Urban Forestry & Urban Greening 107 (2025) 128784

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Promoting native biodiversity: An evaluation of multifactorial and bioclimatic selection criteria for street trees in Italian cities

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ARTICLE INFO

Keywords:
Green corridors
Native species
Urban ecology
Climatic changes

ABSTRACT

Street trees provide numerous benefits (or ecosystem services) to citizens, as they reduce urban heat, improve air quality, and mitigate intense rainfall events. On the other end, the urban environment is challenging for trees for various reasons, such as water availability, humidity, and increased temperatures (currently exacerbated by current climatic changes). Street trees, however, are rarely chosen according to the benefits they provide or their ecological needs. In Italy, for instance, despite its high biodiversity, species used as urban street trees are relatively limited due to the limited availability of species on the market, historical or cultural preferences, and economic reasons. This study aims to develop a preliminary methodology for selecting native tree species, considering their ecological requirements and potential suitability for the urban environment, factoring in the future warming of temperatures. Our proposed methodology consists of culling species from floristic databases and applying a series of ecological and bioclimatic filters to obtain a list of species that can potentially be used as street trees. When we applied our methodology to Italian cities, we obtained a list of 190 native species (among which 44 species are already used as street trees) that can potentially be recommended for the urban habitat. On the other hand, our analysis highlighted an underutilization of several native species (39 species) and that many species (177) are not suited for the climatic context in which they are used. Our results also suggest a pool of species (22 already used as street trees and 19 not used) that, in the Italian context, can be better suited to withstand the expected temperature increases. The selection of species should primarily be based on their being native but also on their ecological requirements to increase urban biodiversity, reduce tree mortality, and reduce management costs.

1. Introduction

The global urban population is increasing and will continue to grow, impacting not only the environment but also the socio-cultural fabric of cities (Henderson, 2010; Hoornweg and Pope, 2017). Cities are significantly affected by the current climatic changes, facing escalating temperatures and altered precipitation patterns, which exacerbate the urban heat island effect and increase the likelihood of flooding (Kumar et al., 2024; Mullaney et al., 2015; Tan et al., 2021). As part of the urban green infrastructure, street trees provide numerous environmental and social benefits in contemporary urban settings. They enhance environmental quality, mitigate climate change impacts, and promote human well-being in urban environments (Mullaney et al., 2015; Salmond et al., 2016; Soares et al., 2011). By providing shade, improving air quality, moderating temperatures, and reducing stormwater runoff, street trees contribute to making urban ecosystems more sustainable and livable and possibly more resilient to future climatic changes (D'Amato et al., 2023; Bartoli et al., 2022; McPherson et al., 2016; Revelli and Porporato, 2018; Salmond et al., 2016; Tan et al., 2021).

However, different tree species provide these benefits to variable extents and have different ecological requirements and needs. They should also have some characteristics for enduring the harsh environmental conditions of cities. For instance, these species should be robust (without significant phytopathological problems), hardy, and aesthetically pleasing (Donovan and Butry, 2010; Liu and Slik, 2022; Savo et al., 2024; Yau, 1982), providing multiple ecosystem services while

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https://doi.org/10.1016/j.ufug.2025.128784
Received 30 September 2024; Received in revised form 16 March 2025; Accepted 16 March 2025
Available online 24 March 2025

mitigating potential disservices (Von Döhren and Haase, 2019). Trees have different tolerance to drought, heat, air pollution, and root confinement, and these elements are crucial to consider for enhancing root development, tree growth, canopy expansion, and improving tree stability in urban environments (Grabosky and Bassuk, 2016; Mullaney et al., 2015; Ow et al., 2018; Ow and Ghosh, 2017). Biodiversity is also a factor to consider when setting an urban tree species. Planting multiple native tree species can prevent the homogenization of the urban flora (Alvey, 2006; Liu and Slik, 2022; Mata et al., 2021; Mullaney et al., 2015). At the same time, vegetation complexity and connectivity help maintain higher urban biodiversity levels (Threlfall et al., 2017).

In a previous study on Italy's street trees (Bartoli et al., 2022), we determined the biodiversity of street trees in 15 Italian cities across various bioclimates, identifying a wide number of species (277). In Caneva et al. (2020), we highlighted historical motivations and urban changes that have driven the establishment of street trees, such as programs of urban reconfiguration and beautification during the Napoleonic era (Caneva et al., 2020). Today, the urban reforestation guidelines, approved by the Ministry of Environment and Ecological Transition and developed within the PNRR project, provide key guidelines for planting native species within Italian metropolitan areas. These guidelines aim to restore cities' potential vegetation (Ministry of the Environment and Ecological Transition, MASE, 2021). While street trees are not explicitly mentioned in the urban reforestation plan, they also contribute to making cities greener and more sustainable (Seamans, 2013; Turner-Skoff and Cavender, 2019; Savo et al., 2024). According to this plan, only native woody species, subspecies, and local ecotypes should be used in urban forestry. Also, according to the FAO Guidelines on Urban and Peri-urban Forestry (Salbitano et al., 2016) and research in the international literature (de Barros Ruas et al., 2022; Hou et al., 2023), urban forests should also prioritize the conservation of native vegetation and species as they are the most threatened by urbanization.

Some studies argue that exotic species can better withstand projected climatic changes in urban environments (Borden and Flory, 2021). Others even argue that non-native species can provide more benefits than native species (Conway et al., 2019; Schlaepfer et al., 2020). In regions where native biodiversity is low and native trees are less resistant to challenging urban environmental conditions, exotic trees can increase urban plant biodiversity (Sjöman et al. 2016). Exotic and native species can both provide various ecosystem services, depending on their functional traits (Savo et al., 2024). Other benefits often sought in exotic species are primarily aesthetic, while the ecological benefits provided by native species outweigh those provided by exotic species (de Carvalho et al., 2022). In an Italian context, research has suggested that native species can also be more tolerant to the specific local environmental conditions and have a better chance of survival in the mid and long-term compared to biogeographically and ecologically incoherent species, subspecies and individuals (Capotorti et al., 2016; Frigerio et al., 2023).

Yet, street tree species are still mostly chosen without considering their potential ecological role within, or suitability for, the urban environment (Farrell et al., 2022; Savo et al., 2024). Therefore, this study aims to develop a multifactorial evaluation method for selecting native tree species based on ecological requirements, factoring in their suitability for urban environmental conditions. Given the high variability of the bioclimatic conditions in Italy, this study also aims to identify potentially suitable native species not currently utilized in Italian cities that have wider tolerance for changes in bioclimatic conditions and, as such, that could possibly be more resistant to future climatic conditions.

2. Materials and methods

We developed a methodological approach that can be useful in selecting native tree species potentially suitable for urban streets. This selection process involves several steps of culling species and interpolating available data (Fig. 1). The general methodological proposal and a preliminary application of the methodology to the Italian context are detailed in the following paragraphs.

2.1. *The first set of keys of the species selection process: floristic, structural and biogeographic parameters*

We assumed that the first step of the selection procedure (Fig. 1, point 1) should determine which are the "*wild*" species, i.e., plants that grow spontaneously in the wild (native species and naturalized species), of the considered country. As a second step, we should then apply a structural filter (i.e., the growth form of the species) and select the wooden species, such as arboreal phanerophytes (P scap= Arboreal Phanerophytes), from the wild species pool (Fig. 1, point 2). However, we also included shrubby phanerophytes that could be planted and managed as trees (P scap/P caesp, P caesp = Shrubby Phanerophytes, NP =Nano-Phanerophytes; https://www.actaplantarum.org/) with a height of three or more meters. We have not included shorter shrubs because they cannot provide the benefits usually sought in street trees; also, in natural vegetation, they generally represent early-succession species with slow growth, and, as such, their cultivation and management as street trees would require an excessively high effort. As a third step (Fig. 1, point 3), we applied a biogeographical filter, selecting native and archaeophyte species and obtaining the first pool of native tree species. We also included archaeophyte species because although they are exotic, they were introduced in ancient times and are now naturalized and integrated into the local flora (Preston et al., 2004). This first set of keys should produce a list of trees and tall shrubs that grow naturally in the analyzed country.

