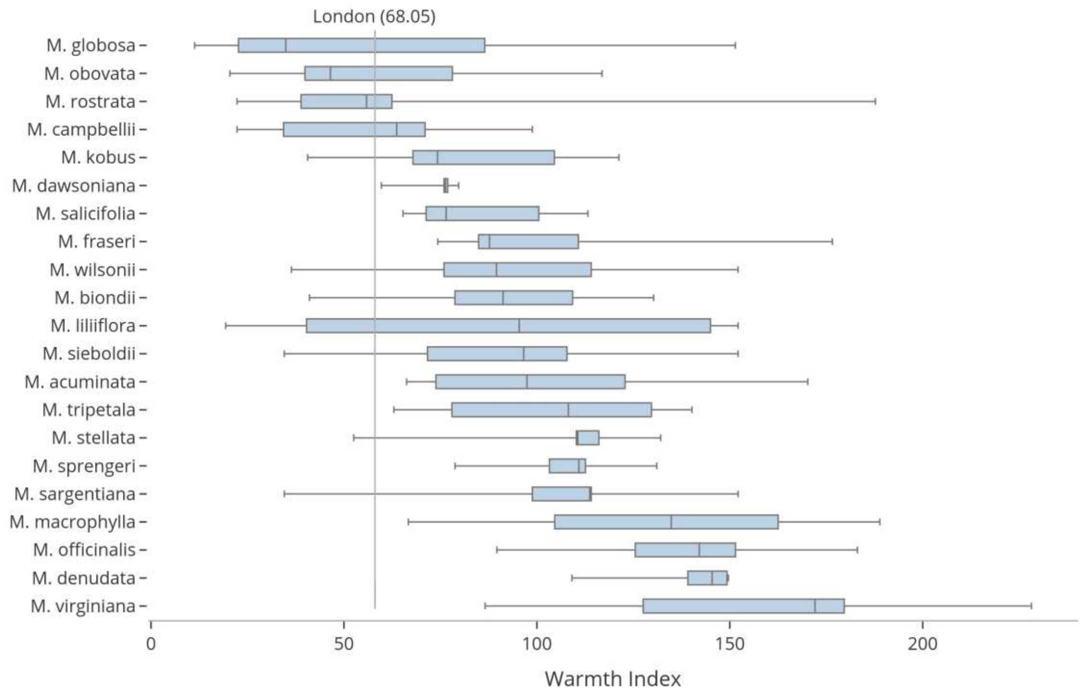
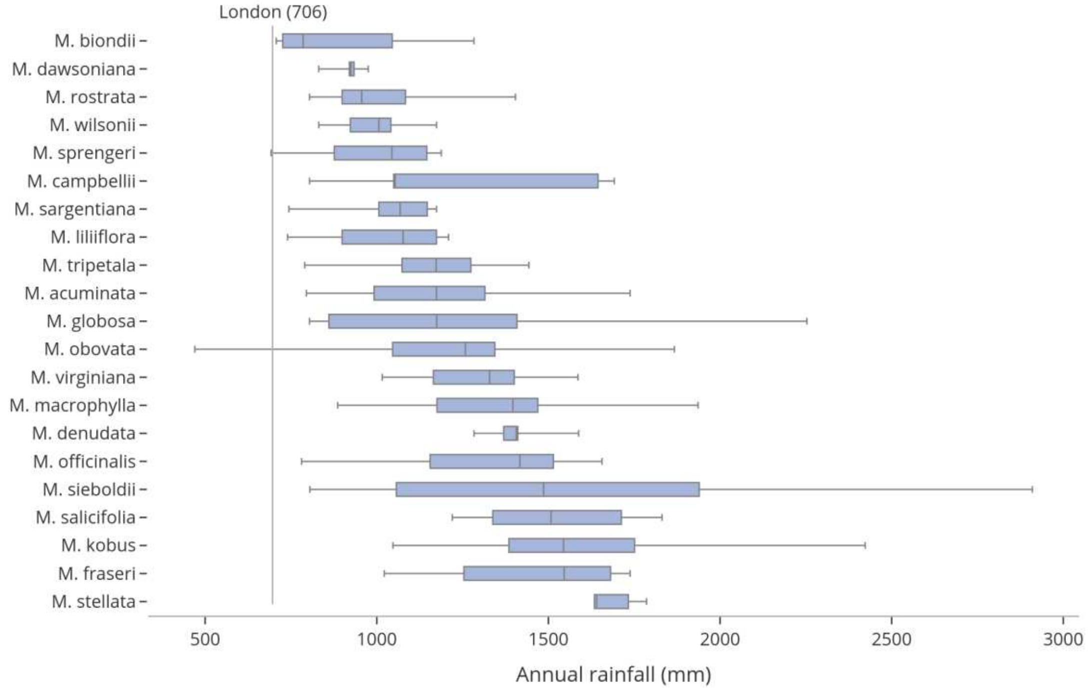


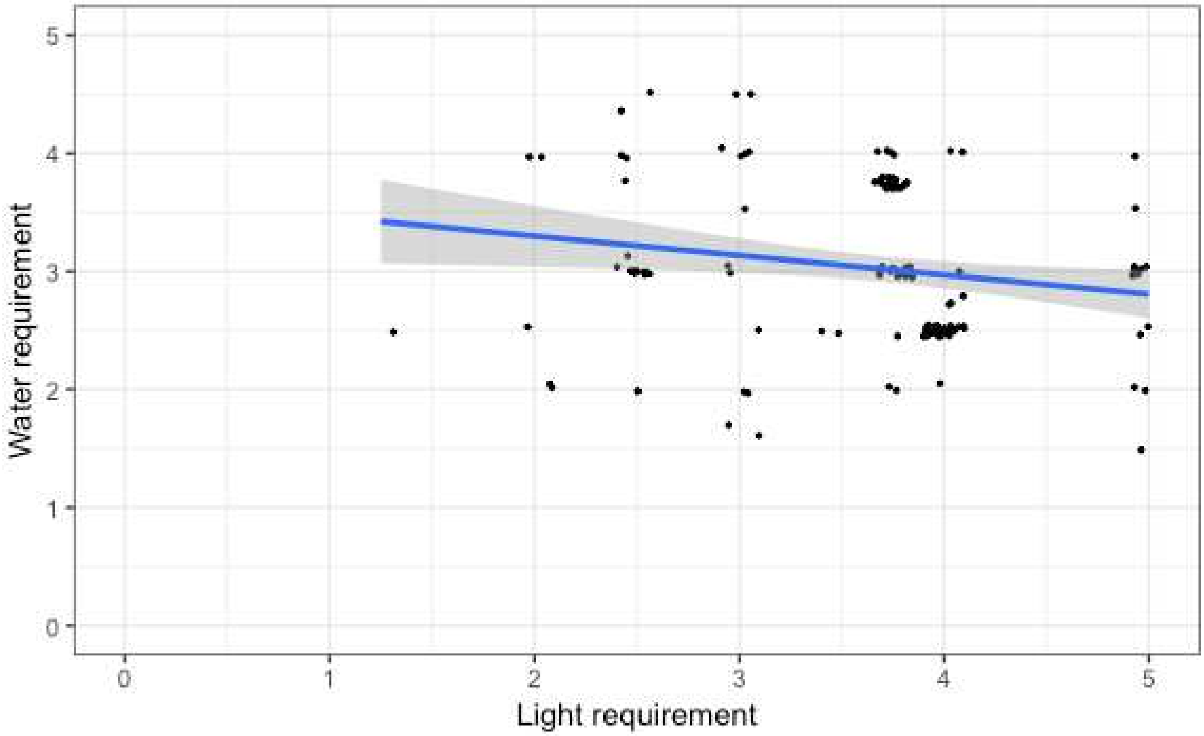
Figure 2b. Annual Rainfall experienced by wild-growing Magnolia species, as reported in the observational literature



