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Adaptive planting design and management framework for urban climate change adaptation and mitigation

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A B S T R A C T

Implementing measures to adapt and mitigate climate change effects in cities has been considered increasingly urgent since the quality of life, health, and well-being of urban residents is threatened by this change. Novel communities of plant species that emerge and thrive in the harsh conditions of cities may represent a promising opportunity to address climate change adaptation and mitigation through the planting design and management of urban green spaces. The objective of this study is to develop an adaptive planting design and management framework. The proposed framework is grounded on previous adaptive approaches and focuses on the opportunities emerging from novel plant communities in urban conditions. The framework comprises three main steps (1 – Climate change assessment, 2 – Plant species database, and 3 – Planting design and management procedure). A proposal on how the framework could be tested was developed for the city of Porto, Portugal. Still, the application of the framework can also be adjusted to other urban contexts, offering a starting point for experimentation and assessment of plants' adaptation and mitigation capacities through design and management. As lack of knowledge and uncertainty about climate change limits global capacity to implement robust adaptation and mitigation strategies, building knowledge in an adaptive way and context-specific locations will be of paramount interest to tackle climate change in cities.

1. Introduction

Climate change negatively affects urban areas' livelihood and sustainability, threatening the quality of life, health, and well-being of urban residents (IPCC, 2021). Due to a population concentration in cities, the heat island effect, and the impacts of anthropogenic activities, urban areas are often considered to be both the most vulnerable to climatic events and those that more significantly contribute to climate change (Rosenzweig et al., 2010). For that reason, the implementation of measures to tackle climate change in cities has been considered increasingly urgent (Zölch et al., 2016). The complexity of urban ecosystems makes responding to climate change more challenging and difficult (Carter, 2018). Still, urban areas are also centers of economic and political power, thus gathering the ideal conditions to test and implement innovative solutions (Carter et al., 2017; Rosenzweig et al., 2010). Cities have inherent characteristics that create opportunities to prepare for current and future conditions and to reduce greenhouse gas production (Hami et al., 2019; van Staden, 2014).

Besides the projected changes in temperature or precipitation, climate change is also indirectly responsible for dramatic changes in ecosystems' patterns and processes (IPCC, 2021). The modification of the urban abiotic conditions can decrease species fitness, affect their physiological, reproductive, and phenological responses, and disrupt interactions at the community level (Hunter, 2011; Starzomski, 2013). Driven by these effects, species shift their distribution patterns and reorganize themselves into unprecedented novel combinations, leading to the emergence of Novel Urban Ecosystems (Kowarik, 2011). In the same way that the effects of climate change are more intense in cities, for similar reasons, ecological novelty is also widespread in urban areas (Hobbs et al., 2014; Kowarik, 2011; Perring et al., 2013).

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Even though Novel Urban Ecosystems are driven by climate change, this concept can provide insights on how to understand and manage climate change impacts on species, communities, and ecosystems (Starzomski, 2013). Novel combinations of native and non-native species are already thriving in challenging urban environmental conditions, despite human intervention or management, suggesting that these ecosystems are well prepared to handle climate change effects. In this way, Novel Urban Ecosystems may be “pre-adapted” to future climates and environmental stresses (Ahern, 2016; Bakshi and Gallagher, 2020; Del Tredici, 2020; Standish et al., 2013) and, in some cases, perhaps better prepared than previous combinations of native species only (Kowarik, 2011).

In response to increasing global urbanization, cities are progressively implementing green infrastructure and nature-based solutions to deliver specific ecosystem functions (Carter, 2018; Carter et al., 2017; EEA, 2016; Zölch et al., 2016). A multifunctional network of green spaces in cities can support both ecological and social goals (Klaus and Kiehl, 2021). Additionally, informed selection and combination of specific plant species in the urban space can be explored due to its potential crucial role in adapting and reducing climate change effects in cities (Dunnett and Hitchmough, 2004; Espeland and Kettenring, 2018; Hunter, 2011).

Growing concern and urgency in preparing cities for current and future environmental conditions (adaptation) and in minimizing the impacts and causes of climate change (mitigation) has led several authors to contribute important planting design and management guidelines grounded on ecological theory, scientific evidence, and specifically focused on climate change-related problems and impacts (e.g., Alizadeh and Hitchmough, 2019; Hami et al., 2019; Hunter, 2011; Köppler and Hitchmough, 2015; Rainer and West, 2015). Nevertheless, these guidelines may remain limited due to the uncertainty and context specificity of climate change effects. The increasing ambiguity of climate change demands innovation and experimentation (Felson and Pickett, 2005; Kato and Ahern, 2008). Therefore, urban areas can function as living laboratories to build unprecedented, local, context-specific knowledge and understanding (Light et al., 2013).

This way, this article aims to develop an adaptive planting design and management framework and illustrate how it could be applied in the city of Porto, Portugal. The proposed framework is grounded on previous adaptive environmental approaches for management (Holling, 1978), planning (Ahern et al., 2014; Kato and Ahern, 2008) and design (Felson and Pickett, 2005; Lister, 2007): a strategy that allows learning from context-specific experience in order to create more robust, flexible, and adjustable proposals informed by the theoretical and practical knowledge gained. The framework also builds on existing planting design and management guidelines for climate change adaptation and mitigation while focusing on the opportunities emerging from novel plant communities already thriving in the extreme urban conditions.

2. Adaptive planting design and management framework

The adaptive framework assists the development of planting design and management proposals based on the assumed plants' potential to adapt and mitigate climate change effects in order to make urban areas more comfortable, healthier, and safer for people. Following an adaptive approach, the feasibility, effectiveness, and risks of the planting design and management decisions can be evaluated post-planting. This way, gaps in scientific knowledge can be bridged through experimentation in a more realistic and complex urban landscape (Felson and Pickett, 2005). This way, there is an increasing opportunity to minimize uncertainty, maximize resilience, and create a learning loop that will adjust the strategies whenever necessary, for example, as new data becomes available or when implemented strategies are not succeeding as expected (Kato and Ahern, 2008; Pickett et al., 2004).

The framework aims to be applied in existing urban green spaces with varying degrees of urban ecological novelty (Teixeira et al., 2021), which can include interventions in parks and gardens, urban woodlands, or in smaller-scale or neglected green spaces that had not been formally recognized and planned for public use before (i.e., informal green spaces), such as vacant lands, street verges, traffic islands, or brownfields (Klaus and Kiehl, 2021).

The proposed adaptive planting design and management framework (Fig. 1) starts with (1) the assessment of climate change effects expected in the study area that can be actively addressed using plants or through planting design or management. Secondly, (2) a plant species database is produced to collect and classify a set of plant species for their capacity to adapt and mitigate climatic extremes. Finally, (3) the planting design and management procedure is developed with the following steps: i) definition and prioritization of design and management goals to respond to climate change problems in the study area; ii) assessment of the current status of the intervention site to examine the required modifications; iii) selection of plant species to remove, monitor, keep, or add; iv) combination of plant species to increase redundancy and diversity; and v) elaboration of the monitoring protocol to evaluate the effectiveness of the proposals after implementation. All the steps in the framework must be coordinated in an iterative process and adjusted whenever necessary.