2.2. *The second set of keys of the species selection process: Usage (as street trees) and bioclimatic characterization of the cities*

The bioclimatic conditions can strongly influence the growth and health of street trees (McBride and Laćan, 2018; Brandt et al., 2021). To create a pool of species that are suitable for several cities within a country, we should consider all its different bioclimatic regions and ecoregions. Instead, suppose we want to select street tree species for a specific city. In that case, we should only consider its bioclimatic region or ecoregion (whether we want to keep our options more or less open). The bioclimatic characterization of a country or a city can be evaluated using climatic data and/or the worldwide characterization of Rivas-Martinez et al. (2011).

At the same time, in this step, we should search for species already used as street trees in the country, regions, ecoregions, or cities of interest. We can use bibliographic or satellite data, field surveys, municipality inventories, etc. For instance, if we want to obtain a pool of street tree species countrywide, we can select representative cities within the country located in the various bioclimatic regions and ecoregions (Fig. 1, points 4,5). Once we have assembled the dataset of the street trees, we need to apply the biogeographical filter (Fig. 1, point 3) to recognize the native, archaeophyte, and exotic species used in the cities. This second step can parallel the first, as these two steps produce two separate datasets.

2.3. *The third set of keys of the species selection process: Ecological features of the species*

The urban environment may be quite different from a natural one and, hence, it might present ecological challenges for the urban flora (Aronson et al., 2017). To sort out the species that are already adapted to the urban environment (within Appendix 1), we need to screen the literature reporting guidelines for the urban reforestation of the analyzed country (or region, ecoregion, or city) or dealing with the natural potential vegetation of peri-urban areas (Fig. 1, point 6). The first choice would be a guideline that rules urban reforestation, but if not available, it will become necessary to analyze other literature of reference or make further ecological evaluations. The second choice would

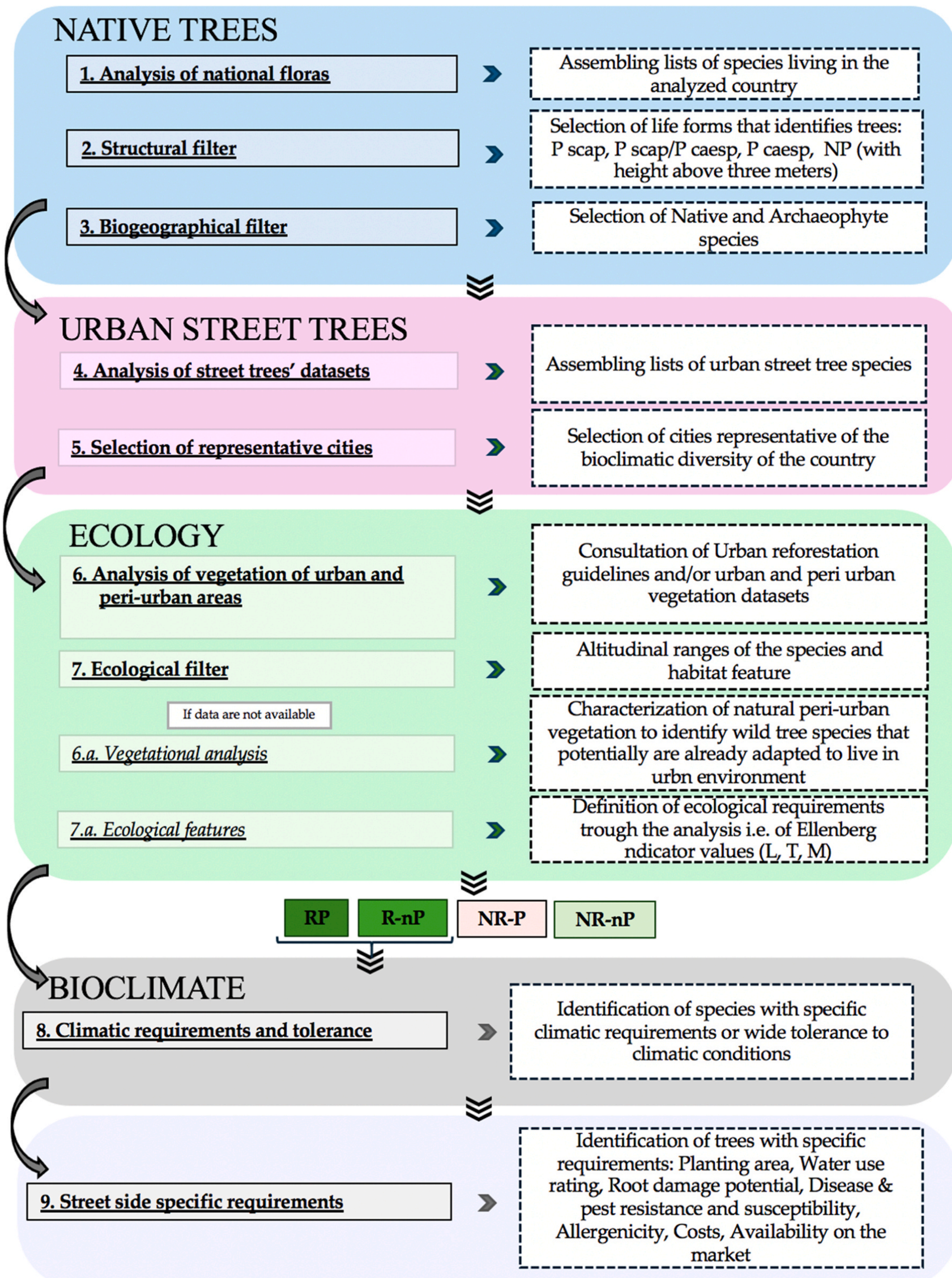

Fig. 1. Structure of the selection keys and filters for choosing street tree species. The first set of keys (1−3) produces the first tree species pool. The second set of keys (4−5) produces a second tree species pool. Both pools are then compared with (eventually) available lists of species that are suitable for urban environments (suggested by guidelines and/or research) or filtered using the ecological filters (either 6 and 7 or 6a and 7a). At this point, datasets are cross-referenced to produce four groups of species. Notes [RP]: species Recommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) from a bioclimatic perspective for the analyzed cities and already Present as street trees; [R-nP]: species Recommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) but not Present as street trees; [NR-P]: species Not Recommended in the urban reforestation guidelines (or not ecologically congruent with the urban environment) but Present as street trees in the considered cities; [NR-nP]: species Not Recommended (or not ecologically congruent) and not Present as street trees; L: Light, T: Temperature, M: Moisture.

be the literature reporting the characterization of the natural vegetation (Fig. 1, point 6a) in the peri-urban areas to obtain a checklist of the potential tree species suitable for our city of interest. If this kind of literature is also unavailable, it would be useful to screen vegetation classes according to the phytosociological method developed by Braun-Blanquet (1932). In this method, data on the presence of plant species are combined with quantitative data related to species' cover. Specific species tend to group according to similar ecological needs (plant association). These associations constitute bioecological units and, hierarchically, are grouped into larger clusters of vegetation types with similar ecology (classes) (Ivanova, 2024). These vegetation classes can be found in digital platforms such as FloraVeg (https://floraveg.eu) or specific literature reporting vegetation studies carried out in the analyzed country. The application of this methodology to peri-urban habitats can provide the characterization of species and communities that would naturally grow in the city (i.e., that potentially constitute the natural vegetation of the area). However, given that spontaneously occurring species do not invariably demonstrate adaptability to urban environments, the selected tree species should be screened and filtered considering also other features as those suggested here (point 7 and onwards).In the selection process, point 6a might replace point 6. Regardless of the path we take (either 6 or 6a), we need to consider only appropriate woody species (see point 2, structural filter) as some species (short shrubs) may not be suitable for urban and street environments.