Identifying inter- and intra-specific variation

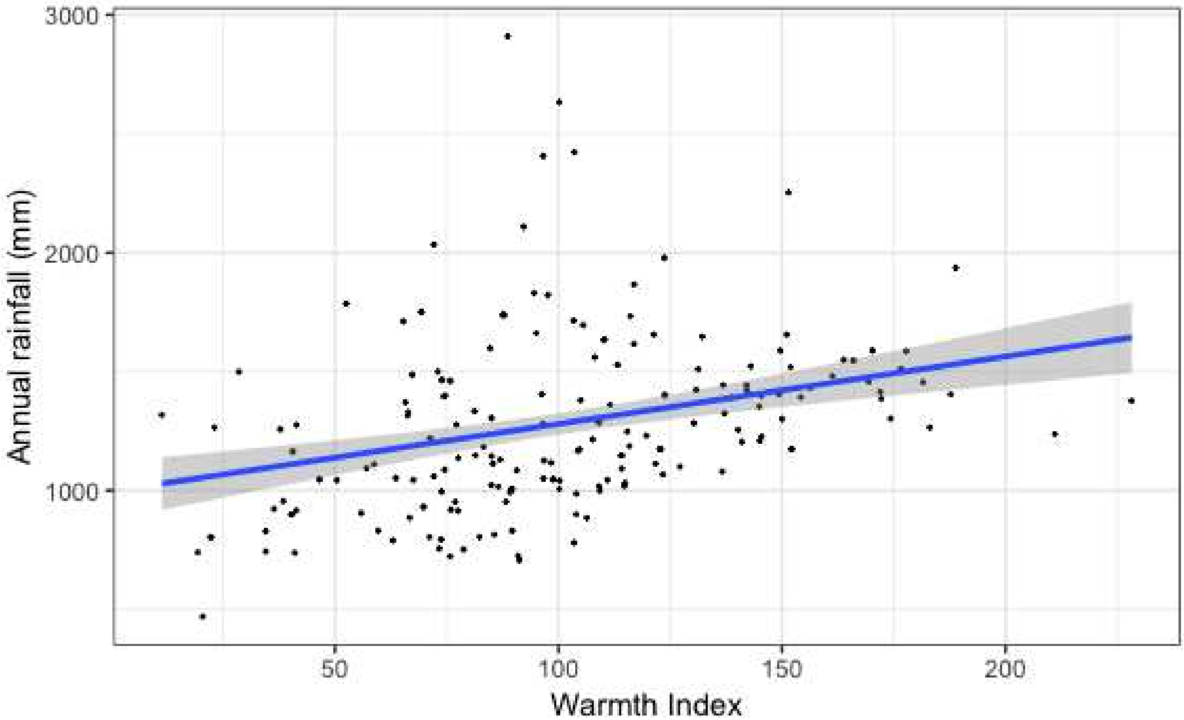
Figure 3 describes the preferred growing conditions for horticultural situations as reported in the heuristic literature, demonstrating that although this literature describes a wide range of species, it identifies weak inter-specific variation in *Magnolia*, suggesting that most Magnolias are fairly similar in a functional sense. Most records suggest that the preferred conditions are for relatively high levels of light and water, with little acknowledgement of how these levels might vary in a global context and little capacity to identify the limits of stress tolerance that they could endure. By contrast, Figure 4 identifies not only a range in experienced conditions but also a potential trade-off in the water-energy balance.

Figure 3. Genus-level description of the preferred conditions for cultivating Magnolias, reported within the heuristic literature



r = -0.1968675, $p \leq 0.1$, n = 204, $R^2 = 0.3199$

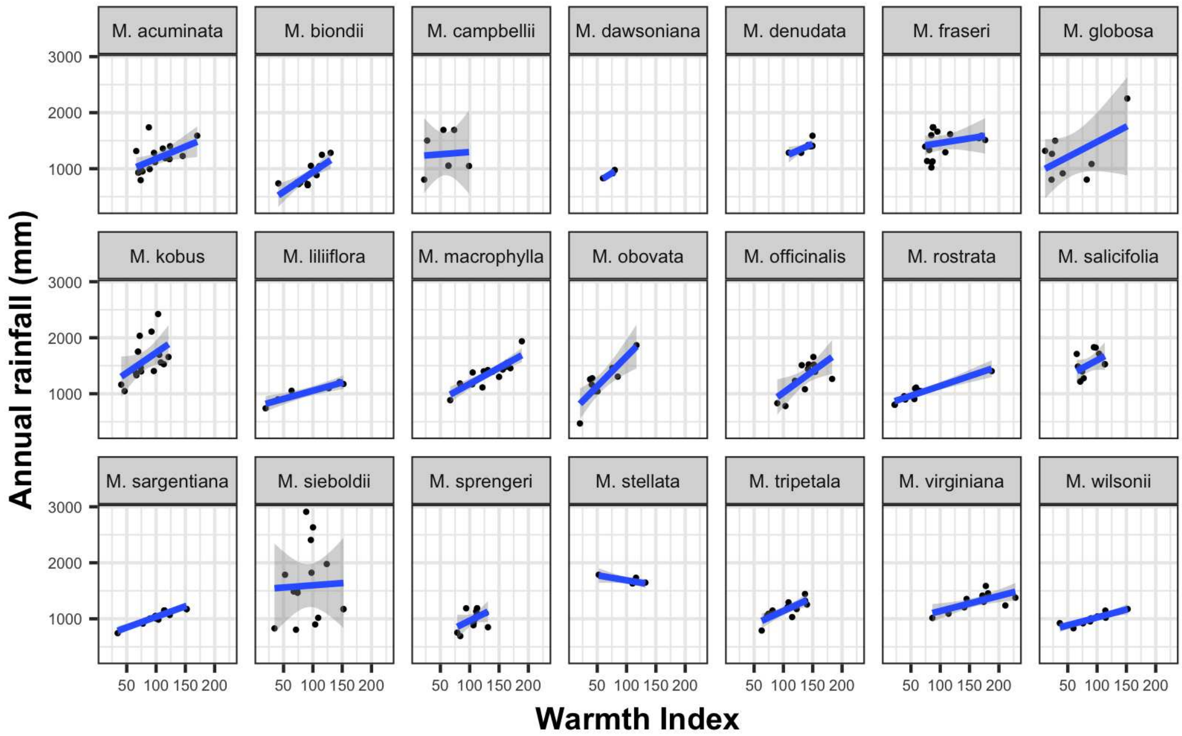
Figure 4. Genus-level distribution model for Magnolias in terms of annual rainfall and warmth index, as reported within the observational literature



r = 0.3161698, $p \leq 0.000001$, n= 248, $R^2 = 0.09629$

On the basis of the weak inter-specific variation found in the heuristic literature, further analysis was only carried out for the observational literature. To explore these inter-specific differences, SDMs for each species were created, again plotting Annual rainfall against Warmth Index in Figure 5. In these models, intercept and slope vary, as does the degree of fit between the regression line and the distribution of populations, with species such as *M. globosa* and *M. sieboldii* showing eurytopic tolerances (i.e., an ability to adapt to a wide range of conditions) and *M. liliiflora, M. rostrata* and *M. sargentiana* showing stenotopic behaviours (i.e., occupation of a restricted range of conditions).

