LETICIA FIGUEIREDO CANDIDO

Monitoramento da alocação de carbono em árvores urbanas

Tese apresentada ao Instituto de Pesquisas Ambientais, da Secretaria de Meio Ambiente, Infraestrutura e Logística, como parte dos requisitos exigidos para a obtenção do título de DOUTORA em BIODIVERSIDADE VEGETAL E MEIO AMBIENTE, na Área de Concentração de Plantas Vasculares em Análises Ambientais .

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ORIENTADOR: DR. GIULIANO MASELLI LOCOSSELLI

CO-ORIENTADOR: DRA. ADRIANA GRANDIS

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BANCA EXAMINADORA

Dr. Giuliano Maselli Locosselli (Orientador)

Centro de Energia Nuclear em Agricultura, Universidade de São Paulo (CENA-USP)

Dr. Emerson Alves da Silva

Instituto de Pesquisas Ambientais de São Paulo (IPA)

Dr. Peter Stoltenborg Groenendyk

Instituto de Biologia, Universidade Estadual de Campinas (IB-UNICAMP)

Dra. Demóstenes Ferreira da Silva Filho

Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo (ESALQ-USP)

Dr. Marcos Silveira Buckeridge

Instituto de Biociências, Universidade de São Paulo (IB-USP)

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In nature, we find connection.

The connections are the answer.

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RESUMO

As árvores urbanas prestam serviços ecossistêmicos essenciais para resolver problemas ambientais, como calor excessivo, poluição do ar ou inundações. No entanto, sua persistência nas cidades depende da seleção cuidadosa de espécies que equilibrem serviços ecossistêmicos, tolerância e disserviços. Esta tese avança o conhecimento sobre a ecologia das árvores urbanas, integrando três perspectivas complementares. Primeiro, elaboramos uma revisão sistemática para avaliar o estado do conhecimento sobre a seleção de espécies de árvores urbanas nos três pilares: serviços ecossistêmicos, tolerância e disserviços. Descobrimos que os serviços ecossistêmicos são os pilares mais pesquisados e geralmente estão associados à tolerância, mas há uma lacuna no conhecimento sobre os disserviços. Existem apenas alguns estudos que atribuem os três pilares juntos, e eles usam bancos de dados ou modelagem. Em segundo lugar, investigamos o crescimento das árvores e o déficit hídrico sob o clima urbano de espécies nativas da Mata Atlântica em um parque urbano e uma floresta urbana na megacidade de São Paulo. Além da diferença nos padrões de crescimento e características fenológicas, todas as sete espécies apresentam padrões semelhantes em relação ao déficit hídrico das árvores sob pressão VPD, indicando uma vulnerabilidade ao clima em ambas as áreas verdes. Em terceiro lugar, aprofundamos a alocação não estrutural de carbono das espécies, monitorando trimestralmente o açúcar solúvel e o amido da madeira branca. Identificamos diferentes concentrações de açúcares para as espécies, mas um padrão semelhante durante o crescimento, em que vemos um pico de glicose e frutose no início do crescimento, que diminui no final do crescimento, aumentando a concentração de sacarose. Esta tese reúne as escalas macro e micro do crescimento das árvores urbanas, de um país tropical, preenchendo lacunas na literatura e gerando informações para decisões baseadas em evidências no reflorestamento urbano.

Palavras-chave: Soluções baseadas na natureza; carbono não estrutural; dendrômetro; crescimento de árvores; déficit hídrico das árvores;

ABSTRACT

Urban trees provide essential ecosystem services to solve environmental problems, such as excessive heat, air pollution, or floods. Yet their persistence in cities depends on the careful selection of species that balance ecosystem services, tolerance, and disservices. This thesis advances knowledge on urban tree ecology by integrating three complementary perspectives. First, we elaborated a systematic review to assess the state of knowledge on urban tree species selection at the three pillars: ecosystem services, tolerance, and disservices. We found that ecosystem services are the most researched pillars and are usually associated with tolerance, but there is a gap in knowledge on disservices. There are just a few studies assigning the three pillars together, and they use databases or modelling. Second, we investigated the tree growth and water deficit under the urban climate of Atlantic Rainforest native species at an urban park and one urban forest in the megacity of São Paulo. Besides the difference in growth patterns and phenology characteristics, all seven species present similar patterns on tree water deficit under VPD pressure, indicating a vulnerability to climate in both green areas. Third, we deep dive into the non-structural carbon allocation of the species, monitoring quarterly the soluble sugar and starch of the sapwood. We identified different concentrations of sugars for species, but a similar pattern during the growth, where we see a peak on glucose and fructose in the early growth, and this decreases at late growth, increasing the sucrose concentration. This thesis brings together the macro and micro scales of growth in urban trees, from a tropical country, filling gaps in the literature and generating information for evidence-based decisions in urban afforestation.

Key words: Nature-based solutions; non-structural carbon; dendrometer; tree growth; tree water deficit;

LISTA DE ABREVIATURAS

At = *Alchornea triplinervia*

BAI = basal area increment

Cf = *Cedrela fissilis*

Cm = *Cryptocaria mandiocanna*

Co = *Cupania oblongifolia*

Ct = *Centrolobium tomentosum*

Ep = *Eugenia pruinosa*

Eu = *Eugenia uniflora*

GRO = growth

Iso = isolated

NSC = non-structural carbon

TWD = tree water deficit

UF = urban forest

UP = urban park

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1. Introduction

The rapid growth of cities has promoted significant changes in land use and occupation, resulting in profound impacts on biogeochemical cycles, such as those of carbon and water (Vitousek et al., 1997; Rojstaczer et al., 2001; Pataki et al., 2011), as well as contributing to climate change on a global and local scale (Forster et al., 2007; IPCC, 2014a,b). Although they occupy less than 3% of the Earth's surface, urban areas are responsible for about 78% of global CO_2 emissions, mainly associated with the burning of fossil fuels in transport, energy production, and industrial activities (Velasco & Roth, 2010). These characteristics, combined with the use of materials with high heat retention capacity, favour the formation of urban heat islands, which intensify local temperatures and reduce thermal comfort, especially in regions with little tree cover (Hunt & Watkiss, 2011; Silva et al., 2019; Ferreira & Duarte, 2019). In addition, urbanisation intensifies convective processes that alter atmospheric circulation, cloud formation, and rainfall patterns (Baklanov et al., 2016), contributing to an increase in extreme events, such as extreme rainfall events, which are becoming more common and intense in São Paulo Metropolitan Area over the last eight decades (Marengo et al., 2020). This set of transformations highlights how urbanisation, while driving economic development, exacerbates environmental and social problems by compromising water security, thermal comfort, and the resilience of urban populations (Romero-Lankao, 2011; Locosselli & Buckeridge, 2023).

The environmental changes resulting from urbanisation are not limited to ecological or climatic impacts, but also pose serious public health problems. Warming and heat excess in urban areas are directly associated with the risk of cardiovascular and respiratory diseases, contributing to higher premature mortality rates (Analitis et al., 2008; The Eurowinter Group, 1997). In Brazilian cities, including São Paulo, deaths related to temperature variations and extreme heat waves have been reported, which can increase mortality by between 8.9% and 12.1% (Rooney et al., 1998; Peng et al., 2011; Gasparrini et al., 2015; Baccini et al., 2011). In addition, rising temperatures intensify energy demand for climatization, whose demand grows between 0.45% and 4.6% for every 1–2 °C increase in air temperature (Voogt, 2004; Nuruzzaman, 2015; Santamouris et al., 2015). Likewise, changes in precipitation patterns increase hydrometeorological risks, favouring natural disasters such as floods, landslides, and droughts, which compromise health, water security, and the urban economy (Romero-Lankao, 2011; Young, 2013; Assad & Young, 2018; Nobre et al., 2011). São Paulo is a critical example of this reality: the 2014–2015 water crisis severely impacted the population's water supply (Jacob et al., 2013; Nobre et al., 2016), while rapid urban expansion since the 1950s, which transformed the metropolis into the fifth

largest urban conglomerate in the world, has intensified socio-environmental inequalities and reduced vegetation cover in densely populated areas, especially in subnormal agglomerations (Torres et al., 2007; Baklanov, 2016; Silva et al., 2019).

In response to these climate crises, nature-based Solutions (NbS) have been established as an effective set of strategies for and the adaptation of cities to climate change (Kabisch et al., 2016; Lafortezza et al., 2017). As an umbrella concept, NbS encompasses initiatives such as river restoration, creation of green spaces, and implementation of green infrastructure, which integrate natural elements into the urban environment to generate multiple benefits (Pataki, 2011). In this context, urban forests, comprising forest fragments, parks, gardens, green corridors, and roadside trees, play a central role. Urban trees provide a wide range of ecosystem services, such as heat island mitigation (Livesley et al., 2016), carbon sequestration and storage (Pataki et al., 2006; Edmondson et al., 2012), water regulation through reduced surface runoff, and improving air quality, which together have a direct impact on the health and well-being of the population (Brack, 2002; Escobedo & Nowak, 2009; Escobedo et al., 2011; Livesley et al., 2014; McPherson et al., 2011; Pataki et al., 2011). The effectiveness of these solutions, however, depends on understanding the biological processes that underpin such benefits, including the role of non-structural carbon (NSC´s) compounds, which are fundamental not only as energy reserves but also as mechanisms for tree resilience to environmental stresses (D'Andrea et al., 2021).

Urban trees play a central role in carbon and water cycles by assimilating CO_2 through photosynthesis and releasing water through evapotranspiration, processes that together contribute to climate change mitigation and urban microclimate regulation (Tyree & Sperry, 1989; Tyree & Ewers, 1991; Pataki et al., 2011). The carbon fixed in chloroplasts is exported in the form of triose phosphate, used in the synthesis of sucrose, which can be directed to immediate metabolism, to the formation of structural tissues, or allocated as non-structural carbon (Kozlowski, 1992; Locosselli & Buckeridge, 2017). These reserves, composed of long-term starch and readily mobilisable soluble sugars (Chapin, 1990; Hoch et al., 2003; D'Andrea et al., 2021), are fundamental to the resilience of trees in the face of stress conditions, ensuring metabolic support in periods of water deficit or photosynthetic seasonality. The magnitude of these processes varies between species, reflecting morphological, physiological, and phenological differences, which result in different potentials for providing ecosystem services, such as thermal regulation, carbon sequestration, rain interception, and biodiversity support (Eviner, 2004; Livesley et al., 2016; Silva Luz et al., 2024; Locosselli et al., 2024). In this sense, understanding the physiology and carbon allocation of urban species is essential to guide the planning of functional and resilient urban forests, maximising the ecosystem services provided to cities (Rötzer et al., 2019; Kumar et al., 2024).

Thus, while urban trees offer essential benefits through ecosystem services, their permanence in cities also depends on their ability to tolerate adverse environmental conditions and the risks associated with so-called disservices. Climate stress, such as heat waves, drought, and intensification of urban heat islands, poses challenges to the survival and physiological performance of species (Silva et al. 2019; Percival 2023). This vulnerability can result in high mortality rates, reduced growth, and compromised service provision (Britt et al. 2008; Locosselli et al. 2019, 2024). In addition, the disservices generated by trees, such as damage to infrastructure, risk of falling, seasonal allergies, and emissions of volatile organic compounds (BVOCs), can directly impact human well-being and generate significant economic costs (Schmidlin 2009; Shackleton et al. 2016; Roman et al. 2021; Sgrigna et al. 2020). Therefore, urban tree planting planning needs to consider three pillars in an integrated manner: the provision of ecosystem services, the tolerance of species to urban conditions, and the potential associated disservices. This balance is essential to ensure the appropriate selection of species and to ensure that urban afforestation contributes effectively and sustainably to the quality of life in cities.

To understand the tolerance of tree species, it is necessary to recognise that the climate of cities acts as a primary environmental filter, modulating the growth, reproduction, and longevity of urban trees (Sjoman et al. 2018; Esperon-Rodriguez et al. 2025). In densely urbanised areas, high temperatures associated with heat islands, increased evaporative demand, and irregular rainfall increase the risk of water stress, imposing direct restrictions on cambial expansion and biomass accumulation (Silva et al. 2019; Percival 2023). Chronic water deficit forces trees to make complex physiological adjustments, such as reducing stomatal conductance and photosynthetic rate, as well as prioritising carbon allocation to non-structural reserves as a survival mechanism at the expense of growth (Sjöman et al. 2018; Locosselli et al. 2024). Despite the relevance of these processes, there remains a critical gap in scientific knowledge in tropical regions, where high biodiversity contrasts with a scarcity of studies on the functioning of species in urban contexts (Giraldo et al. 2025). This gap is particularly worrying because it is precisely these megadiverse regions that are home to most of the planet's large cities, which are the most exposed to extreme weather events and therefore the ones that most need robust information to guide species selection (Estrada et al. 2023; Khanh et al. 2023).

The dynamics of carbon allocation in urban trees reflect fundamental physiological strategies for stress tolerance, connecting growth, maintenance, and resilience in heterogeneous and challenging environments (Ramirez et al. 2021). The partitioning between structural growth and non-structural reserves (NSCs) does not occur randomly, but rather as an adaptive strategy that regulates the tree's ability to cope with limitations imposed

by the urban environment, including water deficit, high temperatures, and abrupt microclimate variations (Martínez-Vilalta et al., 2016; Locosselli & Buckeridge, 2017). Species that prioritise NSC accumulation have greater physiological security, sustaining respiration, osmotic adjustment, and hydraulic integrity during periods of prolonged stress, while species that direct more carbon towards immediate growth may be more vulnerable to failure in extreme conditions (Dietze et al., 2014; Ramirez et al., 2021). Thus, the study of carbon allocation not only clarifies the internal mechanisms that determine the performance and resilience of urban trees but also provides the basis for a conceptual approach to tree planting planning, in which species selection should consider the coordination between ecosystem service potential, reserve maintenance capacity, and tolerance to adverse urban conditions.

Based on the concepts presented, this thesis is divided into three chapters that explore different dimensions of urban forest management. The first chapter, ´Is science covering the complexity behind urban tree species selection? A systematic review on the integration of ecosystem services, tolerance, and disservices´ assesses how the literature addresses the integration of ecosystem services, tolerance and disservices in species selection, identifying gaps and opportunities for improvement. The second chapter, 'Does tree diversity translate into greater resilience of urban forests to climate change? A case study in the megacity of São Paulo, Brazil,' empirically examines how native tree species behave in the urban climate in parks with different levels of diversity, considering responses to growth and water deficit. The third chapter, 'The dynamics of non-structural carbohydrates to couple with growth and water deficit in native tropical tree species,' investigates the physiological mechanisms underlying tree tolerance, analysing the allocation of non-structural carbon in native tropical species and its relationship with growth and water stress. Together, these chapters provide an integrated view that connects ecology, physiology, and urban planning, offering insights for species selection and the implementation of more resilient and effective nature-based solutions in cities.

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2. Chapter 1

Is science addressing the complexity behind urban tree species selection? A systematic review on the integration of ecosystem services, stress tolerance, and disservices.

In collaboration with: Cíntia Luíza Silva-Luz, Ricardo Reale, Augusto Akio Lucchezi Miyahara, Giulia Nunes de Aguiar Souto, Tom Wild, Plinio Barbosa de Camargo, Lucas William Mendes, Giuliano Maselli Locosselli

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Highlights:

1. Science must support urban forestry through an integrative approach.
2. The integration of ecosystem services, tolerance, and disservices is incipient.
3. The few integrative studies point to trade-offs and synergisms among pillars.
4. Integrative research is challenging but possible through trait-based frameworks.

2.1 Abstract

The principle of “right tree in the right place” has long guided tree species selection through planting manuals and guidelines, which are grounded in practitioners’ experience and scientific evidence. Yet, science still falls short in integrating different pillars in species selection, given the current level of specialization in the assessment of, for instance, species’ ecosystem services, stress tolerance, and disservices. In this systematic review, we evaluated how science combines these three pillars to ease the knowledge burden on decision-makers. We surveyed 293 studies using the PRISMA framework and found that most studies focused on ecosystem services, followed by tolerance and disservices. Only 29% of the studies addressed multiple pillars, 40% of them combined air pollution regulation and tolerance, reflecting its relevance to public health and tree development. Studies also evaluated trade-offs by combining the air pollution regulation and species' potential emission of BVOCs and allergens or explored synergies between species tolerance to local conditions and benefits like social cohesion and interest in nature. These few examples reveal that integrating these pillars is challenging but possible, particularly through the assessment of common traits. The assessment of common traits like tree height and diameter underpins the prospects of a holistic assessment of species based on tree size to better predict species performance and senescence. Despite over a thousand species have been studied, knowledge remains limited in terms of climate coverage and pillar integration. To foster integrative studies on species selection for urban afforestation, we outlined six recommendations for future research..

Keywords: urban afforestation; climate change; climate resilience; tree selection.

2.2 Introduction

Urban trees are at the core of solutions for the cities' environmental challenges in the 21st century. It is clear by now that enhancing tree cover is a fundamental step in promoting citizens' well-being (Pincetl, 2010; Campbell, 2014; Konijnendijk, 2023), for all the benefits urban trees provide, including aesthetic and cultural values (Goodness et al, 2016). Focusing solely on the benefits of trees provides a narrow perspective for planning urban tree cover, which must also include other critical aspects, such as the suitability of species to local conditions (Vogt et al, 2017). These two principles underpin the well-known mantra in urban forestry - "the right tree, in the right place" - (Langenheim et al 2020; Summit and Sommer, 2018), originally proposed in the early 1940s (Minckler, 1941). Even though species choice can still be driven by the personal opinion of practitioners and decision-makers (Roy 2017), the importance of the combination of the species' potential benefits and local suitability is relatively well-covered in planting manuals and guidelines worldwide (e.g., Forestry Commission UK 2018, Voigt et al 2017, Farrell et al 2022). All of which were built over decades of practitioners' experience and empirical evidence, and to some extent scientific knowledge (e.g., Speak et al, 2018). Yet, tree selection remains a core and complex activity in urban forestry, a complexity that tends to increase with local tree biodiversity peaking at the tropics, where knowledge to support tree selection may be currently limited compared to the number of native species available for a diverse urban afforestation (Hortal et al, 2015), often dominated by exotic species (e.g. Dos Santos et al 2010). Despite the advances in species selection over the decades, increasingly based on well-informed decision-making, it is still unclear if science is keeping pace to tackle the urgency in re-greening cities. Particularly, if studies are truly able to combine the different aspects of urban tree selection, and communicate it well, given the level of scientific specialization (von Winterfeldt 2013).

Science is bound to a specific method based on observation, raising hypotheses, and testing them. It is through testing that science on urban trees delves into the mechanisms behind the observed patterns, enabling decision-making based on accurate and credible evidence (von Winterfeldt 2013, Newman et al 2017). To achieve this goal, science must assess various biological aspects of trees, from form to function, to provide valuable evidence on the benefits they provide (Liang and Huang 2023). The benefits that society obtains from ecosystem elements and processes are known as ecosystem services (M.E.A. 2005), which are categorized in provision, regulation, cultural, and support (Wallace 2007),

all stemming from species' morphological, physiological, and phenological characteristics (Silva-Luz et al 2024). For instance, trees contribute to the urban carbon cycle (Shadman et al. 2022) through carbon assimilation, allocation, and mobilization in structural tissues and non-structural reserves, offsetting to some extent urban carbon emissions (Russo et al. 2014; Pincetl 2017). Urban trees further contribute to mitigation by reducing carbon emissions from climatization (Reynolds et al. 2017, Hardiman et al. 2017) through shade depending on species crown and leaf characteristics, and conversion of sensible heat into latent heat according to species hydraulic strategies and transpiration rate (Ferreira and Duarte 2019, Manoli et al. 2019, Kumar et al. 2024). These are just a couple of examples of how science addresses the ecosystem services through several plant traits that translate into benefits (Farrell et al, 2022). Based on the current literature, some of these plant traits are measured for specific services, whereas others provide insights into various ecosystem services simultaneously (Silva-Luz et al, 2024). Like the consensus around the direct association between the delivery of various ecosystem services and tree size (Rötzer et al, 2019). Thus, finding common biological attributes, oftentimes referred to as traits, provides a fast track to assess multiple benefits from trees (Silva-Luz et al, 2024).

Other than their benefits, science has also supported the decision-making on species suitability for a given site. Firstly, tree species must withstand the intrinsically stressful urban environmental conditions (Locosselli and Buckeridge 2023, Locosselli et al. 2024), where mortality rates can be higher than 20% at early development stages and trees' lifespan is significantly shortened (Britt et al 2008, Saebo et al 2003). For instance, climate is one of the main sources of stress for trees in both natural and urban environments (Nitschke et al. 2017). Unfavorable climate conditions like heat and droughts in combination with the urban heat islands (Silva et al. 2019) increase vapor pressure deficit, evaporative demand, photo-oxidative stress, premature leaf abscission, risking growth and services provision (Percival 2023) of over 70% of tree species worldwide (Esponon-Rodriguez 2022). Climate adds to other sources of stress found in cities, like air pollution that poses further limitations to growth (Locosselli et al. 2019). Species tolerance to stress (Zabotto et al. 2020) is defined as their ability to survive, function, and complete a lifecycle under moderate to severe stress (Tardieu and Tuberosa 2010). Trees cope with limiting conditions by adjusting, for instance, their stomatal conductance, photosynthetic rates, carbon allocation, and mobilization, and other traits (Sjöman et al 2018), often at the cost of benefit delivery as trees grow older and bigger (Mullaney et al. 2015, Rahman et al. 2020, Grantz et al. 2013, Locosselli et al. 2019, 2024, Wood & Dupras, 2021). For some species selection frameworks, tolerance to the heterogeneous urban conditions and trade-offs between stress tolerance and services

provision are top priority in species recommendation (Vogt et al 2017, Farrell et al 2022).

Secondly, the suitability of a species to a given site also depends on the potential problems trees might pose. The ecosystem disservices - defined as "ecosystem-generated functions, processes, and attributes that result in perceived or actual negative impacts on human well-being" (Shackleton et al. 2016) are an aspect relatively overlooked by the literature (Lyytimäki and Sipilä 2009) despite the economic losses and risks to health and well-being (James et al., 2006; Schmidlin, 2009; van Haaften et al., 2016). The disservices include risks to grey infrastructure from tree failure (Schmidlin 2009), obstruction of vehicular traffic and pedestrians on roads and sidewalks, and damage to the pavement or sewer pipes (Roman et al 2021) as a consequence of specimens growth rate and size, biomechanical characteristics, wood density, distinct rooting strategies, to name a few (Delshammar et al. 2015; Lyytimäki 2017). Trees can also attract unwanted animals and produce allergenic pollen seasonally according to their reproductive strategies, and further contribute to atmospheric O_3 concentrations through biogenic volatile organic compound (BVOC) emissions (Eisenman et al. 2019; Sgrigna et al. 2020). Altogether, some of these functional traits can dictate tree species' potential benefits, tolerance, and disservices, and support a more integrative science to support evidence-based decision making in species selection.

Whereas these three aspects, or pillars, to support decision-making do not fully convey the complexity in species selection (Vogt et al, 2017), which includes other aspects like personal preferences (Gerstenberg and Hofmann, 2016). They give a broad overview of the main aspects considered by practitioners (Roy 2017) and manuals or guidelines for species selection worldwide (Vogt et al, 2017). These three pillars have been extensively covered individually by past reviews (e.g., van Haaften et al., 2016, Payne et al, 2018, Rahman et al, 2019) that provided insights to steer science towards future research avenues to support decision-making. But their combination to support the elaboration of manuals, guidelines, and ultimately decision-making seems to be a burden carried mostly by those working at the front line of urban forestry, like practitioners, planners, and decision-makers, with few attempts of integration by science (e.g., Speak et al, 2021; Farrell et al, 2022). To assess the scientific effort to combine different aspects in tree species selection, and foster more integrative research to reduce the knowledge burden on decision-makers (Cortinovis et al, 2021), we conducted a systematic review to assess the combination of the different aspects in tree species selection to choose the "right tree, for the right place". Based on the present reasoning, we raised five key questions: (I) Where is this integration more common

along the biodiversity gradient? (II) Which pillar is most frequently addressed in the literature? (III) Do existing studies integrate all three pillars in their objectives? (IV) What are the key traits used to assess each pillar? (IV) What are the key traits commonly used to assess these pillars in combination? (IV) How diverse is the range of tree species covered by these studies? (V) What species have multiple pillars covered by the literature, in a single study and in multiple studies?

2.3 Material and Methods

2.3.1 Study design

We followed the Preferred Reporting Items for Systematic Reviews (PRISMA) framework to guide this review. PRISMA provides a standardized, peer-reviewed methodology based on a checklist of guidelines, according to Page et al. (2021), contributing to the quality of the systematic review process and its replicability. We systematically surveyed the literature using the Scopus and Web of Science platforms, including all the studies available until 2023. We defined a broad search expression to initially identify as many eligible studies as possible: ("street trees" OR "urban forestry" OR "City trees" OR "Greening cities" OR "urban park" OR "urban forest" OR "urban green space" OR "Urban landscape" OR "Urban plants" OR "Urban woodland" OR "Urban trees") AND ("species select" OR "species choice" OR "species decision" OR "species option" OR "species preference"). We decided not to add the words ecosystem services, tolerance, and disservices to avoid restricting the studies to these terms, as studies may not refer directly to them or may use synonyms instead, limiting the reach of the search. This first step resulted in 1399 studies (Figure 1).

We first assessed the titles and abstracts to check their inclusion in the dataset. We excluded the records not related to the urban environment; pre-prints or conference abstracts; records that only mention tree selection but do not study it; had any information supporting urban tree selection; if the study was conducted in the urban environment for convenience only; or were written in a language other than English. This step narrowed the eligible studies to 460 (Figure 1). Subsequently, we read in full the studies to double-check their eligibility. We excluded papers that could not be found in usual scientific databases; if the study is about forest areas with no urban influence; refer to cities in the text, but was not conducted in the urban environment; studies about the structure of urban green areas and tree

species distribution, but not referring to species selection; review or opinion papers; in other language than English. This second step further narrowed the final dataset to 293 studies (Figure 1). At least two researchers reviewed all the papers.

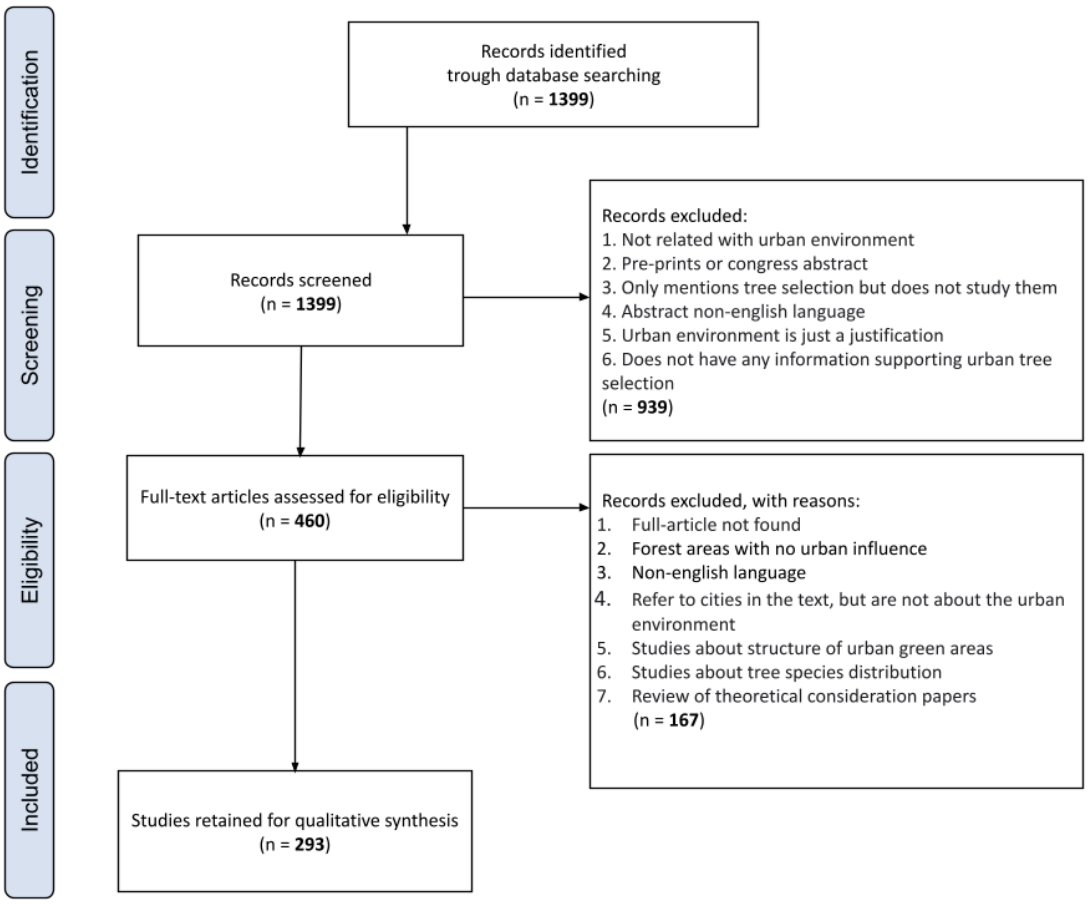


Figure 1. PRISMA flow diagram detailing the survey steps and inclusion and exclusion criteria of the papers in this systematic review.

2.3.2. Data acquisition and analyses

After the study selection, we collected qualitative and quantitative data. We obtained from each study the title, year of publication, authors, location of study, number of species, tree species, measured functional traits or characters, the pillars (ecosystem services, disservices, tolerance), and their sub-categories.

2.3.3. Geographical patterns and temporal trends

To access the geographical distribution of the studies in the final dataset, we plotted the coordinates on a world map using Software QGIS 3.36 (2024), as well as plotted the proportion of studies combining at least two pillars per country, to check for the level of

integration. Then, we evaluated the Publication temporal trends using bar plots representing the number of studies by year for each one of the three pillars, and their combinations, using R packages “ggplot2” (Wickham, 2016) and “reshape2” (Wickham, 2007). We also assessed the total number of studies from each pillar independently, and the number of studies combining them using an Upset Plot using the R package "UpSetR" (Gehlenborg, 2019).

2.3.4. Functional and morphological variables

We predefined key functional and morphological variables to be collected in the studies based on the literature, like diameter breast height (DBH), phenology, leaf area density (LAD), leaf area (LAI), leaf morphology, specific leaf area (SLA), tree height, tree biomass, sap flow, wood density, particulate matter retention (PM), among others. However, during data collection, additional variables were identified in the studies and included in the analysis, such as leaf reflectance, ring width index (RWI), stomatal conductance, metal accumulation index, leaf components, transpiration rate, etc (Table 1). We associated them with the three pillars and displayed their sum using bubble charts. We used the packages "hpackedbubble", "ggplot2”, “packcircles”, "randomcoloR” (Cheng, 2019; Wickham, 2016; Bedward et al, 2023; Ammar, 2019).

Table 1. Functional and morphological variables used by the surveyed studies.

Acronym	Description
Age	Age
BAI	Branch area index
BVOC	Biogenic Volatile Organic Compounds
C. Store	Carbon store
Canopy D.	Canopy Diameter
Canopy Den.	Canopy density
Chl	Chlorophyll concentration
Chl-a	Chlorophyll-a fluorescence
Crown A	Crown area
Crown V.	Crown volumn
Crown H.	Crown height
DBH	Diameter at breast height
ET	Evapotranspiration
GR	Growth rate
LA	Leaf Area
LAI	Leaf Area Index
Lcar/Lasc	Leaf Components (Carotenoids and Ascorbic Acid)
Leaf An.	Leaf anatomy
Leaf M.	Leaf morphology
Tleaf	Leaf temperature
Leaf W.	Leaf weight
Leaf G.E.	Leaf gas exchange
LWP	Leaf Water Potential
LL	Leaf litter

Mort. R.	Mortality rate
Pheno.	Phenology
Photo E.	Photosynthetic Efficiency
PM	Particulate matter
Pc	Pollen concentration
Reprod.	Characteristics of Reproductive Organs
Root B.	Root Biomass
Root M.	Root morphology
Rain I.	Rainfall interception
S. Flow	Sap flow
Sap	Sapwood
Ci	Stomatal conductance
T. Height	Tree height
TB	Tree biomass
TLP	Turgor Loss Point
WC	Wood core
WD	Wood Density
WU	Water Use
Φ	Quantum yield

2.3.5. Applications

We detailed each one of the three pillars - namely: ecosystem services, tolerance, and disservices - by dividing them into subcategories. We divided the ecosystem services as follows: I) regulation and support, covering windbreak, thermal comfort, fauna support, rainfall interception, carbon sink, air pollution reduction, noise reduction, soil benefits, and pollination; II) provision, including timber, fuel, food, medicinal, and III) cultural, covering recreation, aesthetic, cognitive development, place value, interest in nature, and social cohesion. We also assessed the tolerance of trees to urban conditions, including microclimate, flooding, local conditions, management, soil conditions, wind stress, parasite species, herbicides, and air pollution. Finally, we assessed the disservices related to tree failure, BVOC emission, allergens production, water-use cost, plant waste, infrastructure damage, vector attraction, grey-infrastructure damage, maintenance, and cost. We present the proportion of each sub-category and the co-occurrence of these sub-categories in the studies through a circular graph using the package "ggraph" (Pedersen, 2025) in R 4.4.1 (R Core Team, 2024).