Another useful screening would entail evaluating the species' ecological features (Fig. 1, point 7) considering their ecological niche and altitudinal range. The ecological niche can be considered as the multidimensional space defined by the set of abiotic variables within which a species persists (Colwell and Rangel, 2009). To reduce the dimension of our species pool, we should also eliminate the species linked to particular habitats (e.g., strictly saline, sandy, rocky, riverine, alpine). Moreover, the altitudinal range is generally an ecological limiting factor for the growth of plant species. Indeed, species with similar ecological requirements for this factor (i.e., altitude) usually cluster into vegetation types distributed along altitudinal ranges. However, these vegetation types may vary across countries, as latitude also influences the general climatic conditions. As such, the subsequent step in the selection process is evaluating the requirements of tree species for the altitudinal range in relation to the evaluated cities. If these data about the species are not available, we should consider the parameters of the Ellenberg index (Tichý et al., 2023 and references therein), which in general describe the growing requirements of a given species as regards light (L), temperature (T), continentality (C), moisture (M), pH (R), nitrogen (N), and salinity (S). We considered only the parameters (L), (M), and (T) that are mostly limiting in the urban environment (Fig. 1, point 7a). Regarding the Ellenberg values concerning the parameters mentioned above, we recommend considering values of $T \geq 5$, $M \leq 5$ but ≥ 3, and $L \geq 5$ (Pignatti et al., 2005). However, these values should change according to the bioclimatic and geographical characteristics of the analyzed country/cities.

2.4. *Cross-referencing junction of the species selection process: Categorization of street tree species*

Once all the above-mentioned filters are applied, we will obtain three pool of species that should be cross-referenced. The first species pool includes filtered wild tree species. The second pool of species consists of trees already used as street trees, and the third pool consists of trees ecologically suitable for an urban environment, according to the literature. If all three pools are available, the cross-referencing process should yield four possible pools of species:

[**RP**]: species **R**ecommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) from a bioclimatic perspective for the analyzed cities and already **P**resent as street trees.

[**R-nP**]: species **R**ecommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) but **n**ot **P**resent as street trees.

[**NR-P**]: species **N**ot **R**ecommended in the urban reforestation guidelines (or not ecologically congruent with the urban environment) but **P**resent as street trees in the considered cities.

[**NR-nP**]: species **N**ot **R**ecommended (or not ecologically congruent) and **n**ot **P**resent as street trees.

The categorization resulting from this cross-referencing can help us identify a pool of species that could be used as street trees in different climatic contexts. To improve the biodiversity of native species, we should especially focus on the species that are recommended but not used [R-nP].

2.5. *The fourth set of keys for the species selection: the bioclimatic range of the species*

As a final step, we included a final screening to point out the species that can thrive in a larger range of bioclimatic conditions (Fig. 1, point 8), especially in the perspective of the future increasing temperatures. As such, it is possible to group the species in relation to their ecological requirements for temperature and precipitation (Schulze et al., 2005) (i.e., Thermophilic species, Mesophilic species, etc.).

2.6. *The fifth set of keys for the species selection: street-side specific requirements*

The selection keys from points 1–8 (Fig. 1) can be eventually used to select any other kind of urban trees (i.e., trees for urban parks, gardens, etc.), just removing the consultation of street trees' datasets (Fig. 1, point 2) and the consequent cross-referencing (Fig. 1, between point 7 and 8). On the other hand, an additional key point of the selection process (9) entails screening the specific features that might be required for living along streets. These features, however, might vary across countries, cities, and even within the same city, as they should be tailored to the specific planting site. These features include the planting area (the space required by the species to thrive), water use rating (the general requirements in terms of watering), root damage potential (UFEI; https://selectree.calpoly.edu/), disease & pest resistance and susceptibility (UFEI, EPPO; https://gd.eppo.int/), allergenicity (UFEI), costs, availability on the market. Data on these features can be found online (UFEI, EPPO) or by consulting scientific literature of reference (e.g., Cariñanos and Marinangeli, 2021; D'Amato et al., 2023). Instead, for the last item on the list, we suggest searching the costs of the specimens (which may also vary with their age) by consulting plant nurseries in the country where the methods are applied.

2.7. *Application of the methodology to the Italian context*

We applied our methodology to the Italian context for a preliminary screening of street tree species, using the first eight sets of selection keys. We excluded the last set of keys as they are site-specific. For our case study, we applied the first set of keys (1) to select wild plant species of Italy, consulting the available Italian Floras (Pignatti, 2017; https://www.actaplantarum.org/; https://dryades.units.it/home/?lang=it). Using the same bibliographic sources, we were able to filter (2) the wild species to obtain a pool of trees (i.e., we culled the species according to their life form). At last, to apply the biogeographical filter (3) (i.e., to separate native and archaeophyte species from the allochthonous species), we consulted the checklist of the Italian vascular flora (Bartolucci et al., 2018, 2024) and the checklists of the Italian allochthonous species (Celesti-Grapow et al., 2010; Galasso et al., 2018).

We applied the second set of keys to build a (4) dataset of street tree species present in Italian cities, consulting the databases of urban street trees collated in previous papers (Bartoli et al., 2022; Caneva et al., 2020; D'Amato et al., 2023). Then, we characterized the (5) bioclimate of Italy, which falls within a Mediterranean climate that shifts into a

Temperate bioclimate (Fig. 2) (Pesaresi et al., 2014; Blasi et al., 2018). Finally, we selected the cities that are deemed representative of each bioclimate (Blasi et al., 2018): Turin, Milan, Padua, Bologna, and Florence, which fall within the Temperate bioclimate, and Rome, Naples, Cagliari, Bari, and Palermo, which have a Mediterranean bioclimate (Table 1) (Fig. 2). Once we had assembled the street tree dataset, we culled the exotic species (i.e., applying the biogeographical filter, point 3) to obtain a list of native and archaeophyte trees.

To apply the third set of keys, we consulted the Italian guidelines for urban reforestation (6), which suggest species suitable for the urban reforestation of Italian cities (MASE, 2021). Specifically, these guidelines provide lists of species for several major Italian cities. Among these species are mostly trees but also some short shrubs that are unsuitable as street trees. Therefore, from these species lists, we selected only suitable tree like species (i.e., structural filter, point 2).

We compared our list of native tree species with the lists of street trees and the list of species suggested by these guidelines (MASE, 2021) for the same cities. We obtained a matrix of potential street tree species *x* city, subdivided into the four above-mentioned categories (RP, R-nP, NR-P, NR-nP) (Appendix 1). We evaluated the distribution of R-nP that are RP in at least one city to understand if these species are underused in street tree planting campaigns. From Table 2, we calculated, for each species, the percentage of each category (RP, R-nP, NR-P, NR-nP) in relation to the number of cities falling within the two bioclimates of Italy.

Finally, we applied the fourth set of keys. Specifically, in relation to which bioclimatic area the selected cities and the vegetational cluster identified in MASE (2021) fall, we (7) divided the species into:

- *Thermophilic species*: plants adapted to living in warm or mild temperate climates.
- *Mesophilic species*: plants adapted to living in cold and temperate climates that need moderate amounts of water.

Fig. 2. The bioclimatic classification of the Italian peninsula with the analyzed cities (modified from Blasi et al., 2018).

- *Meso-thermophilic species*: plant species that can thrive in both bioclimatic regions, which are potentially more tolerant to the different climatic changes that can occur in Italy (i.e., drier conditions in Southern Italy and wetter conditions in Northern Italy; Faggian, 2021).

Then, we performed a comprehensive analysis concerning the bioclimatic congruence of the Recommended tree species (RP, R-nP) to understand the bioclimatic range of the different species. Specifically, we calculated the percentage of cities where the species was RP or R-nP in the two bioclimates of Italy.

3. Results

3.1. Selection of street tree species in the Italian context

Fig. 3 summarizes the application of the methodology to the Italian case study. We have applied all the selection keys but one, specifically those related to the street-side-specific requirements. As already mentioned in the methods, this last set of selection keys includes the screening of features that are site-specific and, as such, cannot be generalized.