Figures 5. Intraspecific variation in climate niche in 21 wild-growing, deciduous Magnolia species, as reported by the observational literature



Identifying Magnolia populations suitable for urban forestry under climate change

In the final step of the analysis, selected species that showed a range of gradients, intercepts and fit were re-plotted in the context of cities that represent a range of urban forestry conditions (Figs 6a-c). In these figures the regression line of the *Magnolia* species distribution allows hypothetical fundamental niches to be identified and compared with conditions currently experienced by major cities. This study found that the regression line in certain species is very close to environments found in European cities (e.g. *M. biondii, M. officinalis*), suggesting that they would be better fitted to urban forestry applications in some cities than others, and that within these species, certain populations are likely to be particularly well fitted. Nevertheless, even within species that do not show a regression line closely intersecting with some cities, it is not uncommon to find outlier populations that may be appropriate. Across most species it was found that while there was often an overlap between the Warmth Index in northern European cities and naturally distributed *Magnolia* populations, there was typically a shortfall of rainfall in the urban situations, which would create an imbalance in the water-energy relations in urban forestry.

Figure 6a. The climate niches experienced by M. acuminata in relation to those found in selected major cities

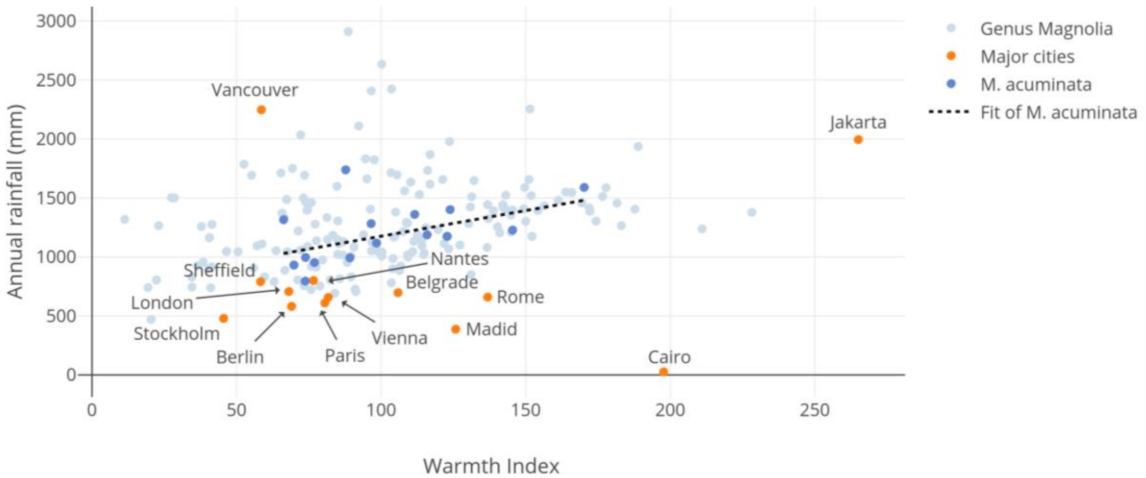


Figure 6b. The climate niches experienced by M. biondii in relation to those found in selected major cities

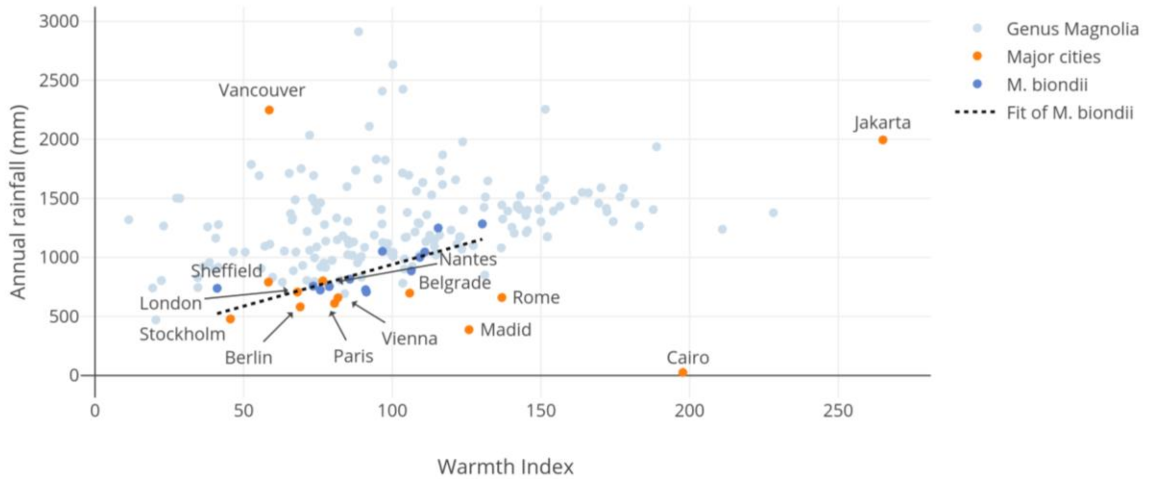
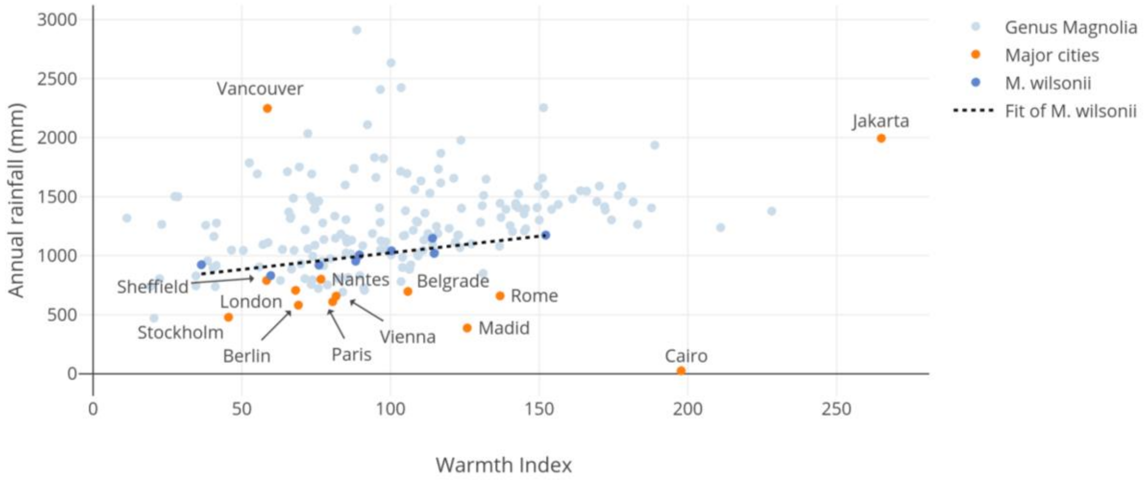