2.1. Climate change assessment

Understanding the climate change projections expected for the study area is an essential starting-point for developing context-specific and city-scale strategies. Global and regional climate change projections have been recently documented by IPCC (2021). More detailed projections should also be investigated since there is a growing understanding that climate change effects are mainly experienced locally (Aguiar et al., 2018), especially those affecting human comfort: temperature, ventilation, and humidity (Geiger et al., 1995).

Climate change hazards will represent different risks depending on how prepared the study area and its inhabitants are to handle climate change effects. This way, it is helpful to evaluate the most concerning climate change risks in the study area considering its current response capacity. Patterns of vulnerability regarding climate change scenarios are not homogeneously distributed in cities (Carter, 2018). Thus, priority areas and sub-populations targeted for climate change adaptation and mitigation should also be identified (Carter et al., 2017).

2.2. Plant species database

The database assembles the set of plant species to work with in the following steps of the framework. It should include (but not be limited by) species that are already occurring in the study area. Following an adaptive approach, assisted migration (Hughes et al., 2008) of particular beneficial plant species could also be tested assuming that the experiment is closely monitored and held in a controlled setting (e.g., in botanical gardens or research plots to assess how adapted plants are to the climate, the risk of becoming invasive, and potential negative and positive impacts or traits). In this case, assisted migration does not have to be necessarily about non-native plants, as it can target native plants from other parts of the study area's country that are more adapted to certain environmental conditions.

Species included in the database must be organized and classified according to traits that will facilitate their selection and combination (Hunter, 2011; Vogt et al., 2017), including climate adapting traits (e.g., tolerances to extreme conditions) and mitigating traits (e.g., canopy density and size). It is important to ensure that the database contains species with varied habits, life cycles, functions, and origins.

Although a native-species-only policy is often emphasized in the literature as a crucial step to ensure an optimum level of biodiversity, we urge that in urban areas, mixtures of native and non-native species may be better prepared to cope with climate change (Ahern, 2016; Del Tredici, 2020; Kowarik, 2011; Standish et al., 2013). The use of a vast

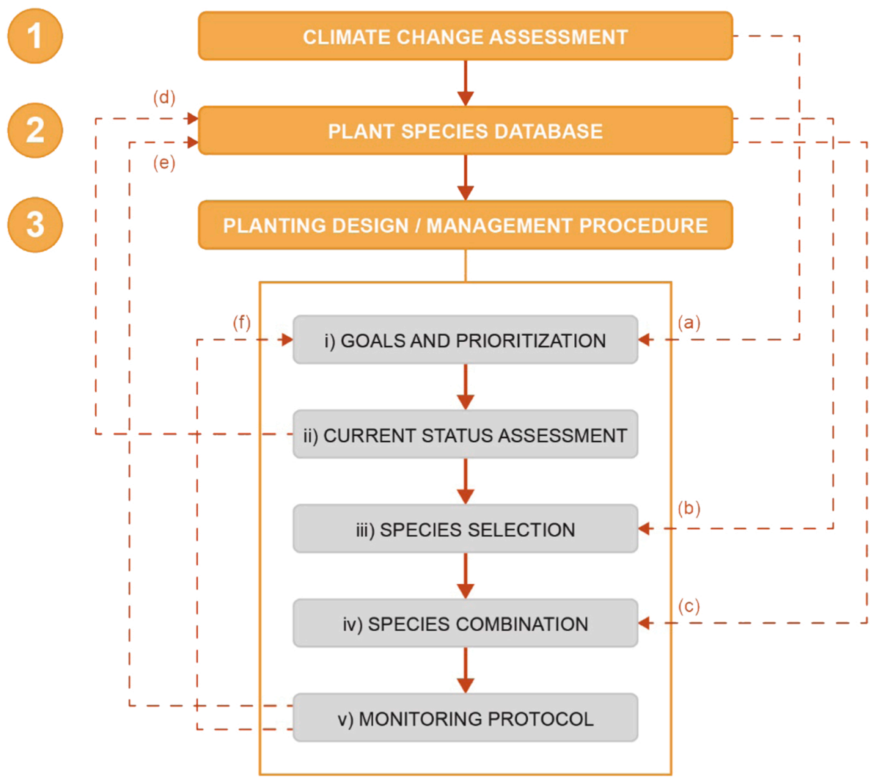

Fig. 1. Conceptual diagram of the proposed framework. Main sequence of steps (bold arrow) and secondary and dynamic links between steps (dashed arrow). (a) The climate change assessment will instruct the definition of goals; (b, c) The plant species database will instruct both species selection and combination; (d, e) New species can be included in the database following the current status assessment (i.e., species that exist in the intervention area) and monitoring process (i.e., new species that emerge in the intervention area over time); (f) The monitoring process can as well dictate the need to redefine goals.

selection of both native and non-native species will ensure a wide range of response to climate change problems, so excluding from the start the species based on their origin may only decrease the potential of the proposals (Alizadeh and Hitchmough, 2019; Davis et al., 2011).

2.3. Adaptive planting design and management procedure

2.3.1. Goals and prioritization

Based on the climate change projections, risks, and priority areas for the study area, it is essential to define goals to solve one or more context-specific problems (Hunter, 2011; Windhager et al., 2011). Goals must address both adaptation and mitigation concerns. Encouraging biodiversity should always be an underlying goal since overall ecosystems' diversity, health, and resilience will determine the ecosystem capacity to survive change and perform essential functions (Hunter, 2011; Schwarz et al., 2017). Likewise, esthetic quality should not be disregarded as it plays an important role in people's perception and well-being.

Proposals should be set to respond to a wide range of problems, which is not always easy to achieve (Windhager et al., 2011). This way, it may be helpful to prioritize goals, anticipate potential ecosystem conflicts and problems, and identify eventual trade-offs (Ahern et al., 2014). Prioritization should depend on climate change projections' risks in both short- and long-term and rely on social and political discernment (e.g., available resources, cost-benefits, probability of success, public acceptance) (Hobbs et al., 2014).

2.3.2. Current status assessment

The next step comprises the assessment of the current status of the area we intend to intervene on. This assessment should collect data about the species present at the intervention area such as the plant list, species richness and cover. If they are not yet contemplated there, the plant species in the intervention area must be included in the database (step 2). Afterwards, it will be possible to assess which of the targeted traits needed to achieve the established goals are already present, lacking, or underrepresented.

2.3.3. Species selection

Based on the combined information from all of the previous steps, species selection will involve four operations: remove, monitor, keep, or add.