Starting from the numerous species listed in the flora of Italy (7620 species), we performed the first selection filter (analysis of national flora and structural filter; points 1 and 2 of Fig. 2), which led to a significant reduction in the number of species that can be potentially used as street trees (377 species) (Fig. 3a). Cross-referencing this list of species with the dataset of street trees related to the selected cities (265) and the urban reforestation guidelines (140) allowed us to recognize 367 species divided into four groups of species. These groups include: a first pool of species with 190 native and archeophyte trees, of which 44 species have been recommended by the reforestation guidelines (MASE, 2021) and are currently present as street trees in the analyzed cities (RP); 39 are suggested by the reforestation guidelines, but not present as street trees (R-nP); 19 are archaeophytes (NR-P(A)) and 88 not recommended and not present (NR-nP) (Fig. 3b). The last 177 species are exotic neophytes present as street trees (NR-P). At last, we applied the bioclimatic filter and differentiated 19 Mesophilic, 22 Thermophilic, and 42 Meso-thermophilic species (Fig. 3c). We report the selection of the Recommended species in Table 2. Here, we differentiated the RP species, which includes trees that are present in at least one of the analyzed cities, from the Rn-P species, which includes only those species that are not used in any of the considered cities.

3.2. Evaluation of species as potential street trees in the different bioclimatic ecoregions of Italy

Fig. 4 highlights the species recommended by the Italian reforestation guidelines but not used (R-nP, in dark green), even if they could be ecologically suitable. In some cases, certain species are present in at least one city in the same ecoregion but can also be suitable for other cities within the same ecoregion. This figure also highlights that some species are planted out of their ecoregion, so they are not coherent from an ecological point of view, also in relation to the urban reforestation guidelines (MASE, 2021). More species are ecologically congruent but not used (R-nP) in the Temperate ecoregion (Fig. 4a, dark green) than in the Mediterranean ecoregion (Fig. 4b, dark green). In some cases, however, they are present in at least one city in the same ecoregion. For instance, in the temperate ecoregions, we can find *Corylus avellana, Quercus cerris, Carpinus betulus, Prunus avium, Ulmus minor, Fraxinus ornus,* and *Quercus robur*; while in Mediterranean ecoregions we highlight *Arbutus unedo, Fraxinus ornus,* and *Quercus pubescens*. In other cases, they are instead recommended in some cities and not used but present in others. For instance, in the temperate ecoregions, we can find *Arbutus unedo, Viburnum tinus,* and *Tamarix gallica*; while in the Mediterranean ecoregions, we highlight *Alnus glutinosa, Cornus mas,* and *Acer opalus*.

Table 1
Terrestrial ecoregions of the analyzed Italian cities with their main bioclimate*.

Terrestrial Ecoregion		Sections	subsections	Cities	Altitude	Mean T(°C) 1980	Mean T(°C) 2020	P ∑(mm) 2020
TEMPERATE MACROCLIMATE	Po Plain Province	Temperate semi-continental	Western Po basin subsection	Turin	239 m	11.4°	13°	582
		Temperate sub-continental	Central Plain subsection	Milan	120 m	11.7°	14.3°	869
				Padua	12 m	12.2°	14.8°	704
	Appennine Province	Temperate semi-continental		Bologna	54 m	12.5°	14.8°	567
			Tuscan basin subsection	Florence	50 m	12.8°	16°	646
MEDITERRANEAN MACROCLIMATE	Tyrrhenian Province	Mediterranean oceanic	Rome area subsection	Rome	21 m	14.3°	16.6°	624
			Western Campania Tyrrhenian subsection	Naples	17 m	14.5°	17.2°	523
			Southwestern Sardinia subsection	Cagliari	4 m	15.9°	17.8°	365
			Western Sicily subsection	Palermo	14 m	17.8°	18.7°	418
	Adriatic Province	Mediterranean oceanic	Murge and Salento subsection	Bari	5 m	15.3°	17.6°	507

(*bioclimatic classification according to Blasi et al., 2018 and climatic data from visualcrossing.com (https://www.visualcrossing.com/). Notes: T = Temperature; P = Precipitation; C°= Celsius degrees; ∑= Sum.

3.3. *Tree species in the Italian context in relation to their bioclimate coherence*

Fig. 5 presents a comprehensive analysis of the tree species concerning their different bioclimatic congruence. Among the species recommended and used in both bioclimates are *Meso-thermophilic* species already used as street trees (dark blue and dark orange in Fig. 5a) that potentially have a wider range of tolerance concerning climatic factors (i.e., *Celtis australis*, *Populus alba, Laurus nobilis*). Among these, some are underused (light blue and light orange in Fig. 5a) (i.e., *Corylus avellana, Crataegus monogyna, Quercus pubescens*) as they are used only in a few cities, although recommended in several others. On the other hand, there are Meso-thermophilic species recommended but not used (Figure dark blue and dark orange in 5b) (i.e., *Crataegus laevigata, Cornus sanguinea, Prunus spinosa, Sambucus nigra*) that could widen the selection choices in many Italian cities while planting street trees. Interestingly, there are two species (*Quercus petraea* and *Chamaerops humilis*) (dashed lines in Fig. 5b) that are only suggested for a specific bioclimatic context while being used in some instances as street trees out of their suggested bioclimatic area. This might indicate that these two species' tolerance regarding climatic factors might be wider than expected.

4. Discussion

Our paper aims to provide some guidance for possibly improving urban planning while keeping native biodiversity in mind. Planting as street trees native tree species that have not previously been used would, subject to their suitability, likely increase species and genus diversity and thereby improve the resilience of street tree populations. Our methodology provides a step-by-step selection process that, we believe, is replicable and could be utilized to enhance the sustainability of cities. By leveraging native biodiversity, cities can improve their green infrastructure and contribute to broader conservation goals. In our study, we introduce a methodological applicative approach that is organized in eight steps.

Our first selection step entails a selection based on structure and nativeness. In many cities, urban planners favor exotic species as street trees (Moro and Westerkamp, 2011; Sjöman et al., 2012; Anderson et al., 2023). This preference may be due to the limited availability of suitable native species, challenges in adapting native trees to urban environments, economic factors (limited availability on the market), cultural preferences (favoring exotic species for aesthetic purposes) (Schroeder et al., 2006) or functional concerns (management difficulties, allergenicity, susceptibility to pathogens) (D'Amato et al., 2023). For instance, in cold and harsh climates, such as those found in Northern Europe, the limited native species diversity poses some challenges in using only native species to increase urban biodiversity (Sæbø et al., 2003; Sjöman et al., 2012, 2016). Even if street trees are not all the same and some species are better suited for specific urban contexts and provide more benefits than others (Seamans, 2013; Soares et al., 2011), the use of native trees offers substantial economic, ecological, and social benefits and, above all, can promote urban biodiversity. The literature suggests that while exotic species may show better performance in some specific situations (particularly in disturbed environments), native species generally provide more comprehensive ecological benefits and pose fewer risks to ecosystem stability and biodiversity (de Carvalho et al., 2022). Also, research has shown that native species provide a higher number of ecosystem services (e.g., Arcos-LeBert et al., 2021; Esperon-Rodriguez et al., 2020; Jimenez et al., 2022; Säumel et al., 2016) although some researchers have contrary opinions (e.g., Conway et al., 2019; Schlaepfer et al., 2020). For instance, researchers suggest that when properly selected, exotic species can enhance ecosystem resilience to climate change by providing additional functional traits and adaptive capacity to urban green infrastructures (Sjöman et al., 2016). Nevertheless, the selection of native species, particularly in the Mediterranean area, which is characterized by high plant biodiversity (Fady and Conord, 2010; Kier et al., 2005) should be preferred for ecological integrity and ecosystemic functioning (Blasi et al., 2011; Conway et al. 2019).

In Italy, several native species are used as street trees, although exotic ones are predominant (Bartoli et al., 2022). Biodiversity is generally relatively high, although some cities host more species than others, and Santamour's benchmark rule for urban forestry (Santamour, 1990) is respected (Bartoli et al., 2022). This ubiquitous rule in urban management establishes specific thresholds for improving urban biodiversity and disease resilience: there should not be more than 10 percent of any single species, 20 percent of any genus, and 30 percent of any family within urban tree populations. For instance, while Rome exhibits exceptional street tree biodiversity, if planting native trees was determined to be a priority, then our analysis suggests that several other species might be used to enrich Rome's biodiversity, such as *Euonymus europaeus*, *Crataegus laevigata,* and *Phillyrea latifolia.*

The cross-referencing analysis resulted in new lists of species (Table 2). Comparing Recommended and Planted [RP] species with Recommended but not Planted [R-nP] species revealed new potentially suitable species across different bioclimatic ecoregions and sections. For instance, species such as *Euonymus europaeus*, *Malus sylvestris*, *Quercus cerris*, *Fraxinus ornus*, and *Quercus robur* might be suitable for the Temperate ecoregions, and *Arbutus unedo* and *Quercus pubescens* in the Mediterranean ecoregions. These species are used in several cities but not in others, suggesting that they can grow and thrive in urban environments, and they can be considered for a replacement or new implantation in urban areas.