Figure 6c. The climate niches experienced by M. wilsonii in relation to those found in selected major cities



Discussion

Clear differences between literature sources

The results of this literature review demonstrate clear differences between the three literature sources (see Table 6). The experimental literature is highly focussed, offering insights into specific physiological traits and at times, intra-specific variation in response to stresses, but whilst it may yet be possible to create a comprehensive understanding of how functional ecology concepts might influence urban forestry in some genera, this is not currently possible for the genus *Magnolia* given the small number of studies that have been carried out. In addition, there remain numerous methodological issues with recording functional traits that may complicate specification for urban foresters, primarily that individual traits are not significant unless they are contextualised either against other species, or are shown to trade-off against other traits within the same species. Further inherent complications exist with using traits presented in large datasets, such as TRY (Kattge *et al.*, 2011) or Bien R (Maitner *et al.*, 2018), given that the reported traits have been collected on different individuals under different conditions (e.g. some under manipulated conditions (Toledo-Aceves, López-Barrera and Vásquez-Reyes, 2017), others in common garden experiments whilst yet others are gathered in the wild). Other studies in this literature present findings from trait studies but not the data themselves, making them impossible to interrogate or contextualise (Kitaoka *et al.*, 2016; Oguchi, Hiura and Hikosaka, 2017). Attempts to explain trait coordination through strategies or Plant Functional Types are highly attractive and hold great promise for specification in urban forestry but at the time of writing, remain elusive: conceptually elegant schemes such as the Fast Slow Spectrum (Reich, 2014) or the CSR triangle (Pierce *et al.*, 2017) rely upon proxy traits to too great an extent at present to explain functional trait coordination within woody plants. It is not yet clear how leaf data, for example, can be reliable proxies for reproductive traits (which are highly important sources of photosynthetic investment in *Magnolia*), nor how leaf turgor loss point (as reported by Sjöman et al. (2018)) is traded-off against other traits. Whilst a great deal of research has been carried out in these areas for forestry trees, species appropriate for urban forestry and horticulture have not been assessed using the same methodologies and bridging this gap should be a priority for researchers. Perhaps most problematic for this literature is the fact that although relationships between tolerance of stresses such as drought, soil salinity or winter cold have been hypothesised in woody plants and experimentally shown in herbaceous plants (Grime et al. 2007), this relationship has yet to be resolved and does not in itself help urban foresters infer resource demand or optimal opportunities for species selection in urban forest.

The heuristic literature is extensive, but in most cases rather superficial, typically giving an overview of the genus *Magnolia*, making it difficult to compare the qualities of different species let alone the different characteristics of populations found within a species. Much of the focus in this literature is on ornamental qualities rather than functional or ecological aspects, making it difficult to accurately assess the likely fit between a species and a planting situation in urban forestry. Further, the lack of consistent vocabulary across these sources (Table 4) means that factors such as reported hardiness are difficult to interpret consistently, not only because of the variation in hardiness schemes used (this might be either the USDA or RHS hardiness ratings, although some sources discuss hardiness in terms of tolerance of other stresses such as soil alkalinity) but also because different standards have been applied to categorise plants within the scheme and often without using standardised trials.

The observational literature illustrates many of the challenges of using big data to answer practical challenges, the first being the quality of the data that is used. Gathering the records for the plant occurrence data was a long-winded process, with each of the large databases presenting their own challenges: GBIF, for example, holds relatively few verified observations of naturally occurring *Magnolia* populations but offers excellent data transfer capabilities, Global Plants hosts a large number of records but makes data transfer challenging, whilst the Chinese Virtual Herbarium requires translation from Mandarin and an iterative process of positive identification and filtering to derive accurate records. The archival research in herbaria was highly effective but corroborated reports that only a small fraction of plant records are hosted by online databases (Harris and Marsico, 2017; Kirchhoff *et al.*, 2018), and as a result future applications of this methodology should factor in the extensive desktop research. By contrast, climate data was straightforward to derive, with the principal short-comings being the grain and accuracy of the data, especially when assessing urban environments in comparison to their rural hinterlands. Given that urban forestry sites are typically affected by urban heat island effects in combination with localised variation in solar reflectivity, salt spray and soil compaction, this methodology should perhaps be seen as a framework which can guide experimental research rather than a stand-alone decision making tool. Interpolation of climate data for locations between climate stations allows for an estimate to be generated for any given location but it is not clear to what extent these models account for elevation, aspect, slope or surface features, i.e. factors that affect temperature and vapour pressure deficit, which is particularly important in mountainous areas. Nevertheless, temperature and precipitation have been demonstrated to be key determinants of a Grinnellian niche (i.e., the effect of the environment on species distribution (Gravel *et al.*, 2018)) and should data become more nuanced, readily available or easier to use, this methodology would have strong potential for urban forestry specification as it appears to reveal not only intra-specific variation but also the climate niche occupied by various populations, thereby making it possible to match naturally-distributed populations to actual planting locations in designed landscapes. It is not clear at this stage whether the variation found at intraspecific levels are a result of genetic variation, other factors such as Cold Index, timing of resource availability, edaphic factors or cultural processes, or simply due to species occupying ranges outside their fundamental niche but this might also be resolved through more complex studies using hierarchical framework models or more data. From an urban forestry perspective, as opposed to a horticultural process where greater management resources are available, the tipping points that trigger mortality or poor performance are essential to understand and whilst this literature has the potential to explain environmental resource availability, it does not yet reveal the thresholds for fatal decline that are triggered by phenomena such as aseasonal drought or extended periods of anoxia due to soil flooding or mechanical compaction.