2.3.6. Species representativeness

We detailed the data of the tree species assessed by all studies to gain insights into species representativeness and the potential of results extrapolation. We represent the data of 56 species, each assessed by at least eight studies using a dendrogram, using the Euclidean distances in the Ward method, which grouped them according to the assessment of each

pillar, combined or not. For this analysis, we used R 4.4.1 (R Core Team 2024) packages “dendextend” and “ggplot2” (Galili, 2015; Wickham, 2016). We also listed all species used in each study, which pillar has been assessed, and the geographical coordinates of the studies. We also gathered additional information on the main traits used to assess their ecosystem services, resilience, and/or disservices. We selected the 10 species with the highest number of studies, plus the 2 most studied species from tropical regions, to explore their climatic envelope and potential for results extrapolations. For that purpose, we obtained the species' worldwide distribution based on the Global Biodiversity Information Facility data (GBIF). We filtered only the occurrences in urban areas by cross-checking the occurrence data with the data from the global shape file of grey areas (European Commission, 2019). With the same shapefile, we mapped the temperature and precipitation of these grey areas to characterize the urban climate envelope of the 10 most studied species. We also characterized the climatic range of these species across the sampling sites of studies covered by this systematic review. We contrasted the distribution of the current urban climate envelope of the species using density plots and the studies' climate range using the maximum and minimum values of climate data for the study site. Analyses were undertaken using the R packages “sf”, “dplyr” and “ggplot2” (Pebesma & Bivand, 2023; Wickham et al. 2023; Wickham, 2023).

2.4. Results and Discussion

2.4.1. Global overview

The 293 studies cover 55 countries across six continents (Fig. 2, S1). Most research has been conducted in the Global North, with the United States leading (22 studies, 7.5%), followed by Germany (14 publications, 4.7%). China stands out globally and within the Global South, contributing with 34 studies (11.6%), followed by Australia (16 studies, 5.4%). In contrast, developing countries in the Global South are underrepresented; for example, Brazil accounts for only six studies (2.0%). The dominance of developed countries from the Global North is consistent with findings from other systematic reviews in urban forestry (e.g., Song et al., 2018; Ordónez et al., 2019; Huff et al., 2020; Araujo et al., 2021) and reflects the historical development of the field. Urban forestry was first consolidated as a practice and research field in the US (Johnston, 1996) followed by European countries (Konijnendijk, 2003). It also reflects access to resources and research opportunities, a recurrent issue reported in systematic reviews (e.g., Reidpath & Allotey, 2019). Whereas the number of studies is higher in the Western Global North (Figure S1), the proportion of

studies that attempted to integrate distinct pillars is higher in the Eastern Global South (Figure 2). The reason behind this Western and Eastern trade-off between the number of publications and integrativeness likely underlies historical and philosophical aspects of science, as some researchers point to a more holistic approach in the East (Rolston 1987, Memmi 2019), a topic outside the scope of this review. Nonetheless, China is an iconic example that faces significant environmental challenges (Cai et al. 2019) and has put into practice ambitious re-greening programs of cities in recent decades, increasing substantially its vegetation cover influenced by governmental policies (Feng et al. 2021; Xu et al. 2024). China and the US are also renowned for the creative methods to establish innovative and creative use of green areas in the cities (Wolch, Byrne & Newell, 2014).

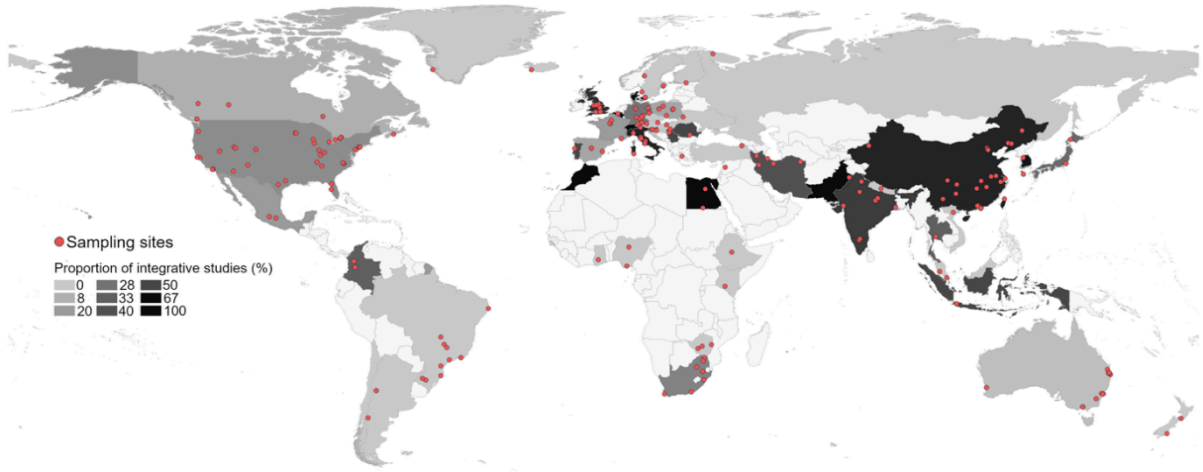


Figure 2. Geographical distribution of the study sites (pink circles) focused on urban tree selection surveyed in this systematic review. The shades of gray represent the proportion of studies with at least two integrated pillars by country.

2.4.2. Current efforts for integrative research in urban forestry

Ecosystem services are the main subject in our dataset, accounting for 44.00% of all studies (Figure 3). This predominance stems from the need to transform cities through ecosystem processes that support quality of life, aligning with their strong appeal in urban agendas worldwide (United Nations, 2024; Global Goals, 2024). Tolerance ranks second, representing 23.20% of the studies, which reflects the recognition that urban trees are also vulnerable to urban environmental stressors and the further impacts of climate change, risking their provision of ecosystem services (Nitschke et al. 2017). Finally, the disservices remain significantly underrepresented, comprising only 4.10% of studies, a gap already identified by scientists and the decision-makers (van Haaften et al., 2021; Roman et al, 2021). The individual assessment of these pillars dominated the literature over the years, mostly focused on either ecosystem services or stress tolerance. Thus, the individual assessment of these pillars is the current status quo in the science of urban trees.

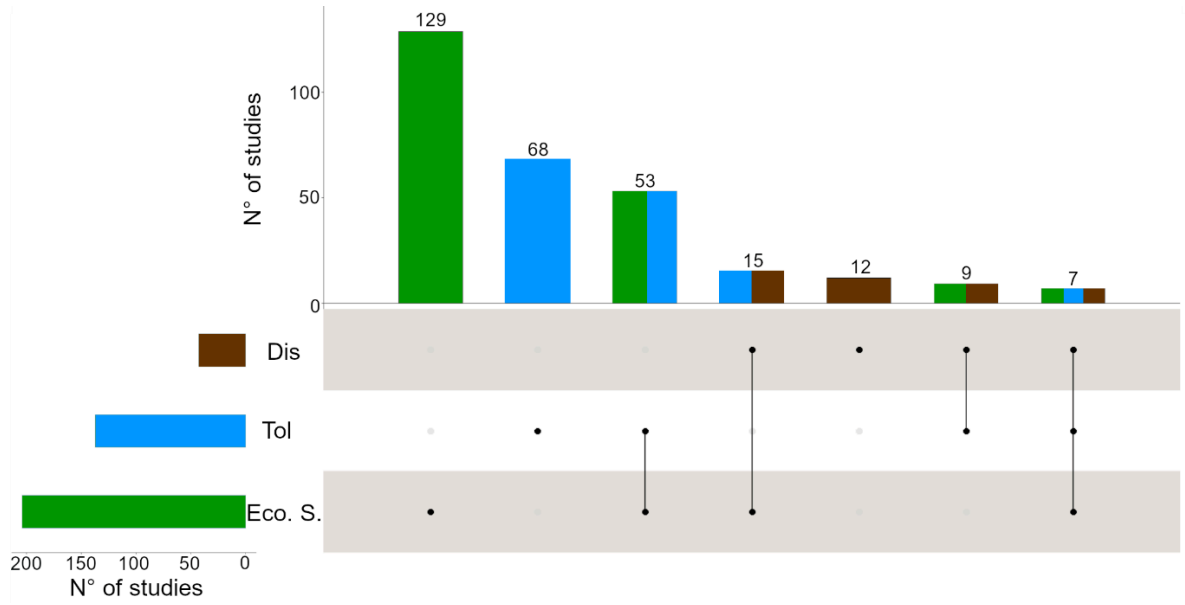


Figure 3. The number of studies assessing ecosystem services, disservices, and tolerance independently and the number of studies that evaluate two or more pillars.

Nonetheless, substantial integrative advances have taken place over the last two decades (Figure 4, S2), enabling a more comprehensive assessment of tree species performance in cities. The combination of ecosystem services and tolerance has been the most frequently addressed in the literature, reported in 53 studies (e.g., Jim, 1999; Liu, Zhu, & Ding, 2007; Swoczyna, 2010), and it is where the scientific efforts of integration were concentrated since the early 2000s. This combination arises from the undeniable need for ecosystem services in the cities and the fact that trees only fulfil this goal if they withstand the unfavourable urban conditions (Locosselli and Buckeridge 2023, Locosselli et al. 2024). This approach is in consonance with the widespread conundrum of the "right tree in the right place" (Morakinyo et al. 2020). In contrast, the results also reveal a fundamental gap in the support to choose the "right tree in the right place". Species suitability to the local conditions depends not only on their stress tolerance, but also on their potential disservices, a combination mostly overlooked by scientists to this date (but see, Asgarzadeh et al. 2014; Tiwary et al. 2016; Muhammad, Wuyts & Samson 2022).

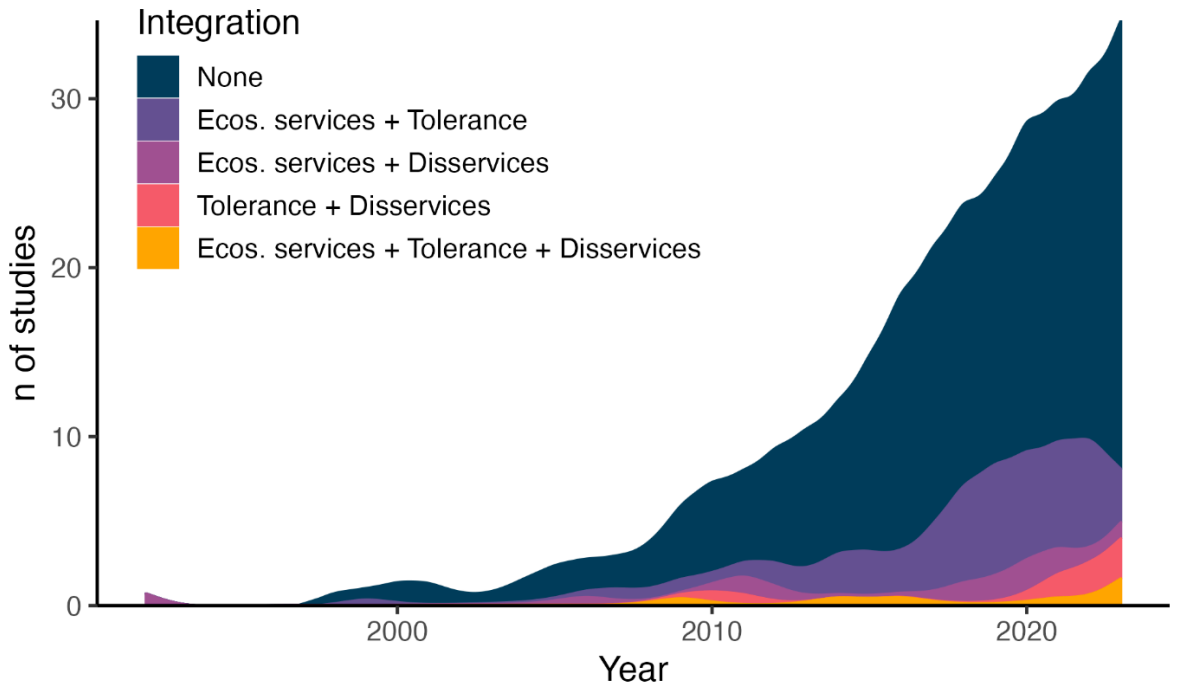


Figure 4. Temporal trends in the publication of studies with and without the combination of different pillars, namely: ecosystem services, stress tolerance, and disservices.

The combination of different aspects of ecosystem services or stress tolerance is relatively well covered in the literature. For instance, studies commonly evaluate the species' potential contributions to thermal comfort together with rainfall interception, carbon sequestration, and air pollution regulation. These topics cover the most discussed urban environmental problems, like heat islands and cities' vulnerability to heat waves (Correa et al. 2012; Lin et al. 2010), potential floods as the worst natural hazard in cities (Asadian & Weiler, 2009; Kirnbauer et al. 2013), urban carbon emission (Tiwary et al. 2016; Xu et al. 2018), and the exposure to high levels of air pollution (Przybysz et al. 2019; Chaudhary et al. 2019). Thermal comfort is also assessed together with social cohesion, interest in nature, and place value, as a means to promote climate justice in cities. Other than the ecosystem services, climate is also evaluated in terms of potential stress tolerance of trees, as climate is the main growth regulator of trees' worldwide (Babst et al., 2019; Pretzsch et al., 2017), and the tolerance to the local conditions that tend to strengthen the physiological and metabolic stress. Overall, the integration within each pillar is rather straightforward and well-documented in the studies, but the same does not hold true for the integration between pillars.

The most common co-occurrence found in the studies is the assessment of air pollution regulation by trees together with their tolerance to atmospheric pollution (Figure 5). Whereas, air pollution is a serious public health issue, with 99% of the global population exposed high levels of air pollution (WHO, 2022), being the second leading cause of

premature death globally (State of Global Air, 2024), it is also a known threat to trees' functioning limiting up to 30% of their growth and associated ecosystem services delivery (Locosselli et al 2019). Studies also address air pollution through the trade-off between species' potential to reduce air pollution mainly by adsorption (Zhao et al. 2019; Pace & Grote, 2020), and the species' potential emission of BVOCs, specifically because isoprene and monoterpenes are the precursors of tropospheric ozone and secondary aerosols (Fitzky et al. 2019), posing significant health risks in high-traffic / vegetated areas (Nuvolone et al. 2018). Other than the emission of BOVCs, studies also cover the allergenic potential during trees' reproductive phase (Fitzky et al. 2019). Studies also cover the trade-off between species contribution to thermal comfort and their tolerance to the local urban conditions and climate stress (Takács et al. 2016; Wang et al. 2020). Particularly because heat is a known threat to citizens, causing thousands of deaths every year (Gasparrini et al. 2017), as well as a threat to trees' functioning (Teskey et al. 2014; Wei et al. 2023). The assessment of these trade-offs, and perhaps other ones like the benefits to soil and the tolerance to unfavourable soil conditions (Edmonson et al. 2014; Asgarzadeh et al. 2014), seems to be a natural pathway to integrate different pillars in science.

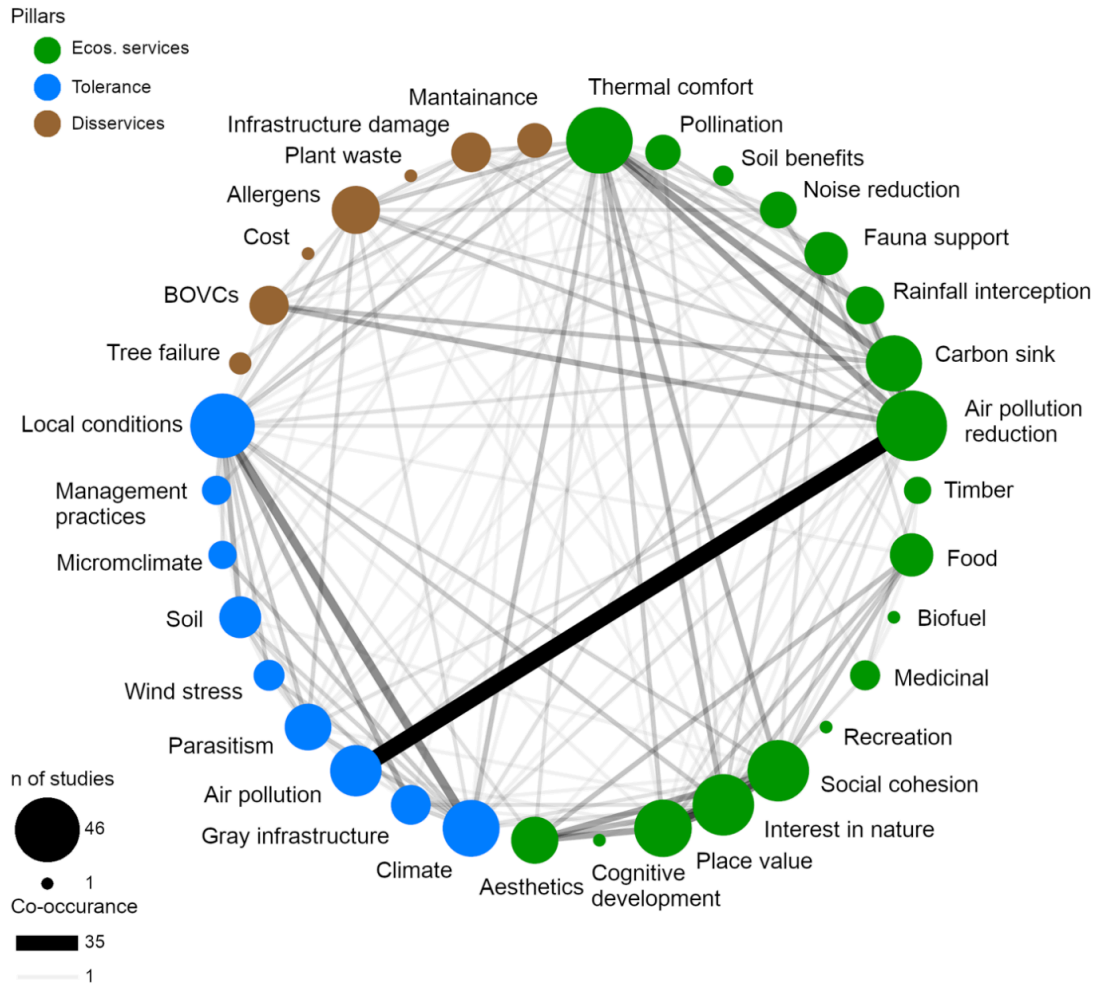


Figure 5. Detailed overview of the application of the studies across three pillars namely: ecosystem services, resilience, and disservices.

The combination of all three pillars is a challenging task, and the studies combining all three pillars point to two possible integration pathways: either the use of species' secondary data or the use of modelling tools. On one hand, studies like Asgarzadeh et al. (2014) developed a method for selecting species, using the city of Tehran as a model. The model ranks species based on cultural services, growth characteristics, environmental tolerance, and maintenance costs from a secondary database developed by landscape architects and planting design experts. Similarly, Tiwary et al. (2016) developed a performance evaluation framework for streetscape vegetation for fifteen species based on primary and secondary data, namely: the potential pollution regulation, carbon sequestration, thermal comfort, noise attenuation, biomass energy, environmental stress tolerance, and crown projection factor. Another example worth mentioning is the study by Muhammad et al. (2020) that ranked species based on their ecosystem services like airborne PM removal, urban heat island effect reduction, and net carbon sequestration, food source, together with their resilience to drought, and eventual disservices such as emission of BVOC and allergenicity. This study pointed to Tilia cordata Mill., Tilia platyphyllos Scop., Alnus incana (L.) Moench, Acer campestre L., and Picea abies (L.) H. Karst as optimal tree species offering a balance among the three pillars. On the other hand, studies relied on well-established models like the i-Tree Eco Model to address these pillars (Koricho et al. 2022). Still, even in such attempts of integrating all pillars, studies undertake an unbalanced approach focusing on ecosystem services and tolerance to stress at the detriment of disservices.

2.4.3. The pursuit for integrative research in urban forestry

It does not go unnoticed the potential of integrating the three pillars, not only because of their fundamental role in urban tree species selection but also because they can be evaluated through a common set of traits. Plant functional traits are characteristics of plants that influence how they interact with their environment, other species, and different trophic levels (Pérez-Harguindeguy et al., 2016), used for studying the impacts of large-scale changes in land use and climate (Díaz & Cabido, 2001; Suding et al., 2008). Tree height and DBH (Figure 6) emerged as the most assessed traits in our dataset, in the full dataset, and in those studies that combined two or more pillars. This is a common approach not only in the constellation of this review but in virtually any forestry study (Helletsgruber et al. 2020; Dey, Ahmed & Islam, 2021; Liu et al. 2021). Not only are tree size traits easily measured in the field by any research group, but they are also a valuable source of information on trees' performance and represent the second most important functional trait axis, orthogonal to the

fast-slow plant economic trait spectrum (Joswig et al. 2022; Maynard et al. 2022; Diaz et al. 2016). Tree size is directly related to functioning (Mecuccini et al. 2005), more so than age (Gora and Esquivel-Muelbert 2021), and thus, an effective trait to assess the three pillars simultaneously.

The literature shows that the provision of ecosystem services increases with tree size. For instance, Sydnor and Subburayalu (2011) found that long-lived honey locusts (Gleditsia triacanthos L.) provide 3.8 times more environmental benefits than the smaller growing hawthorns (Crataegus monogyna Jacq.), a pattern confirmed in experiments measuring tree height and diameter. The benefits of larger trees extend to the potential provision of shade, rainfall interception, carbon sequestration, and biodiversity support, to name a few (Cheela et al. 2021). Tree tolerance also increases as they grow to an optimum size, and it tends to decrease as trees grow to senescence (Lloret et al. 2011; Lindenmayer et al. 2012). Tree size is also a better predictor of tree senescence than age (Gora and Esquivel-Muelbert 2021), and tree senescence is one of the main causes of disservice in cities (van Haaften et al. 2016). The association between tree size and the three pillars is non-linear, and yet they tend to show distinct trajectories as trees grow. There is evidence that ecosystem services increase rapidly as trees grow bigger up to a point where they level off (Rötzer et al. 2019, Cheela et al. 2021), whereas trees tend to have an optimum size for resilience, and an exponential increase in disservices probability of disservices after a certain size (Hilbert et al. 2019). These lines of evidence open new avenues for holistic management of urban trees based on their development trajectories to maximize the benefits of ecosystem services while strengthening tolerance and minimizing disservices.

Still, there are nuances in these pillars that can be jointly assessed by other traits. Canopy diameter, leaf area index, and leaf morphology are long used traits to assess ecosystem services like air pollution reduction (63 studies) and thermal comfort (57) (Lin & Lin 2010; Liu et al. 2019), the tolerance of trees to stress including tree height, leaf morphology and leaf temperature to assess environmental tolerance (19) (Sjoman & Nielsen, 2010; Equiza et al. 2017), and disservices like BVOCs emission, crown area and canopy diameter to address allergens (8) (Speak et al., 2018; Aerts et al. 2021). Phenology is another frequently measured variable that provides fundamental information on the seasonal presence or absence of vegetative organs, which influence the provision of ecosystem services such as air filtering, thermal comfort, and rainfall interception throughout the year (Silva Brito et al. 2022), the latter still underrepresented in our dataset, even though floods pose the greatest natural hazard in cities (Zhang, 2015).

In addition, reproductive phenology—such as flowering and fruiting cycles—plays a crucial role in supporting urban biodiversity by providing key resources for wildlife (Silva Brito et al. 2022), and can also appeal to auto-declared well-being (Elsadek et al. 2019). There is a consensus in the studies that the public perception and consequent support of the population are fundamental to implementing effective planting programs in cities (Wolf et al. 2010). These benefits associated with the phenological phases add to the gains in stress tolerance, particularly drought tolerance, supported by the loss of leaves in deciduous trees (Stratópoulos et al. 2019; Hirsch et al. 2023). Leaf shedding, on the other hand, is a known disservice of trees resulting in the accumulation on sidewalks, streets, and drainage systems, causing clogs, urban flooding, and higher maintenance costs (Hobbie et al. 2014; Berland et al. 2018). Some leaf characteristics also create slippery surfaces, increasing the risk of accidents (Roman et al. 2021). Finally, the emission of pollen during the reproductive phase of certain tree species increases the demand for hospital admission due to allergenic outcomes (Dale et al. 2008; Guilbert et al. 2018).

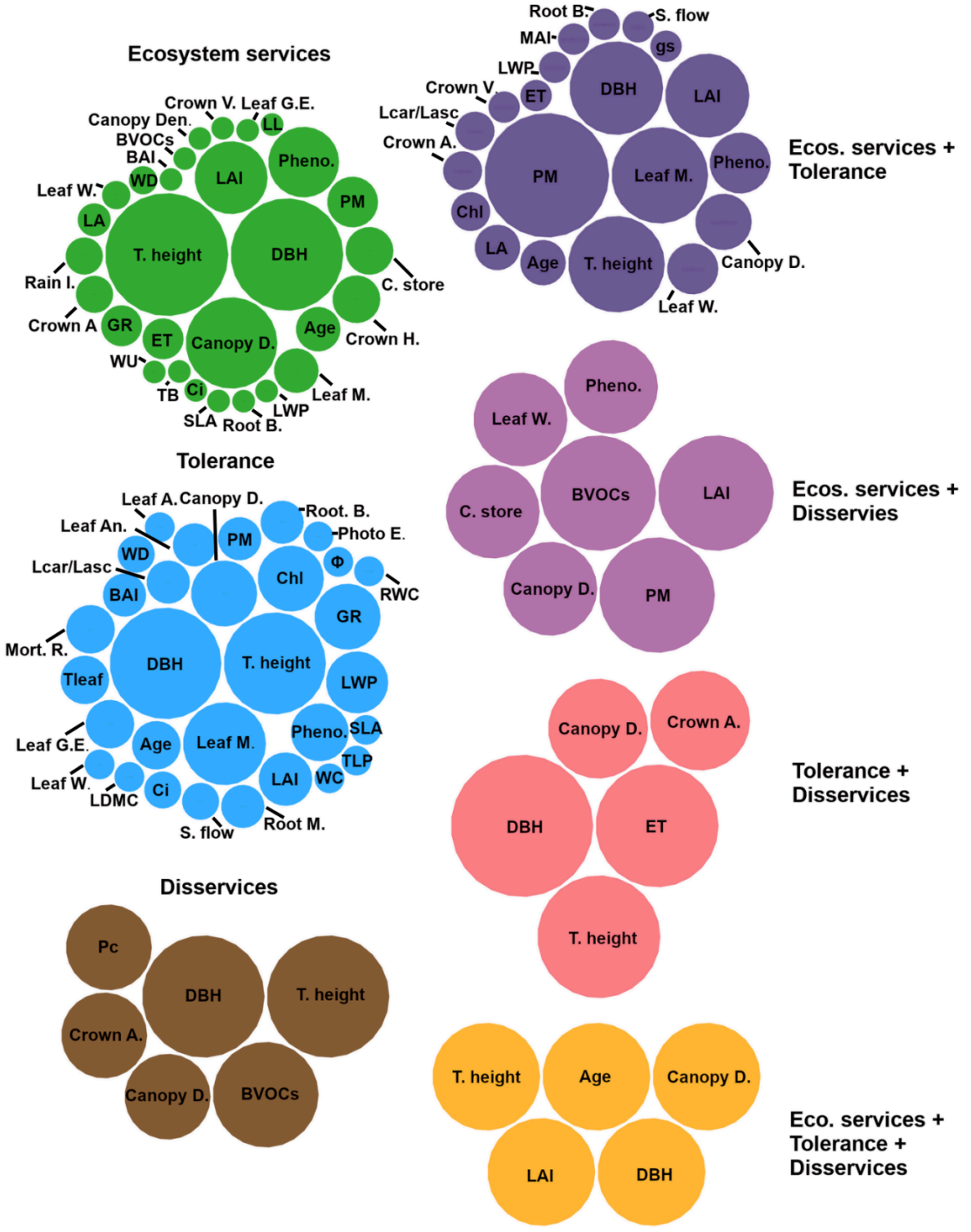


Figure 6. Main traits assessed in the tree species selection studies, according to the three pillars and it is integration: ecosystem services, tolerance and disservices. Only traits reported in more than two studies are displayed. Bubble sizes are proportional to the number of studies.

A question remains: can one extrapolate the results of these studies to support decision-making on urban afforestation? A total of 1352 species have been assessed by the urban tree species selection studies. There is a predominance of temperate species, probably because of the studies' provenance (see supplementary material Table S1), and the

long-rooted culture of using temperate exotic tree species dating back to the colonial period (Beinart & Middleton, 2004), making exotic tree species part of the urban biodiversity (Faeth, Bang & Saari, 2011). Among the most studied species, Platanus × acerifolia (Aiton) Willd (total of 44 studies) stood out for its favourable characteristics in support of rainfall interception and thermal comfort (e.g., Kirnbauer, Baetz & Kenney 2013, Correa et al. 2012), while it displays a high tolerance to drought, and low BVOCs emission as a precursor of O3 (Swoczyna et al. 2015, Curtis et al. 2014). Second in the ranking, Ginkgo biloba L. (42 studies), stands out for its known ability to remove air pollutants (Liu et al. 2007; Fini et al. 2022), tolerance to paved areas, but still a substantial source of hydrocarbon and isoprenoid as a disservice (Corchnoy et al. 1992; Shi et al. 2011). Notably, the 56 species assessed by more than eight studies are predominantly from temperate regions and are primarily investigated in the context of services, tolerance, or the combination of both (Fig. 7). The full list of species (Table S1) provides valuable opportunities for decision-makers to ground urban tree selection and management in the available evidence, at least for these well-studied species.

It is reasonable to expect that the most studied species likely cover a representative part of their current urban climate envelopes, which is true for *P. acerifolia* and *G. biloba* (Fig. S3). For these species, the annual precipitation and temperature from the studied sites cover most of the climate conditions where they are currently found, and the results have the potential to be extrapolated to cities worldwide. Still, the urban climate envelope of a significant part of the studied species is underrepresented. In such cases, a more careful evaluation of the local conditions must be taken to evaluate the potential extrapolation to support evidence-based decision-making.

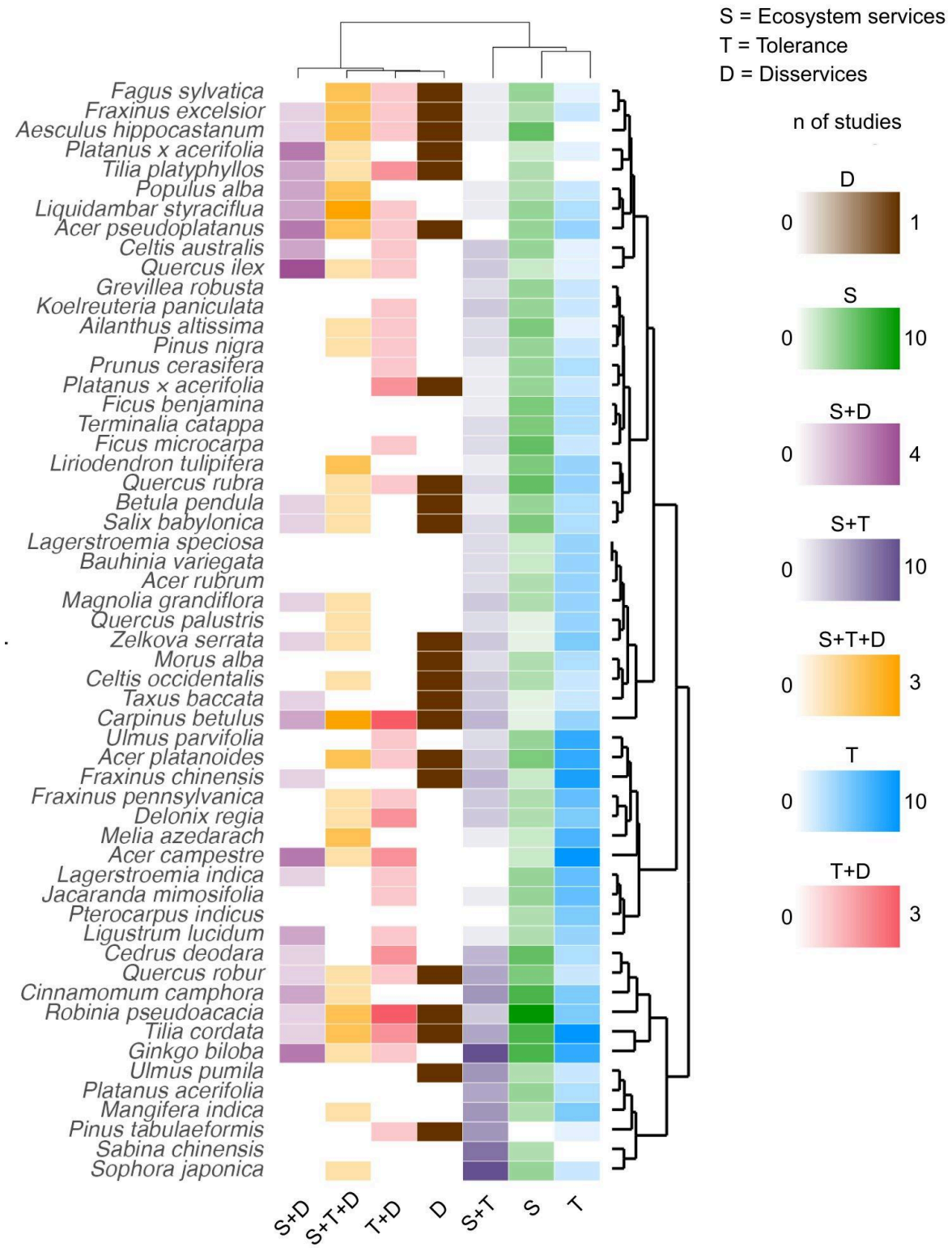


Figure 7. Dendrogram of the most studied tree species. On the horizontal, we observe the clustering by pillars and pillar integration. On the other hand, vertical clustering is by species frequency studies. Here we present the species approached in more than 8, and the heatmap intensity presents the number of studies by species.