Harmful and undesirable species should be removed considering both expert and public perspectives (Dunnett and Hitchmough, 2004). Depending on the species, context, and legislation, these can include, for instance, excessively dominant invasive species, damaged species (i.e., diseased, spoiled, or broken), or species with unwanted features (i.e., dangerous for people or posing high public health risks) (Del Tredici, 2020). Removing such species should be gradual and calculated. For instance, there are situations where invasive species are already performing vital ecosystem functions or could be useful to achieve particular management conditions, even only as temporary solutions.

On the other hand, species that can be problematic in the future should be closely monitored and flagged instead of removed from the start. Otherwise, the adaptation potential of this species would be overlooked and experimentation and creativity in the design and management process would be compromised (Fernandes et al., 2018). These can include, for instance, species that have higher risk of becoming invasive (Marchante et al., 2014) or mature invasive species (e.g., fully developed trees). Likewise, species that can be perceived as an indicator of neglect should also be kept and monitored following interventions that enhance their appearance and care (Nassauer, 1995).

Species already occurring in the intervention site that are more beneficial than harmful should be kept. For example, desirable and advantageous spontaneous vegetation can be maintained or integrated in the proposals at different stages (Bakshi and Gallagher, 2020; Dunnett and Hitchmough, 2004; Kowarik, 2018; Kühn, 2006). Spontaneous vegetation is generally tolerant and pre-adapted to the extreme conditions of urban environments and, therefore, offering potentially valuable contributions for climate change adaptation and mitigation (Del Tredici, 2020).

Finally, targeted species can be added to perform specific and critical functions, either absent functions that we wish to include in a particular location or selected functions that we intend to maximize (Ahern, 2016; Klaus and Kiehl, 2021; Perring et al., 2013). It may also refer to the inclusion of more cosmopolitan species, species with wider ranges of tolerances and functions, or species that require minimal management (Del Tredici, 2020).

2.3.4. Species combination

The way species are assembled will be crucial for the desired outcome. When combining species, it is imperative to consider the species dynamics, ecological compatibility, and habitat preferences in the long-term. For instance, assemblages of species with very distinct growth rates (fast and slow-growing) or heights (short and tall) may lead to higher levels of incompatibility if other features of the species (e.g., shade tolerance, phenology, growth season) are overlooked (Dunnett and Hitchmough, 2004; Köppler and Hitchmough, 2015; Rainer and West, 2015). Plant species combinations should ultimately aim to increase redundancy and diversity as much as possible, once this is infrastructural to provide multiple ecosystem functions (Hunter, 2011; Van Mechelen et al., 2015).

Functional redundancy will ensure that the same function or trait (e.g., shading or drought tolerance) is provided by more than one species in the plant community and, therefore, throughout different seasons (Elmqvist et al., 2003). Functional diversity will increase the number of ecological functions the system can perform throughout the year and decrease the risk of collapsing due to environmental disturbances and climatic changes (Alizadeh and Hitchmough, 2019; Dunnett and Hitchmough, 2004). Lastly, physical configurations and the vertical structural complexity of plant communities (e.g., layers, height, shape) will determine the variety of shelter and refuge opportunities for wildlife (Hunter, 2011; Threlfall et al., 2017; Van Mechelen et al., 2015). It will also influence the capacity to mitigate climatic extremes and increase human comfort since it will largely determine the microenvironment around plants (e.g., temperature, airflow, precipitation) and energy exchanges.

2.3.5. Monitoring protocol

This framework represents an ongoing, dynamic, and nonlinear process that allows a constant learning loop and the adjustment of steps and decisions whenever necessary or pertinent. In the future, new and more recent climate change data may be available. Likewise, the plant species database may also expand, allowing the integration of other relevant species. Performance analysis can dictate the necessity to refine the initially established goals and priorities and force alterations. This way, the monitoring protocol should aim to measure if the proposals are performing and adapting as expected, allowing ongoing adjustments based on updated information and upcoming challenges (Ahern et al., 2014; Kato and Ahern, 2008). To this end, monitoring plots and transects could be permanently field-marked to enable monitoring over time to observe evolution in the context of actual climate change.

3. Application of the framework to Porto, Portugal

3.1. Study area

We developed a proposal on how the framework could be tested in Porto, a city located in the coastal area of northern Portugal. The city of Porto is geographically framed by two natural elements, the Atlantic Ocean at the west and the Douro River at the south. With 4140 ha, Porto is the center of the country's second-largest metropolitan area, with 1.7 million inhabitants. The city has an Atlantic (sub-Mediterranean) climate with warm and rainy winters and dry and mild summers.

In the last decades, Porto has experienced a rapid urbanization process associated with demographic and economic growth, resulting in drastic changes in land-use and an overall increase in greenhouse gas emissions (Monteiro and Madureira, 2009; Rafael et al., 2016). The high rate of urbanization of Porto has resulted in a massive reduction of green areas (Madureira et al., 2011). These factors make the city highly vulnerable to climate change effects despite the influence of sea breezes and the proximity to the Douro River (Monteiro and Madureira, 2009).

The elaboration of a "Strategic Municipal Plan for Climate Change Adaptation" (SMPCCA) for Porto (CMP, 2016) was a critical starting point to address these relevant challenges at a local level. The plan presents an overview of Porto's current and future climate change situation but lacks a more focused and localized myriad of adaptation and mitigation options regarding the green infrastructure.

3.2. Climate change assessment in Porto

Porto's climate change projections until the end of the 21st century Table S1 include an increase in average temperature, leading to more frequent and intense heatwaves. Annual average precipitation is expected to decrease, resulting in severe droughts. Nonetheless, extreme precipitation events and winter storms are expected to increase (CMP, 2016). Based on the projected climate changes and on what is already considered Porto's major climate change risks today, the SMPCCA (CMP, 2016) identifies the main priority risks for Porto in the medium- and long-term: heatwaves (associated with high temperatures) and pluvial flooding (related to extreme precipitation events).

These priority risks were spatially assessed through maps (Fig. 2a, b) obtained from open-source reports developed in the scope of the Porto's Master Plan review process (Monteiro et al., 2018). Additionally, since socio-economic factors strongly influence the cities' overall susceptibility to climate change risks (Carter et al., 2017), we developed a map to identify which areas in Porto have more socio-economic vulnerability (Fig. 2c). For that, we considered the following aspects: resident population under four and over 65 years old, resident population with higher education, resident population with their own accommodation, an average monthly wage, and unemployment rate (CMP, 2016).

The most concerning areas for each priority risk and socio-economic vulnerability were overlapped using ArcGIS 10.6 to determine the overall priority areas for climate change adaptation and mitigation in Porto (Fig. 2d). Areas with an overlap of three priority risks were considered to have overall high priority. Areas with an overlap of two priority risks were supposed to have medium priority. Lastly, areas without priority risks' overlapping were considered to have low priority.

According to Fig. 2, it is possible to verify that the areas with the greatest heat anomalies are mostly co-incident with the socioeconomic vulnerability, mainly located in the city center. Hence, it is also where there is a higher priority to implement adaptation and mitigation measures. Higher impermeability and lower share of green spaces in this area of the city may explain these results (Hami et al., 2019). Still, areas with either medium or low priority should not be overlooked if there is an opportunity to implement measures in these areas.