Table 6. Efficacy of literature sources for specifying diverse ecotypes of trees in urban forestry

	Heuristic literature	**Experimental literature**	**Observational literature**
Discusses broad range of species	Yes	Yes	Yes

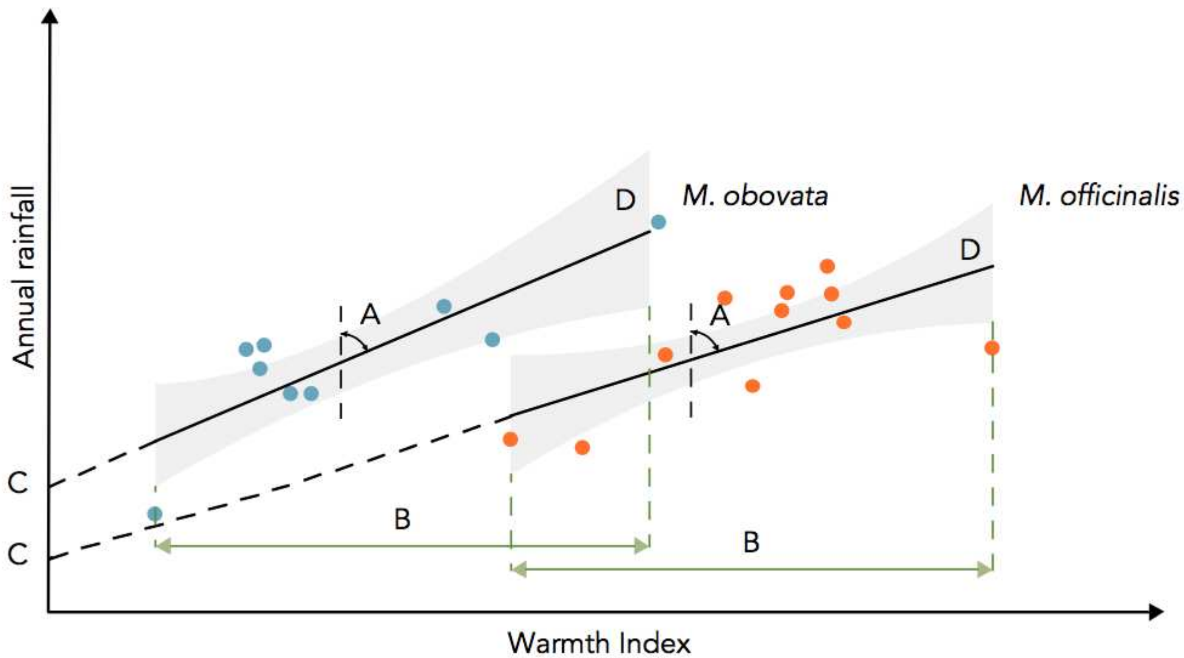
Identifies intra-specific genetic variation	No	Potentially	Yes
Effective at identifying urban-fit species	No	Potentially	Yes
Effective at screening for new ecotypes	No	No	Yes

Species Distribution Models and ecotype matching

The big data held in herbaria and in climate models offer tantalising opportunities to improve urban forestry specification but assessing these data in SDMs needs careful examination to understand their implications. Fig 7 uses the data from *M. obovata* and *M. officinalis,* two closely related species that are often seen as having similar horticultural requirements, to identify four key concepts that demonstrate the practical applications of using SDMs in ecotype selection: the gradient of the slope (A) describes the underlying metabolism of the species, showing how constrained water – energy relations are: a shallow gradient, for example, would indicate that warmth index (energy) is not a constraint upon photosynthesis whilst a steep gradient would indicate that it is a critical factor for growth. Comparing the lengths of the regression lines (B) in each species allows us to ask 'what are the factors that determine the start and end points of slope, and thus limit the distribution of populations within the species?' These limiting factors are likely to be different at each end of the regression line – evapotranspiration may be too great in ranges with high annual rainfall and warmth index, for example, whilst insufficient solar radiation or temperature during the growing season may prevent some populations from creating enough lignin during the growing season to tolerate winter cold. Further, these limiting factors do not need to be lethal in order to be effective, rather they may be just enough to stop physiological or reproductive processes from being sufficiently effective to ensure species range extension. The location of the intercept (C) on the other hand, indicates the relative effect of water as a constraint upon growth, with intercepts higher up the y axis indicating increasing importance of this resource. The 95% confidence interval (D) the regression line indicates the degree of variability between the samples and can be used to assess the robustness of the data. The sum of these subtle differences demonstrates that the two species occupy two different niches, with *M. obovata* distributed in ranges with more rainfall per unit of warmth index than *M. officinalis*, suggesting that *M. obovata* may be more water-demanding than *M. officinalis*.

Future studies should test these hypotheses using other bioclimatic variables such as soil pH, soil oxygen or community-level factors, with trials to test the thresholds for mortality under stress. Such studies would also be able to answer questions of whether the degree of variance from the regression line corresponds to geographic range and whether the regression line corresponds to abundance models along gradients of physical environmental conditions (Cox and Moore 2010).

Figure 7. A conceptual implications of Species Distribution Models for urban foresters



Intra-specific variation is revealed in Species Distribution Models.

Cox and Moore (2010) argue that given the climatic fluctuations of past 2 million years, extant *Magnolia* species are likely to be the most competitive species in the genus's history: species with older phylogenies were often too small and slow-growing to compete with faster growing species as the planet warmed, shaping the possibilities for future evolutionary outcomes. As a result, the range of traits possessed by *Magnolia* species that we observe today are unusually conserved and may, in relation to other genera, present a picture of relatively narrow variation. Nevertheless, as reported in

Quercus (Barbero, Loisel and Quézel, 1992; García-Nogales *et al.*, 2016) and *Nothofagus* (Fajardo and Piper, 2011; Richardson *et al.*, 2013), trees have remarkable capacity to adjust their physiology and morphology to different climates and that these adjustments can be explained either through varying evolutionary strategies to tolerate stress (Grime and Pierce, 2012) or sub-specific / population level genotype or phenotype variation. Understanding the source and level of variation is likely to be critical to successful urban forestry specification and it appears that when combined with target design sites, these basic SDMs are capable of identifying populations of particular relevance both to specifiers who wish to select plants from a particular provenance or for producers who wish to identify populations with particular promise for breeding or selection studies. The 'stable rear edge' of a population identified by (Hampe and Petit, 2005) can be located using these SDMs, making it possible to identify populations with higher levels of genetic diversity- and conversely, leading edges of a population with reduced diversity and therefore a greater probability of possessing specific traits.

Water - energy relations appear to be important drivers of species distribution- and trait variation

Although current climate is not the only factor that affect species distribution or genetic diversity, the energy hypothesis proposed by Hawkins *et al.* (2003) provides a compelling explanation for the distribution of species within two axes of variation. Water-use strategies have been shown to be related to environmental conditions (Baastrup-Spohr *et al.*, 2015; Aguilar-Romero *et al.*, 2017) and the distribution models in Figures 7 and 8 illustrate these mechanisms in genus *Magnolia*, supporting the proposal by Hawkins *et al*. (2003) that water variables tend to be stronger predictors in sub-tropical and warm temperate climates, whilst water-energy variables tend to be stronger predictors in cold temperate regions. There appears to be a strong consensus that climate is a significant determinant of a species range (Normand *et al.*, 2011), with plant trait variation associated with adaption to light and water availability, and a coordinated tolerance of plants to shortages of both resources proposed (Cavender-Bares, Kitajima and Bazzaz, 2004; Castellanos-Castro and Newton, 2015).