2.4.4. Limitations of this systematic review

There are two main limitations in this systematic review. The choice of the pillars to

build the reasoning behind this review, although comprehensive and supported by the literature, may not cover all aspects used in species selection for urban afforestation, such as personal preferences (Gerstenberg and Hofmann 2016). Nonetheless, the addition of more specific pillars used in species selection is unlikely to change the observed patterns and insights of this systematic review. In addition, this systematic review was able to assess the integration of the three pillars at the study level only. Depending on the focus of each study, detailed analyses of individual pillars are often required, which may methodologically constrain the possibility of addressing all three pillars simultaneously within a single publication. Thus, principal investigators may be integrated them at the research project level to inform decision-making, which is an alternative pathway for integration. Information on the project level integration is usually not accessible in the individual studies and, thus, beyond the scope of this review.

2.4.5. Future prospects

Studies on urban forestry that focus on different pillars to support species selection - as the example used here covering ecosystem services, tolerance, and disservices - are a fundamental source of evidence to remove the knowledge burden from decision-makers and support better practices on tree species selection. Based on the analyses conducted here and the gaps and opportunities revealed by them, we defined six propositions for a more holistic approach in urban tree species selection research.

Proposition 1. Promote more intensive research in the biodiverse and still underrepresented areas of the Global South. And foster more integrative research in the Western Global North, where the number of studies is substantially high, but the level of integration is still low.

Proposition 2. Foster the integration of disservices in studies concerning tree species for cities. Disservices remain the least studied pillar individually or in combination with other ones, but pose a high risk to the urban infrastructure and citizens' well-being.

Proposition 3. Future research could adopt a trait-based framework that jointly evaluates: the capacity of tree species to deliver ecosystem services, their tolerance to urban stressors, and their potential to generate disservices across different urban contexts. This strategy can be achieved through a set of common traits like DBH, tree height, phenology, and others, to allow the development of predictive models that optimize species selection for

multifunctionality. Furthermore, researchers can invest in additional traits to support integrative studies.

Proposition 4. This dependence on tree stature opens new avenues to propose management practices based on the development of trees. Since the association between tree size and the pillars is not linear, and each pillar is likely described by a different curve, one can define the optimal range of sizes of urban trees to enhance the benefits and resilience while minimizing the disservices.

Proposition 5. Expanding studies of native and exotic tree species across diverse urban climate envelopes would improve the reliability of extrapolations, strengthening the evidence base for species selection and management in cities worldwide.

Proposition 6. Encourage authors to explicitly report how individual studies on specific pillars relate to broader integrative research projects, so that integration across multiple outputs can be more easily identified. Clearer referencing of these connections in the individual studies would facilitate knowledge integration by scientists, practitioners, and decision-makers.

2.5 Conclusions

This systematic review reveals that ecosystem services, tolerance, and disservices of urban trees are typically studied independently, with ecosystem services being the most extensively studied pillar. This emphasis aligns with the strong appeal of ecosystem services in urban agendas worldwide. However, a handful of studies demonstrate that these three pillars can and should be studied together so one can solve the conundrum of the “right tree in the right place”. Notably, tree height and DBH are the most frequently assessed traits across all three pillars, as assessable traits and the second most important functional trait axis in trees, influencing both their performance and senescence. These shared traits highlight the potential of integrating the three pillars into a holistic framework that considers tree development over time, to uncover trade-offs and synergistic effects in species selection. Nonetheless, the potential extrapolation of these results to support decision-making is still limited by the underrepresented urban climate envelope of the study species. To bridge these gaps and enhance urban tree selection research, we recommend: I) broaden geographic coverage, II) address disservices, III) adopt trait-based frameworks, IV) link tree size to management, V) expand species and climate coverage, VI) improve reporting of integration.

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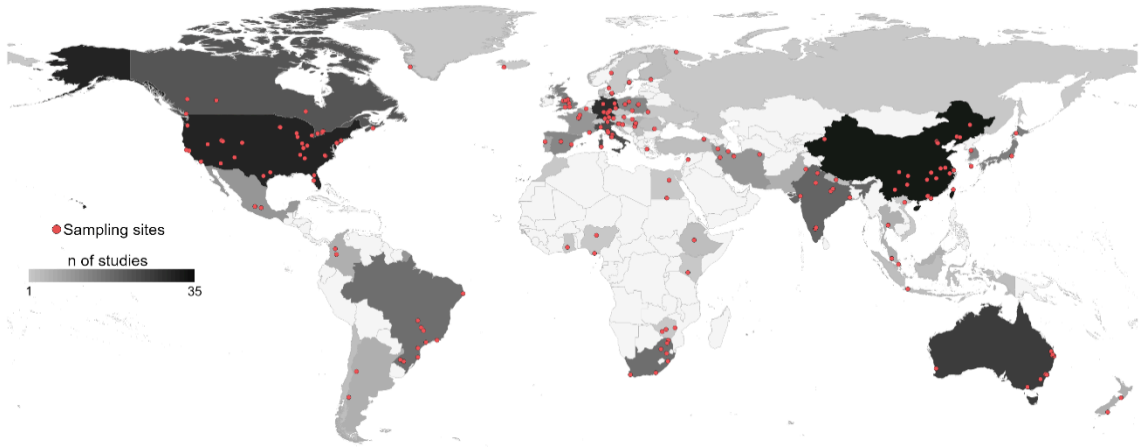
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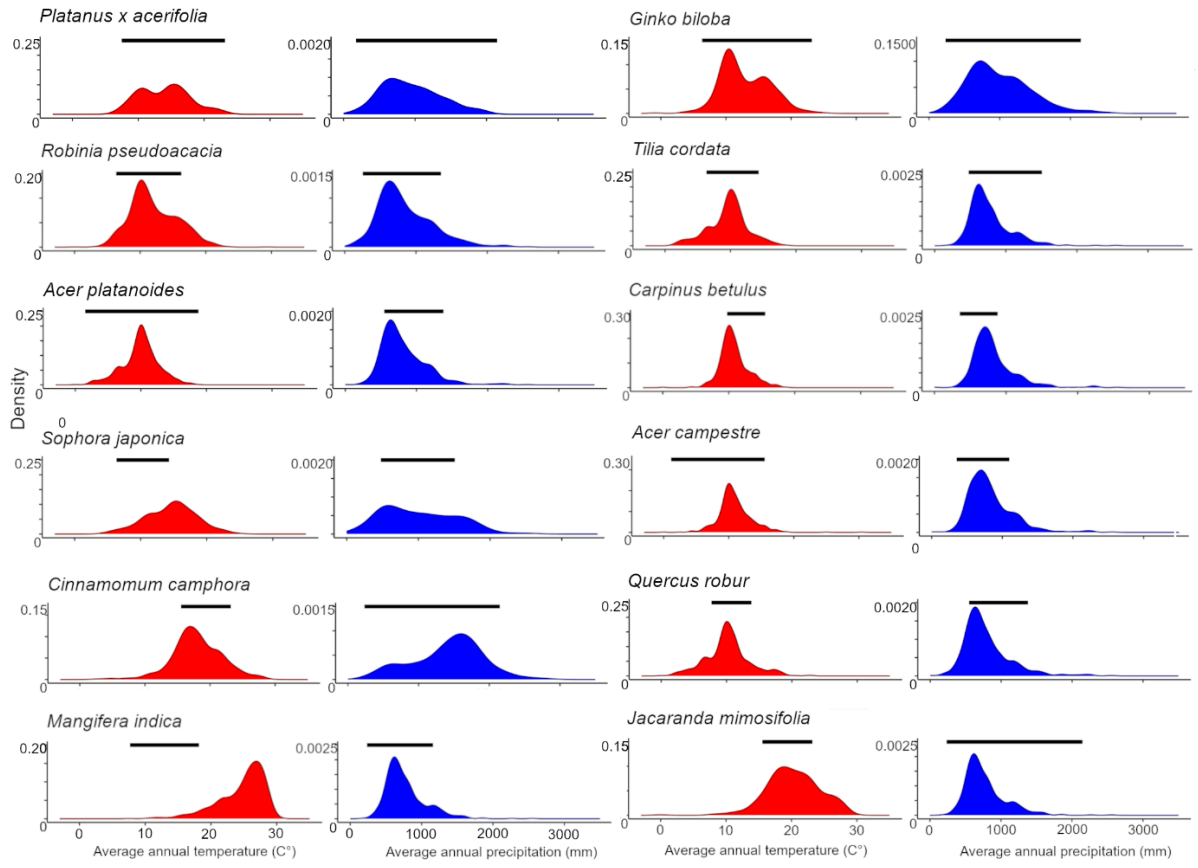
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2.7 Suplementary material



SM Figure 1. Geographical distribution of the study sites (red circles) on urban tree selection surveyed in this systematic review. The shades of grey represent the number of studies that were realized in each country.



SM Figure 2. Urban climate envelops of commonly studied tree species for urban afforestation. The density plots show the distribution of temperature and precipitation across the cities according to the occurrence and observational records of each species. Black line displays the temperature and precipitation range of the studies conducted with each species. Species were selected based on the five most studied for each pillar, except for of *M. indica* and *J. mimosifolia* that was selected to have a different climate envelop sample.

Table S1. Táxon ranking by number of studies. Scientific name of plants and family names are in accordance with the tropicos (https://www.tropicos.org/home) and / or IPNI databases (https://www.ipni.org/).

Ranking	Taxon	Family	Services	Disservice	Resilience
1°	*Platanus × acerifolia*	Platanaceae	X	X	X
2°	*Ginkgo biloba*	Ginkogoaceae	X	X	X
3°	*Robinia pseudoacacia*	Fabaceae	X	X	X
4°	*Tilia cordata*	Malvaceae	X	X	X
5°	*Acer platanoides*	Sapindaceae	X	X	X
6°	*Carpinus betulus*	Betulaceae	X	X	X
6°	*Sophora japonica*	Fabaceae	X	X	X
7°	*Acer campestre*	Sapindaceae	X	X	X
7°	*Cinnamomum camphora*	Lauraceae	X	X	X
7°	*Quercus robur*	Fagaceae	X	X	X
8°	*Aesculus hippocastanum*	Sapindaceae	X	X	X
8°	*Betula pendula*	Betulaceae	X	X	X
8°	*Liquidambar styraciflua*	Altingiaceae	X	X	X
8°	*Quercus rubra*	Fagaceae	X	X	X
9°	*Mangifera indica*	Anacardiaceae	X		X
10°	*Cedrus deodara*	Pinaceae	X	X	X
10°	*Morus alba*	Moraceae	X	X	X
10°	*Salix babylonica*	Salicaceae	X	X	X
11°	*Fraxinus excelsior*	Oleaceae	X	X	X
11°	*Jacaranda mimosifolia*	Bignoniaceae	X	X	X
11°	*Liriodendron tulipifera*	Altingiaceae	X	X	X
11°	*Pinus nigra*	Pinaceae	X	X	X
11°	*Ulmus parvifolia*	Ulmaceae	X		X
11°	*Zelkova serrata*	Ulmaceae	X	X	X
12°	*Ailanthus altissima*	Simaroubaceae	X	X	X
12°	*Fagus sylvatica*	Fagaceae	X	X	X
12°	*Fraxinus chinensis*	Oleaceae	X		X
12°	*Fraxinus pennsylvanica*	Oleaceae	X	X	X
12°	*Pinus tabuliformis*	Pinaceae	X	X	X
13°	*Acer negundo*	Sapindaceae	X	X	X
13°	*Celtis occidentalis*	Cannabaceae	X	X	X
13°	*Delonix regia*	Fabaceae	X		X
13°	*Gleditsia triacanthos*	Fabaceae	X	X	X
13°	*Lagerstroemia indica*	Lythraceae	X	X	X
13°	*Melia azedarach*	Meliaceae	X		X
13°	*Ulmus pumila*	Ulmaceae	X	X	X
14°	*Ligustrum lucidum*	Oleaceae	X	X	X
14°	*Magnolia grandiflora*	Magnoliaceae	X	X	X
14°	*Pinus pinea*	Pinaceae	X	X	X
14°	*Pinus sylvestris*	Pinaceae	X		X
14°	*Populus alba*	Salicaceae	X	X	X
14°	*Quercus ilex*	Fagaceae	X	X	X
15°	*Acer rubrum*	Sapindaceae	X		X
15°	*Celtis australis*	Cannabaceae	X	X	X
15°	*Ficus microcarpa*	Moraceae	X	X	X
15°	*Koelreuteria paniculata*	Sapindaceae	X	X	X
15°	*Tilia platyphyllos*	Malvaceae	X		X
16°	*Ficus benjamina*	Moraceae	X		X
16°	*Picea abies*	Pinaceae	X	X	X
17°	*Juglans regia*	Juglandaceae	X	X	X

17°	*Prunus cerasifera*	Rosaceae	X		X
17°	*Quercus palustris*	Fagaceae	X		
17°	*Sabina chinensis*	Cupressaceae	X		X
17°	*Taxus baccata*	Taxaceae	X	X	X
17°	*Terminalia catappa*	Combretaceae	X		X
18°	*Acer palmatum*	Sapindaceae	X	X	X
18°	*Ficus religiosa*	Moraceae	X		
18°	*Salix alba*	Salicaceae	X	X	X
18°	*Sorbus aucuparia*	Rosaceae	X	X	X
19°	*Alnus glutinosa*	Betulaceae	X		X
19°	*Eriobotrya japonica*	Rosaceae	X	X	X
19°	*Eucalyptus globulus*	Myrtaceae	X		X
19°	*Eucalyptus sp.*	Myrtaceae	X		
19°	*Grevillea robusta*	Proteaceae	X		X
19°	*Lophostemon confertus*	Myrtaceae	X		X
19°	*Ostrya carpinifolia*	Betulaceae		X	X
19°	*Prunus sp.*	Rosaceae	X		X
19°	*Syzygium cumini*	Myrtaceae	X		X
19°	*Taxodium distichum*	Cupressaceae	X	X	X
19°	*Tilia tomentosa*	Malvaceae	X	X	X
20°	*Acer saccharinum*	Sapindaceae	X		X
20°	*Acer saccharum*	Sapindaceae	X	X	X
20°	*Acer sp.*	Sapindaceae	X		X
20°	*Bauhinia variegata*	Fabaceae	X		X
20°	*Carya illinoinensis*	Juglandaceae	X	X	X
20°	*Cassia fistula*	Fabaceae	X		X
20°	*Celtis sinensis*	Cannabaceae	X		X
20°	*Cercis canadensis*	Fabaceae	X		X
20°	*Cupressus sempervirens*	Cupressaceae	X		X
20°	*Lagerstroemia speciosa*	Lythraceae	X		X
20°	*Metasequoia glyptostroboides*	Cupressaceae	X		X
20°	*Platanus occidentalis*	Platanaceae	X	X	X
20°	*Platanus orientalis*	Platanaceae	X	X	X
20°	*Platycladus orientalis*	Platanaceae	X	X	X
20°	*Pterocarpus indicus*	Fabaceae	X		X
20°	*Pyrus calleryana*	Rosaceae	X	X	X
20°	*Quercus sp.*	Fagaceae	X		
20°	*Spathodea campanulata*	Bignoniaceae	X		X
20°	*Thuja occidentalis*	Cupressaceae	X	X	X
20°	*Tipuana tipu*	Fabaceae	X		X
21°	*Acer buergerianum*	Sapindaceae			
21°	*Acer truncatum*	Sapindaceae	X		X
21°	*Albizia julibrissin*	Fabaceae	X	X	X
21°	*Albizia lebbeck*	Fabaceae	X		X
21°	*Broussonetia papyrifera*	Moraceae	X	X	X
21°	*Callistemon viminalis*	Myrtaceae	X		X
21°	*Casuarina equisetifolia*	Casuarinaceae	X		X
21°	*Eucalyptus camaldulensis*	Myrtaceae	X		
21°	*Fraxinus americana*	Oleaceae	X		X
21°	*Larix decidua*	Pinaceae	X	X	X
21°	*Olea europaea*	Oleaceae	X		X
21°	*Pinus elliottii*	Pinaceae	X		X

21°	*Polyalthia longifolia*	Annonaceae	X		X
21°	*Populus sp.*	Salicaceae	X		X
21°	*Populus tomentosa*	Salicaceae	X		X
21°	*Quercus suber*	Fagaceae	X		X
21°	*Quercus virginiana*	Fagaceae	X		X
21°	*Salix matsudana*	Salicaceae	X		X
21°	*Sapium sebiferum*	Euphorbiaceae	X		X
21°	*Tilia sp.*	Malvaceae	X	X	X
22°	*Araucaria heterophylla*	Araucariaceae	X		X
22°	*Azadirachta indica*	Meliaceae	X		X
22°	*Bauhinia × blakeana*	Fabaceae	X		X
22°	*Cassia siamea*	Fabaceae	X	X	X
22°	*Cedrus atlantica*	Pinaceae	X		
22°	*Cornus florida*	Cornaceae	X	X	
22°	*Corylus colurna*	Betulaceae	X	X	X
22°	*Eucalyptus grandis*	Myrtaceae	X	X	X
22°	*Ficus elastica*	Moraceae	X		X
22°	*Ficus virens*	Moraceae	X		X
22°	*Fraxinus ornus*	Oleaceae	X	X	X
22°	*Liquidambar formosana*	Altingiaceae	X		X
22°	*Malus domestica*	Rosaceae	X	X	X
22°	*Malus sp.*	Rosaceae	X		X
22°	*Mimusops elengi*	Sapotaceae	X		
22°	*Osmanthus fragrans*	Oleaceae	X		X
22°	*Peltophorum pterocarpum*	Fabaceae	X		X
22°	*Pinus pinaster*	Pinaceae	X	X	X
22°	*Pinus sp.*	Pinaceae			X
22°	*Platanus × hispanica*	Platanaceae	X		X
22°	*Platanus hybrida*	Platanaceae	X		
22°	*Pongamia pinnata*	Fabaceae	X		X
22°	*Populus deltoides*	Salicaceae	X	X	X
22°	*Prunus avium*	Rosaceae	X	X	X
22°	*Pseudotsuga menziesii*	Rosaceae	X		X
22°	*Quercus alba*	Fagaceae	X		X
22°	*Sequoiadendron giganteum*	Cupressaceae	X	X	X
22°	*Tilia americana*	Malvaceae	X	X	X
23°	*Acacia auriculiformis*	Fabaceae	X		X
23°	*Alstonia scholaris*	Apocynaceae	X		
23°	*Amygdalus persica*	Rosaceae	X		X
23°	*Artocarpus heterophyllus*	Moraceae	X		X
23°	*Betula platyphylla*	Betulaceae	X		X
23°	*Betula sp.*	Betulaceae	X		
23°	*Callistemon citrinus*	Myrtaceae	X		X
23°	*Casuarina cunninghamiana*	Casuarinaceae	X		
23°	*Cercis siliquastrum*	Fabaceae	X		X
23°	*Crataegus monogyna*	Rosaceae	X		X
23°	*Cupaniopsis anacardioides*	Sapindaceae	X		X
23°	*Dalbergia sissoo*	Fabaceae	X		
23°	*Eucalyptus citriodora*	Myrtaceae	X		X
23°	*Ficus benghalensis*	Moraceae	X		X
23°	*Ficus carica*	Moraceae	X	X	X
23°	*Fraxinus angustifolia*	Oleaceae	X	X	X

23°	*Ilex rotunda*	Aquifoliaceae			X
23°	*Juniperus chinensis*	Cupressaceae	X		X
23°	*Ligustrum japonicum*	Oleaceae	X	X	X
23°	*Melaleuca quinquenervia*	Myrtaceae	X		X
23°	*Michelia alba*	Magnoliaceae	X		X
23°	*Morus nigra*	Moraceae	X	X	X
23°	*Picea asperata*	Pinaceae	X		X
23°	*Picea pungens*	Pinaceae	X		X
23°	*Pinus canariensis*	Pinaceae	X	X	X
23°	*Pinus densiflora*	Pinaceae	X		X
23°	*Pinus halepensis*	Pinaceae	X	X	
23°	*Prunus padus*	Rosaceae	X		X
23°	*Punica granatum*	Lythraceae	X	X	X
23°	*Quercus agrifolia*	Fagaceae	X	X	X
23°	*Quercus cerris*	Fagaceae	X		X
23°	*Salix sp.*	Salicaceae	X		
23°	*Schinus molle*	Anacardiaceae	X	X	
23°	*Schinus terebinthifolia*	Anacardiaceae	X	X	
23°	*Sequoia sempervirens*	Cupressaceae	X	X	X
23°	*Swietenia macrophylla*	Meliaceae	X		X
23°	*Swietenia mahagoni*	Meliaceae	X		X
23°	*Tectona grandis*	Lamiaceae	X		X
23°	*Ulmus americana*	Ulmaceae	X		X
23°	*Ulmus minor*	Ulmaceae	X	X	X
24°	*Abies alba*	Pinaceae	X		
24°	*Acacia melanoxylon*	Fabaceae	X		X
24°	*Acacia tortilis*	Fabaceae	X		
24°	*Agonis flexuosa*	Myrtaceae	X		
24°	*Aleurites moluccana*	Euphorbiaceae	X		X
24°	*Alnus incana*	Betulaceae	X	X	X
24°	*Anacardium occidentale*	Anacardiaceae	X		
24°	*Arbutus unedo*	Ericaceae	X		
24°	*Bauhinia purpurea*	Fabaceae	X		X
24°	*Betula nigra*	Betulaceae			X
24°	*Betula pubescens*	Betulaceae	X		X
24°	*Brachychiton populneus*	Malvaceae	X	X	X
24°	*Carpinus caroliniana*	Betulaceae	X	X	X
24°	*Castanea sativa*	Fagaceae			X
24°	*Catalpa bignonioides*	Bignoniaceae	X	X	X
24°	*Cercis chinensis*	Fabaceae	X	X	X
24°	*Chamaecyparis lawsoniana*	Cupressaceae	X	X	X
24°	*Chukrasia tabularis*	Meliaceae	X		
24°	*Cinnamomum burmannii*	Lauraceae	X		X
24°	*Cornus mas*	Cornaceae	X		
24°	*Crataegus sp.*	Rosaceae	X	X	
24°	*Ekebergia capensis*	Meliaceae	X		X
24°	*Eucalyptus robusta*	Myrtaceae			X
24°	*Firmiana simplex*	Malvaceae	X	X	X
24°	*Ilex aquifolium*	Aquifoliaceae	X		
24°	*Juniperus virginiana*	Cupressaceae	X	X	
24°	*Khaya senegalensis*	Meliaceae	X		X
24°	*Machilus thunbergii*	Lauraceae			X

24°	*Magnolia stellata*	Magnoliaceae	X	X	
24°	*Malus sylvestris*	Rosaceae	X		X
24°	*Paulownia tomentosa*	Paulowniaceae	X	X	X
24°	*Persea americana*	Lauraceae	X		
24°	*Phoenix dactylifera*	Arecaceae	X		
24°	*Pinus radiata*	Pinaceae	X	X	X
24°	*Pistacia chinensis*	Anacardiaceae	X	X	X
24°	*Platanus racemosa*	Platanaceae	X	X	X
24°	*Platanus sp.*	Platanaceae	X		
24°	*Populus alba × berolinensis*	Salicaceae		X	
24°	*Populus canadensis*	Salicaceae	X	X	
24°	*Populus nigra*	Salicaceae	X		
24°	*Prunus persica*	Rosaceae	X		X
24°	*Pterocarya stenoptera*	Juglandaceae			X
24°	*Quercus mongolica*	Fagaceae	X		
24°	*Quercus petraea*	Fagaceae	X	X	X
24°	*Quercus rugosa*	Fagaceae	X		X
24°	*Rhus typhina*	Anacardiaceae	X		X
24°	*Schima superba*	Theaceae	X		X
24°	*Sterculia lanceolata*	Malvaceae	X		X
24°	*Styphnolobium japonicum*	Fabaceae	X		
24°	*Syringa reticulata*	Oleaceae			X
24°	*Tamarindus indica*	Fabaceae	X		
27°	*Tristaniopsis laurina*	Myrtaceae			X
24°	*Ulmus glabra*	Ulmaceae			X
24°	*Xanthostemon chrysanthus*	Myrtaceae	X		X
24°	*Ziziphus spina-christi*	Rhamnaceae			
25°	*Abies concolor*	Pinaceae	X	X	
25°	*Abies holophylla*	Pinaceae			X
25°	*Acacia longifolia*	Fabaceae	X		X
25°	*Acer griseum*	Sapindaceae			X
25°	*Adenanthera pavonina*	Fabaceae			X
25°	*Aesculus glabra*	Sapindaceae	X	X	X
25°	*Aesculus x carnea*	Sapindaceae	X		
25°	*Albizia saman*	Fabaceae			X
25°	*Artocarpus altilis*	Moraceae	X		X
25°	*Betula utilis*	Betulaceae	X		
25°	*Bischofia javanica*	Phyllanthaceae	X		X
25°	*Bombax malabaricum*	Malvaceae			X
25°	*Bowdichia virgilioides*	Fabaceae	X		
25°	*Brachychiton populneus*	Malvaceae	X		
25°	*Buddleja cordata*	Scrophulariaceae	X		X
25°	*Calophyllum inophyllum*	Calophyllaceae	X		
25°	*Carica papaya*	Caricaceae	X		
25°	*Cedrus libani*	Pinaceae	X	X	X
25°	*Celtis africana*	Malvaceae	X		X
25°	*Chionanthus retusus*	Oleaceae	X		X
25°	*Choerospondias axillaris*	Anacardiaceae			X
25°	*Citrus reticulata*	Rutaceae	X		
25°	*Citrus sinensis*	Rutaceae	X		X
25°	*Corylus avellana*	Betulaceae	X	X	X
25°	*Corymbia maculata*	Myrtaceae	X		

25°	*Couroupita guianensis*	Lecythidaceae	X		
25°	*Cupressus arizonica*	Cupressaceae	X		
25°	*Elaeocarpus decipiens*	Elaeocarpaceae	X		X
25°	*Erythrina speciosa*	Fabaceae			X
25°	*Erythrina variegata*	Fabaceae	X		X
25°	*Eucalyptus nicholii*	Myrtaceae	X	X	
25°	*Eucalyptus saligna*	Myrtaceae	X		X
25°	*Eucalyptus sideroxylon*	Myrtaceae	X		
25°	*Eugenia uniflora*	Myrtaceae	X		
25°	*Fagus grandifolia*	Fagaceae	X	X	X
25°	*Ficus rubiginosa*	Moraceae	X		
25°	*Fraxinus griffithii*	Oleaceae	X	X	X
25°	*Fraxinus mandshurica*	Oleaceae	X		
25°	*Fraxinus sogdiana*	Oleaceae	X		
25°	*Fraxinus sp.*	Oleaceae	X		
25°	*Fraxinus uhdei*	Oleaceae	X		X
25°	*Handroanthus chrysotrichus*	Bignoniaceae	X		
25°	*Hibiscus tiliaceus*	Malvaceae	X		X
25°	*Juglans nigra*	Juglandaceae	X		X
25°	*Koelreuteria bipinnata*	Sapindaceae			X
25°	*Laburnum x watereri*	Fabaceae	X	X	X
25°	*Larix laricina*	Pinaceae			X
25°	*Laurus nobilis*	Lauraceae	X	X	
25°	*Livistona chinensis*	Arecaceae	X		X
25°	*Magnolia denudata*	Magnoliaceae	X		X
25°	*Moringa oleifera*	Moringaceae	X		X
25°	*Nerium oleander*	Apocynaceae			X
25°	*Olea europaea subsp. africana*	Oleaceae	X		X
25°	*Ostrya virginiana*	Betulaceae	X		
25°	*Phellodendron amurense*	Rutaceae	X		X
25°	*Phoenix canariensis*	Arecaceae			X
25°	*Picea glauca*	Pinaceae	X		X
25°	*Picea omorika*	Pinaceae			X
25°	*Picea sp.*	Pinaceae	X		
25°	*Pinus bungeana*	Pinaceae	X		X
25°	*Pinus ponderosa*	Pinaceae	X		
25°	*Pinus resinosa*	Pinaceae	X		X
25°	*Pinus strobus*	Pinaceae			X
25°	*Pinus wallichiana*	Pinaceae	X	X	
25°	*Populus tremula*	Salicaceae	X		X
25°	*Prunus armeniaca*	Rosaceae	X		X
25°	*Prunus laurocerasus*	Rosaceae	X	X	X
25°	*Prunus serotina*	Rosaceae			X
25°	*Prunus serrulata*	Rosaceae	X		
25°	*Pyrus communis*	Rosaceae	X		
25°	*Quercus acutissima*	Fagaceae			X
25°	*Quercus bicolor*	Fagaceae			X
25°	*Quercus canariensis*	Fagaceae	X		X
25°	*Quercus coccinea*	Fagaceae	X	X	X
25°	*Quercus macrocarpa*	Fagaceae		X	X
25°	*Roystonea regia*	Arecaceae	X		
25°	*Salix caprea*	Salicaceae			X

25°	*Sambucus nigra*	Viburnaceae		X	
25°	*Sapindus mukorossi*	Sapindaceae			X
25°	*Sorbus aria*	Rosaceae	X		
25°	*Syzygium jambos*	Myrtaceae	X		X
25°	*Taxus cuspidata*	Taxaceae	X		X
25°	*Thuja orientalis*	Cupressaceae	X		
25°	*Thuja plicata*	Cupressaceae	X		
25°	*Toona sinensis*	Meliaceae	X		X
25°	*Tsuga canadensis*	Pinaceae			X
25°	*Ulmus sp.*	Ulmaceae	X	X	
25°	*Viburnum odoratissimum*	Viburnaceae			X
26°	*Ziziphus mauritiana*	Rhamnaceae	X		
26°	*Abies pinsapo*	Pinaceae	X	X	
26°	*Acacia confusa*	Fabaceae	X		
26°	*Acacia decurrens*	Fabaceae	X		
26°	*Acacia mangium*	Fabaceae	X		
26°	*Acacia xanthophloea*	Fabaceae	X		X
26°	*Acer grandidentatum*	Sapindaceae			X
26°	*Acer miyabei*	Sapindaceae			X
26°	*Acer monspessulanum*	Sapindaceae			X
26°	*Acer nigrum*	Sapindaceae			X
26°	*Acer pensylvanicum*	Sapindaceae			X
26°	*Acer tataricum*	Sapindaceae			X
26°	*Acer x freemanii*	Sapindaceae	X		
26°	*Acer x zoeschense*	Sapindaceae			X
26°	*Acronychia oblongifolia*	Rutaceae			X
26°	*Aesculus flava*	Sapindaceae			X
26°	*Ailanthus fordii*	Simaroubaceae			X
26°	*Alectryon coriaceus*	Sapindaceae			X
26°	*Alectryon oleifolius*	Sapindaceae			X
26°	*Allocasuarina verticillata*	Casuarinaceae	X		
26°	*Alnus acuminata*	Betulaceae	X		X
26°	*Alnus cordata*	Betulaceae	X		X
26°	*Alnus jorullensis*	Betulaceae			X
26°	*Alphitonia excelsr*	Rhamnaceae			X
26°	*Amelanchier arborea*	Rosaceae			X
26°	*Anthocephalus chinensis*	Rubiaceae	X		X
26°	*Araucaria cunninghamii*	Araucariaceae			X
26°	*Banksia integrifolia*	Proteaceae			X
26°	*Banksia sp.*	Proteaceae	X		
26°	*Betula alleghaniensis*	Betulaceae	X		
26°	*Betula lenta*	Betulaceae		X	X
26°	*Betula papyrifera*	Betulaceae	X		
26°	*Bombax ceiba*	Malvaceae			X
26°	*Brachychiton acerifolius*	Malvaceae			X
26°	*Bridelia micrantha*		X		X
26°	*Bucida buceras*	Combretaceae			X
26°	*Buckinghamia celsissima*	Proteaceae		X	
26°	*Buxus megistophylla*	Buxaceae	X		
26°	*Buxus sinica*	Buxaceae	X		
26°	*Caesalpinia ferrea*	Fabaceae	X		X
26°	*Callistemon rigidus*	Myrtaceae			X