3.3. Plant species database

To elaborate the database, we selected 287 plant species (both cultivated and spontaneous species) from a list of species already occurring in Porto, more precisely in urban green spaces with high urban ecological novelty levels (Teixeira et al., 2021). Traits were selected with a particular focus on adaptation, mitigation, and ornamental characteristics.

Plants' capacity to adapt and survive climate change will depend on their fitness to the site conditions (temperature, water, soil, or light), on their ability to perform across a range of environmental conditions (plasticity), and also on their tolerance to withstand current and future extreme environmental conditions (e.g., heat, drought, pollution) (Dunnett and Hitchmough, 2004; Hunter, 2011). On the other hand, plants' mitigation capacity will relate directly to their potential to minimize negative impacts such as heatwaves and pluvial flooding.

The constructed database (Teixeira et al., 2022) includes a wide array of species with different habits, life cycles, and functions. It also

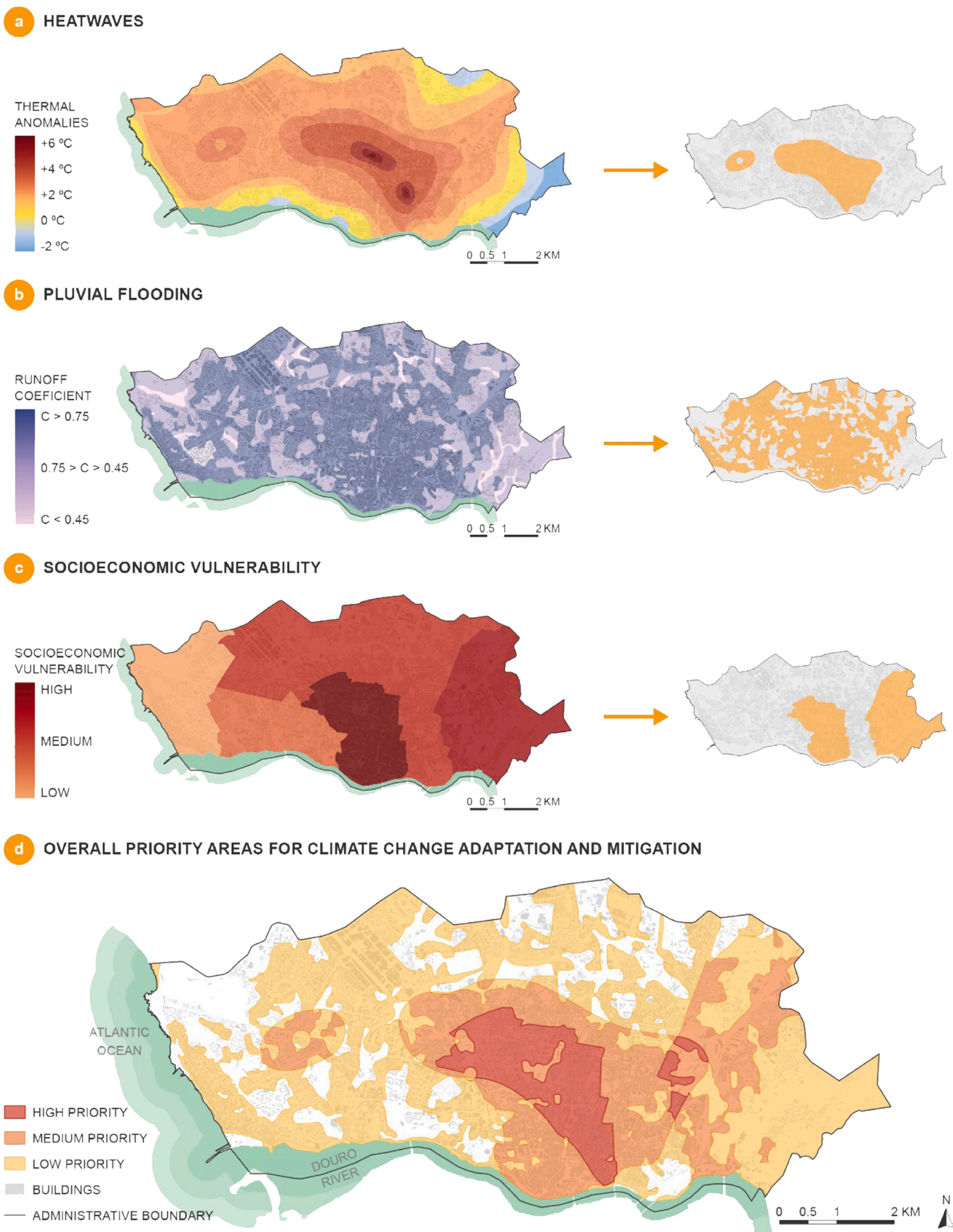

Fig. 2. Priority risks spatially assessed in Porto regarding: a) heatwaves; b) pluvial flooding; c) socio-economic vulnerability; and d) overall priority areas for climate change adaptation and mitigation in Porto.

includes species with different origins and distribution ranges as it is composed of 177 native species and 110 non-native species. From the set of non-native plants, 6 are casual (i.e., non-native species that occasionally reproduce in a given area but do not form self-replacing populations), 7 are naturalized (i.e., non-native species that reproduce consistently and sustain populations over many life cycles without, or in spite of, direct human intervention), and 16 are invasive (i.e., naturalized non-native species that reproduce and expand rapidly over a large area without direct human intervention, producing significant damages in ecosystems) in the Continental Portugal territory (Decreto-Lei no. 92/2019 do Ministério do Ambiente e Transição Energética, 2019; Marchante et al., 2014; Richardson et al., 2000). Following the "Practical guide for the identification of invasive plants in Portugal" (Marchante et al., 2014) casual and naturalized species were also categorized according to the risk of becoming invasive (low, medium, or high), whereas invasive species were categorized according to their invasive gravity in the territory (low, medium, or high).

This database represents a starting point and should continue to be developed, so other relevant species can be included over time. Although it was created for Porto's case, the database may include species that can be used in regions with similar environmental conditions and dynamics, especially if the species have a wide range of adaptation, distribution or do not entail ecological risk.

3.4. Adaptive planting design and management proposals

The final step of the framework was demonstrated in Porto by addressing the previously identified priority risks (i.e., heatwaves and pluvial flooding). For that, we selected two intervention sites formerly surveyed and resorting to the maps in Fig. 2 (i.e., high priority areas). Then, for each intervention site, we defined adaptation and mitigation goals (Table 1) and assessed the current status (Table S2). Two prototype proposals were developed and illustrated through sections (Figs. 3 and 4) that show the current situations (before intervention) and the planting design and management proposals (after intervention). The main plant palette is incorporated in each figure with the following information about the species: action, layer, status, and targeted adaptation traits.