Table 2
List of the tree species recommended by urban reforestation guidelines in relation to the selected Italian cities. The first cluster of species includes trees that are recommended and are used in at least one city. The second cluster of species includes trees that are recommended but are not used in any considered city [Notes: + +: Recommended and Present (RP); 1: Recommended but not Present (R-nP); x: present but not recommended (NR-P); - not present and not recommended (NR-nP). Cities: TO: Turin, MI: Milan, PD: Padua, BO: Bologna, FL: Florence, RM: Rome, NA: Naples, CA: Cagliari, PA: Palermo, BA: Bari. SC: Size Class, (I) tall trees that can grow higher than 30 m; (II) tree height between 20 and 30 m; (III) tree height between 10 and 20 m; (IV) trees smaller than 10 m. Biol. Form: Biological Form, Pscap: Arboreal phanerophytes, Pcaesp: Shrubby phanerophytes, NP: Nanophanerophytes].

SPECIES	SC	Biol. Form	Chorotype	TO	MI	PD	BO	FI	RM	NA	CA	PA	BA
RP (at least in one city)													
Acer campestre L.	IV	P scap/ P caesp	Europ.-Caucas.	+ +	+ +	+ +	+ +	+ +	+ +	1	-	1	-
Acer pseudoplatanus L.	II	P scap	Europ.-Caucas.	+ +	+ +	x	-	x	x	-	-	-	-
Alnus cordata (Loisel.) Duby	II	P scap	Subendem.	-	-	-	-	x	-	+ +	-	-	-
Alnus glutinosa (L.) Gaertn.	II	P scap/ P caesp	Eurosiber.	1	-	+ +	-	1	1	1	-	-	-
Arbutus unedo L.	IV	P scap/ P caesp	Steno-Medit.	-	-	-	-	1	+ +	1	+ +	+ +	1
Carpinus betulus L.	II	P scap/ P caesp	Europ.-Caucas.	+ +	+ +	+ +	1	1	+ +	+ +	-	-	-
Celtis australis L.	II	P scap	Euri-Medit.	x	x	+ +	+ +	x	+ +	x	x	+ +	+ +
Ceratonia siliqua L.	III	P scap/ P caesp	S-Medit.	-	-	-	-	-	x	-	+ +	-	+ +
Cercis siliquastrum L.	IV	P scap	S-Europ.	x	x	x	x	x	+ +	1	x	x	x
Chamaerops humilis L.	IV	P scap/Np	Steno-Medit.	-	-	-	-	x	x	-	1	-	-
Cornus mas L.	IV	P scap/ P caesp	Pontica	1	-	+ +	1	1	1	1	-	-	-
Corylus avellana L.	IV	P caesp	Europ.	1	1	1	1	1	+ +	x	-	-	-
Crataegus monogyna Jacq.	IV	P scap/ P caesp	Eurasiat.	1	+ +	+ +	-	1	1	1	-	1	1
Fagus sylvatica L.	II	P scap	Centroeurop.	+ +	x	-	1	1	x	-	-	-	-
Fraxinus angustifolia Vahl	II	P scap	Pontica	-	x	+ +	+ +	1	+ +	1	x	-	-
Fraxinus excelsior L.	II	P scap	Europ.-Caucas.	+ +	+ +	+ +	x	-	x	-	-	-	-
Fraxinus ornus L.	III	P scap/ P caesp	Eurasiat.	1	+ +	+ +	+ +	+ +	+ +	1	1	1	+ +
Laburnum anagyroides Medik.	IV	P scap/ P caesp	S-Europ.	-	x	-	1	x	1	1	-	-	-
Laurus nobilis L.	III	P scap/ P caesp	Steno-Medit.	-	+ +	-	-	+ +	+ +	x	x	-	-
Nerium oleander L.	IV	P scap/ P caesp	S-Medit.	-	-	-	-	x	x	-	+ +	x	x
Olea europaea L.	IV	P scap/ P caesp	Steno-Medit.	-	-	x	-	-	x	-	+ +	-	+ +
Ostrya carpinifolia Scop.	III	P scap/ P caesp	Pontica	+ +	+ +	x	1	1	1	+ +	-	1	1
Picea abies (L.) H.Karst.	I	P scap	Eurosiber.	+ +	+ +	x	1	+ +	x	-	-	-	-
Pinus halepensis Mill.	III	P scap	Steno-Medit.	-	-	-	-	x	x	x	+ +	-	+ +
Pinus sylvestris L.	II	P scap	Eurasiat.	-	+ +	-	1	x	-	-	-	-	-
Pistacia lentiscus L.	IV	P scap/ P caesp	S-Medit.	-	-	-	-	-	1	1	+ +	+ +	-
Populus alba L.	I	P scap	Paleotemp.	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +	-	-
Populus nigra L.	I	P scap	Paleotemp.	+ +	+ +	x	+ +	+ +	x	+ +	x	-	1
Populus tremula L.	II	P scap	Eurosiber.	1	x	-	-	-	-	x	-	-	-
Prunus avium (L.) L.	III	P scap	Eurasiat.	+ +	+ +	+ +	1	1	x	-	-	-	-
Pyrus communis L.	III	P scap	Eurasiat.	-	-	-	1	1	+ +	1	-	1	-
Quercus cerris L.	II	P scap	Euri-Medit.-Sett.	1	+ +	1	1	1	+ +	+ +	-	1	1
Quercus ilex L.	II	P scap	Steno-Medit.	-	x	+ +	+ +	+ +	+ +	+ +	+ +	x	+ +
Quercus pubescens Willd.	III	P scap	Pontica	1	x	1	-	-	+ +	+ +	1	1	1
Quercus robur L.	I	P scap	Europ.-Caucas.	+ +	1	+ +	+ +	+ +	+ +	+ +	-	-	-
Quercus suber L.	III	P scap	Steno-Medit.	-	-	-	-	x	+ +	-	-	-	-
Salix alba L.	II	P scap	Paleotemp.	1	+ +	+ +	-	x	1	+ +	-	-	-
Tamarix gallica L.	IV	P scap/ P caesp	W-Medit.	-	-	1	-	-	-	x	x	x	-
Taxus baccata L.	III	P scap	Paleotemp.	-	x	x	1	-	x	-	-	-	-
Tilia cordata Mill.	II	P scap/ P caesp	Europ.-Caucas.	1	+ +	+ +	+ +	x	x	x	-	-	-
Tilia platyphyllos Scop.	II	P scap	Europ.-Caucas.	-	x	x	+ +	-	+ +	x	-	-	x
Ulmus glabra Huds.	I	P scap	Europ.-Caucas.	+ +	x	x	x	-	x	-	x	-	-
Ulmus minor Mill	II	P scap	Europ.-Caucas.	1	+ +	+ +	+ +	1	+ +	x	-	-	1
Viburnum tinus L.	IV	P caesp	Steno-Medit.	-	-	-	-	1	+ +	1	+ +	-	1
R-nP													
Acer monspessulanum L.	III	P scap/ P caesp	Euri-Medit.	-	-	-	1	-	1	1	1	-	1
Acer opalus Mill.	III	P scap/ P caesp	Atl.	1	-	-	1	-	-	1	-	-	-
Anagyris foetida L.	IV	P caesp	S-Medit.	-	-	-	-	-	-	-	1	-	-
Betula pendula Roth	II	P scap/ P caesp	Eurosiber.	1	-	-	-	1	-	-	-	-	-
Carpinus orientalis Mill.	IV	P scap/ P caesp	Pontica	-	-	-	-	-	1	1	-	-	
Castanea sativa Mill.	II	Pscap	Europ.	1	1	-	1	1	-	1	-	-	-
Colutea arborescens L.	IV	P caesp	Euri-Medit.	-	-	-	-	-	1	1	-	-	-
Cornus sanguinea L.	IV	P caesp	Eurasiat.	1	1	1	1	1	1	1	-	-	-
Crataegus laevigata (Poir.) DC.	IV	P scap/ P caesp	Centroeurop.	1	1	-	1	1	1	1	-	-	1
Erica arborea L.	IV	P caesp/NP	Steno-Medit.	-	-	-	1	-	1	1	1	1	-
Euonymus europaeus L.	IV	P scap/ P caesp	Eurasiat.	1	1	1	1	1	1	1	-	-	-
Frangula alnus Mill.	IV	P scap/ P caesp	Europ.-Caucas.	1	-	1	1	-	-	-	-	-	-
Ilex aquifolium L.	II	P scap/ P caesp	Submedit.	-	-	-	1	-	-	-	-	-	-
Juniperus communis L.	III	P scap/ P caesp	Circumbor.	1	-	1	1	1	1	-	-	-	-
Larix decidua Mill.	II	P scap	Centroeurop.	1	-	-	-	-	-	-	-	-	-
Malus sylvestris (L.) Mill.	IV	P scap	Centroeurop.	1	1	1	1	1	-	1	-	1	-
Mespilus germanica L. A	IV	P scap/ P caesp	Europ.	-	-	-	1	-	1	1	-	-	-
Paliurus spina-christi Mill.	IV	P caesp	Pontica	-	-	-	-	-	1	1	-	-	-
Phillyrea angustifolia L.	IV	P caesp	Steno-Medit.	-	-	-	-	-	-	-	1	-	-
Phillyrea latifolia L.	III	P scap/ P caesp	Steno-Medit.	-	-	-	-	1	-	1	1	-	1
Pistacia terebinthus L.	IV	P scap/ P caesp	Euri-Medit.	-	-	-	-	-	1	1	-	-	1
Prunus padus L.	III	P scap/ P caesp	Eurosiber.	-	1	1	-	-	-	-	-	-	-
Prunus spinosa L.	IV	P caesp	Eurasiat.	-	1	1	1	1	1	1	-	1	1