26°	*Calocedrus decurrens*	Cupressaceae	X	X	
26°	*Camellia japonica*	Theaceae			X
26°	*Campomanesia xanthocarpa*	Myrtaceae			X
26°	*Carpinus caroliniana x tschonoskii*	Betulaceae		X	X
26°	*Carpinus orientalis*	Betulaceae			X
26°	*Carya ovata*	Juglandaceae			X
26°	*Caryota mitis*	Arecaceae	X		
26°	*Catalpa speciosa*	Bignoniaceae			X
26°	*Ceiba pentandra*	Pinaceae	X	X	X
26°	*Celtis laevigata*	Cannabaceae	X		
26°	*Ceratonia siliqua*	Fabaceae	X	X	X
26°	*Cercidiphyllum japonicum*	Cercidiphyllacea e	X		X
26°	*Chamaerops humilis*	Arecaceae	X		
26°	*Chorisia speciosa*	Malvaceae	X		X
26°	*Combretum erythrophyllum*	Combretaceae	X		X
26°	*Combretum molle*	Combretaceae	X		X
26°	*Cornus sp.*	Cornaceae	X		
26°	*Corymbia citriodora*	Myrtaceae	X		X
26°	*Cotinus coggygria*	Anacardiaceae			X
26°	*Crataegus viridis*	Rosaceae			X
26°	*Cratoxylum ligustrinum*	Hypericaceae			X
26°	*Cryptomeria japonica*	Cupressaceae	X		
26°	*Cupressocyparis leylandii*	Cupressaceae			X
26°	*Cupressus lusitanica*	Cupressaceae	X		
26°	*Dillenia indica*	Dilleniaceae	X		X
26°	*Dillenia suffruticosa*	Dilleniaceae	X		
26°	*Diospyros lotus*	Ebenaceae	X	X	
26°	*Elaeocarpus apiculatus*	Elaeocarpaceae	X		X
26°	*Elaeocarpus reticulatus*	Elaeocarpaceae			X
26°	*Elaeocarpus sylvestris*	Elaeocarpaceae	X		X
26°	*Erythrina caffra*	Fabaceae	X		
26°	*Eucalyptus deglupta*	Myrtaceae	X		
26°	*Eucalyptus leucoxylon*	Myrtaceae	X		X
26°	*Eucalyptus microcorys*	Myrtaceae			X
26°	*Eucalyptus polyanthemos*	Myrtaceae	X	X	
26°	*Eucommia ulmoides*	Eucommiaceae			X
26°	*Eugenia involucrata*	Myrtaceae	X		
26°	*Ficus virens var. sublanceolata*	Moraceae			X
26°	*Geijera parviflora*	Rutaceae	X		
26°	*Gleditsia japonica*	Fabaceae		X	X
26°	*Gleditsia sinensis*	Fabaceae	X		X
26°	*Gliricidia sepium*	Fabaceae	X		
26°	*Gmelina arborea*	Lamiaceae	X		
26°	*Gnetum gnemon*	Gnetaceae	X		
26°	*Hakea francisiana*	Proteaceae	X		
26°	*Hakea laurina*	Proteaceae			X
26°	*Handroanthus heptaphyllus*	Bignoniaceae	X		
26°	*Handroanthus sp.*	Bignoniaceae			X
26°	*Harpephyllum caffrum*	Anacardiaceae	X		X
26°	*Hedera helix*	Araliaceae	X		
26°	*Hemerocallis fulva*	Asphodelaceae	X		

26°	*Hevea brasiliensis*	Euphorbiaceae	X		
26°	*Hibiscus syriacus*	Malvaceae	X		
26°	*Hopea odorata*	Dipterocarpaceae	X		
26°	*Hura crepitans*	Euphorbiaceae	X		
26°	*Hymenosporum flavum*	Pittosporaceae	X		
26°	*Hyophorbe lagenicaulis*	Arecaceae	X	X	X
26°	*Inga marginata*	Fabaceae	X		
26°	*Juglans mandshurica*	Juglandaceae	X		X
26°	*Koelreuteria bipinnata var. integrifoliola*	Sapindaceae			X
26°	*Lagerstroemia floribunda*	Lythraceae	X		
26°	*Larix gmelinii*	Pinaceae	X		X
26°	*Larix kaempferi*	Pinaceae	X	X	X
26°	*Leptospermum sp.*	Myrtaceae	X		
26°	*Magnolia acuminata*	Magnoliaceae	X		
26°	*Magnolia sp.*	Magnoliaceae	X	X	X
26°	*Malus halliana*	Rosaceae	X		X
26°	*Melaleuca ericifolia*	Myrtaceae	X		
26°	*Melaleuca nesophila*	Myrtaceae	X		
26°	*Melaleuca sp.*	Myrtaceae	X		
27°	*Mespilus germanica*	Rosaceae	X	X	
26°	*Mesua ferrea*	Calophyllaceae	X		
26°	*Millingtonia hortensis*	Bignoniaceae			X
26°	*Mimosa caesalpiniifolia*	Fabaceae	X		
26°	*Morella rubra*	Myricaceae			X
26°	*Morus sp.*	Moraceae		X	
26°	*Muntingia calabura*	Muntingiaceae	X		
26°	*Myrcia sp.*	Myrtaceae	X		
26°	*Nephelium lappaceum*	Sapindaceae	X		
26°	*Nyssa sylvatica*	Nyssaceae	X		
26°	*Ormosia henryi*	Fabaceae			X
26°	*Paliurus spina-christi*	Rhamnaceae			X
26°	*Peltophorum dubium*	Fabaceae	X		
26°	*Phoenix roebelenii*	Arecaceae			X
26°	*Photinia serrulata*	Rosaceae	X		
26°	*Photinia x fraseri*	Rosaceae	X		
26°	*Picea koraiensis*	Pinaceae	X		X
26°	*Picea mariana*	Pinaceae	X		X
26°	*Picea pungens ‘Glauca’*	Pinaceae			X
26°	*Pinus aristata*	Pinaceae	X		
26°	*Pinus armandi*	Pinaceae	X		X
26°	*Pinus cembra*	Pinaceae			X
26°	*Pinus contorta*	Pinaceae			X
26°	*Pinus koraiensis*	Pinaceae			X
26°	*Pinus massoniana*	Pinaceae	X		X
26°	*Pinus parviflora*	Pinaceae	X		X
26°	*Pinus patula*	Pinaceae	X		X
26°	*Pinus sylvestris var. mongolica*	Pinaceae	X		X
26°	*Pinus tabuliformis var. mukdensis*	Pinaceae	X		
26°	*Pinus taeda*	Pinaceae	X		
26°	*Pithecellobium dulce*	Fabaceae	X		
26°	*Pittosporum angustifolium*	Pittosporaceae	X		
26°	*Plumeria acutifolia*	Apocynaceae	X		

26°	*Plumeria alba*	Apocynaceae			X
26°	*Podocarpus macrophyllus*	Podocarpaceae	X		
26°	*Podocarpus neriifolius*	Podocarpaceae	X		X
26°	*Poincianella pluviosa*	Fabaceae			X
26°	*Populus alba var. bolleana*	Salicaceae	X		
26°	*Populus tremuloides*	Salicaceae	X		
26°	*Prunus × yedoensis*	Rosaceae	X		X
26°	*Prunus caroliniana*	Rosaceae	X	X	X
26°	*Prunus cerasus*	Rosaceae	X		
26°	*Prunus domestica*	Rosaceae	X		
26°	*Prunus sargentii*	Rosaceae	X		
26°	*Prunus spinosa*	Rosaceae			X
26°	*Prunus virginiana*	Rosaceae	X		
26°	*Prunus yedoensis*	Rosaceae			X
26°	*Psidium cattleyanum*	Myrtaceae			X
26°	*Pyrus calleryana 'Chanticleer'*	Rosaceae			X
26°	*Pyrus ussuriensis*	Rosaceae			X
26°	*Quercus douglasii*	Fagaceae	X	X	X
26°	*Quercus laurifolia*	Fagaceae	X		X
26°	*Quercus lobata*	Fagaceae	X		
26°	*Quercus muehlenbergii*	Fagaceae	X		
26°	*Quercus myrsinifolia*	Fagaceae			X
26°	*Quercus phellos*	Fagaceae	X		X
26°	*Quercus pubescens*	Fagaceae	X		
26°	*Quercus shumardii*	Fagaceae		X	
26°	*Salix viminalis*	Salicaceae	X	X	X
26°	*Samanea saman*	Fabaceae			X
26°	*Sandoricum koetjape*	Mellaceae	X		
26°	*Sapindus saponaria*	Sapindaceae	X		X
26°	*Searsia lancea*	Anacardiaceae	X		
26°	*Senna macranthera*	Fabaceae			X
26°	*Senna multijuga*	Fabaceae	X		
26°	*Sorbus intermedia*	Rosaceae			X
26°	*Sorbus sp.*	Rosaceae	X	X	
26°	*Sterculia apetala*	Malvaceae	X		
26°	*Sterculia discolor*	Malvaceae	X		
26°	*Stewartia pseudocamellia*	Theaceae	X		X
26°	*Streblus asper*	Moraceae	X		
26°	*Syringa vulgaris*	Oleaceae	X		X
26°	*Syzygium floribundum*	Myrtaceae			X
26°	*Syzygium hancei*	Myrtaceae	X		X
26°	*Syzygium polyanthum*	Myrtaceae	X		
26°	*Tabebuia argentea*	Bignoniaceae	X	X	
26°	*Tabebuia chrysantha*	Bignoniaceae	X		X
26°	*Tabebuia rosea*	Bignoniaceae			X
26°	*Tamarix parviflora*	Tamaricaceae	X	X	X
26°	*Taxodium ascendens*	Cupressaceae	X		X
26°	*Terminalia arjuna*	Combretaceae			X
26°	*Terminalia bellirica*	Combretaceae			X
26°	*Tilia cordata 'Greenspire'*	Malvaceae			X
26°	*Toona ciliata*	Meliaceae			X
26°	*Tristania conferta*	Myrtaceae	X		

26°	*Ulmus carpinifolia*	Ulmaceae	X	X	X
26°	*Ulmus rubra*	Ulmaceae	X		
26°	*Ulmus thomasii*	Ulmaceae	X		
26°	*Vachellia karroo*	Fabaceae	X		X
26°	*Vachellia nilotica*	Fabaceae		X	
26°	*Viburnum tinus*	Viburnaceae	X		X
26°	*Ziziphus jujuba*	Rhamnaceae	X		X
27°	*Abie nordmanniana*	Pinaceae	X		
27°	*Abies balsamea*	Pinaceae	X		
27°	*Abies fraseri*	Pinaceae	X	X	X
27°	*Abies koreana*	Pinaceae	X		
27°	*Abies sachalinensis*	Pinaceae	X		
27°	*Abies sibirica*	Pinaceae	X		
27°	*Acacia abyssinica*	Fabaceae	X		
27°	*Acacia caven*	Fabaceae	X		
27°	*Acacia dealbata*	Fabaceae	X		
27°	*Acacia holosericea*	Fabaceae	X		
27°	*Acacia implexa*	Fabaceae	X		X
27°	*Acacia iteaphylla*	Fabaceae	X		X
27°	*Acacia karroo*	Fabaceae	X		
27°	*Acacia lahai*	Fabaceae	X		
27°	*Acacia mearnsii*	Fabaceae	X		
27°	*Acacia saligna*	Fabaceae	X		
27°	*Acacia senegal*	Fabaceae	X		
27°	*Acacia seyal*	Fabaceae	X		
27°	*Acacia sieberiana*	Fabaceae	X		
27°	*Acacia sp.*	Fabaceae	X		
27°	*Acacia visco*	Fabaceae		X	
27°	*Acasia confusa*	Fabaceae	X		
27°	*Acer × freemanii*	Sapindaceae			
27°	*Acer campestre ‘Evelyn’*	Sapindaceae			X
27°	*Acer cappdocium*	Sapindaceae	X		X
27°	*Acer carpinifolium*	Sapindaceae			X
27°	*Acer coriaceifolium*	Sapindaceae	X		
27°	*Acer ginnala*	Sapindaceae	X	X	X
27°	*Acer heidrechii*	Sapindaceae			X
27°	*Acer mandshuricum*	Sapindaceae			X
27°	*Acer mono*	Sapindaceae	X		X
27°	*Acer negundo ‘Auratum’*	Sapindaceae	X	X	X
27°	*Acer opalus subsp. opalus*	Sapindaceae			X
27°	*Acer pictum subsp. mono*	Sapindaceae	X		
27°	*Acer platanoides ‘Globosum’*	Sapindaceae	X		
27°	*Acer pseudoplatnus*	Sapindaceae	X	X	X
27°	*Acer pseudosieboldianum*	Sapindaceae	X		
27°	*Acer rubrum "Red sunset"*	Sapindaceae			X
27°	*Acer rubrum 'Northwood'*	Sapindaceae			X
27°	*Acer rubrum 'October Glory'*	Sapindaceae			X
27°	*Acer saccharum 'Caddo'*	Sapindaceae			X
27°	*Acer saccharum 'Green Column'*	Sapindaceae			X
27°	*Acer saccharum 'Green Mountain'*	Sapindaceae			X
27°	*Acer sieboldianum*	Sapindaceae	X		
27°	*Acer spicatum*	Sapindaceae			X

27°	*Acer tegmentosum*	Sapindaceae			X
27°	*Acer triflorum*	Sapindaceae	X		
27°	*Acer truncatum x platanoides*	Sapindaceae	X		
27°	*Acer x freemanii 'Autumn Blaze'*	Sapindaceae			X
27°	*Acokanthera schimperi*	Apocynaceae			X
27°	*Acorus calamus*	Acoraceae	X		
27°	*Adansonia digitata*	Malvaceae	X		
27°	*Aegle marmelos*	Rutaceae			X
27°	*Aesculus chinensis*	Sapindaceae			X
27°	*Aesculus indica*	Sapindaceae	X		
27°	*Aesculus turbinata*	Sapindaceae			X
27°	*Afrocarpus falcatus*	Podocarpaceae	X		
27°	*Agathis borneensis*	Araucariaceae	X		
27°	*Agathis robusta*	Araucariaceae			X
27°	*Albizia gummifera*	Fabaceae	X		
27°	*Alchornea sp.*	Euphorbiaceae	X		
27°	*Aleurites montana*	Euphorbiaceae			X
27°	*Alibertia edulis*	Rubiaceae	X		
27°	*Allocasuarina littoralis*	Casuarinaceae	X		X
27°	*Allocasuarina sp.*	Casuarinaceae	X		
27°	*Allophylus abyssinicusa*	Sapindaceae	X		
27°	*Alnus formosana*	Betulaceae			X
27°	*Alnus hirsuta var. sibirica*	Betulaceae	X		
27°	*Alnus japonica*	Betulaceae	X		
27°	*Alnus kolaensis*	Betulaceae			X
27°	*Alnus nigra*	Betulaceae	X		
27°	*Alnus rhombifolia*	Betulaceae	X		
27°	*Alnus sp.*	Betulaceae	X		
27°	*Alnus x spaethii*	Betulaceae	X		X
27°	*Alnus viridis*	Betulaceae			X
27°	*Alstonia angustifolia*	Apocynaceae	X		
27°	*Alstonia angustiloba*	Apocynaceae	X		
27°	*Alstonia congensis*	Apocynaceae	X		
27°	*Amelanchier × grandiflora 'Autumn Brilliance'*	Rosaceae			X
27°	*Amalanchier canadensis*	Rosaceae		X	X
27°	*Amelanchier laevis*	Rosaceae	X		
27°	*Amelanchier sp.*	Rosaceae	X		
27°	*Amesiodendron chinens*	Sapindaceae	X		
27°	*Amherstia nobilis*	Fabaceae	X		
27°	*Amygdalus communis*	Rosaceae	X		
27°	*Anadenanthera sp.*	Fabaceae	X		
27°	*Anastrabe integerrima*	Stilbaceae			X
27°	*Andira inermis*	Fabaceae	X		
27°	*Angophora costata*	Myrtaceae			X
27°	*Anthocephalus indicus*	Rubiaceae			X
27°	*Apodytes dimidiata*	Metteniusaceae			X
27°	*Aquilaria sinensis*	Thymelaeaceae			X
27°	*Araucaria araucana*	Araucariaceae	X	X	X
27°	*Araucaria bidwillii*	Araucariaceae			X
27°	*Araucaria columnaris*	Araucariaceae	X	X	X
27°	*Araucaria jussieu*	Araucariaceae	X		

27°	*Arbutus andrachne*	Ericaceae			X
27°	*Ardisia elliptica*	Primulaceae	X		
27°	*Areca catechu*	Arecaceae	X		X
27°	*Arfeuillea arborescens*	Sapindaceae	X		
27°	*Aristotelia chilensis*	Elaeocarpaceae	X		
27°	*Armeniaca mume*	Rosaceae			X
27°	*Armeniaca sibirica*	Rosaceae	X		
27°	*Armeniaca vulgaris*	Rosaceae	X		X
27°	*Aronia sp.*	Rosaceae	X		
27°	*Artocarpus champeden*	Moraceae	X		
27°	*Artocarpus hypargyrea*	Moraceae			X
27°	*Artocarpus incisus*	Moraceae	X		
27°	*Arytera littoralis*	Sapindaceae	X		
27°	*Atherosperma moschatum*	Atherospermataceae			X
27°	*Atractocarpus benthamianus*	Rubiaceae			X
27°	*Atractocarpus fitzalanii*	Rubiaceae			X
27°	*Backhousia citriodora*	Myrtaceae			X
27°	*Backhousia myrtifolia*	Myrtaceae			X
27°	*Baeckea frutescens*	Myrtaceae	X		
27°	*Banksia serrata*	Proteaceae			X
27°	*Baphia nitida*	Fabaceae	X		
27°	*Barringtonia asiatica*	Lecythidaceae	X		
27°	*Bauhinia acuminata*	Fabaceae			X
27°	*Bauhinia sp.*	Fabaceae	X		
27°	*Bauhinia variegata var. candida*	Fabaceae			X
27°	*Beilschmiedia miersii*	Lauraceae	X		
27°	*Berberis sp.*	Berberidaceae	X		
27°	*Berberis thunbergii var. atropurpurea*	Berberidaceae	X		X
27°	*Berberis thunbergii*	Berberidaceae	X		X
27°	*Berchemia discolor*	Rhamnaceae	X		
27°	*Bersama abyssinica*	Francoaceae	X		
27°	*Betula platyphylla var. japonica*	Betulaceae	X	X	X
27°	*Betula populifolia*	Betulaceae	X		
27°	*Betula subarctica*	Betulaceae			X
27°	*Biota orientalis*	Cupressaceae			X
27°	*Bischofia polycarpa*	Phyllanthaceae			X
27°	*Bixa orellana*	Bixaceae	X		
27°	*Bombax buonopozene*	Malvaceae	X		
27°	*Brachychiton discolor*	Malvaceae		X	X
27°	*Brachychiton rupestris*	Malvaceae			X
27°	*Brachychiton sp.*	Malvaceae	X		
27°	*Brachystegia spiciformis*	Fabaceae	X		
27°	*Bridelia monoica*	Phyllanthaceae	X		
27°	*Buxus microphylla*	Buxaceae	X		X
27°	*Buxus sempervirens*	Buxaceae	X	X	
27°	*Caesalpinia ferrea var. leiostachya*	Fabaceae			X
27°	*Caesalpinia pluviosa var. peltophoroides*	Fabaceae			X
27°	*Caesalpinia sappan*	Fabaceae	X		X
27°	*Callerya atropurpurea*	Myrtaceae	X		
27°	*Callistemon lanceolatus*	Myrtaceae	X		
27°	*Callistemon sp.*	Myrtaceae	X		
27°	*Callitris cupressiformis*	Cupressaceae			X

27°	*Callitris glaucophylla*	Cupressaceae	X		
27°	*Callitris gracilis*	Cupressaceae	X		
27°	*Callitris rhomboidea*	Cupressaceae	X		
27°	*Callitris verrucosa*	Cupressaceae	X		
27°	*Calotropis procera*	Apocynaceae	X		
27°	*Camellia crapnelliana*	Theaceae			X
27°	*Camptotheca acuminata*	Nyssaceae	X		
27°	*Cananga odorata*	Annonaceae	X		
27°	*Capparis mitchellii*	Capparaceae	X		
27°	*Caragana arborescens*	Fabaceae			X
27°	*Carissa spinarum*	Apocynaceae	X		
27°	*Carpinus betulus 'Fastigiata'*	Betulaceae	X		
27°	*Carpinus betulus x tschonoskii*	Betulaceae		X	X
27°	*Carpinus caroliniana x cordata*	Betulaceae		X	X
27°	*Carpinus caroliniana x coreana*	Betulaceae		X	X
27°	*Carpinus caroliniana x betulus*	Betulaceae		X	X
27°	*Carpinus caroliniana x coreana*	Betulaceae		X	X
27°	*Carpinus caroliniana x orientalis*	Betulaceae		X	X
27°	*Carpinus caucasica*	Betulaceae		X	X
27°	*Carpinus cordata*	Betulaceae		X	X
27°	*Carpinus cordata x japonica*	Betulaceae		X	X
27°	*Carpinus coreana*	Betulaceae		X	X
27°	*Carpinus fargesii*	Betulaceae		X	X
27°	*Carpinus japonica*	Betulaceae		X	X
27°	*Carpinus laxiflora*	Betulaceae		X	X
27°	*Carpinus sp.*	Betulaceae	X		
27°	*Carpinus tschonoskii*	Betulaceae		X	X
27°	*Carpinus turczaninowii*	Betulaceae		X	X
27°	*Carya cordiformis*	Juglandaceae	X		
27°	*Carya sp.*	Juglandaceae	X		
27°	*Caryocar brasiliense*	Caryocaraceae	X		
27°	*Casimiroa edulis*	Rutaceae	X		
27°	*Cassia ferruginea*	Fabaceae	X		
27°	*Cassia javanica*	Fabaceae			X
27°	*Cassia nodosa*	Fabaceae			X
27°	*Cassia spectabilis*	Fabaceae			X
27°	*Cassia surattensis*	Fagaceae			X
27°	*Castanopsis fissa*	Fagaceae			X
27°	*Castanospermum australe*	Fabaceae			X
27°	*Casuarina junghuhniana*	Casuarinaceae	X		
27°	*Casuarina obesa*	Casuarinaceae	X		
27°	*Casuarina pauper*	Casuarinaceae	X		
27°	*Casuarina sp.*	Casuarinaceae	X		
27°	*Casuarina stricta*	Casuarinaceae			X
27°	*Catalpa ovata*	Bignoniaceae	X		
27°	*Catha edulis*	Celastraceae			X
27°	*Ceanothus thyrsiflorus*	Rhamnaceae			X
27°	*Cedrus sp.*	Pinaceae			X
27°	*Ceiba speciosa*	Malvaceae			X
27°	*Celtis sp.*	Cannabaceae	X		
27°	*Cenostigma pluviosum*	Fabaceae	X		
27°	*Centrolobium tomentosum*	Fabaceae	X		

27°	*Cephalotaxus fortunei*	Taxaceae	X	X	
27°	*Cerasus serrulata*	Rosaceae	X		X
27°	*Cerasus serrulata var. lannesiana*	Rosaceae	X		
27°	*Cerasus speciosa*	Rosaceae	X	X	
27°	*Cerasus yedoensis*	Rosaceae			X
27°	*Ceratopetalum apetalum*	Cunoniaceae			X
27°	*Cerbera odollam*	Apocynaceae	X		
27°	*Cercis occidentalis*	Fabaceae	X		X
27°	*Chamaecyparis obtusa*	Cupressaceae	X		
27°	*Chamaecyparis pisifera*	Cupressaceae	X		
27°	*Chamaecyparis thyoides*	Cupressaceae	X		
27°	*Chamaerops excelsa*	Arecaceae			X
27°	*Chilopsis linearis*	Bignoniaceae	X		X
27°	*Chrysophyllum cainito*	Sapotaceae	X		
27°	*Chrysophyllum viridifolium*	Sapotaceae	X		
27°	*Cinchona sp.*	Rubiaceae	X		
27°	*Cinnamomum bodinieri*	Lauraceae	X		
27°	*Cinnamomum iners*	Lauraceae	X		
27°	*Cinnamomum japonicum*	Lauraceae	X		
27°	*Cinnamomum sp.*	Lauraceae	X		
27°	*Cinnamomum tamala*	Lauraceae	X	X	X
27°	*Citrus aurantifolia*	Rutaceae	X		
27°	*Citrus limon*	Rutaceae	X		
27°	*Citrus maxima*	Rutaceae			X
27°	*Cladrastis kentukea*	Fabaceae	X		
27°	*Coccoloba uvifera*	Polygonaceae	X		
27°	*Colophospermum mopane*	Fabaceae	X		
27°	*Colotropis procera*	Apocynaceae	X		
27°	*Conocarpus erectus*	Combretaceae	X		
27°	*Cordia africana*	Cordiaceae	X		
27°	*Cordia caffra*	Cordiaceae			X
27°	*Cordyline australis*	Asparagaceae			X
27°	*Cornus wilsoniana*	Cornaceae			X
27°	*Corylus sp.*	Betulaceae	X		
27°	*Corymbia ficifolia*	Myrtaceae	X		
27°	*Cotoneaster multiflorus*	Rosaceae		X	
27°	*Cotoneaster sp.*	Rosaceae	X		
27°	*Crataegus crus-galli*	Rosaceae	X		
27°	*Crataegus laevigata*	Rosaceae	X		
27°	*Crataegus oxyacantha*	Rosaceae	X	X	X
27°	*Crataegus phaenopyrum*	Rosaceae	X		
27°	*Crataegus pinnatifida*	Rosaceae			X
27°	*Crataegus viridis 'Winter King'*	Rosaceae			X
27°	*Crateva magna*	Capparaceae	X		
27°	*Crateva religiosa*	Capparaceae			X
27°	*Crateva unilocularis*	Capparaceae			X
27°	*Cratoxylum formosum*	Hypericaceae	X		
27°	*Croton macrostachyus*	Euphorbiaceae	X		
27°	*Croton megalocarpus*	Euphorbiaceae	X		
27°	*Croton sylvaticus*	Euphorbiaceae			X
27°	*Cryptocarya alba*	Lauraceae	X		
27°	*Cryptocarya laevigata*	Lauraceae			X

27°	*Cryptocarya mackinnoniana*	Lauraceae			X
27°	*Cunninghamia lanceolata*	Cupressaceae			X
27°	*Cupania anacardioides*	Sapindaceae	X	X	
27°	*Cupressus funebris*	Cupressaceae	X		
27°	*Cupressus macrocarpa*	Cupressaceae	X		
27°	*Cupressus macrocarpa "Goldcrest"*	Cupressaceae			X
27°	*Cupressus nootkatensis*	Cupressaceae	X		
27°	*Cupressus sp.*	Cupressaceae		X	
27°	*Cupressus torulosa*	Cupressaceae	X	X	
27°	*Cupressus pyramidalis*	Cupressaceae	X		
27°	*Curatella americana*	Dilleniaceae	X		
27°	*Cyclobalanopsis glauca*	Fagaceae			X
27°	*Cydonia oblonga*	Rosaceae	X		
27°	*Cytisus prolifer*	Fabaceae	X		
27°	*Cytisus scoparius*	Fabaceae	X		
27°	*Dalbergia balansae*	Fabaceae			X
27°	*Dalbergia hupeana*	Fabaceae			X
27°	*Dalbergia latifolia*	Fabaceae	X		
27°	*Dalbergia oliveri*	Fabaceae	X		
27°	*Daphniphyllum macropodum*	Daphniphyllaceae			X
27°	*Dichrostachys cinerea*	Fabaceae	X		
27°	*Didymopanax morototoni*	Araliaceae	X		
27°	*Dillenia ovata*	Dilleniaceae	X		
27°	*Dillenia philippinensiss*	Dilleniaceae	X		
27°	*Dimocarpus longan*	Sapindaceae			X
27°	*Dimorphandra mollis*	Fabaceae	X		
27°	*Diospyros discolor*	Ebenaceae	X		
27°	*Diospyros kaki*	Ebenaceae	X		
27°	*Diospyros virginiana*	Ebenaceae	X		
27°	*Dodonaea viscosa*	Sapindaceae	X		
27°	*Dombeya torrida*	Malvaceae	X		
27°	*Dovyalis abyssinica*	Salicaceae	X		
27°	*Dovyalis caffra*	Salicaceae	X		X
27°	*Dracontomelon duperreanum*	Anacardiaceae	X		X
27°	*Dryobalanops aromatica*	Dipterocarpaceae	X		
27°	*Dryobalanops oblongifolia*	Dipterocarpaceae	X		
27°	*Drypetes roxburghii*	Putranjivaceae	X		X
27°	*Durio zibethinus*	Malvaceae	X		
27°	*Dyera costulata*	Apocynaceae	X		
27°	*Dysoxylum fraserianum*	Meliaceae			X
27°	*Dysoxylum spectabile*	Meliaceae	X		
27°	*Elaeagnus angustifolia*	Elaeocarpaceae	X	X	X
27°	*Elaeocarpus balansae*	Elaeocarpaceae	X		X
27°	*Elaeocarpus hainanensis*	Elaeocarpaceae	X		X
27°	*Elaeodendron buchananii*	Celastraceae	X		
27°	*Elateriospermum tapos*	Euphorbiaceae	X		
27°	*Enterolobium saman*	Fabaceae	X		
27°	*Erica arborea*	Ericaceae	X		
27°	*Erythrina brucei*	Fabaceae	X		
27°	*Erythrina corallodendron*	Fabaceae			X
27°	*Erythrina crista-galli*	Fabaceae			X

27°	*Erythrina glauca*	Fabaceae	X		
27°	*Erythrina indica*	Fabaceae			X
27°	*Erythrina orientalis*	Fabaceae	X		
27°	*Erythrina vespertilio*	Fabaceae			X
27°	*Erythrina americana*	Fabaceae	X		
27°	*Erythrophleum guineense*	Fabaceae	X		
27°	*Eschweilera luschnatii*	Lecythidaceae	X		
27°	*Eucaliptus globulus*	Myrtaceae	X		X
27°	*Eucalyptus cinerea*	Myrtaceae	X		
27°	*Eucalyptus cladocalyx*	Myrtaceae	X		
27°	*Eucalyptus ficifolia*	Myrtaceae	X		
27°	*Eucalyptus largiflorens*	Myrtaceae	X		
27°	*Eucalyptus mannifera*	Myrtaceae	X		X
27°	*Eucalyptus marginata*	Myrtaceae	X	X	
27°	*Eucalyptus melliodora*	Myrtaceae	X		X
27°	*Eucalyptus obliqua*	Myrtaceae	X		
27°	*Eucalyptus pauciflora*	Myrtaceae	X		X
27°	*Eucalyptus populnea*	Myrtaceae			
27°	*Eucalyptus pulchella*	Myrtaceae	X		X
27°	*Eucalyptus scoparia*	Myrtaceae	X		X
27°	*Eucalyptus tereticornis*	Myrtaceae	X		
27°	*Eucalyptus torelliana*	Myrtaceae	X		
27°	*Eucalyptus torquata*	Myrtaceae	X		
27°	*Eucalyptus viminalis*	Myrtaceae	X		X
27°	*Eucryphia lucida*	Cunoniaceae			X
27°	*Euonymus sp.*	Euphorbiaceae	X		
27°	*Euphorbia pulcherrima*	Euphorbiaceae	X		
27°	*Euphorbia sp.*	Euphorbiaceae	X		
27°	*Euonymus europaeus*	Gentianaceae	X		
27°	*Eysenhardtia polystachya*	Fagaceae	X		
27°	*Fagraea crenulata*	Fagaceae			X
27°	*Fagus orientalis*	Fabaceae	X		
27°	*Faidherbia albida*	Fabaceae	X		
27°	*Ficus altissima*	Moraceae	X		X
27°	*Ficus brachypoda*	Moraceae			X
27°	*Ficus celebensis*	Moraceae	X		
27°	*Ficus concinna*	Moraceae	X		
27°	*Ficus elastica var. variegata*	Moraceae			X
27°	*Ficus glomerata*	Moraceae			X
27°	*Ficus macrocarpa*	Moraceae		X	X
27°	*Ficus macrophylla*	Moraceae	X		
27°	*Ficus mucoso*	Moraceae			X
27°	*Ficus mysorensis*	Moraceae			X
27°	*Ficus ngii*	Moraceae	X		
27°	*Ficus nitida*	Moraceae	X		
27°	*Ficus platyphylla*	Moraceae			X
27°	*Ficus racemosa*	Moraceae	X		
27°	*Ficus retusa*	Moraceae	X		
27°	*Ficus roxburghii*	Moraceae	X		
27°	*Ficus rumphii*	Moraceae			X
27°	*Ficus sp.*	Moraceae	X		
27°	*Ficus superba*	Moraceae	X		X