Based upon this understanding of water-energy relations, ecologists are modelling environmental niches from traits (Cadotte *et al.*, 2015) but the question for urban foresters is whether the reverse can be modelled, i.e., whether we can speculate that traits vary in accordance to climate niche: this process is well established in commercial forestry in Western Europe, drawing on decades of spruce evaluation but this process is not as developed in broadleaf woody plants. Cavender-Bares et al. (2004) argued that phenotype specialisation explains niche adaptation but it is not yet clear to what extent phenotype traits are inheritable or under epigenetic control. Carmona et al. (2016) offer a potential methodology for resolving using highly complex models that require higher levels of sophistication and data than assessed in this study; similarly, advances in molecular ecology establish links between populations and traits, with Beaulieu et al. (2011) finding relationships between phenotype SNPs and traits, paving the way for marker-assisted selection in tree species.

What have we learnt about using Magnolia species in urban forestry?

Urban foresters wish to maximise the fit between trees and their environment and typically this means knowing whether some species are better suited to certain roles than others: by using the results set out in Fig 6 it is possible to hypothesise that *M. biondii* and *M. wilsonii*, for example, are likely to be well-suited to use in north-western European urban forestry due to the current close overlap between the climatic conditions in their natural habitat and cities in these locations, although this might be expected to evolve under climate change. Designers might use this information to select *M. biondii* as street trees and *M. wilsonii* in situations where shrubbier forms are more appropriate such as stylised-coppice communities: by contrast, it appears that whilst *M. acuminata* displays cold-tolerance, water availability is likely to be an important factor in determining fit and as such, these species might be more appropriate in SuDS environments where a greater water availability can be designed. Most importantly, this research shows it is possible to specify *Magnolia* in urban forestry with much greater precision than the 'species' level, allowing us to identify alternative species or ecotypes based on the constraints of a given location, accounting for micro-climatic variations due to factors such as the albedo effect (which increases evapotranspiration) or SuDS design (which would increase available water in the root zone). The findings demonstrate not only that there are a range of niches occupied by each species (and therefore some degree of niche adaptation) but that the tools to identify these niches and match them to existing and future urban environments exist. This finding creates exciting opportunities for collection strategies and the introduction of new genetic material to horticulture (Kardos and Shafer, 2018).

Future applications and further studies

Following early attempts to use biogeography concepts to specify street trees (Jim, 1988), the availability of large data sets of plant occurrences and climate open new opportunities for urban foresters to reinvigorate this area of research, building upon well-established biogeographical practices (Elith and Leathwick, 2009). Indeed, alongside improving specification practices, urban foresters could become part of climate adaptation and assisted migration strategies if provenance identification and ecotype selection were developed (Fontaine and Larson, 2016). Given the specialist skills required to gather and interpret the necessary data, in the first instance it should be possible to create a proof-of-concept website that pulls plant occurrence data from online data repositories (such as GBIF) and uses a pivot table to interact with climate data, and then perform the basic mathematics to produce a basic SDM for a given species in relation to a urban forestry target sites: although these graphs would draw upon a limited number of occurrences, such an application would powerfully illustrate the capabilities of this line of research and rapidly identify knowledge gaps in other genera.

A similarly important step would be to assess whether climatic factors have the same degree of explanatory power in both natural and designed environments: whilst water-energy balances might account for the greatest degree of fit in 95% cases of naturally-distributed plants (Hawkins *et al.*, 2003), factors such as soil anaerobia, compaction, pollution or disturbance would be expected to play significant roles in urban environments. These relationships could be tested through further desktop studies, using complex hull analysis to incorporate soils data and traits (where available) or in common garden experiments, examining chloroplast and carbon allocation through time under a range of stressful conditions would allow the limits of big data's utility to urban foresters to be explored.

Conclusion

In this paper we review the literature that is available to urban foresters to specify trees and quantitatively review the aims and reliability of the sources. Using *Magnolia* as a case-study genus, we find that there are considerable differences between the literatures, ranging from broad stereotypes of ideal growing environments in the heuristic literature to highly precise, non-contextualised studies examining single traits within a species in the experimental literature. Whilst the experimental literature provides a gold-standard of evidence for understanding plant functioning, only a small proportion of the plants that urban foresters might be interested in have been studied and most of these studies are reported in academic journals, resenting barriers to access. In spite of its short-comings the heuristic literature is therefore the first port of call for most practitioners, with the result that they are unlikely to specify novel species or provenances with confidence.

To overcome this, we identify a new literature source and develop a methodology for ecotype selection that could be used both by urban forestry researchers and the nursery trade, drawing upon well-established biogeographical theory and big data. The development and availability of big data allows urban foresters to harness biogeographical techniques, combining precise, quantitative empirical studies within a holistic understanding of plant-environment relations. Whilst this approach requires further testing in other genera and testing against other variables that affect species distribution and fit, using species distribution modelling holds considerable promise for recognising the fundamental distinction between preferred growing conditions and the environmental limits that trees can withstand, and developing urban forestry discourse and practice.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Bibliography

Acuto, M. *et al.* (2018) *Science and the Future of Cities*. London and Melbourne. doi: 10.13140/RG.2.2.27706.64969.

Aguilar-Romero, R. *et al.* (2017) ‘Differentiation in the water-use strategies among oak species from central Mexico’, *Tree physiology*, 37, pp. 915–925. doi: 10.1093/treephys/tpx033.

Allen, C. D., Breshears, D. D. and McDowell, N. G. (2015) ‘On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene’, *Ecosphere*, 6(8), pp. 1–55. doi: 10.1890/ES15-00203.1.

Allen, J. M. *et al.* (2018) ‘Biodiversity synthesis across the green branches of the tree of life’, *Nature Plants*. Springer US. doi: 10.1038/s41477-018-0322-7.

Azuma, H. *et al.* (2001) ‘Molecular phylogeny of the Magnoliaceae: The biogeography of tropical and temperate disjunctions’, *American Journal of Botany*, 88(8812), pp. 2275–2285. Available at: http://www.jstor.org/stable/3558389.

Azuma, H. *et al.* (2011) ‘Intraspecific Sequence Variation of cpDNA Shows Two Distinct Groups Within Magnolia virginiana L. of Eastern North America and Cuba’, *Castanea*, 76(1), pp. 118–123. Available at: http://www.jstor.org/stable/41301586.

Azuma, H., Toyota, M. and Asakawa, Y. (2001) ‘Intraspecific Variation of Floral Scent Chemistry in Magnolia kobus DC. (Magnoliaceae)’, *Journal of Plant Research*. doi: 10.1007/PL00014006.

Baastrup-Spohr, L. *et al.* (2015) ‘From soaking wet to bone dry: Predicting plant community composition along a steep hydrological gradient’, *Journal of Vegetation Science*, 26, pp. 619–630. doi: 10.1111/jvs.12280.

Barbero, M., Loisel, R. and Quézel, P. (1992) ‘Biogeography, ecology and history of Mediterranean Quercus ilex ecosystems’, *Vegetatio*, 99, pp. 19–34. doi: 10.1007/BF00118207.

Barbrook, J. *et al.* (2018) *The Right Tree in the Right Place for a Resilient Future*.

Bassuk, N. L. *et al.* (2009) *Recommended Urban Trees: Site Assessment and Tree Selection for Stress Tolerance*. Urban Horticulture Institute.