The complete plant palettes for each proposal are present in Table S2 and only include species from the database. Added species serve to illustrative purposes since other species can also represent good options. Traits information about each species refers only to data that we were able to access. Thereby, we do not exclude the possibility that some of the referenced species can have more tolerances or functions apart from the identified. Finally, we compared the before and after situations to quantify improvement and understand which variables and traits were suppressed or minimized and which were achieved or maximized (Table 3). These proposals were only conceptualized and not realized interventions.

3.4.1. Proposal to address heatwaves

To address heatwaves, the main goals of the first proposal (Fig. 3) were to adjust the plant community to heat and drought (adaptation) and to regulate the temperature (mitigation) to improve human comfort. This proposal is located where positive thermal anomalies reach up to a magnitude of +5 degrees and where there is a greater distance to the sea, a lower share of green spaces, and higher impermeability.

Regarding the current situation, we propose the gradual removal and substitution of excessively dominant invasive species in the Portuguese territory such as *Cortaderia selloana*. This species grows vigorously and forms dense clusters that dominate the herbaceous layer, taking over the available resources in the area (Marchante et al., 2014).

Other invasive species with lower gravity were kept and flagged to be closely monitored. For instance, *Acer negundo* is well adapted and tackling the heatwaves problem, but the species was recently identified as an invasive plant in Portuguese legislation (Decreto-Lei no. 92/2019 do Ministério do Ambiente e Transição Energética, 2019), so its expansion in the territory requires caution. Species with risk of becoming invasive (i.e., casual and naturalized) were also kept and flagged to be monitored (*Pittosporum tobira, Acanthus mollis*).

We also propose monitoring native plants with an infesting behavior and features that can be perceived as an indicator of neglect (*Rubus ulmifolius*, *Pteridium aquilinum*). Other species in the current situation providing more benefits than problems (e.g., *Hedera helix*, *Populus nigra*) were kept and marked to be accommodated over time, as they have spontaneously emerged in this location. Finally, we propose the addition of 11 species with key traits to achieve and maximize the established goals.

This proposal mainly focuses on improving three factors that influence human comfort during heat events: shade, ventilation, and evapotranspiration (Table 1). This way, we suggested to increase the canopy cover in most of the intervention area as it will provide shade and improve evapotranspiration (Zölch et al., 2016). Canopy cover can also allow airflow beneath (Brown, 2010; Windhager et al., 2011), if trees are correctly positioned in relation to the prevailing wind direction and if the understory remains relatively open (Table 2). For instance, *Pinus pinaster* provides an elevated canopy (i.e., not close to the ground), allowing airflow and thermal regulation at the human scale. In that sense, planting locations, arrangements, patterns, and the orientation according to surrounding elements (e.g., other plants or buildings) have a decisive role in improving thermal comfort and should be carefully considered (Hami et al., 2019).

The shade provided will be proportional to the intercepted light, so more mature, denser, wider, and taller trees (e.g., *Platanus hispanica, Castanea sativa, Populus nigra*) have greater shading potential (Hami et al., 2019; Windhager et al., 2011). Shade can be strategically planned for the whole year (e.g., *Pinus pinaster*) or just for the warmest season with deciduous trees (e.g., *Fraxinus angustifolia*), which is more relevant for the case of Porto (Brown, 2010; Windhager et al., 2011). Shade can also be stronger or softer depending on the planting arrangement or crown density (e.g., *Castanea sativa* forms dense canopies while *Jacaranda mimosifolia* forms sparse canopies). In the latter, there is an opportunity to combine shading and ventilation strategies (Table 2). When using strong shading covers it is also vital to ensure that the understory is shade-tolerant (e.g., *Aucuba japonica, Bergenia cordifolia, Hedera helix)*. In this case, it can be useful to include species with higher light plasticity. For instance, some species can grow in full shade, partial shade, and full sun (e.g., *Acanthus mollis*, *Dactylis glomerata*, *Ligustrum ovalifolium*).

Species with high evapotranspiration potential may also represent interesting solutions to decrease temperatures and improve thermal comfort (Hami et al., 2019; Zölch et al., 2016). However, in this case, the water consumption is higher, which can become a disadvantage. Species with higher leaf surfaces and no water-saving mechanisms will transpire more moisture but will be more vulnerable to dry seasons. On the other hand, higher evapotranspiration capacity can usually allow species to remove more pollutants in the smog (Windhager et al., 2011). In this case, a vertical structure with more layers will enhance evapotranspiration (Hami et al., 2019), but it will not be compatible with a strategy that intends to promote ventilation (Table 2), so both factors must be strategically designed or managed.

Even though increasing canopy can be highly effective to reduce temperatures, we also included an open area in our proposal so that the space is not excessively enclosed and dark which can lead to feelings of insecurity and oppressiveness (Asgarzadeh et al. 2014). In this case, clearings enhance ventilation (Table 2) and can provide recreational and contemplative opportunities. Using a woodland-edge-clearing continuum model based on Appleton's (1975) prospect-refuge theory, we ensured a diverse spatial organization through the vegetation to respond to multiple urban dwellers needs, preferences, and interests beyond thermal comfort.

In this proposal, we used heat-tolerant and, when possible, drought-tolerant species as well (e.g., *Quercus rubra, Platanus hispanica*). We also considered if the species had higher temperature hardiness plasticity, i.e., more than four hardiness zones covered (e.g., *Liriodendron tulipifera, Vinca major*), as it will determine if they are prepared to wider ranges of temperatures (Hunter, 2011).

3.4.2. Proposal to address pluvial flooding

To address pluvial flooding, the main goals of the second proposal (Fig. 4) were to adjust the plant community to waterlogging, drought, and pollution (adaptation) and to manage flood risk and stormwater (mitigation). This proposal is located in Porto's central region, where there is a continuous patch with higher run-off coefficient value.

Regarding the current situation, we also suggested to remove invasive species that expand in the Portuguese territory aggressively. Besides *Cortaderia selloana*, we also removed *Acacia dealbata* (which germinates rapidly and vigorously, promotes soil alterations, and forms very dense

Table 1
Adaptation and mitigation goals to address climate change priority risks in Porto, plant traits and trait values involved, supporting references, and potential performance metrics to evaluate their effectiveness and success.