27°	*Ficus sur*	Moraceae	X		
27°	*Ficus sycomorus*	Moraceae	X		
27°	*Ficus tomentosa*	Moraceae	X		
27°	*Ficus tsjakela*	Moraceae	X		
27°	*Ficus variegata var. chlorocarpa*	Moraceae			X
27°	*Ficus vasta*	Moraceae	X		
27°	*Filicium decipiens*	Sapindaceae	X		
27°	*Firmiana malayana*	Malvaceae	X		
27°	*Flindersia australis*	Rutaceae			X
27°	*Flindersia brayleyana*	Rutaceae			X
27°	*Flindersia maculosa*	Rutaceae			X
27°	*Flindersia xanthoxyla*	Rutaceae			X
27°	*Fagraea fragrans*	Gentianaceae	X		
27°	*Fraxinus angustifolia subsp. oxycarpa*	Oleaceae			X
27°	*Fraxinus bungeana*	Oleaceae	X		
27°	*Fraxinus excelsior subsp. excelsior*	Oleaceae			X
27°	*Fraxinus formosana*	Oleaceae	X		
27°	*Fraxinus insularis*	Oleaceae	X		
27°	*Fraxinus nigra*	Oleaceae	X		
27°	*Fraxinus ornus subsp. ornus*	Oleaceae			X
27°	*Fraxinus pallisae*	Oleaceae	X		
27°	*Fraxinus pennsylvanica 'Patmore'*	Oleaceae			X
27°	*Fraxinus profunda*	Oleaceae	X		
27°	*Fraxinus quadrangulata*	Oleaceae	X		
27°	*Fraxinus rhynchophylla*	Oleaceae	X		
27°	*Fraxinus rotundifolia*	Oleaceae	X		
27°	*Fraxinus velutina*	Oleaceae	X		
27°	*Fuchsia excorticata*	Onagraceae	X		
27°	*Garcinia atroviridis*	Clusiaceae	X		
27°	*Garcinia hombroniana*	Clusiaceae	X		
27°	*Garcinia mangostana*	Clusiaceae	X		
27°	*Garcinia subelliptica*	Clusiaceae	X		X
27°	*Gardenia carinata*	Rubiaceae	X		
27°	*Gardenia tubifera*	Rubiaceae	X		
27°	*Gironniera nitida*	Cannabaceae	X		
27°	*Gleditsia triacanthos 'Halka'*	Fabaceae	X	X	X
27°	*Gochnatia polymorpha*	Asteraceae			X
27°	*Gordonia lasianthus*	Theaceae	X		
27°	*Grevillea baileyana*	Proteaceae			X
27°	*Grevillea banksii*	Proteaceae			X
27°	*Grevillea parallela*	Proteaceae	X		
27°	*Guarea trichilioides*	Meliaceae	X		
27°	*Gymnocladus dioicus*	Fabaceae	X		
27°	*Gymnostoma nobile*	Casuarinaceae	X		
27°	*Gymnostoma rumphianum*	Casuarinaceae	X		
27°	*Hagenia abyssinica*	Rosaceae	X		
27°	*Hakea salicifolia*	Proteaceae			X
27°	*Halesia monticola*	Styracaceae			X
27°	*Hancornia speciosa*	Apocynaceae	X		
27°	*Harpullia pendula*	Sapindaceae			X
27°	*Harpullia pendula*	Sapindaceae	X	X	
27°	*Heritiera littoralis*	Malvaceae	X		X

27°	*Heteromeles arbutifolia*	Rosaceae	X		
27°	*Heteropanax fragrans*	Araliaceae	X		X
27°	*Hibiscus rosa-sinensis*	Malvaceae	X		
27°	*Holoptelea integrifolia*	Ulmaceae			X
27°	*Hymenaea courbaril*	Fabaceae	X		
27°	*Idesia polycarpa var. vestita*	Salicaceae			X
27°	*Ilex chinensis*	Aquifoliaceae			X
27°	*Ilex rotunda var. microcarpa*	Aquifoliaceae	X		X
27°	*Ilex sp.*	Aquifoliaceae	X		
27°	*Ilex vomitoria*	Aquifoliaceae	X	X	X
27°	*Inga alba*	Fabaceae	X		
27°	*Inga bahiensis*	Fabaceae	X		
27°	*Inga fagifolia*	Fabaceae	X		
27°	*Jacaranda acutifolia*	Bignoniaceae	X	X	
27°	*Jacaranda chelonia*	Bignoniaceae		X	X
27°	*Jacaranda filicifolia*	Bignoniaceae	X		
27°	*Jacaranda sp.*	Bignoniaceae	X		
27°	*Jambosa malaccensis*	Myrtaceae	X		
27°	*Juglans ailantifolia*	Juglandaceae	X		
27°	*Juglans cinerea*	Juglandaceae	X		
27°	*Juglans sp.*	Juglandaceae	X		
27°	*Juniperus communis*	Cupressaceae	X		
27°	*Juniperus formosana*	Cupressaceae	X		
27°	*Juniperus oxycedrus*	Cupressaceae			X
27°	*Juniperus procera*	Cupressaceae	X		
27°	*Juniperus sp.*	Cupressaceae	X		
27°	*Kerria japonica*	Rosaceae	X		X
27°	*Khaya grandifoliola*	Meliaceae	X		
27°	*Kielmeyera coriacea*	Calophyllaceae	X		
27°	*Kigelia africana*	Bignoniaceae			X
27°	*Kigelia pinnata*	Bignoniaceae			X
27°	*Koelreuteria henryi*	Sapindaceae	X		
27°	*Kopsia singapurensis*	Apocynaceae	X		
27°	*Kunzea ericoides*	Myrtaceae	X		
27°	*Laburnum anagyroides*	Fabaceae			X
27°	*Laegerstroemia 'Tuscoroa'*	Lythraceae			X
27°	*Lafoensia pacari*	Lythraceae	X		
27°	*Lagerstroemia langkawiensis*	Lythraceae	X		
27°	*Lagerstromia indica*	Lythraceae	X		X
27°	*Lagerstrormia arborescens*	Lythraceae			X
27°	*Lagunaria patersonia*	Malvaceae			X
27°	*Lannea acida*	Anacardiaceae	X		
27°	*Larix europea*	Pinaceae			X
27°	*Larix sibrica*	Pinaceae			X
27°	*Lecythis zabucajo*	Lecythidaceae			X
27°	*Lepisanthes alata*	Sapindaceae	X		
27°	*Lepisanthes rubiginosa*	Sapindaceae	X		
27°	*Licania tomentosa*	Chrysobalanaceae	X		
27°	*Ligustrum compactum*	Oleaceae	X		
27°	*Ligustrum quihoui*	Oleaceae	X		X
27°	*Ligustrum sp.*	Oleaceae	X		

27°	*Liquidambar styraciflua var. mexicana*	Altingiaceae	X		
27°	*Liriodendron chinense*	Altingiaceae			X
27°	*Litchi chinensis*	Sapindaceae	X		X
27°	*Litsea glutinosa*	Lauraceae			X
27°	*Litsea monopetala*	Lauraceae			X
27°	*Lonicera maackii*	Caprifoliaceae	X		
27°	*Lysiloma latisiliqua*	Fabaceae			X
27°	*Maackia amurensis*	Fabaceae	X		
27°	*Macaranga gigantea*	Euphorbiaceae	X		
27°	*Maclura pomifera*	Moraceae	X	X	X
27°	*Macropiper excelsum*	Piperaceae	X		
27°	*Madhuca indica*	Sapotaceae			X
27°	*Magnolia × soulangeana*	Magnoliaceae	X		X
27°	*Magnolia fraseri*	Magnoliaceae	X		
27°	*Magnolia kobus*	Magnoliaceae	X		
27°	*Magnolia liliflora*	Magnoliaceae	X	X	
27°	*Magnolia macrophylla*	Magnoliaceae	X		
27°	*Magnolia tripetala*	Magnoliaceae	X		
27°	*Maingaya malayana*	Hamamelidaceae	X		
27°	*Mallotus nudiflorus*	Euphorbiaceae	X		
27°	*Mallotus paniculata*	Euphorbiaceae			X
27°	*Malosma laurina*	Anacardiaceae		X	X
27°	*Malus baccata*	Rosaceae	X		
27°	*Malus coronaria*	Rosaceae	X		
27°	*Malus floribunda*	Rosaceae			X
27°	*Malus hupehensis*	Rosaceae	X		
27°	*Malus ioensis*	Rosaceae	X		
27°	*Malus pumila*	Rosaceae	X		X
27°	*Malus spectabilis*	Rosaceae	X	X	
27°	*Malus trilobata*	Rosaceae	X		
27°	*Malus tschonoskii*	Rosaceae	X		
27°	*Maniltoa browneoides*	Fabaceae	X		
27°	*Markhamia hildebrandtii*	Bignoniaceae	X		
27°	*Melaleuca armillaris*	Myrtaceae	X		X
27°	*Melaleuca cajuputi*	Myrtaceae	X		
27°	*Melaleuca cajuputi subsp. cumingiana*	Myrtaceae	X		X
27°	*Melaleuca citrina*	Myrtaceae			X
27°	*Melaleuca decussata*	Myrtaceae	X	X	
27°	*Melaleuca leucadendra*	Myrtaceae	X		
27°	*Melaleuca linariifolia*	Myrtaceae			X
27°	*Melaleuca styphelioides*	Myrtaceae			X
27°	*Melastoma malabathricum*	Melastomataceae	X		
27°	*Melia excelsa*	Meliaceae	X		
27°	*Melia sp.*	Meliaceae	X		
27°	*Melicytus ramiflorus*	Violaceae	X		
27°	*Metrosideros excels*	Myrtaceae	X		
27°	*Michelia champaca*	Magnoliaceae	X		
27°	*Michelia chapensis*	Magnoliaceae			X
27°	*Michelia figo*	Magnoliaceae	X		
27°	*Michelia maudiae*	Magnoliaceae	X		
27°	*Microcos blattifolia*	Malvaceae	X		
27°	*Millettia atropurpurea*	Fabaceae	X		

27°	*Millettia ferrugina*	Fabaceae	X		
27°	*Millettia peguensis*	Fabaceae	X		X
27°	*Millettia pinnata*	Fabaceae			X
27°	*Mimosa laticifera*	Fabaceae	X		
27°	*Mimosa pudica*	Fabaceae	X		
27°	*Mimosa scabrella*	Fabaceae	X		
27°	*Mollinedia viridiflora*	Monimiaceae	X		
27°	*Monoon longifolium*	Annonaceae			X
27°	*Morus alba 'Pendula'*	Moraceae	X	X	X
27°	*Morus alba 'Platanifolia'*	Moraceae	X		
27°	*Morus bombycis*	Moraceae	X		
27°	*Morus mesozygia*	Moraceae	X		
27°	*Morus rubra*	Moraceae	X		
27°	*Mundulea sericea*	Fabaceae			X
27°	*Murraya paniculata*	Rutaceae			X
27°	*Myoporum montanum*	Scrophulariaceae			X
27°	*Myrcia schiedeana*	Myrtaceae	X		
27°	*Myrica rubra*	Myrtaceae	X		
27°	*Mytilaria laosensis*	Hamamelidaceae			X
27°	*Nageia nagi*	Podocarpaceae	X		X
27°	*Nauclea orientalis*	Rubiaceae	X		X
27°	*Nectandra megapotamica*	Lauraceae	X		
27°	*Neolamarckia cadamba*	Rubiaceae			X
27°	*Neolitsea zeylanica*	Lauraceae	X		
27°	*Nerium indicum*	Apocynaceae			X
27°	*Notelaea microcarpa*	Oleaceae	X		
27°	*Nothofagus fusca*	Nothofagaceae	X		
27°	*Nyctanthes arbor-tristis*	Oleaceae			X
27°	*Nyssa biflora*	Nyssaceae	X		
27°	*Ocotea psychotrioides*	Lauraceae	X		
27°	*Olea africana*	Oleaceae			X
27°	*Olea capensis subsp. hochstetteri*	Oleaceae	X		
27°	*Olea europaea subsp. cuspidata*	Oleaceae	X		
27°	*Olea europea var. sylvestris*	Oleaceae	X		
27°	*Olea sp.*	Oleaceae		X	
27°	*Olinia rochetiana*	Penaeaceae	X		
27°	*Ormosia hosiei*	Fabaceae	X		
27°	*Oroxylum indicum*	Bignoniaceae			X
27°	*Ostrya japonica*	Betulaceae		X	X
27°	*Pachira aquatica*	Malvaceae			X
27°	*Padus virginiana*	Rosaceae	X		
27°	*Palaquium formosanum*	Sapotaceae	X		
27°	*Parapiptadenia rigida*	Fabaceae	X		
27°	*Paraserianthes lophantha*	Fabaceae		X	
27°	*Paraserianthes falcataria*	Fabaceae	X		
27°	*Parinari curatellifolia*	Chrysobalanaceae	X		
27°	*Parmentiera cereifera*	Bignoniaceae			X
27°	*Parrotia persica*	Hamamelidaceae	X	X	X
27°	*Parthenocissus sp.*	Vitaceae	X		
27°	*Paulownia fortunei*	Paulowniaceae			X
27°	*Pentaspadon motleyi*	Anacardiaceae	X		

27°	*Philadelphus incanus*	Hydrangeaceae	X		X
27°	*Philadelphus pekinensis*	Hydrangeaceae	X		X
27°	*Photinia serratifolia*	Rosaceae	X		
27°	*Phyllanthus acidus*	Phyllanthaceae	X		
27°	*Phyllanthus emblica*	Phyllanthaceae	X		
27°	*Picea alba*	Pinaceae			X
27°	*Picea engelmannii*	Pinaceae	X		
27°	*Picea jezoensis*	Pinaceae	X		X
27°	*Picea obovata*	Pinaceae			X
27°	*Picea rubens*	Pinaceae	X		
27°	*Picea sitchensis*	Pinaceae			X
27°	*Pinus australis*	Pinaceae	X		
27°	*Pinus banksiana*	Pinaceae	X		
27°	*Pinus brutia*	Pinaceae			X
27°	*Pinus caribaea*	Pinaceae	X		
27°	*Pinus contorta var. latifolia*	Pinaceae			X
27°	*Pinus coulteri*	Pinaceae	X		
27°	*Pinus eldarica*	Pinaceae	X		
27°	*Pinus flexilis*	Pinaceae	X		
27°	*Pinus mugo*	Pinaceae			X
27°	*Pinus nigra subsp. nigra*	Pinaceae			X
27°	*Pinus peuce*	Pinaceae	X		
27°	*Pinus rigida*	Pinaceae	X		
27°	*Pinus sibirica*	Pinaceae			X
27°	*Pinus thunbergii*	Pinaceae			X
27°	*Pinus tabulaeformnis*	Pinaceae	X	X	X
27°	*Piper aduncum*	Piperaceae	X		
27°	*Piptadenia gonacantha*	Fabaceae			X
27°	*Pisonia alba*	Nyctaginaceae	X		
27°	*Pistacia lentiscus*	Anacardiaceae	X		
27°	*Pittosporum bicolor*	Pittosporaceae			X
27°	*Pittosporum sp.*	Pittosporaceae		X	
27°	*Pittosporum tobira*	Pittosporaceae	X		X
27°	*Pittosporum undulatum*	Pittosporaceae	X		
27°	*Platanus × hispanica 'Acerifolia'*	Platanaceae			X
27°	*Platanus vulgaris*	Platanaceae	X		
27°	*Platanus x hybrida*	Platanaceae	X		
27°	*Plumera sp.*	Cupressaceae	X		X
27°	*Plumeria rubra*	Apocynaceae	X		
27°	*Podocarpus elatus*	Podocarpaceae			X
27°	*Podocarpus falcatus*	Podocarpaceae	X		
27°	*Podocarpus gracilior*	Podocarpaceae	X		
27°	*Podocarpus latifolius*	Podocarpaceae	X		
27°	*Podocarpus nagi*	Podocarpaceae			X
27°	*Podocarpus polystachyus*	Podocarpaceae	X		
27°	*Podocarpus sp.*	Podocarpaceae	X		
27°	*Polyalthia longifolia "Pendula"*	Annonaceae	X		
27°	*Pomaderris apetala*	Rhamnaceae			X
27°	*Pometia pinnata*	Sapindaceae	X		X
27°	*Poncirus trifoliata*	Rutaceae	X	X	
27°	*Populus balsamifera*	Salicaceae	X		
27°	*Populus canescens*	Salicaceae	X	X	

27°	*Populus grandidentata*	Salicaceae	X		
27°	*Populus laurifolia*	Salicaceae	X		
27°	*Populus nigra 'Pyramidalis'*	Salicaceae	X	X	X
27°	*Populus nigra subsp. nigra*	Salicaceae			X
27°	*Populus nigra var. italica*	Salicaceae			X
27°	*Populus simonii*	Salicaceae	X		
27°	*Populus trichocarpa*	Salicaceae			X
27°	*Populus tristis*	Salicaceae			X
27°	*Pouteria obovata*	Sapotaceae	X		
27°	*Pouteria ramiflora*	Sapotaceae	X		
27°	*Prosopis glandulosa*	Fabaceae	X		X
27°	*Prunus africana*	Rosaceae	X		
27°	*Prunus americana*	Rosaceae			X
27°	*Prunus serrulata*	Rosaceae			X
27°	*Prunus davidiana*	Rosaceae	X		X
27°	*Prunus ilicifolia*	Rosaceae	X		
27°	*Prunus jamasakura*	Rosaceae			X
27°	*Prunus lusitanica*	Rosaceae	X	X	
27°	*Prunus maackii*	Rosaceae	X		
27°	*Prunus mahaleb*	Rosaceae		X	X
27°	*Prunus padus subsp. padus*	Rosaceae			X
27°	*Prunus pensylvanica*	Rosaceae	X		
27°	*Prunus serrulata "Kanzan"*	Rosaceae			X
27°	*Prunus spachiana*	Rosaceae			X
27°	*Prunus subhirtella*	Rosaceae	X		
27°	*Pseudobombax longiflorum*	Malvaceae	X		
27°	*Psidium guayava*	Myrtaceae	X		X
27°	*Pteleocarpa lamponga*	Boraginaceae	X		
27°	*Pterocarpus erinaceus*	Fabaceae	X		
27°	*Pterospermum acerifolium*	Malvaceae			X
27°	*Pterospermum semisagittatum*	Malvaceae			X
27°	*Putranjiva roxburghii*	Putranjivaceae			X
27°	*Pyracantha coccinea*	Rosaceae			X
27°	*Pyrus bretschneideri*	Rosaceae	X		X
27°	*Pyrus kawakamii*	Rosaceae	X		
27°	*Pyrus pyraster*	Rosaceae	X		
27°	*Pyrus pyrifolia*	Rosaceae	X		
27°	*Quecus ilex*	Fagaceae	X		
27°	*Quecus rubra*	Fagaceae			X
27°	*Quercus arizonica*	Fagaceae			X
27°	*Quercus coccifera*	Fagaceae	X		
27°	*Quercus ellipsoidalis*	Fagaceae	X		
27°	*Quercus engellemannii*	Fagaceae			X
27°	*Quercus fabrei*	Fagaceae	X		
27°	*Quercus faginea*	Fagaceae	X		
27°	*Quercus frainetto*	Fagaceae			X
27°	*Quercus germana*	Fagaceae	X		
27°	*Quercus ilex subsp. Ilex*	Fagaceae			X
27°	*Quercus imbricaria*	Fagaceae	X		
27°	*Quercus laeta*	Fagaceae	X		X
27°	*Quercus lancifolia*	Fagaceae	X		
27°	*Quercus lyrata*	Fagaceae		X	X

27°	*Quercus nigra*	Fagaceae	X		
27°	*Quercus nuttallii*	Fagaceae		X	X
27°	*Quercus petraea subsp. petraea*	Fagaceae			X
27°	*Quercus prinus*	Fagaceae			X
27°	*Quercus pubescens subsp. pubescens*	Fagaceae			X
27°	*Quercus pyrenaica*	Fagaceae	X		
27°	*Quercus robur subsp. robur*	Fagaceae			X
27°	*Quercus texana*	Fagaceae	X		
27°	*Quercus tomentella*	Fagaceae	X		X
27°	*Quercus variabilis*	Fagaceae	X		X
27°	*Quercus velutina*	Fagaceae			X
27°	*Quercus xalapensis*	Fagaceae	X		
27°	*Quillaja saponaria*	Quillajaceae	X		
27°	*Radermachera hainanensis*	Bignoniaceae			X
27°	*Ravenala madagascariensis*	Strelitziaceae	X		
27°	*Reevesia thyrsoidea*	Malvaceae	X		
27°	*Rhamnus prinoides*	Rhamnaceae	X		
27°	*Rhamnus sp.*	Rhamnaceae			X
27°	*Rhododendron ponticum*	Ericaceae			X
27°	*Rhodoleia championi*	Hamamelidaceae			X
27°	*Rhus coriaria*	Anacardiaceae			X
27°	*Ribes sp.*	Grossulariaceae	X		
27°	*Robinia sp.*	Fabaceae	X		
27°	*Robinia umbraculifera*	Fabaceae	X	X	X
27°	*Robinia viscosa*	Fabaceae		X	X
27°	*Rosa sp.*	Fabaceae	X		
27°	*Rubus sp.*	Rosaceae	X		
27°	*Salix fragilis*	Salicaceae			X
27°	*Salix glauca*	Salicaceae			X
27°	*Salix matsudana var. matsudana*	Salicaceae	X		X
27°	*Salix mucronata*	Salicaceae	X		
27°	*Salix nigra*	Salicaceae	X		
27°	*Salix pentandra*	Salicaceae	X		
27°	*Sambucus javanica*	Viburnaceae	X		
27°	*Sambucus sp.*	Viburnaceae	X		
27°	*Saraca asoca*	Fabaceae	X		
27°	*Saraca cauliflora*	Fabaceae	X		
27°	*Saraca dives*	Fabaceae	X		X
27°	*Sarcopteryx stipata*	Sapindaceae			X
27°	*Sassafras albidum*	Lauraceae	X		
27°	*Schefflera actinophylla*	Araliaceae	X		X
27°	*Schefflera heptaphylla*	Araliaceae	X		X
27°	*Schinus areira*	Anacardiaceae	X		
27°	*Schleichera oleosa*	Sapindaceae			X
27°	*Sciadopitys verticillata*	Sciadopityaceae	X		
27°	*Sclerocarya birrea subsp. caffra*	Anacardiaceae	X		
27°	*Scolopia chinensis*	Salicaceae			X
27°	*Scolopia saeva*	Salicaceae	X		X
27°	*Searsia chirindensis*	Anacardiaceae			X
27°	*Searsia pendulina*	Anacardiaceae	X		
27°	*Senna siamea*	Fabaceae			X
27°	*Sesbania bispinosa*	Fabaceae	X		

27°	*Sesbania grandiflora*	Fabaceae			X
27°	*Shirakiopsis elliptica*	Euphorbiaceae	X		
27°	*Shorea roxburghii*	Dipterocarpaceae	X		
27°	*Shorea sp.*	Dipterocarpaceae	X		
27°	*Shorea sumatrana*	Dipterocarpaceae	X		
27°	*Sorbus alnifolia*	Rosaceae	X		
27°	*Sorbus americana*	Rosaceae	X		
27°	*Hedlundia arranensis*	Rosaceae	X		
27°	*Sorbus aucuparia subsp. aucuparia*	Rosaceae			X
27°	*Sorbus commixta*	Rosaceae	X		
27°	*Sorbus decora*	Rosaceae	X		
27°	*Sorbus domestica*	Rosaceae	X		
27°	*Sorbus folgneri*	Rosaceae	X		
27°	*Sorbus aucuparia var. gorodkowii*	Rosaceae			X
27°	*Sorbus latifolia*	Rosaceae	X		
27°	*Sorbus torminalis*	Rosaceae			X
27°	*Spathodea nilotica*	Bignoniaceae	X		
27°	*Stenobium stans*	Bignoniaceae	X		
27°	*Stenocarpus sinuatus*	Proteaceae			X
27°	*Sterculia foetida*	Malvaceae	X		
27°	*Sterculia parviflora*	Malvaceae	X		
27°	*Strychnos spinosa*	Loganiaceae	X		
27°	*Styrax japonicus*	Styracaceae			X
27°	*Symphoricarpos sp.*	Caprifoliaceae	X		
27°	*Syringa oblata*	Oleaceae	X		
27°	*Syringa sp.*	Oleaceae	X		
27°	*Syzgium samarangense*	Myrtaceae	X		
27°	*Syzigium jambolanum*	Myrtaceae	X		
27°	*Syzygium anisatum*	Myrtaceae			X
27°	*Syzygium campanulatum*	Myrtaceae	X		
27°	*Syzygium luehmannii*	Myrtaceae			X
27°	*Syzygium malaccense*	Myrtaceae	X		X
27°	*Syzygium samarangense*	Myrtaceae			X
27°	*Syzygium smithii*	Myrtaceae			X
27°	*Tabebuia impetiginosa*	Bignoniaceae	X		
27°	*Tabebuia ochracea*	Bignoniaceae	X		
27°	*Tabebuia pallida*	Bignoniaceae	X		
27°	*Tabebuia pentaphylla*	Bignoniaceae	X		
27°	*Tabernaemontana ventricosa*	Apocynaceae			X
27°	*Talisia esculenta*	Sapindaceae	X		
27°	*Tamarix gallica*	Tamaricaceae		X	X
27°	*Tapirira guianensis*	Anacardiaceae	X		
27°	*Taxus sp.*	Taxaceae	X		
27°	*Tecoma stans*	Lamiaceae		X	
27°	*Tectona hamiltonia*	Verbenaceae			X
27°	*Terminalia boivinii*	Combretaceae	X		
27°	*Terminalia buceras*	Combretaceae	X		
27°	*Terminalia mantaly*	Combretaceae	X		X
27°	*Terminalia pyrifolia*	Combretaceae	X		X
27°	*Thespesia populnea*	Malvaceae			X
27°	*Thuja sp.*	Cupressaceae	X	X	X
27°	*Tibouchina granulosa*	Melastomataceae			X

27°	*Tilia × europaea*	Malvaceae			X
27°	*Tilia × europaea 'Pallida'*	Malvaceae			X
27°	*Tilia × phatyphyllos*	Malvaceae			X
27°	*Tilia amurensis*	Malvaceae	X		
27°	*Tilia argentea*	Malvaceae	X		X
27°	*Tilia platyphyllos subsp. grandifolia*	Malvaceae		X	X
27°	*Tilia henryana*	Malvaceae	X		
27°	*Tilia mongolica*	Malvaceae	X		
27°	*Tilia rubra*	Malvaceae	X		
27°	*Toechima erythrocarpum*	Sapindaceae			X
27°	*Torreya nucifera*	Taxaceae	X	X	
27°	*Treculia africana*	Moraceae	X		
27°	*Triadica sebifera*	Euphorbiaceae			X
27°	*Trichilia dregeana*	Meliaceae	X		
27°	*Trichilia emetica*	Meliaceae	X		
27°	*Tristania laurina*	Myrtaceae	X		
27°	*Turpinia insignis*	Staphyleaceae	X		
27°	*Typha orientalis*	Typhaceae	X		
27°	*Ulmus 'Frontier'*	Ulmaceae			X
27°	*Ulmus alata*	Ulmaceae	X	X	X
27°	*Ulmus americana 'Valley Forge'*	Ulmaceae		X	
27°	*Ulmus campestris 'Umbraculifera'*	Ulmaceae	X	X	X
27°	*Ulmus davidiana*	Ulmaceae	X		
27°	*Ulmus glabra 'Pendula'*	Ulmaceae	X	X	X
27°	*Ulmus minor 'Ademuz'*	Ulmaceae			X
27°	*Ulmus minor 'Dehesa de Amaniel'*	Ulmaceae			X
27°	*Ulmus minor 'Dehesa de la Villa'*	Ulmaceae			X
27°	*Ulmus minor 'Fuente Umbría'*	Ulmaceae			X
27°	*Ulmus minor 'Majadahonda'*	Ulmaceae			X
27°	*Ulmus minor 'Retiro'*	Ulmaceae			X
27°	*Ulmus minor subsp. minor*	Ulmaceae			X
27°	*Ulmus minor 'Toledo'*	Ulmaceae			X
27°	*Ulmus procera*	Ulmaceae	X		
27°	*Ulmus propinqua*	Ulmaceae	X		
27°	*Umbellularia californica*	Lauraceae	X		
27°	*Vaccinium sp.*	Ericaceae	X		
27°	*Vachellia sieberiana*	Fabaceae	X		X
27°	*Vachellia xanthophloea*	Fabaceae	X		X
27°	*Veitchia merrillii*	Arecaceae	X		X
27°	*Vepris nobilis*	Rutaceae	X		
27°	*Vepris simplicifolia*	Rutaceae	X		
27°	*Vepris trichocarpa*	Rutaceae	X		
27°	*Viburnum lantana*	Viburnaceae	X	X	X
27°	*Viburnum obovatum*	Viburnaceae	X	X	X
27°	*Viburnum sp.*	Viburnaceae	X		
27°	*Vitex parviflora*	Lamiaceae			X
27°	*Vitex pubescens*	Lamiaceae	X		
27°	*Vitis sp.*	Vitaceae	X		
27°	*Warburgia ugandensis*	Canellaceae	X		
27°	*Wisteria sinensis*	Fabaceae	X		
27°	*Wodyetia bifurcata*	Arecaceae	X		X
27°	*Wormia alata*	Dilleniaceae	X		X

27°	*Xanthophyllum sp.*	Polygalaceae	X		
27°	*Xanthostemon paradoxus*	Myrtaceae			X
27°	*Yulania denudata*	Magnoliaceae	X		
27°	*Zanthoxylum usambarense*	Rutaceae	X		
27°	*Zinowiewia integerrima*	Celastraceae	X		
27°	*Ziziphus mucronata*	Rhamnaceae			
27°	*Zygia longifolia*	Fabaceae	X		X

3. Chapter 2

Homogeneous growth and water-stress responses among functional diverse urban trees: implications for the climate resilience of green areas in São Paulo, Brazil

In collaboration with: Ricardo Reale, Augusto Akio Lucchezi Miyahara, Larissa Alves de Souza, Tom Wild, Marisa Domingos, Adriana Grandis, Tom Wild, Marocs Buckeridge Giuliano Maselli Locosselli

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3.1 Abstract

Functional diversity of trees is a cornerstone in planning green areas to adapt cities to climate change. Partially because diversity begets ecosystem services provision. Yet, it is not clear if functional diversity also enhances green areas' resilience by promoting heterogeneous growth and stress responses to climate. We tested the hypothesis that tree functional diversity improves green areas' resilience by promoting the diversity of trees' response to climate variability. We monitored the basal area increment (BAI) and tree water deficit (TWD) using high-resolution digital dendrometers in seven native tree species ranking among the dominant ones, but differing in phenological strategies and shade-tolerance. We monitored trees in two contrasting urban green areas in São Paulo, Brazil, a public park with mixed vegetation cover and an Atlantic Rainforest patch, over two years. On average, trees from the urban park grow twice as fast, but experience double TWD, suggesting a lower competition and a more acquisitive growth strategy, whereas trees from the urban forest patch display slower GRO and lower TWD, consistent with a conservative strategy. Despite the differences in average BAI and TWD among species and between sites, and contrary to our expectation, all tree species exhibit moderate synchrony in BAI responses to precipitation and strong synchrony in tree TWD responses to vapor-pressure deficit. Consistent patterns to vapor-pressure deficit suggesting similar climate vulnerabilities. These findings question the use of dominant species and underscore the need to evaluate climate responses of non-dominant and more niche-specialist species to design climate-resilient urban green areas.

Keywords: urban tree growth, tree water deficit, dendrometers, climate resilience, urban park.

3.2 Introduction

As cities grow bigger and denser, and climate change unfolds, urban challenges intensify at a fast pace (Scott et al. 2016, IPCC 2023). Climate extremes – including heatwaves, floods, and droughts - risk global urban population, causing substantial economic losses, negative health outcomes, and eventually death (Ebi et al. 2021; Clarke et al. 2022; Pizzorni et al. 2024). These impacts have propelled discussions on tailored solutions to cities' adaptation to the ongoing climate change (Hurlimann et al. 2021). Yet, urban forests are a mainstream measure to promote cities' resilience through multiple ecosystem services (Castelo et al. 2023; Silva-Luz et al. 2024; Salmond et al. 2016). These multifunctional benefits are the cornerstone of ambitious planting goals (Pincetl, 2010, Zhou et al., 2020). Other than the number of trees, promoting diversity is essential for improved benefits of urban forests (Kowarik et al. 2025; Le Provost et al. 2023) since functional diversity enhances ecosystem services delivery (Mace et al. 2012; Le Provost et al. 2023, Ruiz-Benito et al. 2014, Wang et al. 2021, Gamfeldt et al, 2013; Ross et al., 2021). This evidence underpins international mechanisms to promote urban biodiversity, which lies at the core of urban green infrastructure and Nature-based Solutions (Diaz et al. 2020; Wild et al 2020; Kabisch et al. 2022). Whereas the functional diversity gain in benefits delivery is well established in the literature, the interplay between increasingly intense and frequent climate extremes and plant species functioning is poorly understood, at the risk of curbing ecosystem services delivery under extreme events (Pandey & Ghosh, 2023; McPhearson et al., 2015).