Beaulieu, J. *et al.* (2011) ‘Association genetics of wood physical traits in the conifer white spruce and relationships with gene expression', *Genetics*, 188, pp. 197–214. doi: 10.1534/genetics.110.125781.

Bialecki, M. B., Fahey, R. T. and Scharenbroch, B. (2018) 'Variation in urban forest productivity and response to extreme drought across a large metropolitan region', *Urban Ecosystems*. Urban Ecosystems, 21(1), pp. 157–169. doi: 10.1007/s11252-017-0692-z.

Booth, T. H. (2018) 'Species distribution modelling tools and databases to assist managing forests under climate change', *Forest Ecology and Management*, 430, pp. 196–203. doi: 10.1016/j.foreco.2018.08.019.

Budd, C., Zimmer, E. and Freeland, J. R. (2015) 'Conservation genetics of Magnolia acuminata, an endangered species in Canada: Can genetic diversity be maintained in fragmented, peripheral populations?', *Conservation Genetics*, 16, pp. 1359–1373. doi: 10.1007/s10592-015-0746-9.

Cadotte, M. W. *et al.* (2015) 'Predicting communities from functional traits', *Trends in Ecology and Evolution*, 30(9), pp. 510–511. doi: 10.1016/j.tree.2015.07.001.

Carmona, C. P. *et al.* (2016) 'Traits Without Borders: Integrating Functional Diversity Across Scales', *Trends in Ecology and Evolution*, 31(5), pp. 382–394. doi: 10.1016/j.tree.2016.02.003.

Castellanos-Castro, C. and Newton, A. C. (2015) 'Leaf and stem trait variation and plant functional types in 113 woody species of a seasonally dry tropical forest', *Colombia Forestetal*, 18(50), pp. 117–138. doi: 10.14483/udistrital.jour.colomb.for.2015.1.a07.

Cavender-Bares, J., Kitajima, K. and Bazzaz, F. A. (2004) 'Multiple Trait Associations in Relation to Habitat Differentiation among 17 Floridian Oak Species', *Ecological Monographs*, 74(4), pp. 635–662. doi: 10.1890/03-4007.

Cicuzza, D., Newton, A. and Oldfield, S. (2007) *The Red List of Magnoliaceae*. Cambridge: Flora & Fauna International.

Cires, E. *et al.* (2013) 'Gap analyses to support ex situ conservation of genetic diversity in Magnolia, a flagship group', *Biodiversity and Conservation*, 22, pp. 567–590. doi: 10.1007/s10531-013-0450-3.

Díaz, S. *et al.* (2016) 'The global spectrum of plant form and function', *Nature*, 529, pp. 167–171. doi: 10.1038/nature16489.

Elith, J. and Leathwick, J. R. (2009) 'Species Distribution Models: Ecological Explanation and Prediction Across Space and Time', *Annual Review of Ecology, Evolution, and Systematics*, 40(1), pp.

677–697. doi: 10.1146/annurev.ecolsys.110308.120159.

Fajardo, A. and Piper, F. I. (2011) ‘Intraspecific trait variation and covariation in a widespread tree species (Nothofagus pumilio) in southern Chile’, *New Phytologist*, 189, pp. 259–271. doi: 10.1111/j.1469-8137.2010.03468.x.

Fontaine, L. C. and Larson, B. M. H. (2016) ‘The right tree at the right place? Exploring urban foresters’ perceptions of assisted migration’, *Urban Forestry and Urban Greening*, 18, pp. 221–227. doi: 10.1016/j.ufug.2016.06.010.

Fuller, L. and Quine, C. P. (2016) ‘Resilience and tree health: A basis for implementation in sustainable forest management’, *Forestry*, 89, pp. 7–19. doi: 10.1093/forestry/cpv046.

García-Nogales, A. *et al.* (2016) ‘Range-wide variation in life-history phenotypes: spatiotemporal plasticity across the latitudinal gradient of the evergreen oak Quercus ilex’, *Journal of Biogeography*, 43, pp. 2366–2379. doi: 10.1111/jbi.12849.

Gravel, D. *et al.* (2018) ‘Bringing Elton and Grinnell together: a quantitative framework to represent the biogeography of ecological interaction networks’, *Ecography*, 41, pp. 1–15. doi: 10.1111/ecog.04006.

Hallgren, W. *et al.* (2016) ‘The Biodiversity and Climate Change Virtual Laboratory: Where ecology meets big data’, *Environmental Modelling and Software*. Elsevier Ltd, 76, pp. 182–186. doi: 10.1016/j.envsoft.2015.10.025.

Hampe, A. and Petit, R. J. (2005) ‘Conserving biodiversity under climate change: the rear edge matters’, *Ecology Letters*, 8(5), pp. 461–467.

Harris, K. M. and Marsico, T. D. (2017) ‘Digitizing Specimens in a Small Herbarium: A Viable Workflow for Collections Working with Limited Resources’, *Applications in Plant Sciences*, 5(4), p. 1600125. doi: 10.3732/apps.1600125.

Hawkins, B. A. *et al.* (2003) ‘Energy, water, and broad-scale geographic patterns of species richnes’, (July 2003), pp. 3105–3117. doi: 10.1890/03-8024.

Haxeltine, A. and Prentice, I. C. (1996) ‘An equlibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types’, *Global biogeochemical cycles*, 10(4), pp. 693–709.

Hirons, A. D. and Sjoman, H. (2018) *Tree species selection for Green Infrastructure: a guide for specifiers*.

Hitchmough, J. D. and Bonugli, A. M. (1997) ‘Attitudes of residents of a medium sized town in south west Scotland to street trees’, *Landscape Research*, 22(3), pp. 327–337. doi: 10.1080/01426399708706518.

Hoyle, H., Hitchmough, J. and Jorgensen, A. (2017) ‘Attractive, climate-adapted and sustainable? Public perception of non-native planting in the designed urban landscape’, *Landscape and Urban Planning*. Elsevier B.V., 164, pp. 49–63. doi: 10.1016/j.landurbplan.2017.03.009.

Ippoliti, E. (2015) *Heuristic Reasoning: Studies in Applied Philosophy, Epistemology and Rational Ethics.* Switzerland: Springer International Publishing.

James, S. A. *et al.* (2018) ‘Herbarium data: Global biodiversity and societal botanical needs for novel research’, *Applications in Plant Sciences*, 6(2), pp. 1–8. doi: 10.1002/aps3.1024.

Jim, C. Y. (1988) ‘Street tree study as a theme in urban biogeography’, *Geography*, 73(3), pp. 226–232.

Kardos, M. and Shafer, A. B. A. (2018) ‘The Peril of Gene-Targeted Conservation’, *Trends in Ecology and Evolution*. doi: 10.1016/j.tree.2018.08.011.

Kattge, J. *et al.* (2011) ‘TRY - a global database of plant traits’, *Global Change Biology*, 17(9), pp. 2905–2935. doi: 10.1111/j.1365-2486.2011.02451.x.