(*continued on next page*)

Table 2 (*continued*)

SPECIES	SC	Biol. Form	Chorotype	TO	MI	PD	BO	FI	RM	NA	CA	PA	BA
Pyrus spinosa Forssk.	III	P scap/ P caesp	Eurasiat.	-	-	-	-	-	-	-	1	-	1
Quercus congesta C.Presl	III	P scap/ P caesp	Medit	-	-	-	-	-	-	-	-	1	-
Quercus dalechampii Ten.	II	P scap	Endem. Sic.	-	-	-	-	-	-	-	-	1	1
Quercus frainetto Ten.	II	P scap	Pontica	-	-	-	-	-	1	1	-	-	1
Quercus petraea (Matt.) Liebl.	II	P scap	Europ.	1	1	-	1	1	-	x	-	-	-
Rhamnus alaternus L.	IV	P caesp	Steno-Medit.	-	-	-	-	1	1	1	1	1	1
Rhamnus cathartica L.	IV	P scap/ P caesp	Pontica	1	1	1	-	-	-	-	-	-	-
Salix arrigonii Brullo	III	P caesp	Endem. Sar	-	-	-	-	-	-	-	1	-	-
Salix eleagnos Scop.	III	P scap/ P caesp	Europ.	1	1	-	-	-	-	-	-	-	-
Salix purpurea L.	IV	P scap/ P caesp	Eurasiat.	1	-	-	1	-	1	1	1	-	-
Salix triandra L.	IV	P caesp	Eurosiber.	-	-	-	-	-	-	1	-	-	-
Sambucus nigra L.	IV	P caesp	Europ.	1	1	1	1	1	1	1	-	-	-
Sorbus aria (L.) Crantz	IIII	P scap/ P caesp	Paleotemp.	1	-	-	1	-	1	-	-	-	-
Sorbus domestica L.	II	P scap	Euri-Medit.	1	-	-	1	1	-	-	-	-	1
Sorbus graeca (Spach) Lodd. ex S.Schauer	IV	P scap/ P caesp	Pontica	-	-	-	-	-	-	-	-	1	-
Tamarix africana Poir.	IV	P scap	W-Medit.	-	-	-	-	-	-	-	1	-	-

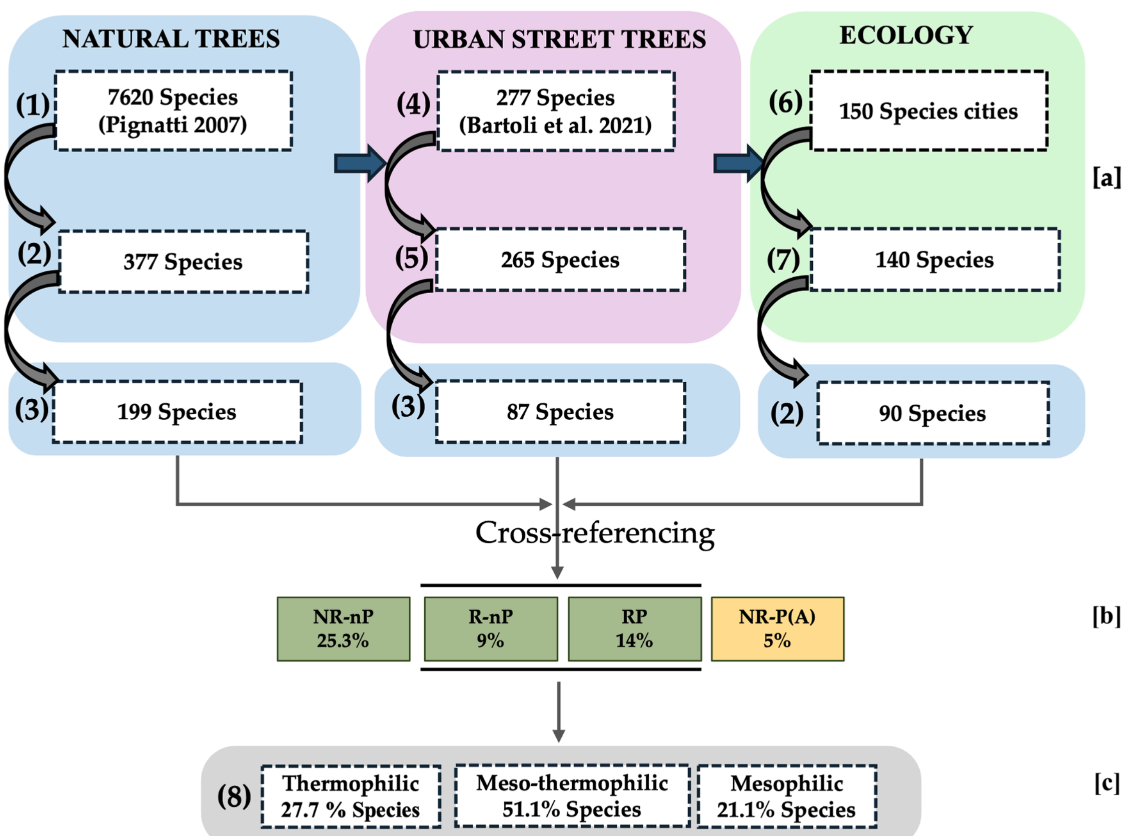

Fig. 3. [a] Application of the methodology to the Italian context: 1. Analysis of national floras; 2. Structural filter; 3. Biogeographical filter, 4. Analysis of street trees' datasets, 5. Selection of representative cities; 6. Analysis of vegetation of urban and peri-urban areas; 7. Bioclimatic congruence. [b] Results of the cross-referencing process Notes [RP]: species Recommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) from a bioclimatic perspective for the analyzed cities and already Present as street trees; [R-nP]: species Recommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) but not Present as street trees; [NR-P]: species Not Recommended in the urban reforestation guidelines (or not ecologically congruent with the urban environment) but Present as street trees in the considered cities (A= Archaephyte); [NR-nP]: species Not Recommended (or not ecologically congruent) and not Present as street trees.[c] Application of the selection process for the bioclimatic congruence (point 8).