In theory, species and functional diversity supports urban forests' resilience in a similar way it copes with ecosystem services delivery (Jactel et al. 2021; Messier et al. 2021). Diverse intervention brings together various forms and functions – spanning vegetative and reproductive strategies – that translate into multiple benefits and likely multiple responses to climate (Silva-Luz et al. 2024, Shin et al. 2022). Given that climate is the dominant driver of growth and reproduction rates worldwide (Wilmking et al. 2020; Peltier & Ogle, 2020), with few exceptions (Locosselli et al 2019), no species can handle all combinations of adverse climate conditions (Booth et al. 1998; Xu et al. 2024). Resilient species are the species able to receive a disturbance and return to their original conditions (Lloret et al. 2011). Ideally, resilient interventions should combine species with contrasting vulnerabilities and adaptive capacities to climate. This diversity ensures that some thriving species compensate for those experiencing stress, buffering the negative impacts of climate extremes in urban green areas (Wood & Dupras, 2021; Paquette et al., 2021; Ammer, 2019). This strategy could potentially result in future-proof interventions based on the assumption that diversity begets not only ecosystem services but also resilience (Wood & Dupras, 2021;

Weiskopf et al., 2020; Hylander et al., 2022).

Based on the assumption that diversity begets resilience, decision-makers and practitioners should aim for a heterogeneous climate response among tree species to promote resilient urban green areas (Jacopetti et al. 2023). Species' responses to climate can be assessed through various approaches. Direct measurements of physiological traits, like P50 and more recently T50, provide an instant picture of the mechanisms behind trees' responses to climate stress, but fail to integrate their systemic responses to stress over prolonged periods. Alternatively, forest plots allow the evaluation of plant species growth and mortality across decades (Corona et al. 2011; Hartmann et al. 2022; Ferretti et al. 2024). Although thousands of plots are monitored annually in natural forests worldwide, urban applications remain limited (Roman et al. 2013). Tree-ring analysis also provides robust insights into the role of climate variability on annual growth of urban trees over decades to centuries (Miyahara et al, 2022). However, this approach fails whenever annual growth layers are visually indistinct, not annual, or complacent and not sensitive to climate variability (Fritts, 2012), common conditions to lowland tropical tree species (Giraldo et al., 2025). High-resolution dendrometers are a valuable alternative to assess changes in the trunk diameter over years at hourly intervals (Sevanto, 2025). Modern dendrometers can record increases in trunk size as a measure of growth, or shrinkages as a measure of tree water deficit. These records allow the assessment of the climate responses of tree species at a very fine scale and provide insights into the climate vulnerability of tree species (Drew & Downes, 2009; Peters et al., 2025).

This study builds upon the premise that a low synchrony between species growth and tree water deficit can be considered a measure of success, as it guarantees that species within the green area will withstand a broad range of climate stressors (Ammer, 2019; Sachsenmaier et al., 2024). Conversely, a high synchrony suggests homogeneous responses to climate, potentially risking systemic failure of trees under stress. Here, we evaluated how growth and tree water deficit responses to climate vary among species and between two contrasting urban green areas in the city of São Paulo, Brazil: an urban park and an urban forest patch. This study is based on two years records of hourly growth and tree water deficit, and monthly phenology. We selected native tree species from the dominant assemblage in each site, following the standard forest ecology protocols, but differing in growth and phenology strategies, to enable us to strive for compelling insights into these green areas' resilience. We hypothesized that: I) species exhibit distinct responses to climate variability, leading to heterogeneous responses and high resilience within each green area. II)

species responses to climate converge according to their phenology and growth strategies, III) responses diverge between the two urban green areas because of their intrinsic environmental characteristics and species composition.

3.3 Materials and methods

3.3.1 Study site

Sampling took place in the megacity of São Paulo, the largest city in South America (Töpfer, 2013). The region is home to more than 11 million people in an area of 1,521.202 km². The city lies in the transition between the Atlantic Forest and Cerrado biomes (IBGE, 2024). Approximately 54 % of its area is covered by green areas, which are unevenly distributed, with the largest extensions located along the northern and southern limits of the city (Secretaria do Verde e Meio Ambiente, 2023). We selected two green areas as monitoring sites: the Ibirapuera park, which is a 158.50 ha recreational public park founded in 1954 with mixed vegetation cover (Fig. 1), and the Fontes do Ipiranga State park, a 526.38 ha Atlantic Rainforest Patch that is a remnant of the vegetation that used to cover the area where the city lies today (Fig. 1). It was designated as a protected area in 1969 due to its scenic and biodiversity values (Barros et al. 2002; SVMA 2002). Together, these green spaces account for almost 5% of all green areas and protected lands in the city of São Paulo and can be considered representative of the city's broader network of over 100 urban parks. As such, they serve as model sites for studies focused on urban green spaces in São Paulo. From now on, these two areas will be referred to as urban park and urban forest for the sake of understanding.

To better characterize the vegetation cover in these two sites, we calculated the Normalised Difference Vegetation Index (NDVI), based on Sentinel-2 satellite images (SR-HARMONIZED level, 10 meters of spatial resolution) processed on the Google Earth Engine platform (GEE ID: COPERNICUS/S2_SR_HARMONIZED). We filtered the scenes with less than 10% cloud cover. Only pixels classified as vegetation and exposed soil were considered, excluding water bodies and built-up areas, based on the scene classification band (SCL). Monthly NDVI averages were extracted for the parks. The data was extracted and then processed in QGIS.

We also characterized the microenvironmental conditions to gain a deeper understanding of the groundwater availability in these sites by monitoring soil moisture,

temperature, and conductivity with a ZL6 Basic (Meter) sensor, one in each monitoring area, at two depths: 15cm and 50cm. Although the data covers the period between 2023 to 2024, and thus outside the timeframe of this study, it aids the interpretation of the results.

3.3.2 Species selection

We selected seven native tree species for this study among the dominant in each site, a strategy commonly employed in ecological studies (da Silva Filho & Tosetti, 2010; Tanus et al., 2012; Avolio et al. 2019; Vellend et al. 2007; Pau & Dee, 2016). Tree species were selected among the dominant taxa according to floristic descriptors, specifically Importance Value (IV) and Cover Value (CV), which reflect species dominance within the community (Hirata, 2006; Kondrat et al. 2020; Kondrat 2014; da Silva Filho & Tosetti, 2010). Species were chosen to also represent a range of phenological and ecological strategies, capturing the functional heterogeneity found in each site. Among them, one species was common to both areas. For this species, we sampled one population in the urban forest and two populations in the urban park: one in a woodland alongside other studied trees and another growing in isolation. Our sampling strategy prioritized representing the spatial and structural heterogeneity of both green areas by including multiple native tree species among the dominant assemblage, but with contrasting functional strategies. This design intentionally maximized interspecific variability within each park, recognizing that it necessarily reduced our ability to characterize intraspecific variability in detail. Given the high cost of continuous dendrometer monitoring and the study's focus on community-level climate responses, we emphasized patterns emerging at the park and assembly scales. The full list of species is provided in Table 1 (also SM Table 11).

Table 1: Characterization of the studies species, their site provenance (UP: urban park, UF: urban forest), number of trees, diameter at breast height (DBH), light tolerance and phenology according to the literature (*Lorenzi, 2000; Kondrat et al. 2020; Barretto e Catharino, 2015).

Specie	Family	Site	n	Mean DBH (cm) Standard error	Light tolerance	Phenology
Eugenia uniflora	Myrtaceae	UP	2	19.5 ± 1.6	Shadow tolerant*	Brevi-deciduous
Alchornea triplinervia	Euphorbiaceae	UP	2	49.35 ± 6.3	Shadow intolerant*	Brevi-deciduous
Centrolobium tomentosum	Fabaceae	UP	2	37.7 ± 18.0	Shadow tolerant*	Deciduous
Cedrela fissilis	Meliaceae.	UP	3		Shadow intolerant*	Deciduous

				50.9 ± 4.0		
Cedrela fissilis isolated	Meliaceae	UP	3	31.9 ± 2.6	Shadow intolerant*	Deciduous
Cedrela fissilis	Meliaceae	UF	3	57.3 ± 3.1	Shadow intolerant*	Deciduous
Eugenia pruinosa	Myrtaceae	UF	2	23.4 ± 2.1	Shadow tolerant*	Evergreen
Cryptocarya mandioccana	Lauraceae	UF	2	23.95 ± 0.5	Shadow tolerant*	Evergreen
Cupania oblongifolia	Sapindaceae	UF	2	27.9 ± 5.6	Shadow intolerant*	Brevi-deciduous

3.3.3 Vegetative phenology

We recorded the phenology of the monitored trees at monthly frequency, analysing the leaf budding, mature leaf, and senescence phenophases according to the Fournier Intensity Percentage. In this scale, 0 = absence of the phenophase; 1 = presence of the phenophase with a magnitude between 0-25%; 2 = presence of the phenophase between 26-50%; 3 = presence of the phenophase between 51-75%; 4 = presence of the phenophase between 76-100% (Bencke and Morellato, 2002).

3.3.4 Growth and tree water deficit monitoring

We installed digital band dendrometers DRL26C (EMS-Brno) capable of recording the changes in trunk diameter at 4 μm of resolution and hourly intervals. We installed the dendrometers at a height of 4 meters in both sites for safety measures against vandalism, an issue particularly in the public park. Having them at the same height is a measure to guarantee their comparability. Overall, trees were not subject to any substantial management practice or damage from windstorms, other than an individual of A. triplinervia that was pruned during the experiment to ensure the safety of the public (Figure 2; SM1).

The dendrometers measure any change in the trunk perimeter. Sustained increases in the trunk perimeter are regarded as Growth, whereas any decrease represents shrinkage due to stem water content fluctuations, regarded as Tree Water Deficit. The data obtained was

processed and analysed in R (R Core Team, 2025) using the dendRoAnalyst package (Aryal et al., 2020). We used this package to identify and interpolate rare data gaps and calculate the effective growth (GRO) and tree water deficit (TWD). We then converted the radial growth (mm) to BAI (Basal area increment) mm².

3.3.5 Climate data

We obtained the climate data from the meteorological station of the Emergency Management Centre of the City of São Paulo (CGE), in the Vila Mariana district, located 1.8 km of distance from de urban park and 5.9 km from the urban forest patch. We obtained daily data on rainfall (mm), air temperature (°C), and relative humidity (%) (CGE, 2025). Based on these variables, the Vapour Pressure Deficit (VPD) was calculated using the formula: VPD = SVP - AVP, where SVP represents the saturation vapour pressure (calculated based on air temperature), and AVP corresponds to the actual vapour pressure (determined from relative humidity. VPD is a strong predictor of plants' stress for combining relative humidity and temperature, and is largely used in ecological studies (Grossiord et al. 2020).

3.3.6 Statistical analysis

We carried out the statistical analyses in the R environment (R Core Team, 2025). To compare the GRO and TWD between sites, we first averaged the species series to avoid biases associated with the distinct sample sizes, and then applied the Wilcoxon non-parametric test for pairwise comparisons because the data did not meet the assumptions of normality nor homoscedasticity. We also used the Kruskal-Wallis and Post-hoc Dunn test to compare the GRO and TWD among species in each site.

We then evaluated the association between the climate variables, precipitation, and VPD, and the daily variation in GRO and TWD, first for all species, and then for the average GRO and TWD series of each site. The results are displayed in correlation matrices. We further scrutinized the association between climate and the dendrometer-derived variables using cross-wavelet analysis. The cross-wavelet is a time series analysis used to compare the spectrum of the variables by assessing the association between two variables at various frequencies along the entire temporal length of the series. Not only does it show at what frequencies the association is statistically significant, but also when. In this analysis, arrows are used to show if these associations are in phase or anti-phase, and which is the leading

and/or lagging variable. Arrows pointing to the right indicate that variables are in phase, and arrows pointing to the left indicate that they are in anti-phase. If in phase, arrows between 0˚ to 90˚, anticlockwise, indicate that GRO / TWD are the leading variables and climate the lagging variables. Whereas, if the arrows are between 270˚ to 360˚, climate is the leading variable and GRO / TWD the lagging variable. We evaluated how the dominant modes change over time by using the WaveletComp package (Roesch and Schmidbauer 2018) in R (R Core Team 2018) (Torrence and Compo 1998). By using $\alpha = 0.10$ by default, the wavelet analysis's significance is based on ten simulations (Roesch and Schmidbauer 2018).

3.4 Results

3.4.1 Site characteristics

In the city of São Paulo, the wet season takes place between October and March, whereas the dry season occurs between June and September, when vapour pressure deficit (VPD) values are at the highest, pushing the atmospheric evaporative demand and, consequently, a greater potential for water stress for the vegetation (Figure 1F). The seasonality in the climate conditions, as well as in water content and soil temperature, drives a substantial variation in the NDVI in both parks, peaking during the wet season. Although the parks share to some extent a seasonal variation in soil conditions and vegetation greenness, they significantly differ in terms of average annual values. The mean soil temperature is higher in the urban park than in the urban forest, while the soil water content is higher in the urban forest. Where, at both depths (10 cm and 50 cm), the values fall within a similar range (SM Fig 2-3). In addition, the average monthly NDVI is significantly higher at the urban forest compared to the urban park in the two years of monitoring (Figure 1D; 1E).

3.4.2 Vegetative phenology

The observed variability in the NDVI reflects the seasonal vegetative phenology of the monitored tree species. The seven tree species displayed distinct phenological strategies over the two years of study. Overall, C. tomentosum and C. fissilis displayed typical deciduous behavior (Fig. 2), remaining leafless for between three and four months, respectively. Whereas E. pruinosa, C. oblongifolia, and A. triplinervia replaced all the leaves during the dry season, but remained leafless only for a very short period, a strategy regarded as brevi-deciduous. Finally, *E. uniflora* and *C. mandioccana* maintained their green canopies

throughout the year, being regarded as evergreen species.

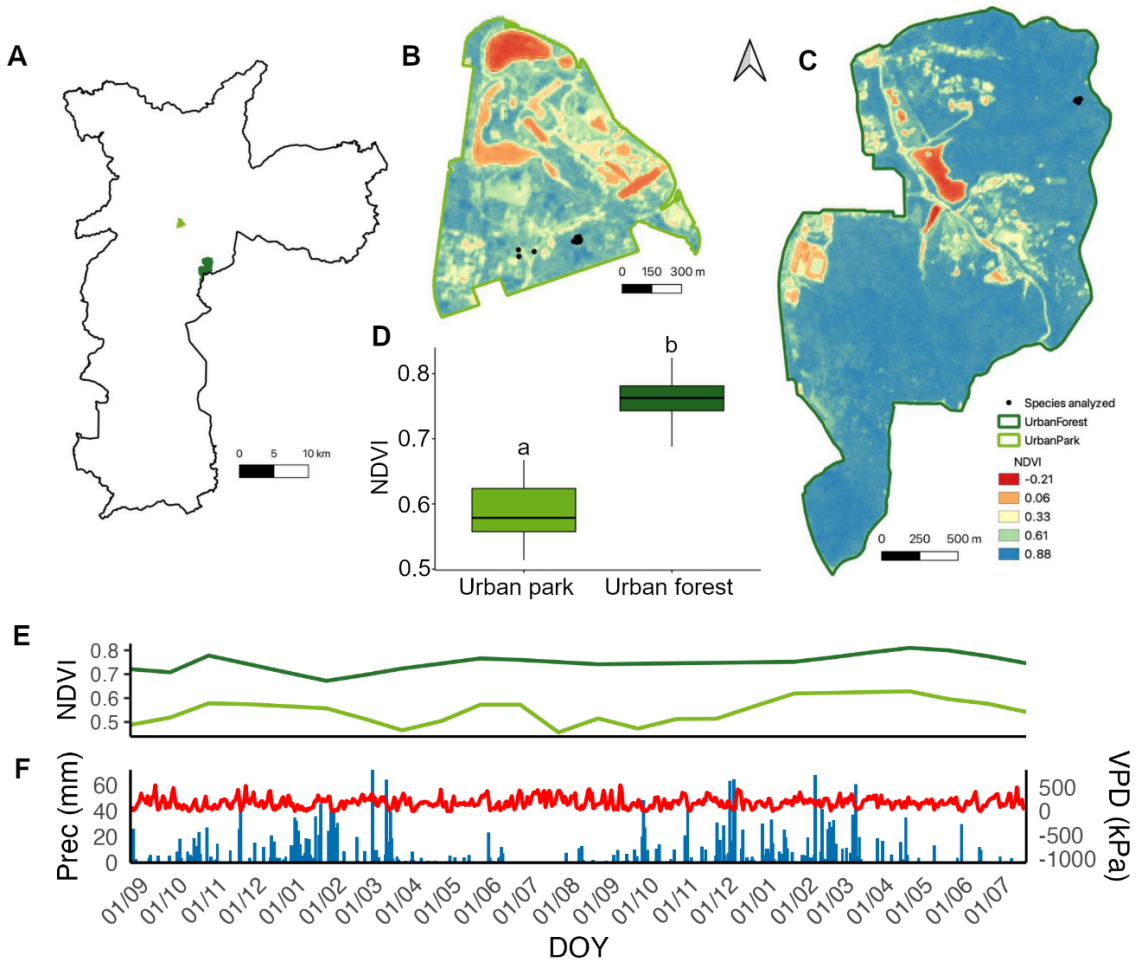


Figure 1. Characterization of study areas' vegetation and climate. (A) Geographic location of the study sites within the city of São Paulo, Brazil; (B) Normalized Difference Vegetation Index (NDVI) over the urban park; (C) NDVI over the urban forest site; (D) Differences in NDVI for both sites, different letters indicate statistically differences for α = 0.05; (E) Temporal trends of monthly NDVI during the monitoring period; and (F) Daily precipitation and vapor pressure deficit (VPD) trends over the same period.

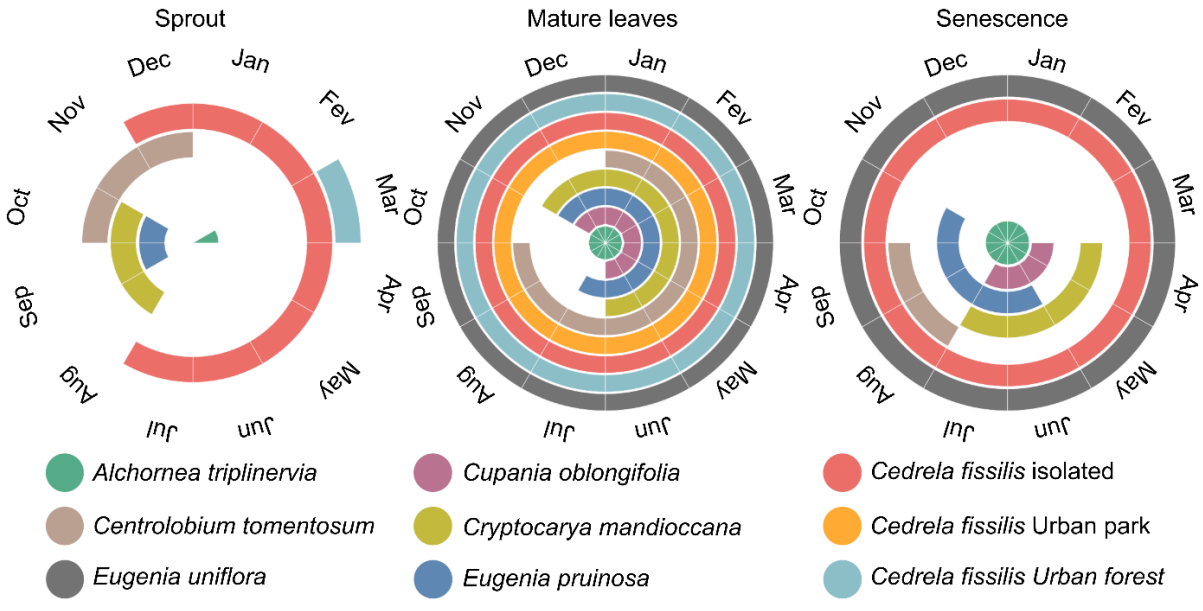


Figure 2. Average monthly occurrence of each vegetative phenophase (sprout, mature leaf, and senescence) recorded for the monitored tree species over two years. Species are identified by the different colors. The presence of a species' color within a phenophase circle denotes that the corresponding phenophase was observed in that month.

3.4.3 Growth rate

The average growth rate of the studied tree species shows substantial variation. Trees of C. fissilis, C. tomentosum, and A. triplinervia displayed the highest absolute growth rates, whereas E. uniflora displayed the slowest growth rate among the studied species (Figure 3 and S1). C. fissilis is the only common tree species to both study sites, and it displays the highest growth rates in the isolated trees in the urban park, while the growth rate is not statistically different between the group of C. fissilis trees growing in the urban park woodland and in the urban forest (Figure 3 and S1). As the overall dominant native tree species in the assembly of these sites, the trees from the urban park display an average 81% higher growth rate than in the urban forest patch (Figure 4).

Other than the average growth rate, C. fissilis, C. tomentosum, A. triplinervia, and E. pruinosa present a clear seasonality in the growth rate, with distinct growing and dormant seasons that are in phase with the wet and dry seasons, respectively (Figure 3). There is no evidence of a substantial difference in the growth seasonality of the C. fissilis trees regardless of the studied site. In contrast, E. uniflora, C. oblongifolia, and C. mandioccana slow down growth rate, but do not reach dormancy, during the dry season (Figure 3).

3.4.4 Tree water deficit

Tree water deficit (TWD) is also seasonal for all the studied species, peaking during the dry season (Figure 3). Despite the shared seasonal pattern, the average tree water deficit shows substantial variation among the studied species. Cedrela trees display the highest values of TWD, particularly in the trees growing in the urban park woodland. Other tree species also display higher TWD in the urban park, like *C. tomentosum* and *A. triplinervia*. The display of an unusually prolonged period of high TWD during the summer of 2021 to 2022, explained by the fact that one of *A. triplinervia* tree was pruned by the park administration for safety reasons. Conversely, *C. tomentosum* displayed the lowest TWD among the urban park species (Figure 3; SM2). Overall, the TWD is substantially lower in the species from the urban forest, with the exception of *C. fissilis*. A. triplinervia stands out in the analysis as having a particularly long period of high TWD during the first growing

season. Overall, the average TWD is approximately four times higher in the studied trees of the urban park compared to the urban forest (Figure 4).

3.4.5. Climate effect and synchrony among species and sites

The correlations between BAI series and daily precipitation showed a positive and statistically significant association (correlation values between 0.32 and 0.52; Table S8-S9) for all species, and a negative and weaker, but still significant, association with daily VPD (correlation values between -0.38 and -0.16, Table S8-S9; Figure 5). The correlation matrix also shows a positive and significant correlation among the BAI of the different species in the study (r = -0.38 to 0.61), except for *E. uniflora* from the urban park *C. mandioccana* (r = 0.06; p = 0.12). In contrast, TWD has a positive and stronger association with VPD (correlation values between 0.10 to 0.45) and a relatively weaker association with precipitation (correlation values between -0.31 a -0.12). The synchrony among all studied species is also stronger and significant, as revealed by the correlation values (between 0.32 and 0.86).

These observed associations remain coherent at the study site level, using the average site TWD and BAI (Figure 7, Table 10 SM). At the site level, precipitation remains as the strongest driver of BAI variability (Urban park r =0.62, $p < 0.01$; Urban forest r =0.52, $p < 0.01$) compared to the VPD (Urban park r = -0.37, $p < 0.01$; Urban forest r = -0.33, $p < 0.01$). And VPD remains as the strongest driver of TWD variability (Urban park r =0.29, $p < 0.01$; Urban forest r =0.24, $p < 0.01$) compared to the precipitation (Urban park r = -0.27, $p < 0.01$; Urban forest r = -0.18, $p < 0.01$). The average BAI of the species, and particularly the TWD, remains strongly associated between the two sampling sites (r = 0.72 and p = < 0.01, and r = 0.81 and $p < 0.01$, respectively).

Although these correlation analyses are a line of evidence of the association between the climate and sites' average BAI and TWD, they do not provide a clear understanding of how climate interacts with BAI and TWD. If it is on a daily or seasonal basis. The cross-wavelets allow the decomposition of the modes of variability to understand how climate and the dendrometers' derived variables are associated at different frequencies along the entire time series.

The cross-wavelet analyses are coherent with the correlation analyses, showing significant associations between climate and GRO and TWD both at the species (Figure S5-S47) and site levels (Figure 8 and 9). Regarding growth, the cross-wavelet shows that the association between GRO and precipitation cover most of the high to low frequencies, on

periods ranging from 2 to 64 days, and a seasonal effect around 365 days, in both study sites. The arrows further evidence that the variables are in phase; therefore, the growth rate increases with precipitation, and climate is overall the leading variable. These results reinforce the direct influence of rainfall variability on the growth of the species, but only during the two wet seasons. (Figure 8). In contrast relationship between vapor pressure deficit (VPD) and tree water deficit showed a significant association throughout the entire studied period, both at the wet and dry seasons (Figure 9). This association is mainly concentrated in the lower frequencies, particularly evident on periods between 64 and 128 days.

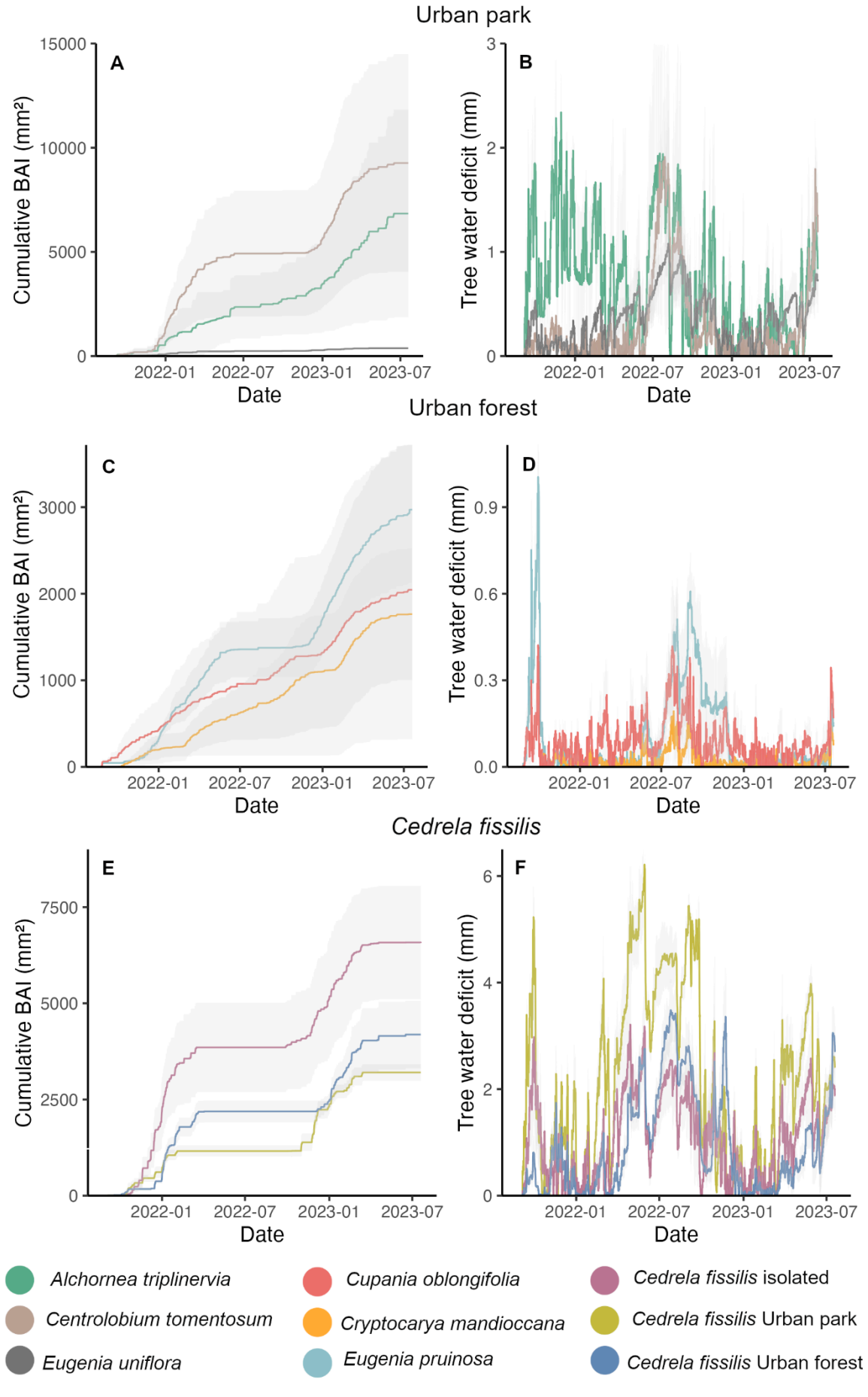


Figure 3. Cumulative basal area increment (BAI) and tree water deficit (TWD) over the monitoring period, illustrating growth performance and water status of urban trees. Panels depict: (A) BAI and (B) TWD for tree species in the urban park; (C) BAI and (D) TWD for tree species in the urban forest; and (E)

BAI and (F) TWD for Cedrela fissilis across both sites. Solid lines represent mean values over time, and shaded bands indicate the 95% confidence interval.

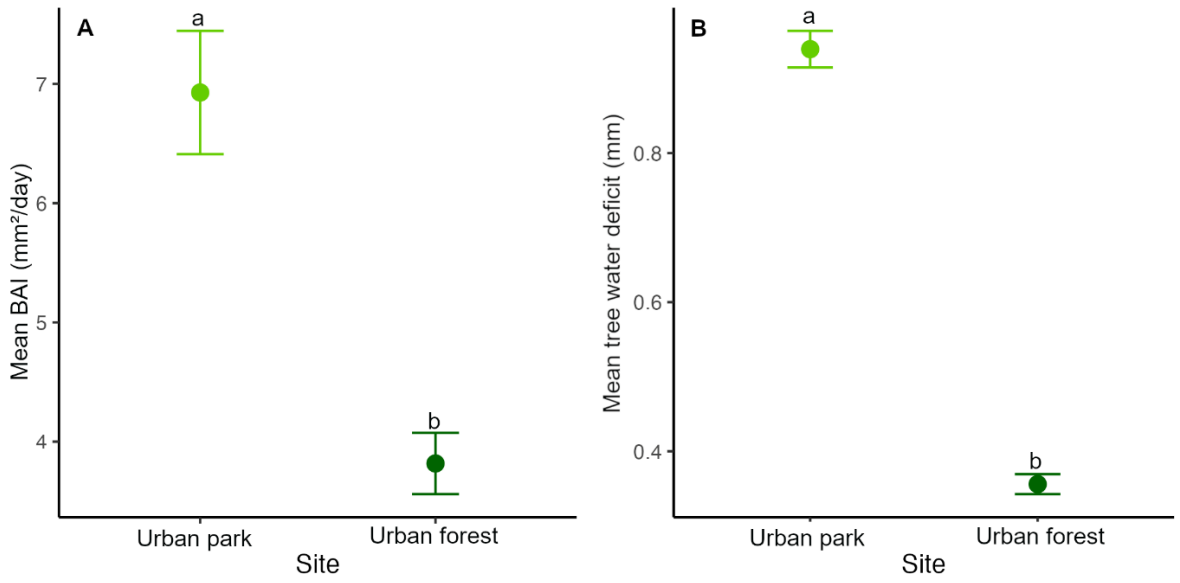


Figure 4. Differences in mean basal area increment (BAI) and tree water deficit (TWD) between the urban park and urban forest. Panels show (A) mean BAI and (B) mean TWD for the two sites. Error bars represent ± standard error (SE). Distinct letters above bars indicate statistically significant differences between sites at α = 0.05.