Kirchhoff, A. *et al.* (2018) ‘Toward a service-based workflow for automated information extraction from herbarium specimens’, *Database : the journal of biological databases and curation*, 2018, pp. 1–11. doi: 10.1093/database/bay103.

Kitaoka, S. *et al.* (2016) ‘The photosynthetic response of four seral deciduous broad-leaved tree seedlings grown under elevated CO2 concentrations’, *Journal of Agricultural Meteorology*, 72(1), pp. 43–49. doi: 10.2480/agrmet.D-14-00016.

Krajter Ostoić, S. and Konijnendijk van den Bosch, C. C. (2015) ‘Exploring global scientific discourses on urban forestry’, *Urban Forestry and Urban Greening*, 14, pp. 129–138. doi: 10.1016/j.ufug.2015.01.001.

Kreft, H. and Jetz, W. (2007) ‘Global patterns and determinants of vascular plant diversity’, 104(14), pp. 5925–5930. doi: 10.1073/pnas.0608361104.

Maitner, B. S. *et al.* (2018) 'The bien r package: A tool to access the Botanical Information and Ecology Network (BIEN) database', *Methods in Ecology and Evolution*, 9(2), pp. 373–379. doi: 10.1111/2041-210X.12861.

Morgenroth, J. *et al.* (2016) 'Urban tree diversity-Taking stock and looking ahead', *Urban Forestry and Urban Greening*, 15, pp. 1–5. doi: 10.1016/j.ufug.2015.11.003.

Muranishi, S. *et al.* (2013) 'Asymmetric introgression between Magnolia stellata and M. salicifolia at a site where the two species grow sympatrically', *Tree Genetics and Genomes*, 9, pp. 1005–1015. doi: 10.1007/s11295-013-0612-1.

Normand, S. *et al.* (2011) 'Postglacial migration supplements climate in determining plant species ranges in Europe', *Proceedings of the Royal Society B: Biological Sciences*, 278(1725), pp. 3644–3653. doi: 10.1098/rspb.2010.2769.

Oguchi, R., Hiura, T. and Hikosaka, K. (2017) 'The effect of interspecific variation in photosynthetic plasticity on 4-year growth rate and 8-year survival of understorey tree seedlings in response to gap formations in a cool-temperate deciduous forest', *Tree Physiology*, 37(8), pp. 1113–1127. doi: 10.1093/treephys/tpx042.

Ordóñez Barona, C. (2015) 'Adopting public values and climate change adaptation strategies in urban forest management: A review and analysis of the relevant literature', *Journal of Environmental Management*, 164, pp. 215–221. doi: 10.1016/j.jenvman.2015.09.004.

Pelletier, T. A. *et al.* (2018) 'Predicting plant conservation priorities on a global scale', *Proceedings of the National Academy of Sciences*, 115(51), p. 201804098. doi: 10.1073/pnas.1804098115.

Pierce, S. *et al.* (2017) 'A global method for calculating plant CSR ecological strategies applied across biomes world-wide', *Functional Ecology*, 31, pp. 444–457. doi: 10.1111/1365-2435.12722.

Reich, P. B. (2014) 'The world-wide "fast-slow" plant economics spectrum: A traits manifesto', *Journal of Ecology*. doi: 10.1111/1365-2745.12211.

Richardson, S. J. *et al.* (2013) 'Intraspecific Relationships among Wood Density, Leaf Structural Traits and Environment in Four Co-Occurring Species of Nothofagus in New Zealand', *PLoS ONE*, 8(3), pp. 24–26. doi: 10.1371/journal.pone.0058878.

Rivers, M. *et al.* (2016) *The Red List of Magnoliaceae*. London: Botanic Gardens Conservation International.

Roloff, A., Korn, S. and Ã, S. G. (2009) ‘The Climate-Species-Matrix to select tree species for urban habitats considering climate change’, *Urban Forestry & Urban Greening*. Elsevier, 8(4), pp. 295–308. doi: 10.1016/j.ufug.2009.08.002.

Samson, R. *et al.* (2017) ‘Species-Specific Information for Enhancing Ecosystem Services’, in Pearlmutter, D. et al. (eds) *The Urban Forest*. Heidelberg: Springer Nature, pp. 114–144.

Santamour, F. S. (1990) ‘Trees for urban planting : diversity, uniformity , and common sense’, *Agriculture*, 7, pp. 57–65. Available at: http://books.google.com/books?hl=en&lr=&id=SAJQhK1fWDoC&oi=fnd&pg=PA396&dq=Trees+for+urban+planting:+Diversity,+uniformity,+and+common+sense&ots=RklXdDqjbJ&sig=7QcH6Fg_aOv-bY6DefzVboGZBAM.

Serra-Diaz, J. M. *et al.* (2017) ‘Big data of tree species distributions: how big and how good?’, *Forest Ecosystems*. Forest Ecosystems, 4(1). doi: 10.1186/s40663-017-0120-0.

Sjöman, H., Hirons, A. D. and Bassuk, N. L. (2018) ‘Magnolias as urban trees–a preliminary evaluation of drought tolerance in seven magnolia species’, *Arboricultural Journal*. Taylor & Francis, 40(1), pp. 47–56. doi: 10.1080/03071375.2017.1415554.

Toledo-Aceves, T., López-Barrera, F. and Vásquez-Reyes, V. (2017) ‘Preliminary analysis of functional traits in cloud forest tree seedlings’, *Trees - Structure and Function*. Springer Berlin Heidelberg, 31(4), pp. 1253–1262. doi: 10.1007/s00468-017-1543-5.

Vogel, B. and Henstra, D. (2015) ‘Studying local climate adaptation: A heuristic research framework for comparative policy analysis’, *Global Environmental Change*. Elsevier Ltd, 31, pp. 110–120. doi: 10.1016/j.gloenvcha.2015.01.001.

Vogt, J. *et al.* (2017) ‘Citree: A database supporting tree selection for urban areas in temperate climate’, *Landscape and Urban Planning*. Elsevier B.V., 157, pp. 14–25. doi: 10.1016/j.landurbplan.2016.06.005.

Wang, S. *et al.* (2018) ‘Prediction of Lime Tolerance in Rhododendron Based on Herbarium Specimen and Geochemical Data’, *Frontiers in Plant Science*, 9(October), pp. 1–14. doi:

10.3389/fpls.2018.01538.
Wilson, A. (2016) *Future of Cities: The Science of Cities and Future Research Priorities*. Government Office for Science.
Woodward, F. I., Lomas, M. R. and Kelly, C. K. (2004) 'Global climate and the distribution of plant biomes', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 359(1450), pp. 1465–1476. doi: 10.1098/rstb.2004.1525.
Wright, I. J. *et al.* (2004) 'The worldwide leaf economics spectrum', *Nature*. doi: 10.1038/nature02403.
Wright, I. J. *et al.* (2017) 'Global climatic drivers of leaf size', *Science*, 357, pp. 917–921.
Yim, Y.-J. and Kira, T. (1975) 'Distribution of forest vegetation and climate in the Korean peninsula', *Japanese Journal of Ecology*, 25(2), pp. 77–88.