Climate change priority risk	Goals	Traits (trait values) and examples	References	Potential performance metrics*
Heatwaves	**Adaptation –** Improve tolerance and plasticity to withstand heat and drought.	• Heat tolerance (tolerant) – e.g., *Cedrus atlantica, Ligustrum ovalifolium, and Bergenia cordifolia* tolerate heat; • Temperature hardiness plasticity (more than 4 hardiness zones) – e.g., *Populus nigra*, *Hedera helix*, and *Poa pratensis* tolerate and range between 7 hardiness zones; • Drought tolerance (tolerant) – e.g., *Arbutus unedo*, *Tamarix gallica*, and *Foeniculum vulgare* tolerate drought; • Light plasticity (more than 1 light type) – e.g., *Ligustrum vulgare*, *Camellia japonica*, and *Acanthus mollis* tolerate 3 light types (full sun, partial sun/shade, and full shade).	Del Tredici (2020); Hunter (2011); Vogt et al. (2017)	• ↓annual number of species unable to resist extreme heat events (number/year) • ↑overall green cover (area or %) • ↑tree canopy (area or %) • ↑vertical layers (number) • ↓air or surface temperature (degrees or %) • ↑annual atmospheric CO_2 sequestration (weight/year) • ↑quality of visitor experience and thermal comfort (surveys)
	Mitigation – Regulate temperature by maximizing: shade, wind ventilation, evapotranspiration, and carbon sequestration and storage.	• Height and width (high values) – e.g., *Platanus hispanica*, *Cedrus atlantica*, and *Quercus robur* are large and wide (more shade); • Crown density (high) – e.g., *Acer pseudoplatanus*, *Magnolia grandiflora*, and *Pinus pinea* have dense crowns (stronger shade); • Crown height (high values) – e.g., *Pinus pinaster*, *Liriodendron tulipifera*, and *Quercus rubra* do not have the crown close to the ground (more ventilation); • Crown shape (variable) – e.g., *Ligustrum lucidum* has a round shape and *Pinus pinea* has an umbrella shape (more shade than plants with pyramidal and columnar shapes); • Foliage persistence (variable) – e.g., *Metrosideros excelsa* is evergreen (shade throughout the year) and *Fraxinus angustifolia* is deciduous (summer shade); • Evapotranspiration rate (high) – e.g., *Alnus glutinosa*, *Acer pseudoplatanus*, and *Sambucus nigra* have high rates of evapotranspiration.	Brown (2010); Hami et al. (2019); Kennen and Kirkwood (2015); Santiago et al. (2019); Van Mechelen et al.(2015); Windhager et al. (2011)	
Pluvial flooding	**Adaptation –** Improve tolerance and plasticity to withstand waterlogging, drought, pollution.	• Waterlogging tolerance (tolerant) – e.g., *Alnus glutinosa*, *Salix atrocinerea*, and *Cyperus longus* tolerate waterlogging; • Drought tolerance (tolerant) – e.g., *Thuja plicata*, *Ulex europaeus*, and *Ophiopogon japonicus* tolerate drought; • Pollution tolerance (tolerant) – e.g., *Castanea sativa*, *Sambucus nigra*, and *Agrostis capillaris* tolerate pollution; • Soil moisture plasticity (more than 1 soil moisture type) e.g., *Platanus hispanica*, *Acer negundo*, and *Stenotaphrum secundatum* tolerate 3 soil moisture types (dry, fresh, and moist); • Life form (suitable to the habitat) – e.g., *Apium nodiflorum*, *Cyperus esculentus*, and *Lythrum salicaria* are suitable to aquatic conditions (hydrophytes).	Del Tredici (2020); Hunter (2011); Vogt et al. (2017)	• ↓annual number of species unable to resist extreme precipitation events (number/year) • ↓impervious surface (area or %) • ↑flood storage (volume or %) • ↓annual frequency of localized flooding events (number of events/year) • ↓annual costs associated with flooding events (currency/year) • ↓ area affected by erosion (area or percent) ↑annual amount of pollutants removed (weight/year)
	Mitigation – Manage stormwater and reduce the risk of flooding and landslide by maximizing: stormwater interception (slow water movement), stormwater infiltration and storage, erosion control.	• Height and width (high values) – e.g., *Liriodendron tulipifera*, *Castanea sativa*, and *Quercus rubra* are large and wide (more water interception); • Crown density (high) – e.g., *Populus nigra*, *Robinia pseudoacacia*, and *Pinus pinaster* have dense crowns (more water interception); • Foliage persistence (variable) – e.g., *Camellia japonica* is evergreen (water interception throughout the year) and *Liriodendron tulipifera* is deciduous (water interception in summer); • Multi-stem development (yes) – e.g., *Metrosideros excelsa*, *Magnolia stellata*, and *Camellia japonica* have multiple stems (more water interception); • Stem flexibility (high) – e.g., *Paspalum dilatatum*, *Holcus lanatus*, and *Festuca rubra* have flexible stems (slow water movement and more infiltration); • Leaf area, anatomy and shape (variable) – e.g., *Cercis yunnanensis* has large leaves with trichomes (more water interception and storage) and *Ligustrum lucidum* has small leathery leaves with no trichomes (less water interception and storage).	Espeland and Kettenring (2018); Hami et al. (2019); Van Mechelen et al. (2015); Xiao and McPherson (2016); Yan et al. (2021); Windhager et al. (2011)	

↑ (increase in); ↓ (decrease in).
* *based on* Rainer and West (2015) and LAF (2018).