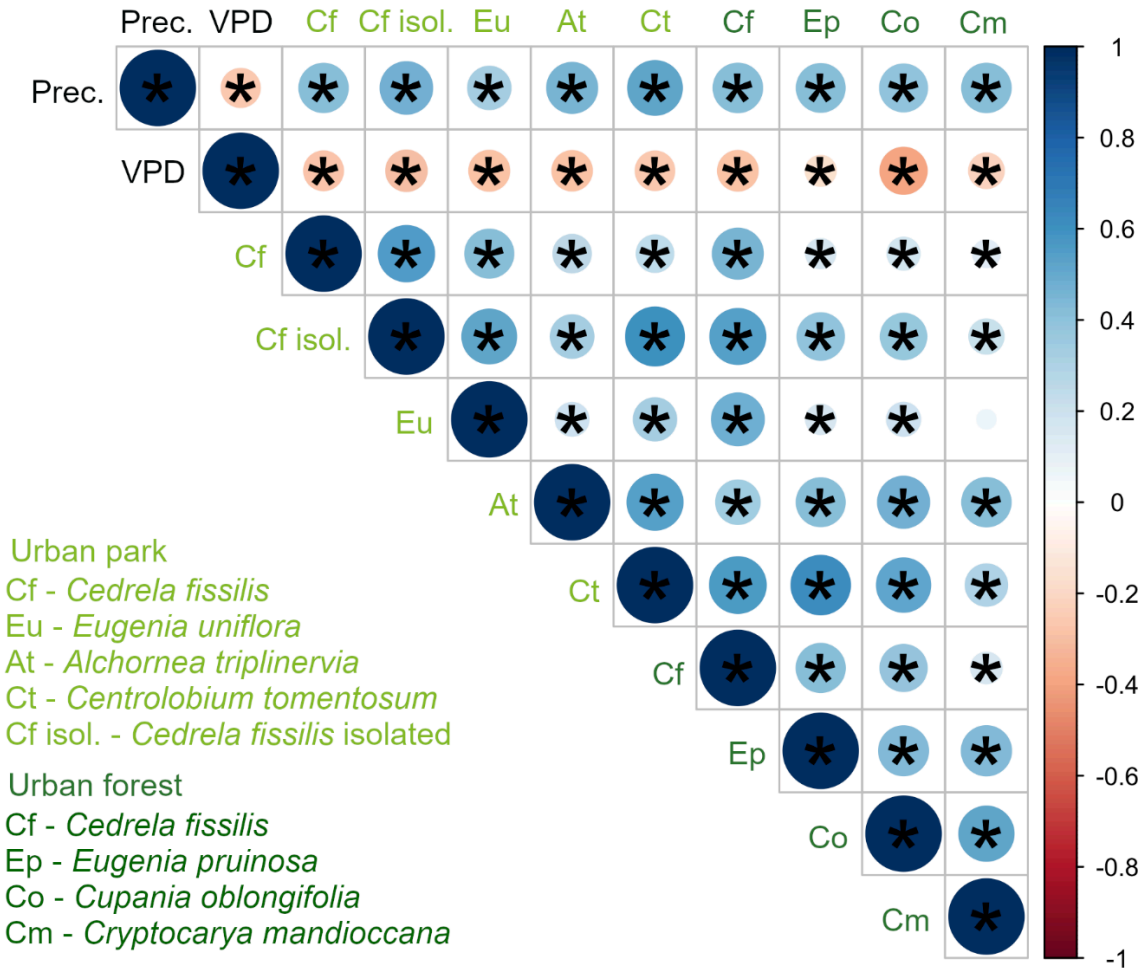


Figure 5. Pearson correlation matrix for climate variables and species basal area increment (BAI). Correlations are shown between precipitation, vapor pressure deficit (VPD), and species BAI. Dark green squares highlight species from the urban forest, while light green squares highlight species from the urban park. Correlation coefficients are represented by both the size and color intensity of the squares, with blue indicating positive correlations and red indicating negative correlations. Dark green letters highlight species from the urban forest, while light green letters highlight species from the urban park. The asterisk (*) indicates statistically significant correlations at $\alpha = 0.05$.

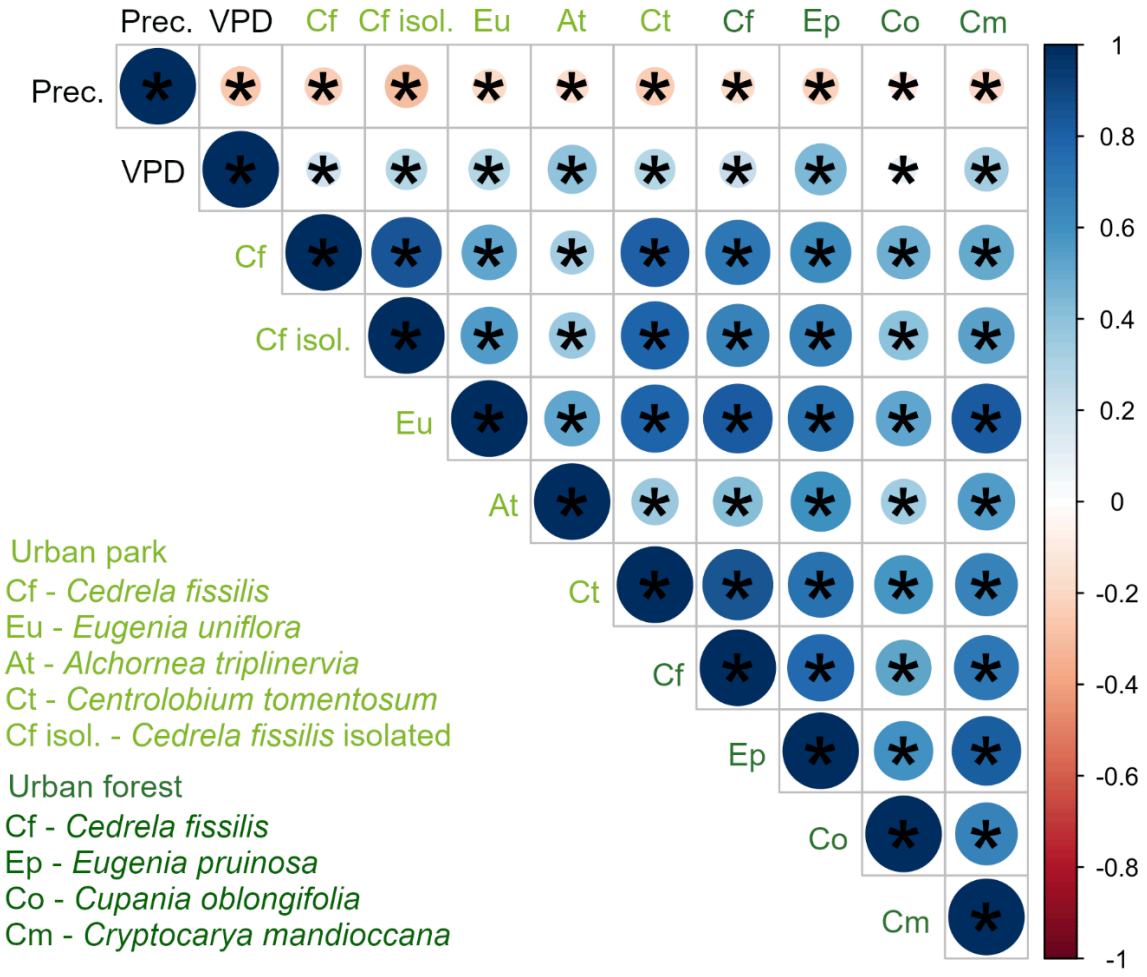


Figure 6. Pearson correlation matrix for climate variables and species tree water deficit (TWD). Correlations are shown between precipitation, vapor pressure deficit (VPD), and species TWD. Dark green squares highlight species from the urban forest, while light green squares highlight species from the urban park. Correlation coefficients are represented by both the size and color intensity of the squares, with blue indicating positive correlations and red indicating negative correlations. Dark green letters highlight species from the urban forest, while light green letters highlight species from the urban park. The asterisk (*) indicates statistically significant correlations at $\alpha = 0.05$.

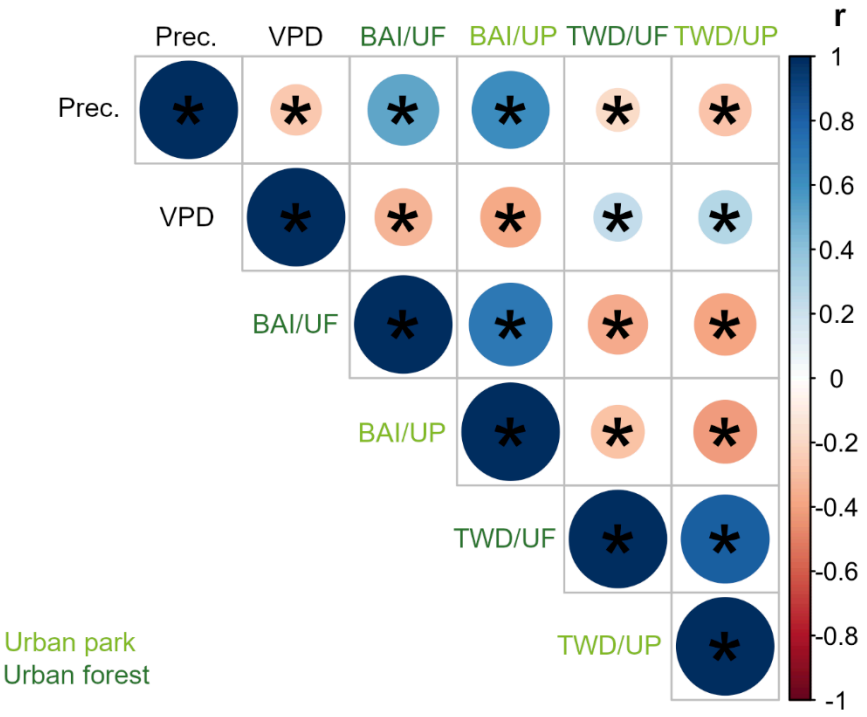


Figure 7. Pearson correlation matrix between climate indicators and species tree water deficit (TWD) and basal area increment (BAI) for all species from the urban park and urban forest. Correlations are shown between precipitation, vapor pressure deficit (VPD), species TWD, and species TWD. Dark green letters highlight species from the urban forest, while light green letters highlight species from the urban park. Correlation coefficients are represented by both the size and color intensity of the squares. All correlations are statistically significant ($p < 0.01$, see Statistics in SM Table 10). VPD = Vapor Pressure Deficit.

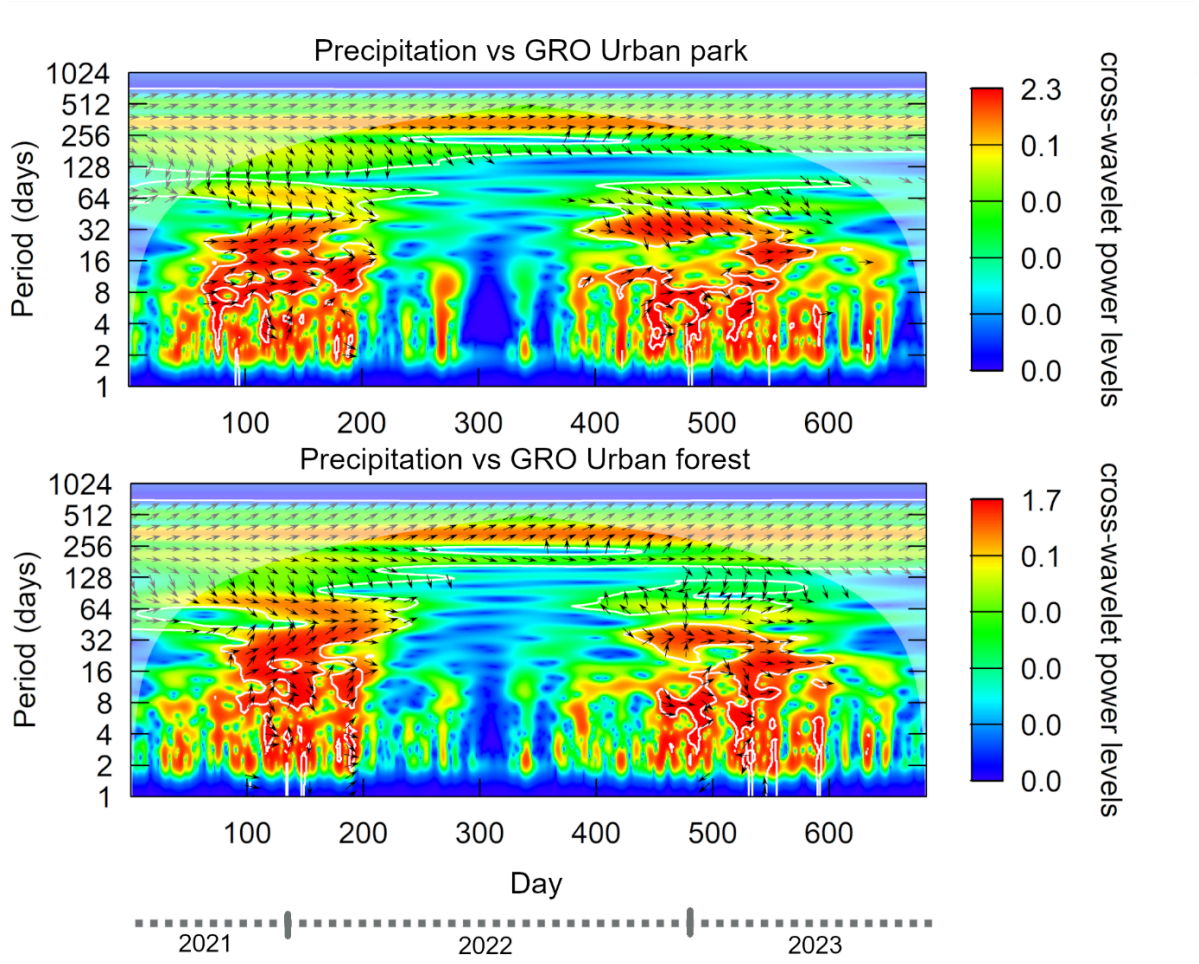


Figure 8. Cross-wavelet analysis of precipitation and growth. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated on red tones, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). The white outline indicates a significant association between time series.

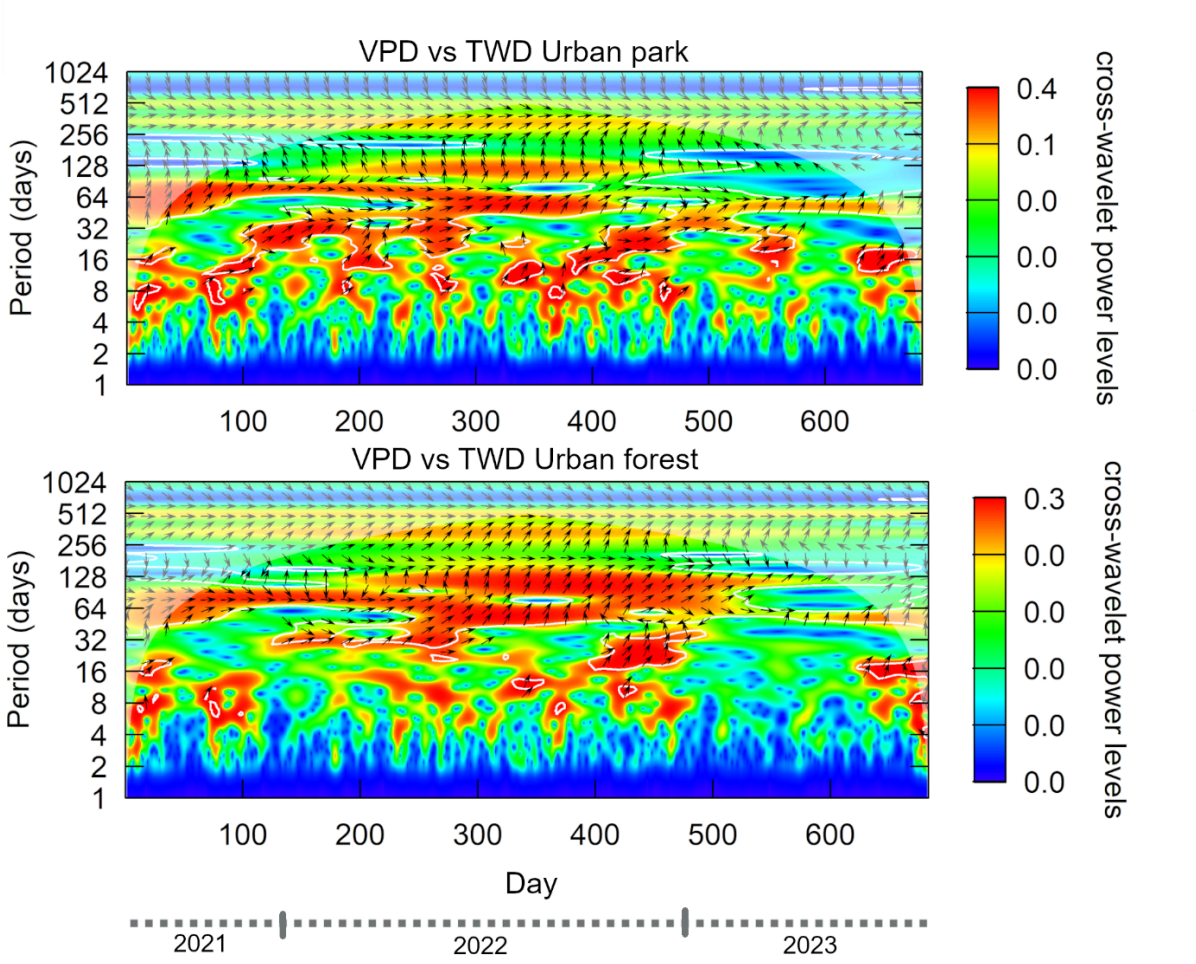


Figure 9. Cross-wavelet analysis of VPD and tree water deficit. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). The white outline indicates a significant association between time series.

3.4 Discussion

3.5.1 Differences in site conditions between the urban forest and park

The sampling sites differ substantially in environmental conditions. The NDVI values indicate higher greenness, or leaf biomass, and lower seasonality in the urban forest compared to the urban park (Li et al. 2023). Differences in average and seasonal NDVI values likely reflect the interplay between floristic composition and growth conditions, particularly water availability. Both sites differ in floristic composition and forest structure (da Silva Filho & Tosetti, 2010; Tanus et al., 2012; Avolio et al., 2019; Vellend et al., 2007; Pau & Dee, 2016), and soil sensors confirm that moisture is higher, less seasonal, and evenly distributed in depth in the urban forest.

The urban forest soil benefits from the intense nutrient cycling and less compacted

structure, enhancing water infiltration and retention (Sarah et al. 2015; Edmondson et al. 2011; Phillips et al. 2019, Rasheed et al. 2022), as observed in the soil sensors data. Under such favorable soil conditions, trees can develop deeper and more efficient root systems, to access deep water sources (Watson et al. 2014) and maintain water supply even during the dry season (Chow et al. 2016; Martini et al. 2017; De Pauw et al. 2023). Conversely, the urban park soil is disturbed due to land reclamation in the 1960s (Prefeitura do Município de São Paulo, 2025). Its low vegetation cover and human use promote compaction and weathering, which limit nutrient and water availability and increase soil temperature variability (Miller et al. 2002), also confirmed by the soil sensors data. Intensive leaf litter management in the urban park, further interrupts nutrient cycling, reduces organic matter, and decreases the soil's ability to retain water (Rudresh et al., 2025; Ferlauto et al., 2024). Altogether, these differences in forest structure, composition, and soil characteristics (Riddle et al. 2022) have the potential to buffer the climate effect on the growth and tree water deficit in the urban forest.

3.5.2 Growth and water deficit evidence contrasting strategies of trees in the urban forest and park

Overall, the growth rate of the studied species follows the expected patterns according to their shade tolerance and phenological strategies. Literature shows that shade-intolerant species - like *Cedrela fissilis, Alchornea triplinervia*, and *Centrolobium tomentosum* - display higher growth rates to maximize the exposure to solar radiation (Valladares & Niinemets, 2008; Muscas et al., 2023). Whereas the shade-tolerant species *Cryptocaria mandiocana* and the understory species *Eugenia uniflora* displayed the lowest growth rates. Seasonal growth patterns also align with vegetative phenology. Deciduous species like *C. fissilis* and *C. tomentosum* undergo dormancy during the dry season, coinciding with leaf shedding (Santos et al. 2025; Fadón et al. 2020). Whereas brevi-deciduous species like *A. triplinervia, C. oblongifolia,* and *C. madioccana* only display a temporary reduction in growth activity, similar to evergreen species, which only experience a slowdown in growth during the dry season.

The studied species also exhibited substantial variation in average tree water deficit (TWD), a measure of stem shrinkage that reflects midday water potential and stomatal conductance (Ziegler et al. 2024). On average, the *C. fissilis* trees showed the highest TWD, followed by *C. tomentosum* and *A. triplinervia*, indicating a low hydraulic safety

(Markesteijn et al. 2011). This low hydraulic safety is likely mitigated by their deciduousness, which limits transpiration during the dry season (Liu et al. 2020; Masha et al. 2019). Conversely, the shade-tolerant species displayed the lowest TWD, consistent with a conservative hydraulic strategy. Despite these interspecific differences, all trees exhibited higher TWD values during the dry season. One *A. triplinervia* individual exhibited an unusually prolonged period of high TWD following pruning, which can lead to transient water loss through evaporation (Alcorn et al. 2013). Other than this case, trees follow consistent TWD over species strategies and seasonal patterns.

C. fissilis is the only studied species common to both sites. Overall, the growth rate and TWD are higher in the park, particularly among isolated trees. These findings align with a multi-proxy tree-ring assessment of the growth of *C. fissilis* trees and their responses to drought in the same two sites (de Souza under review). The tree-ring series reveals a 70% faster growth rate in the urban park compared to the urban forest trees. Tree rings further revealed that park trees responded to water limitations through leaf physiological adjustments, whereas urban forest trees relied on wood-density adjustments. Together, these pieces of evidence suggest an acquisitive strategy in the park and a conservative strategy in the urban forest (de Souza et al. under review).

Notably, this pattern seems to extend to the other studied species across the two sites. Average growth and TWD are consistently higher in the urban park - by 100% and 400% respectively - aligning with an acquisitive strategy, characterized by rapid resource uptake, higher photosynthetic rates, and lower stress resistance (Augusto et al, 2025; Tamene et al., 2024). Conversely, the lower growth rate and TWD in the urban forest align with a conservative strategy, emphasizing hydraulic safety, resource-use efficiency, and long-term survival under variable conditions (Maracahipes et al. 2018; Wigley et al. 2016; Augusto et al. 2025). These contrasting strategies could emerge from distinct soil characteristics, stand density, and multi-strata canopies that result in intense competition for light, water, and nutrients, particularly in the urban forests (Craine & Dybzinski 2013, Rozendaal et al. 2020), which contrast with the reduced competition for light and nutrients in mixed vegetation urban parks (Craine & Dybzinski 2013, Postma et al. 2021).

3.5.3 Growth and tree water deficit sensitivity to climate

Water availability is a key driver of tree growth in the tropics (Zuidema et al, 2022). It supports higher stomatal conductance, CO_2 diffusion, photosynthetic rates (Vieira et al. 2020, Zhao & Zhao, 2025), and cell division and expansion during xylogenesis (Silva et al. 2023). Consequently, trees are likely to increase growth following a rainfall event (Li et al.

2024) or reduce it under water stress (Peters 2025). Although all species responded positively to water availability as expected, response intensity varied.

The BAI of deciduous species showed a stronger correlation with precipitation regardless of their provenance. Species like *C. tomentosum* and *C. fissilis* exhibited particularly pronounced responses, while others showed moderate correlations. The weakest correlations were found for *E. uniflora*, a tree species adapted to the buffered and light-limited conditions of the forest understory (Gil et al., 2024). These results reinforce that, even under similar climate conditions, tree growth maintains a degree of specificity. These findings are consistent with Anderegg et al. (2016), who emphasized that hydraulic strategies and traits largely determine how species respond to water availability.

When water demand is higher than the availability, trees must rely on internal water storage, particularly from parenchyma cells in the trunk and branches, to maintain transpiration and delay hydraulic limitations (Matheny et al. 2025). Thus, higher VPD intensifies water loss and triggers greater use of internal reserves, making it a strong predictor of short-term tree water status (Harmon et al. 2021). Higher VPD dries the air, increasing the evaporative pull from leaves and leading to greater transpiration (Grossiord et al. 2020). There is a small degree in studied species modularity in the TWD responses to VPD, being higher in *A. triplinervia, E. pruinosa,* and *C. mandiocana*, and lower in *C. oblongifolia*, which cannot be explained by their growth strategy nor vegetative phenology. VPD is known to exert a strong control on stomatal conductance, which in turn depends on the water-use strategy of the species (Grossiord et al. 2020), a feature yet to be characterized for the studied species.

The relationship between climate and BAI or TWD remains consistent when averaged by site. Nonetheless, there are important nuances in the correlation strengths. Correlation values tend to be stronger in the urban park. In addition, the association between TWD and VPD takes place year-round in the urban park, confirming that atmospheric dryness (Grossiord et al. 2020) exerts continuous pressure on the tree water balance. Whereas it tends to be weaker during the wet season in the urban forest. While these nuances can reflect the different studied species composition, they are more likely driven by local environmental conditions like forest structure (Moser-Reischl et al. 2019; Braem et al. 2023), and soil water availability (Rissanen et al. 2025).

3.5.4 Growth and tree water deficit synchrony

Despite clear differences in average growth and TWD among species and sites, the observed synchrony of growth – particularly in TWD - is notable. Climate is widely recognized as the main driver of global growth variability, including cities (but see Locosselli et al., 2019). It is also largely recognized that the interplay between climate and growth is species- and site-dependent (Campbell et al. 2021; Di Fabio et al. 2024). The results of the present study show some degree of BAI synchrony among the species and between sites. In contrast, this synchrony was pronounced for TWD, irrespective of growth strategies, phenology, and provenance site. This pattern is consistent with previous findings showing that, regardless of species identity or planting site, canopy conductance tends to decline with increasing VPD, reflecting a convergent hydraulic regulation aimed at preventing excessive water loss (Chen, Zhang, & Ewers, 2012). This uniformity suggests low functional diversity in terms of water stress tolerance strategies in the analyzed species and sites.

The question remains: Does tree species functional diversity translate into resilient urban forests? Focusing on dominant native tree species revealed that, despite the array of species strategies and local conditions, the response to climatic variability is surprisingly homogeneous. Although the number of individuals per species was limited in favour of diversity, the strong convergence of results across species and sites suggests that our findings are robust to sampling constraints and methodological limitations. A larger sample size would certainly enable a more detailed assessment of the range of species responses (Rodrigues-Leite et al., 2024), but it is unlikely to alter the main conclusions drawn here.

Such homogeneous responses of tree species to climate are not unprecedented. Previous studies have shown that different species and sites can exhibit similar responses to stress, both in natural and urban forests (Zweifel et al., 2016; Grossiord, 2020; Fensham et al., 2015), which does not imply that all species respond negatively to thermic and water stress (Locosselli et al., 2024). Nevertheless, the observed homogeneous responses among species from different functional groups and sites highlight a potential vulnerability of urban trees to climate variability in the city. Our approach may not have addressed the full spectrum of functional groups, by adopting a common framework in ecological studies and focusing on trees among the dominant species, particularly in the biodiverse context of the Atlantic Rainforests. The results suggest that dominant species likely share climate responses, and the desired heterogeneous responses likely hide in the details, in the non-dominant species that could play an important role in promoting urban green-areas resilience (Cjaza et al. 2020; Krizek & Dubik 1987, Day et al. 2010).

3.6 Conclusion

This study demonstrated that, regardless of the type of urban green cover, tree growth was consistently influenced by climatic variables, with precipitation as the main determinant of growth and VPD as the controller of TWD. Despite the functional and phenological diversity among the species evaluated, a homogeneous response to climate was observed. This homogeneity of responses indicates climate vulnerability in these urban green areas, with potential to limit ecosystem services during extreme climate events. The species also revealed an acquisitive strategy for the urban park and a conservative strategy for the urban forest patch. Our findings indicate that dominant species may exhibit significant climatic vulnerability. Therefore, future monitoring, particularly during extreme climatic events, should extend beyond dominant taxa and incorporate species from specific or less dominant ecological niches. This broader approach will be fundamental to advancing our understanding of the resilience and ecological functioning of urban forests under climate change.

3.7 References

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3.8 Supplementary material

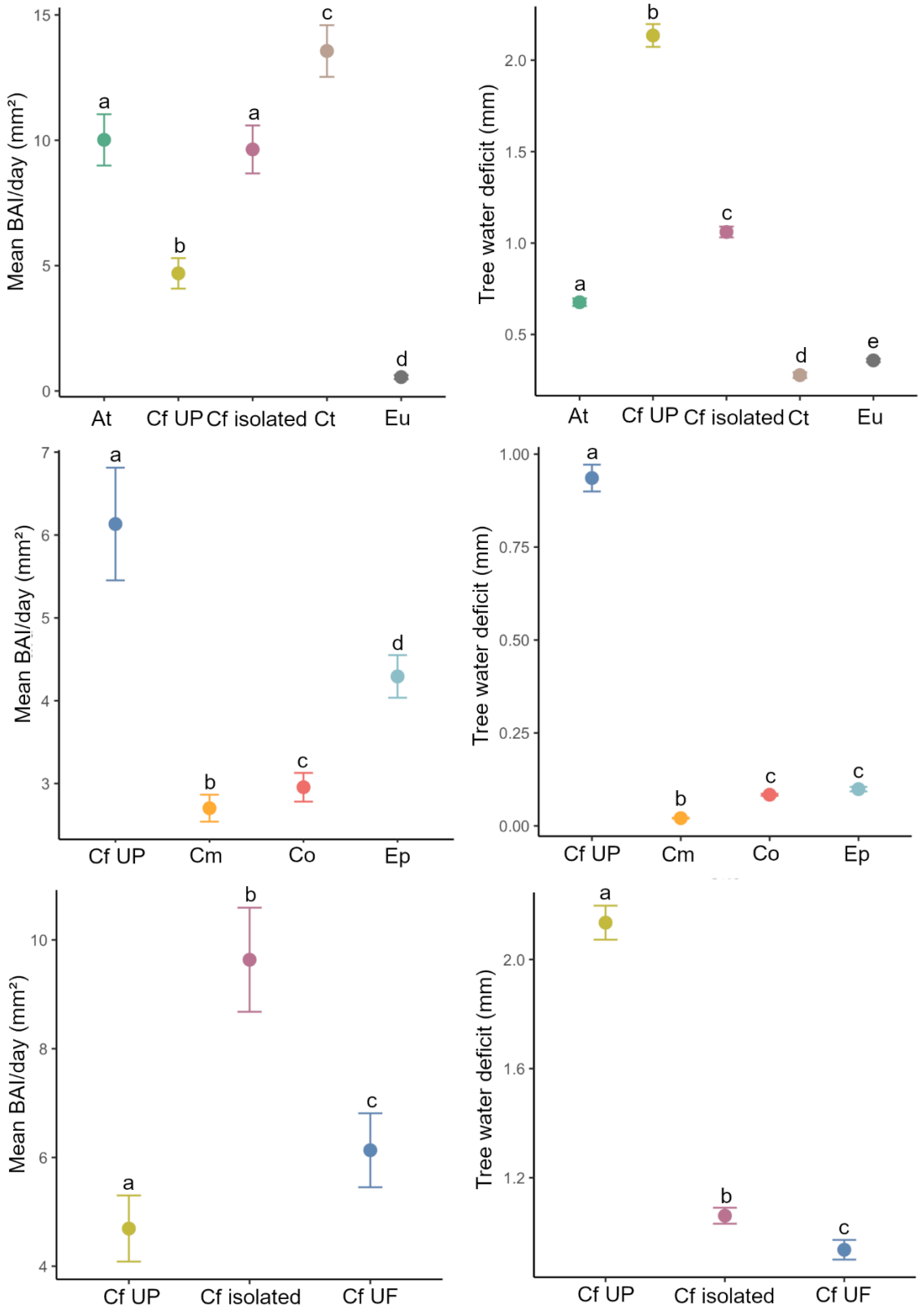


Fig. Sup. 1. Average and standard error for BAI (mm²) and TWD (mm) between species of it respective sites, urban forest and urban park. Duhn test comparison on table S1-S6. Cf = *Cedrela fissilis*, Ct = *Centrolobium tomentosum*, Eu = *Eugenia unifloria*, Al = *Alchornea triplinervia*, Cm = *Cryptocaria mandiocanna*, Ep = *Eugenia pruinosa*, Co = *Cupania oblongifolia*, UP = urban park, UF = urban forest.