Moreover, our study identifies species with wider tolerance to bioclimatic conditions (Fig. 5a). Our application to the Italian context divided species into three main groups according to their ecological preferences regarding temperature and precipitation (Schulze et al., 2005). Our findings suggest a way to diversify urban street trees and enhance their potential resilience to future temperature increases in the cities. For instance, *Celtis australis*, *Laurus nobilis*, *Populus alba*, *Acer campestre*, *Populus nigra*, *Carpinus betulus*, *Quercus robur*, and *Quercus ilex*, already widely used as street trees in Italy (Bartoli et al., 2022; Caneva et al., 2020), could be better prepared to withstand the increasing urban temperatures than others, as they present a wide tolerance to bioclimatic conditions. A study conducted in the US (McBride and Laćan, 2018) has shown that of the 140 street tree species analyzed in California, up to 82 species may not survive in the future warmer climate. They also found that cities located farther from the coast could lose up to 100 % of their street tree species, as these species may become unsuitable for future climate conditions (McBride and Laćan, 2018). Interestingly, even among the species that are

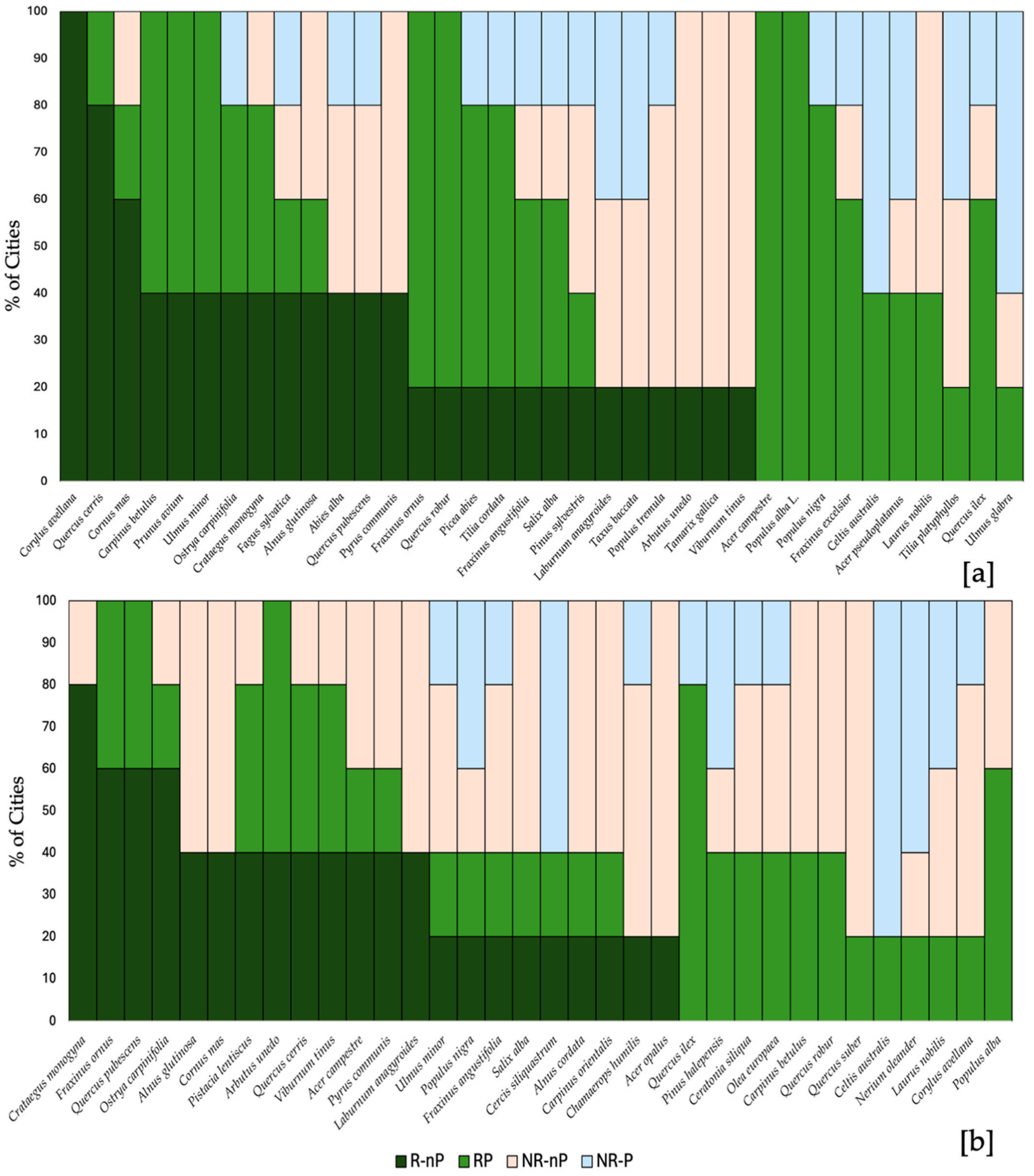

Fig. 4. Percentages of Recommended (R-nP; RP) and not Recommended species (NR-P; NR-nP) for the analyzed cities within the bioclimatic areas of the [a] Temperate ecoregions; [b] Mediterranean ecoregions. Notes [RP]: species Recommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) from a bioclimatic perspective for the analyzed cities and already Present as street trees [R-nP]: species Recommended by the urban reforestation guidelines (or ecologically congruent with the urban environment) but not Present as street trees [NR-P]: species Not Recommended in the urban reforestation guidelines (or not ecologically congruent with the urban environment) but Present as street trees in the considered cities [NR-nP]: species Not Recommended (or not ecologically congruent) and not Present as street trees.