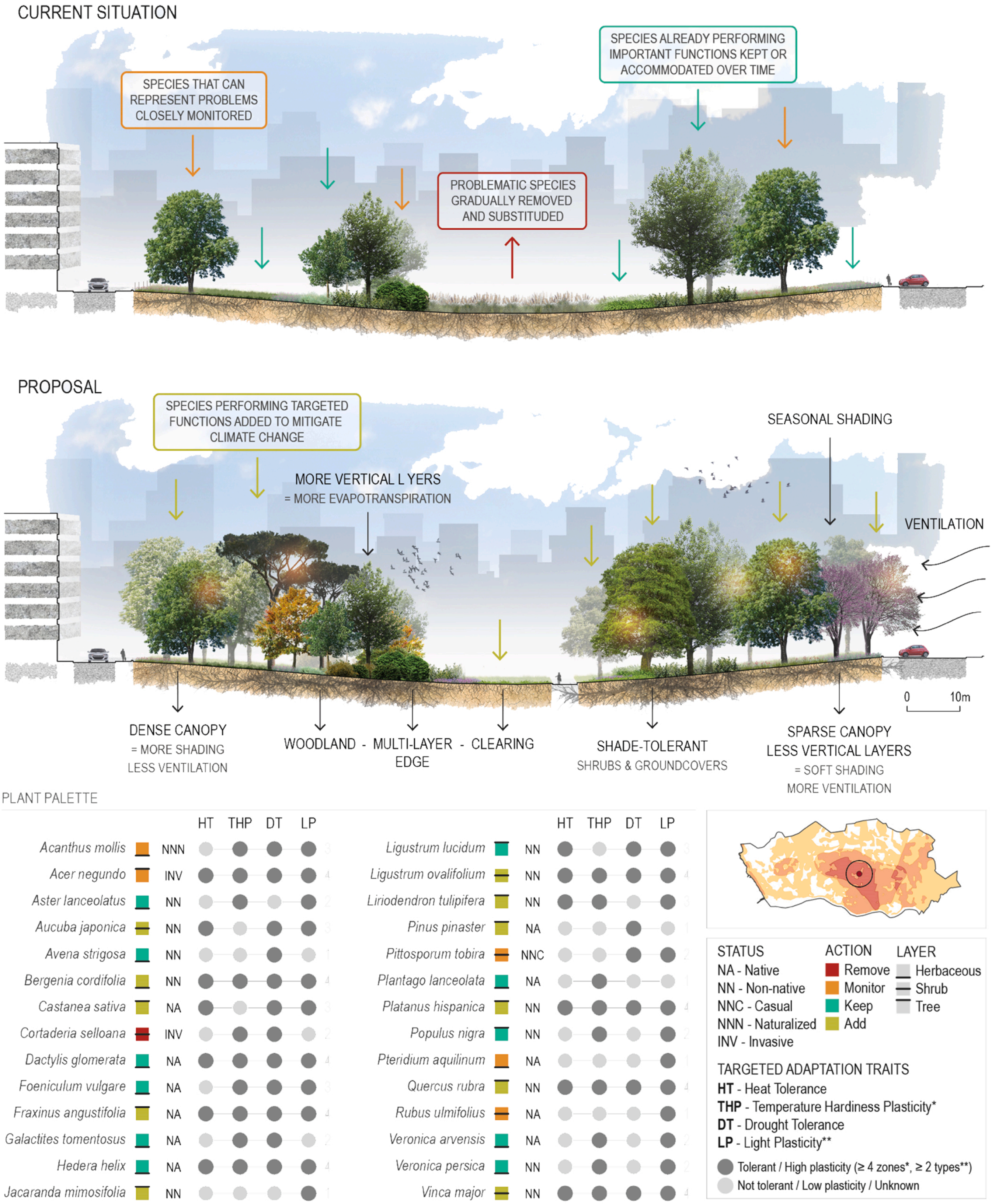

Fig. 3. Illustrative sections and plant palette to address heatwaves.

settlements that impede the development of other species) and *Erigeron karvinskianus* (which reproduces vegetatively through rhizomes, forms continuous mats, and competes with other species for space, water, and nutrients) (Marchante et al., 2014).

We propose to keep and closely monitor casual and naturalized species that represent a risk of becoming invasive (*Oenothera glazioviana*, *Zantedeschia aethiopica*, *Buddleja davidii*). In this case, special attention should be given to species with higher ecological risks (*Reynoutria*

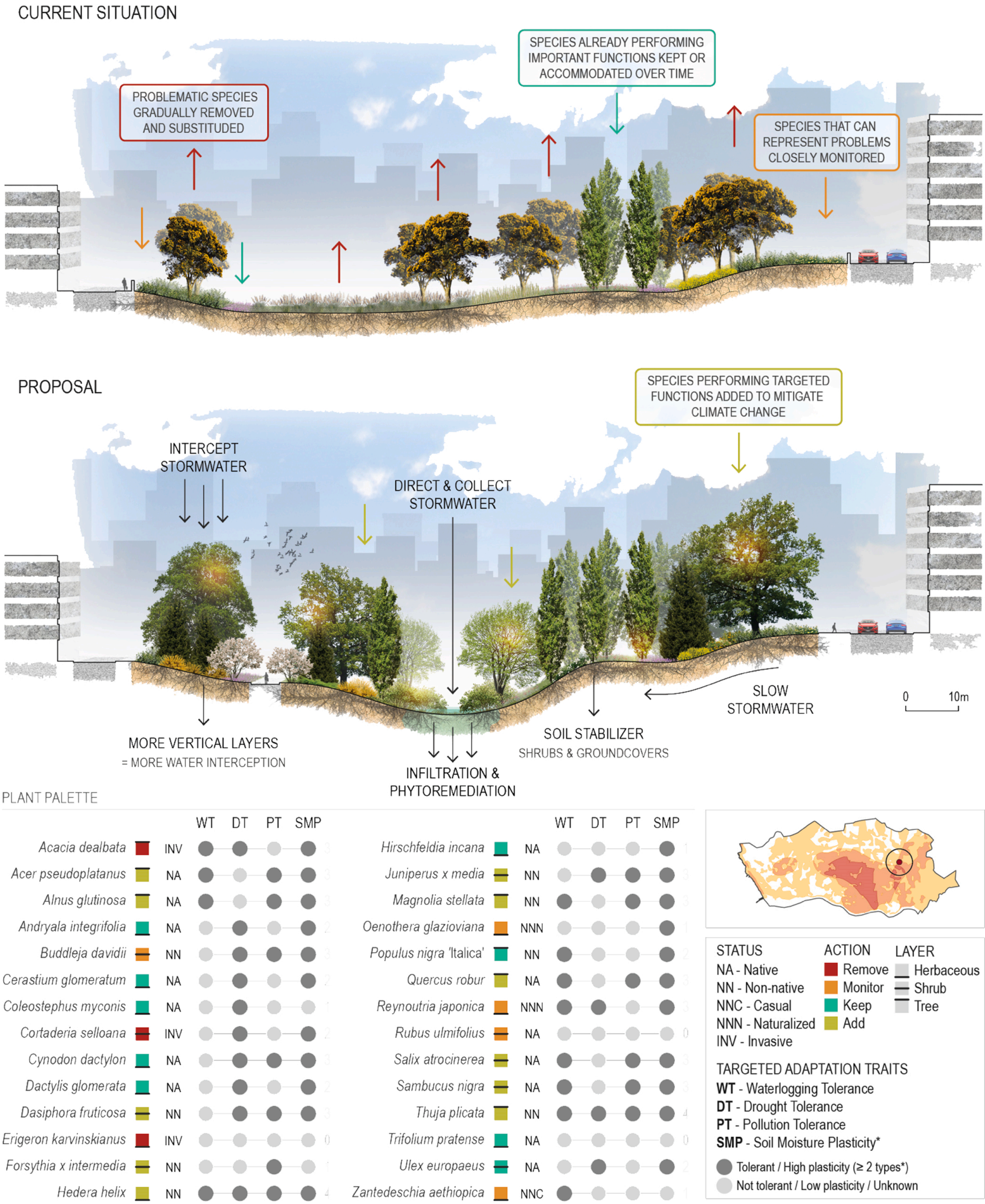

Fig. 4. Illustrative sections and plant palette to address pluvial flooding.

Table 2
General mitigation potential based on the vertical structure and number of layers of plant compositions (Brown, 2010; Hami et al., 2019; Santiago et al., 2019; Windhager et al., 2011).

Vertical Structure Typology	Number of layers	Mitigation factor			
		Shading	Ventilation	Evapotranspiration	Stormwater interception
Canopy only (dense)	1	Moderate-high	Moderate	Moderate-high	Moderate-high
Canopy only (sparse)	1	Moderate	Moderate-high	Moderate	Moderate
Canopy with low shrubs or groundcover	2	High	Low-moderate	High	Moderate-high
Canopy, shrubs, and groundcover	3	Very high	Low	Very high	Very high
Low shrubs or groundcover only	1	Low	Very high	Low-moderate	Low-moderate

Table 3
Number of species in each proposal (before and after) regarding overall diversity (species richness), structural diversity (layer), assemblage of native and non-native species (status), and response diversity (targeted traits). Final net gains and losses resulting from changes between the current (before) and the proposed situation (after). The species numbers refer to the complete plant palette available in Table S2.