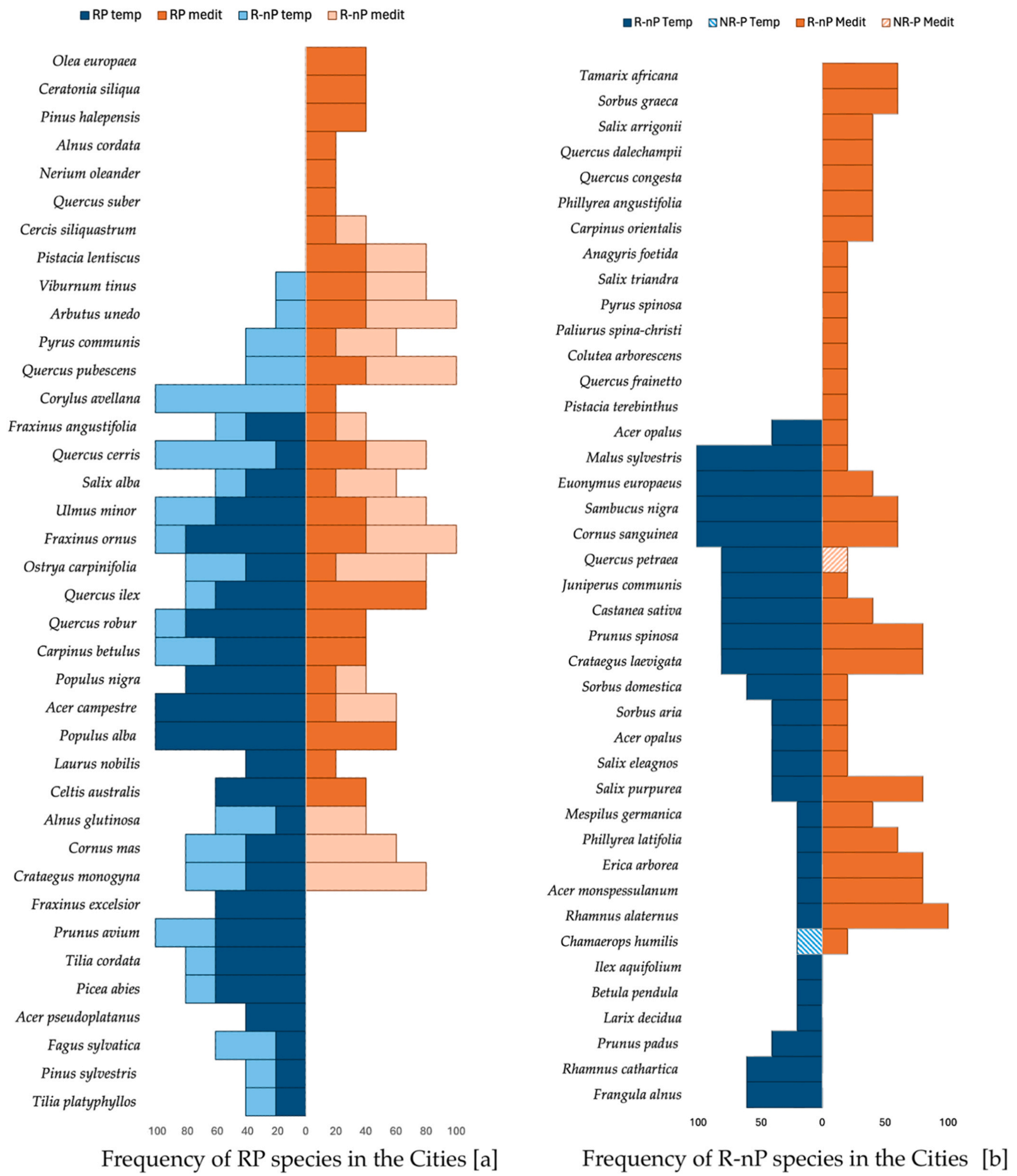

Fig. 5. Distribution frequency of the [a] Recommended and used (RP); [b] Recommended and not used (Rn-P) species in the Temperate and Mediterranean bioclimatic ecoregions. In Fig. 5, we highlight four groups of species: 1. Dark blue: strictly mesophilic species typical of a temperate bioclimate; 2. Dark orange: thermophilic species typical of a mediterranean bioclimate; 3. Dark blue-dark orange: meso-thermophilic species recommended and used in both bioclimates that have potentially a wider range of tolerance concerning climatic factors; 4. Light blue-light orange: meso-thermophilic species recommended but not used.

recommended but not used (Fig. 5b), we found several with potential bioclimatic versatility. Among these unused species, *Rhamnus alaternus*, *Acer monspessulanum*, *Erica arborea*, and *Phillyrea latifolia* are characterized by a wide ecological range and are indeed recommended by MASE (2021) both in the Mediterranean cities and even in some cities of the Temperate ecoregions.

Our study suggests that more attention should be paid to species' ecological preferences in urban contexts. The case of *Phillyrea latifolia* is particularly noteworthy. Extensively studied for its drought tolerance (Filella et al., 1998; Gratani et al., 2013; Ogaya and Penuelas, 2006; Ogaya and Peñuelas, 2003; Penuelas et al., 1998), this species exemplifies the potential of native Mediterranean species to adapt to future temperature increases in urban environments. This species is an example of a species recommended but not used (Rn-P). From an ecological perspective, our analysis suggests *Crataegus laevigata* as a suitable species across all bioclimatic ranges since MASE (2021) recommended it in eight cities from Temperate to Mediterranean contexts. Interestingly, this native species remains underutilized compared to non-native *Crataegus* species in Italian cities (Bartoli et al., 2022). The richness of thermophilic species in the Italian flora, well-adapted to withstand current warming temperatures, provides multiple choices to increase the resilience and sustainability of urban green spaces, especially in the most xeric Mediterranean subsections (i.e., Western Sicily subsection, Table 1). This biodiversity wealth represents an invaluable resource for Italian cities seeking to adapt to future climate challenges while maintaining a strong connection to local ecosystems.

Future research should focus on long-term monitoring of recommended species, their ecosystem interactions, and their performance under various urban stressors, also considering phytopathological aspects. For instance, among the [RP] species, there are two trees, *Fraxinus angustifolia,* and *Fraxinus excelsior,* at risk for the spread of the emerald ash borer (Valenta et al., 2017), a pest that should be countered with multiple preventive measures (Showalter et al., 2020; Valenta et al., 2017). Studies on the economic feasibility of introducing new native species into urban green planning and practices would also be beneficial. Furthermore, investigating public perceptions and cultural factors related to native tree species could provide valuable insights into the social acceptance and success of planting programs (Ordóñez et al., 2019). Finally, we acknowledge that our study remains theoretical, without empirical testing of actual species performance (both for existing and potential plantings). Undoubtedly, targeted studies on species performance in urban environments, including detailed analysis of biotic and abiotic stressors, would be useful for developing a comprehensive and structured understanding of the subject.

While our study provides valuable insights, we acknowledge its limitations. Our analysis considers current and potential climatic changes; however, further research is needed to assess the performance of recommended species in the long term. Additionally, our study does not account for micro-climatic variations within urban areas (Moser-Reischl et al., 2019) or genetic diversity within species (Sæbø et al., 2003), both of which could influence tree performance. Our study specifically focuses on street trees, but with some tweaks, it can also be applied to selecting tree species for urban parks or private gardens.

The methodology is applicable and replicable but requires data that might be challenging to find. For instance, street tree inventories are not always available. In our case study, these were available for large cities as in Italy, Law No. 10/2013 ("Regulation for the development of urban green areas") dictates that Italian municipalities with a population of more than 15,000 inhabitants must keep an inventory of trees located in public green areas (Masini et al., 2023; Rossi et al., 2022). In other countries, regulations might be different, and as such, street tree inventories can be obtained less easily through field investigations (Nagendra and Gopal, 2010) or questionnaires (Ma et al., 2020). These inventories can be helpful to determine whether a species has already demonstrated some ecological compatibility with urban street environments. Also, the availability of urban reforestation studies or guidelines might become challenging when there is insufficient data regarding potential peri-urban vegetation (Dengler, 2017; Pott, 2011). Another limitation of our approach, which we tried to keep simple to facilitate its application, pertains to the bioclimatic characterization of the species. For instance, alternative and more comprehensive approaches exist and can be eventually applied instead of our suggested screening at point 8 (Fig. 1). Kendal et al. (2018) compared the realized climatic niches between native and urban tree populations across 182 global cities, revealing that urban trees are planted beyond their native climatic boundaries, with urban niches being variably wider than native ones. Similarly, Esperon-Rodriguez et al. (2020) proposed a climate risk assessment framework that evaluates species' safety margins and future vulnerability, providing insights for urban forest management and species selection considering future climatic changes. Another potential strategy would entail using climate analogues in relation to climate shifts. Climate analogues identify which regions (or, as in our case, cities) in the future will have climates that resemble the current climate of another region (or city) (Rohat et al. 2018). As such, we suggest that our methodology can be integrated or revised according to specific needs.

5. Conclusions

Our approach can help urban ecologists, botanists, and policymakers to make informed decisions about street tree selection, bridging the gap between scientific knowledge and urban green planning. Selecting street tree species properly in the current urban context is a challenge that needs to be addressed to improve city livability and sustainability. Our approach suggests bringing more natural vegetation within cities and increasing their biodiversity. Specifically, our analysis shows that many native species have not yet been used as street trees and deserve attention. Moreover, many species, both already used or not yet used as street trees in Italy, have wide ranges of tolerance to bioclimatic conditions and thus might be better prepared to withstand future changes in urban climatic conditions. These species certainly need further studies and experimentation in the urban context. However, our methodology can help researchers identify which species possess desirable ecological features. Our methodology has some limitations but still contributes to moving research towards achieving more sustainable cities and increasing urban biodiversity.

CRediT authorship contribution statement

Caneva Giulia: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Savo Valentina:** Writing – review & editing. **Bartoli Flavia:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **D'Amato Luca:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Acknowledgements

This research was supported by funds from the Ministry of Education, University, and Research for the basic research individual activities, and by the Grant of Excellence Departments, MIUR (https://www.mim.gov.it/)-Italy. The authors acknowledge the support of the Italian Ministry of University and Research, National Operational Program "Research and Innovation" 2014 – 2020 (PON (https://www.

ponricerca.gov.it/opportunita/fund-of-funds-for-research-and- innovation/).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.128784.

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