Variable	Proposal 1			Proposal 2		
	Before	After	Gain/ loss	Before	After	Gain/ loss
Species richness	42	52	+ 10	37	45	+ 8
Layer						
Herbaceous	36	37	+ 1	31	31	0
Shrubs	3	5	+ 2	4	8	+ 4
Trees	3	10	+ 7	2	6	+ 4
Status						
Native (NA)	31	34	+ 3	28	33	+ 5
Non-native (NN)	7	15	+ 8	3	9	+ 6
Non-native casual (NNC)	1	1	0	1	1	0
Non-native naturalized (NNN)	1	1	0	2	2	0
Invasive (INV)	2	1	-1	3	0	-3
Targeted adaptation traits						
Heat tolerance (HT) – heat-tolerant species	4	13	+ 9			
Temperature hardiness plasticity (THP) – species ranging between more than 4 hardiness zones	15	21	+ 6			
Light Plasticity (LP) – species ranging between more than 2 light types	21	31	+ 10			
Drought tolerance (DT) – drought-tolerant species	11	19	+ 8	10	12	+ 2
Waterlogging tolerance (WT) – waterlogging-tolerant species				4	11	+ 7
Pollution tolerance (PT) – pollution-tolerant species				2	13	+ 11
Soil Moisture Plasticity (SMP) – species ranging between more than 2 soil moisture types				17	25	+ 8

japonica). Likewise, species that may be perceived as an indicator of dereliction (*Rubus ulmifolius*) should also be monitored and their appearance and care must be enhanced (Nassauer, 1995). We kept the existing desirable and advantageous species (e.g., *Populus nigra* 'Italica', *Ulex europaeus*, *Cerastium glomeratum*) and suggested adding 11 targeted species to achieve and maximize the established goals.

This proposal mainly focuses on improving the factors that influence human safety during flooding events: stormwater interception, infiltration and storage, and erosion control (Table 1). In this case, we proposed to increase the vegetation that will intercept and slow stormwater while also directing the run-off to a location where it can be stored and slowly infiltrated into the soil (Matos Silva, 2016).

Plant traits such as height, width, multi-stem development, stem flexibility, leaf area, crown surface area, and crown density (Table 1) play a vital role in intercepting, slowing, and absorbing stormwater, thereby reducing their impacts (Espeland and Kettenring, 2018; Hami et al., 2019; Xiao and McPherson, 2016; Yan et al., 2021). This way, species with larger and denser crowns (e.g., *Acer pseudoplatanus*) or species with multi-stems development and stem flexibility (e.g., *Salix atrocinerea*) will represent reliable options. Due to stormwater movement and storage, vegetation with erosion control potential (e.g., *Hedera helix, Juniperus x media, Rubus ulmifolius*) will also be critical to prevent the risk of landslide. In this case, the interception provided by the canopy structure will directly affect soil erosion by slowing and redistributing the stormwater (Yan et al., 2021).

We included waterlogging-tolerant species and, when possible, pollution-tolerant as well (e.g., *Alnus glutinosa, Salix atrocinerea, Thuja plicata*), since stormwater is usually very polluted. Pollution in cities associated with flooding and storm events is also strongly linked to negative impacts on human health (viral infections and contaminations), so proposals to address pluvial flooding should focus on improving the quality of water as well (Hami et al., 2019). For that reason, it is advisable to include species with phytoremediation potential (e.g., *Populus spp., Pinus spp., Salix spp., Sambucus spp.*) (Kennen and Kirkwood, 2015).

Flooding events may be more extreme in the future but rarer, so, when possible, it is also relevant to include species that will be drought-tolerant (e.g., *Dasiphora fruticosa, Juniperus x media, Ulex europaeus*). Nevertheless, this is not easily achieved and when exposed to extreme and extended drought periods, plants that are not highly drought-tolerant can and should be watered. Therefore, it can be useful to look to the plants with higher soil moisture plasticity. For instance, some species can grow in dry, fresh, and moist soil types (e.g., *Sambucus nigra, Hedera helix, Thuja plicata*).

3.4.3. Overview of the proposals

The presented proposals focus separately on heatwaves and pluvial flooding based on specific adaptation and mitigation goals (Table 1). However, there may be situations where adaptation and mitigation of both heatwaves and pluvial flooding are necessary. In this case, it is important to set priorities and understand how the strategies can align and complement each other.

Table 3 shows a straightforward way of quantifying the final gains and losses resulting from the decisions made in each proposal. Compared to the current situation, the final species combinations in all the proposals increases the species richness, response diversity, and structural and functional diversity (Table S2). After implementation and based on the established goals and prioritization, the proposals should be monitored according to performance metrics (Table 1).

4. Discussion and conclusion

The proposed framework offers a more experimental and adaptable way of designing and managing plant communities in cities, which may be increasingly mandatory in the face of uncertain future climate change effects and to ensure the comfort and safety of urban dwellers. For that reason, knowledge collected from an implemented adaptive planting design and management proposal can represent a unique opportunity to learn from a complex and real-time urban environment experiment, which is impossible to replicate in a controlled setting (Felson and Pickett, 2005).

We focus on opportunities emerging from novel plant communities for climate change adaptation and mitigation, which are relevant and promising but require further research. Novel and spontaneous assemblages of species can harbor large levels of biodiversity that will influence the adaptive capacity and socio-ecological resilience of cities (Ahern et al., 2014; Light et al., 2013; Van Mechelen et al., 2015). Additionally, by focusing on preserving ecosystem functions, the Novel Urban Ecosystems concept allows an appreciation of the function and adaptability of species or combinations of species above their identity or origin (Davis et al., 2011; Del Tredici, 2020; Starzomski, 2013).

We demonstrated how the framework could be applied in Porto but believe it can also be applied to other urban contexts and regions. This research provides guidance for the design and management of small to intermediate plantings that provide localized benefits. Notwithstanding, interventions at smaller scales can still have an enduring effect across the whole city and its neighborhoods.

Through the proposed adaptive framework, it is possible to value existing formal and informal urban green spaces actively and according to specific goals (e.g., esthetic, cultural, political, ecological, and/or social). The illustrative proposals show planting strategies in urban green spaces that aim to maintain or enhance existing ecosystem functions and to introduce new species and planting types to provide new benefits. The principles suggested in this work can also guide the development of new green spaces. Ultimately, this study offers a starting point for experimentation, a necessary step to construct valuable knowledge to address and tackle forthcoming extreme events and climate change scenarios.

CRediT authorship contribution statement

Catarina Patoilo Teixeira: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. **Cláudia Oliveira Fernandes:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Jack Ahern:** Conceptualization, Writing – review & editing, Supervision.

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.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127548.

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