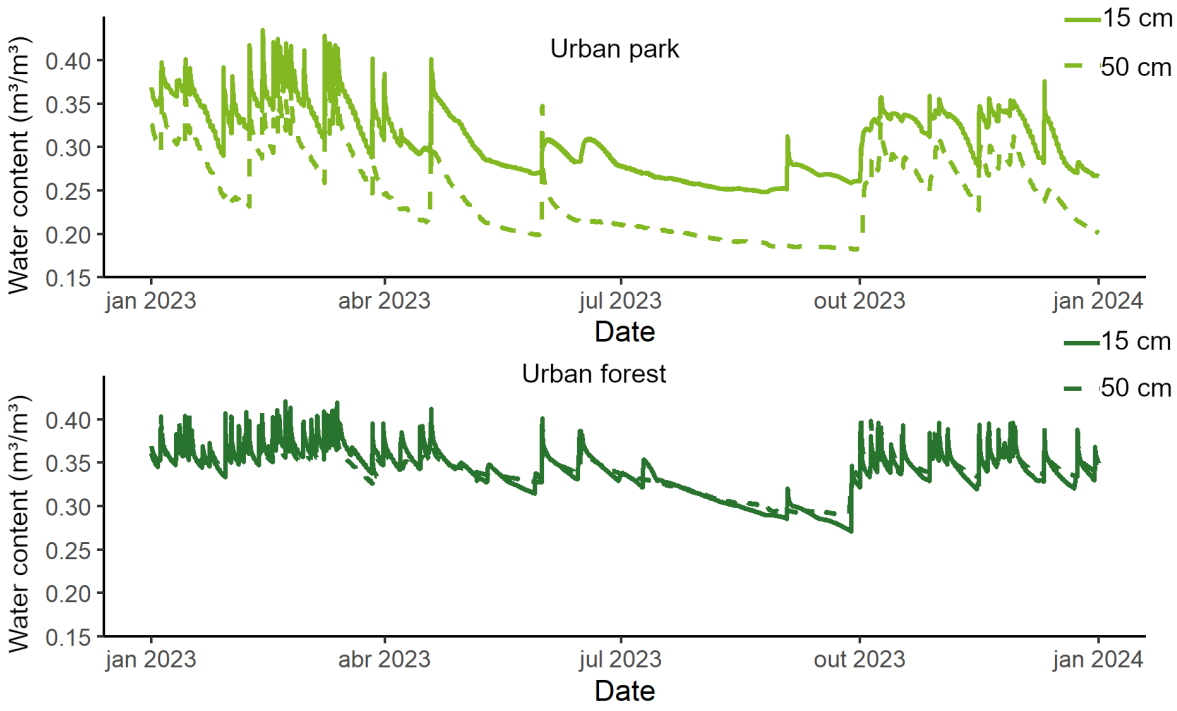


Fig. Sup. 2. Soil water content (m^3/m^3) measured throughout 2023 at two urban green sites: an urban park and an urban forest. Light green represents the urban park and dark green represents the urban forest. The solid line indicates measurements at a soil depth of 15 cm, while the dashed line indicates measurements at a depth of 50 cm.

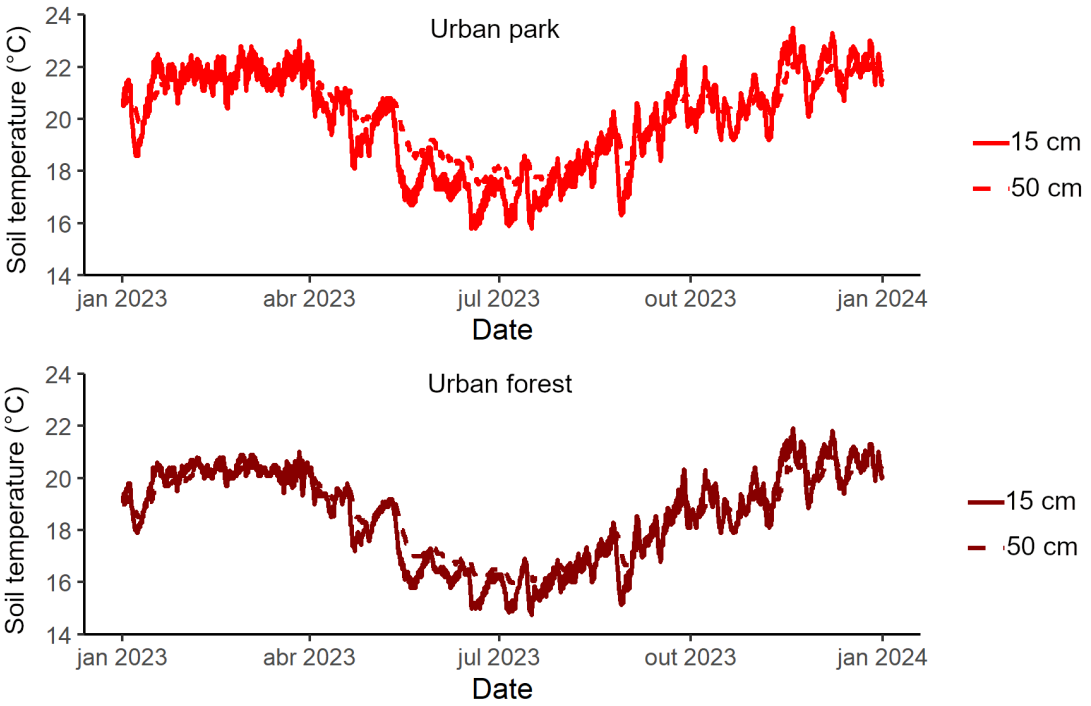


Fig. Sup 3. Soil temperature (C°) measured throughout 2023 at two urban green sites: an urban park and an urban forest. Red represents the urban park and dark red represents the urban forest. The solid line indicates measurements at a soil depth of 15 cm, while the dashed line indicates measurements at a depth of 50 cm.

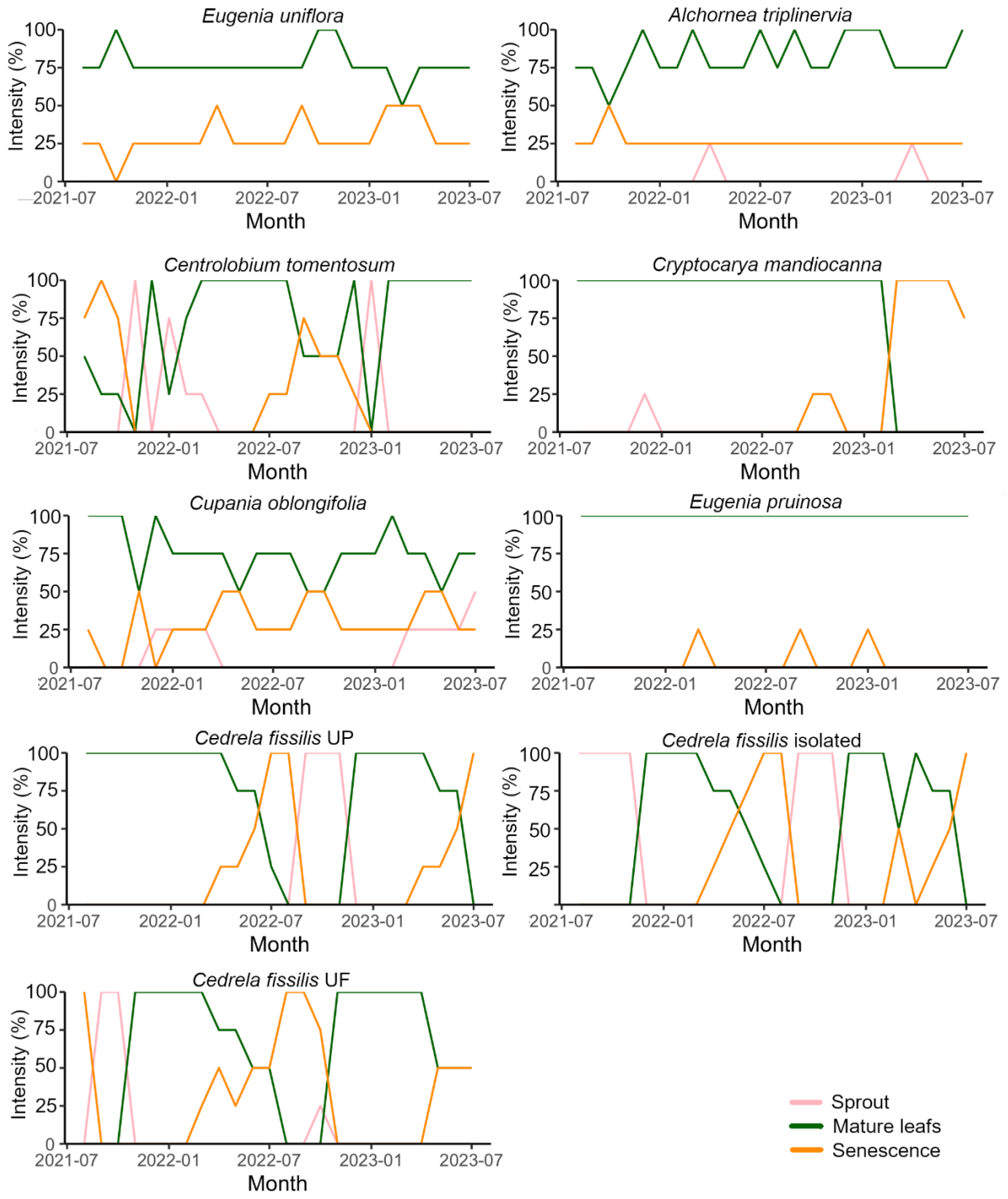


Fig. Sup. 4. Phenological characterization of the studied species based on Fournier Phenology Intensity, where the values represent the percentage of the crown exhibiting the respective phenophase. The phenophases described are sprouting (pink), mature leaves (green), and senescence (orange)

Table S1: Statistics of the mean growth (BAI) of urban park species

Kruskal-Wallis Statistics	Parameter	p-value
253.6173848	4	< 0.001
Dunn-test Comparison	Z	p-value
At – Cf UP	7.75	< 0.001

At – Cf isolated	2.35	< 0.001
Cf UP – Cf isolated	-5.40	< 0.001
At - Ct	-3.70	< 0.001
Cf UP - Ct	-11.45	< 0.001
Cf isolated - Ct	-6.05	< 0.001
At - Eu	10.10	< 0.001
Cf UP - Eu	2.35	0.02
Cf isolated - Eu	7.75	< 0.001
Ct - Eu	13.80	< 0.001

Table S2: Statistics of the mean tree water deficit of urban park species

Kruskal-Wallis Statistics	Parameter	p-value
1046.91215	4	< 0.001
Dunn-test Comparison	**Z**	**p-value**
At – Cf UP	-14.83	< 0.001
At – Cf isolated	-7.28	< 0.001
Cf UP – Cf isolated	7.55	< 0.001
At - Ct	14.05	< 0.001
Cf UP - Ct	28.88	< 0.001
Cf isolated - Ct	21.33	< 0.001
At - Eu	7.30	< 0.001
Cf UP - Eu	22.13	< 0.001
Cf isolated - Eu	14.58	< 0.001
Ct - Eu	-6.75	< 0.001

Table S3: Statistics of the mean growth of urban forest species

Kruskal-Wallis Statistics	Parameter	p-value
1095.068094	3	< 0.001
Duhn-test Comparison	**Z**	**p-value**
Cf UF - Cm	31.45	< 0.001
Cf UF - Co	15.63	< 0.001
Cm - Co	-1610	< 0.001
Cf UF - Ep	24.00	< 0.001
Cm - Ep	-7.82	< 0.001
Co - Ep	8.40	< 0.001

Table S4: Statistics of the mean tree water deficit of urban forest species

Kruskal-Wallis Statistics	Parameter	p-value
1095.068094	3	< 0.001
Duhn-test Comparison	**Z**	**p-value**
Cf UF - Cm	31.45	< 0.001
Cf UF - Co	15.63	< 0.001
Cm - Co	-16.10	< 0.001
Cf UF - Ep	24.01	< 0.001
Cm - Ep	-7.82	< 0.001

Co - Ep	8.40	< 0.001

Table S5: Statistics comparing *C. fissilis* sites' growth

Kruskal-Wallis Statistics	Parameter	p-value
32.24	2	< 0.001
Duhn-test Comparison	**Z**	**p-value**
UP – Isolated	-5.68	< 0.001
UP – UF	-2.94	< 0.001
Isolated – UF	2.73	< 0.001

Table S6: Statistics comparing *C. fissilis* sites' tree water deficit

Kruskal-Wallis Statistics	Parameter	p-value
233.65	2	< 0.001
Duhn-test Comparison	**Z**	**p-value**
UP – Isolated	10.75	< 0.001
UP – UF	14.79	< 0.001
Isolated – UF	4.04	< 0.001

Table S7: Statistics comparing urban park and urban forest

Wilcoxon (Growth) Statistic	p-value
210302	< 0.001
Wilcoxon (Tree water deficit) Statistic	**p-value**
369846	< 0.001

Table S8: Pearson correlation between climate precipitation (PLU) and vapor pressure deficit (VPD) and species growth (GRO); $p < 0.01$. Cf = *Cedrela fissilis*, Ct = *Centrolobium tomentosum*, Eu = *Eugenia unifloria*, Al = *Alchornea triplinervia*, Cm = *Cryptocaria mandiocanna*, Ep = *Eugenia pruinosa*, Co = *Cupania oblongifolia*, Isso = Isolated, UP = urban park, UF = urban forest.

	PLU	VPD	Cf UP	Cf Iso	Eu	At	Ct	Cf UF	Ep	Co	Cm
PLU	1.00	-0.26	0.42	0.48	0.32	0.45	0.52	0.42	0.41	0.40	0.42
VPD	-0.26	1.00	-0.27	-0.30	-0.29	-0.28	-0.27	-0.28	-0.16	-0.38	-0.22
Cf UP	0.42	-0.27	1.00	0.55	0.42	0.25	0.24	0.45	0.15	0.18	0.13
Cf Iso	0.48	-0.30	0.55	1.00	0.52	0.33	0.61	0.55	0.39	0.37	0.21
Eu	0.32	-0.29	0.42	0.52	1.00	0.19	0.32	0.48	0.16	0.20	0.06
At	0.45	-0.28	0.25	0.33	0.19	1.00	0.54	0.34	0.42	0.47	0.42
Ct	0.52	-0.27	0.24	0.61	0.32	0.54	1.00	0.56	0.62	0.51	0.31
Cf UF	0.42	-0.28	0.45	0.55	0.48	0.34	0.56	1.00	0.42	0.38	0.17
Ep	0.41	-0.16	0.15	0.39	0.16	0.42	0.62	0.42	1.00	0.43	0.44
Co	0.40	-0.38	0.18	0.37	0.20	0.47	0.51	0.38	0.43	1.00	0.53
Cm	0.42	-0.22	0.13	0.21	0.06	0.42	0.31	0.17	0.44	0.53	1.00

Table S9: Pearson correlation between climate precipitation (PLU) and vapor pressure deficit (VPD) and species tree water deficit (TWD); $p < 0.01$. Cf = *Cedrela fissilis*, Ct = *Centrolobium tomentosum*, Eu = *Eugenia unifloria*, Al = *Alchornea triplinervia*, Cm = *Cryptocaria mandiocanna*, Ep = *Eugenia pruinosa*, Co = *Cupania oblongifolia*, Isso = Isolated, UP = urban park, UF = urban forest.

	PLU	VPD	Cf UP	Cf Iso	Eu	At	Ct	Cf UF	Ep	Co	Cm
PLU	1.00	-0.26	-0.23	-0.31	-0.19	-0.17	-0.24	-0.18	-0.21	-0.12	-0.2
VPD	-0.26	1.00	0.19	0.28	0.28	0.4	0.27	0.22	0.45	0.1	0.32

Cf UP	-0.23	0.19	1.00	0.85	0.51	0.32	0.81	0.72	0.63	0.48	0.51
Cf Iso	-0.31	0.28	0.85	1.00	0.55	0.36	0.79	0.67	0.66	0.41	0.53
Eu	-0.19	0.28	0.51	0.55	1.00	0.52	0.78	0.82	0.74	0.51	0.83
At	-0.17	0.4	0.32	0.36	0.52	1.00	0.37	0.41	0.61	0.34	0.56
Ct	-0.24	0.27	0.81	0.79	0.78	0.37	1.00	0.86	0.73	0.58	0.67
Cf UF	-0.18	0.22	0.72	0.67	0.82	0.41	0.86	1.00	0.76	0.52	0.71
Ep	-0.21	0.45	0.63	0.66	0.74	0.61	0.73	0.76	1.00	0.59	0.82
Co	-0.12	0.1	0.48	0.41	0.51	0.34	0.58	0.52	0.59	1.00	0.66
Cm	-0.2	0.32	0.51	0.53	0.83	0.56	0.67	0.71	0.82	0.66	1.00

Table S10: Pearson correlation between climate precipitation (PLU) and vapor pressure deficit (VPD), and sites growth (GRO) and tree water deficit (TWD); $p < 0.01$. UP = urban park, UF = urban forest.

	PLU	VPD	GRO UF	GRO UP	TWD UF	TWD UP
PLU	1.00	-0.26	0.52	0.62	-0.19	-0.28
VPD	-0.26	1.00	-0.33	-0.37	0.24	0.29
GRO UF	0.52	-0.33	1.00	0.72	-0.36	-0.39
GRO UP	0.62	-0.37	0.72	1.00	-0.29	-0.41
TWD UP	-0.19	0.24	-0.36	-0.29	1.00	0.81
TWD UF	-0.28	0.29	-0.39	-0.41	0.81	1.00

Table S11: Species characteristics. (DBH) Diameter at breast height; (ID) Identification. *Lorenzi, 2000; Kondrat et al. 2020; Barretto e Catharino, 2015. *Measures taken on August, 2021, on the dendrometers installation.

Specie	Family	Site	ID	DBH (cm)	Light tolerance	Phenology
Eugenia uniflora	Myrtaceae	UP	1	20.7	Shadow tolerant*	Brevi-deciduous
Eugenia uniflora	Myrtaceae	UP	2	17.5	Shadow tolerant*	Brevi-deciduous
Alchornea triplinervia	Euphorbiaceae	UP	3	55.7	Shadow intolerant*	Brevi-deciduous
Alchornea triplinervia	Euphorbiaceae	UP	4	43.0	Shadow intolerant*	Brevi-deciduous
Centrolobium tomentosum	Fabaceae	UP	5	19.7	Shadow tolerant*	Deciduous
Centrolobium tomentosum	Fabaceae	UP	6	55.7	Shadow tolerant*	Deciduous
Cedrela fissilis	Meliaceae .	UP	7	43	Shadow intolerant*	Deciduous
Cedrela fissilis	Meliaceae .	UP	8	54.1	Shadow intolerant*	Deciduous
Cedrela fissilis	Meliaceae .	UP	9	55.7	Shadow intolerant*	Deciduous
Cedrela fissilis isolated	Meliaceae	UP	10		Shadow intolerant*	Deciduous

				27.4		
Cedrela fissilis isolated	Meliaceae	UP	11	31.8	Shadow intolerant*	Deciduous
Cedrela fissilis isolated	Meliaceae	UP	12	36.6	Shadow intolerant*	Deciduous
Cedrela fissilis	Meliaceae	UF	13	54.1	Shadow intolerant*	Deciduous
Cedrela fissilis	Meliaceae	UF	14	63.7	Shadow intolerant*	Deciduous
Cedrela fissilis	Meliaceae	UF	15	54.1	Shadow intolerant*	Deciduous
Eugenia pruinosa	Myrtaceae	UF	16	21.1	Shadow tolerant*	Evergreen
Eugenia pruinosa	Myrtaceae	UF	17	25.5	Shadow tolerant*	Evergreen
Cryptocarya mandioccana	Lauraceae	UF	18	24.5	Shadow tolerant*	Evergreen
Cryptocarya mandioccana	Lauraceae	UF	19	23.4	Shadow tolerant*	Evergreen
Cupania oblongifolia	Sapindaceae	UF	20	33.4	Shadow intolerant*	Brevi-deciduous
Cupania oblongifolia	Sapindaceae	UF	21	22.3	Shadow intolerant*	Brevi-deciduous

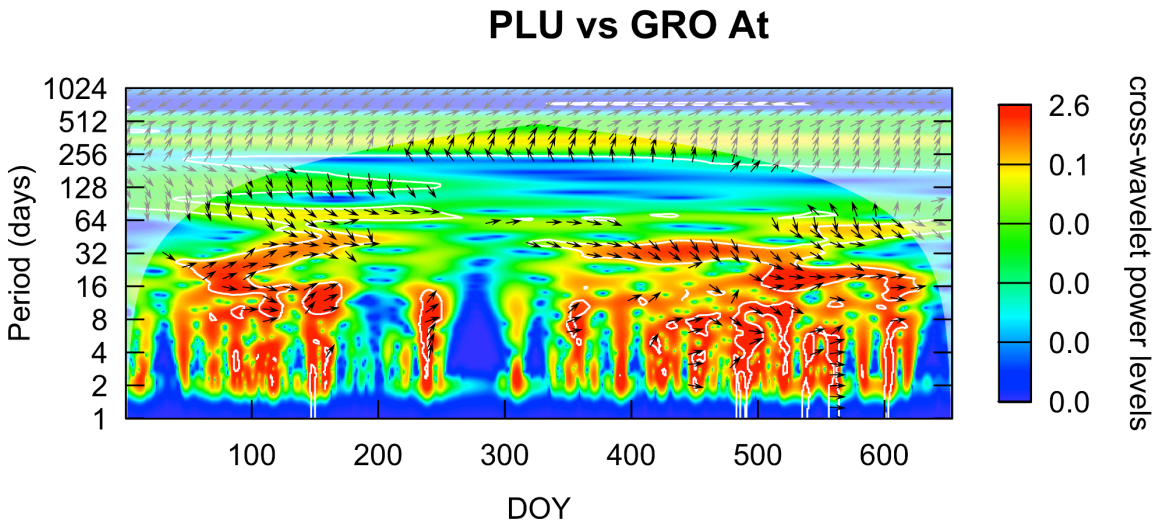


Figure S5: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Alchornea triplinervia* (At). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

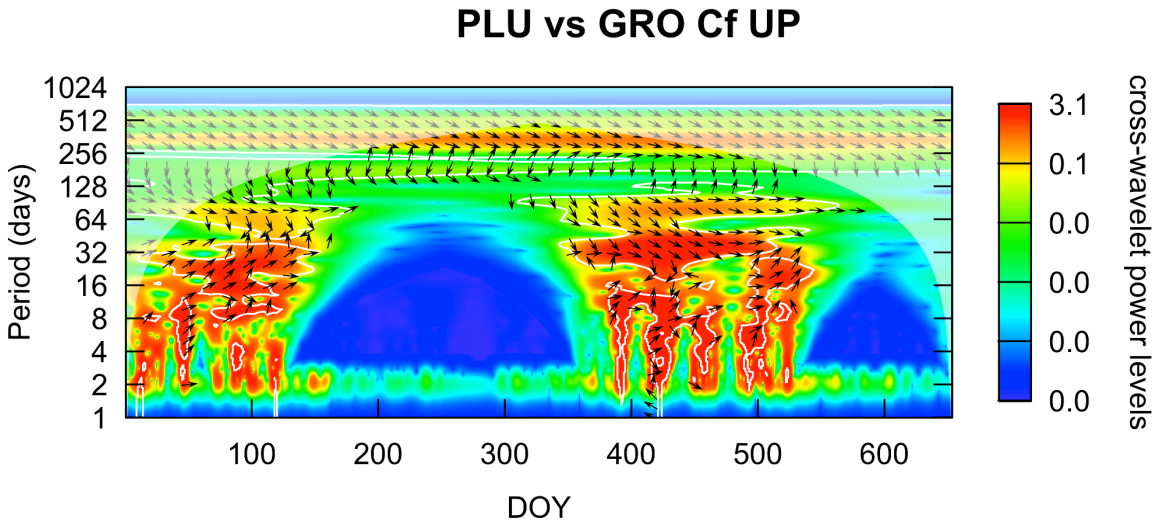


Figure S6: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Cedrela fissilis* (Cf) of the Urban park (UP). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

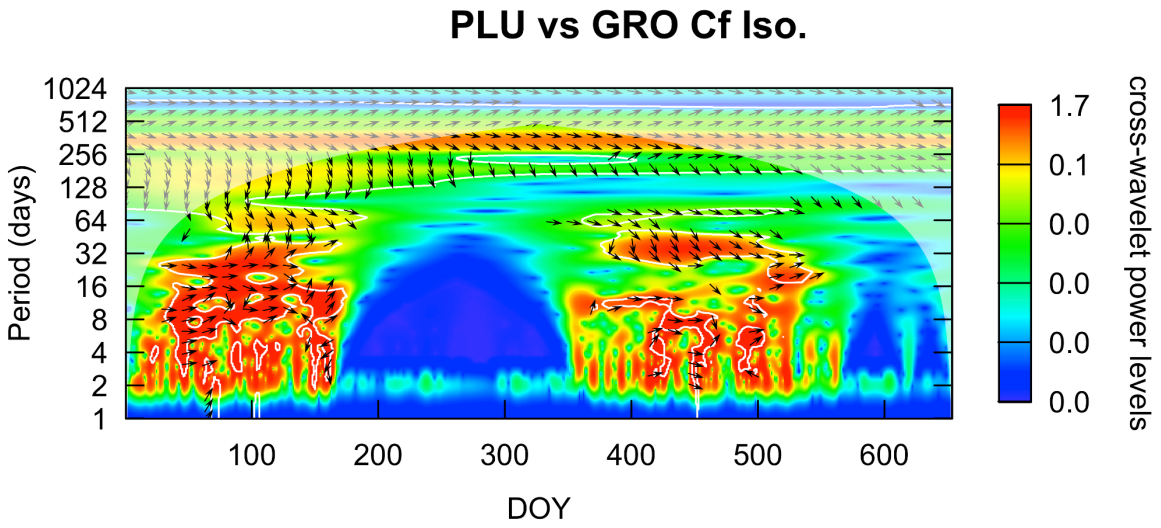


Figure S7: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Cedrela fissilis* isolated (Cf) of the Urban park (UP). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

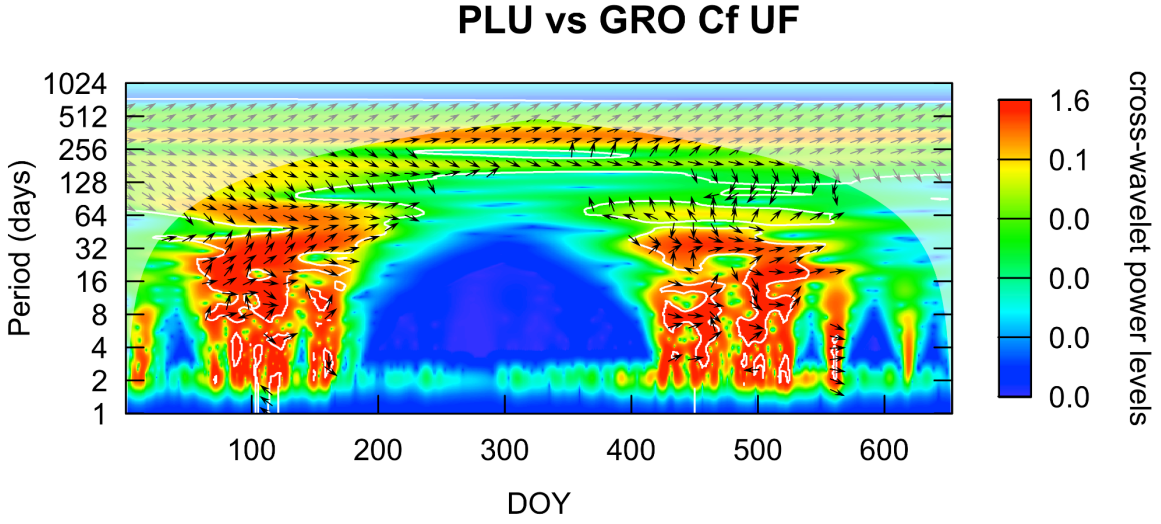


Figure S8: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Cedrela fissilis* (Cf) of the Urban forest (UF). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

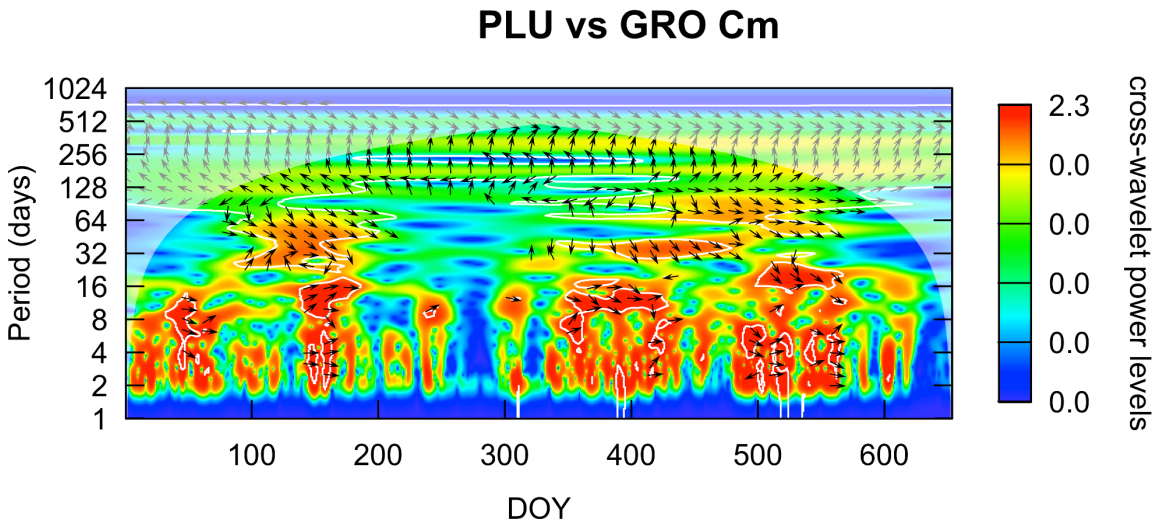


Figure S9: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Cryptocaria mandiocanna.* This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

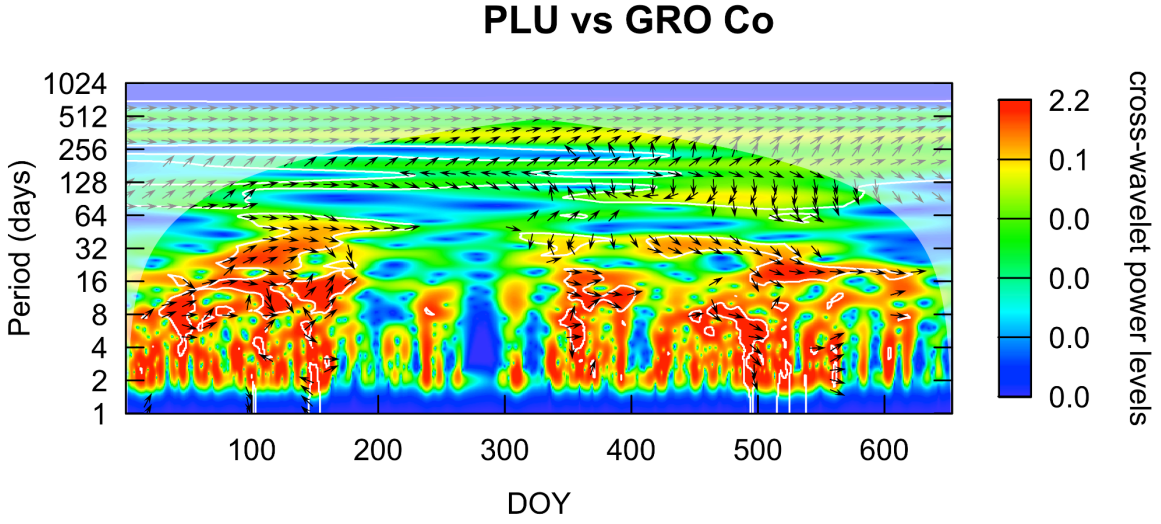


Figure S10: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Cupania oblongifolia.* This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

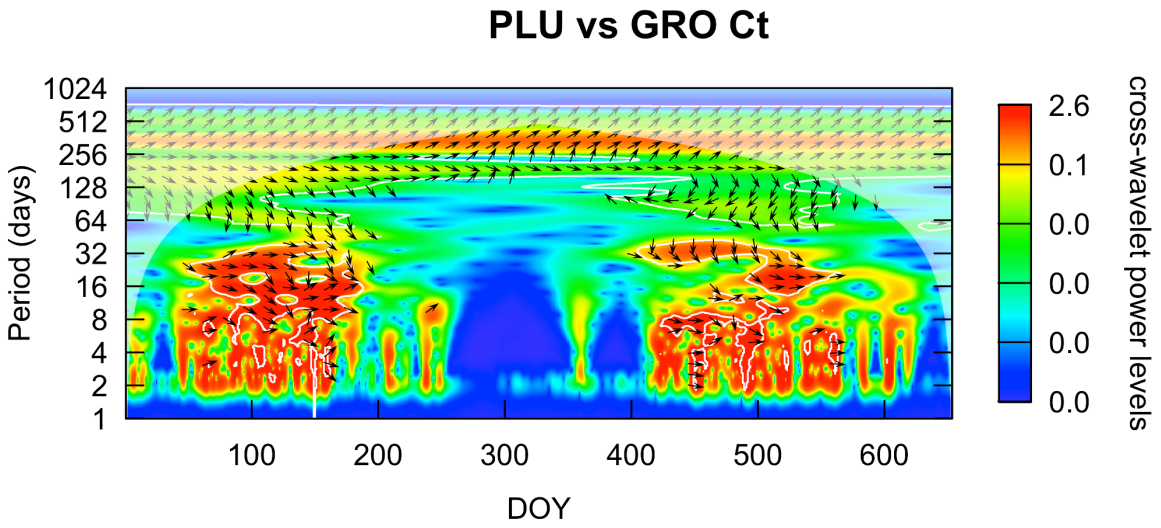


Figure S11: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Centrolobium tomentosum.* This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

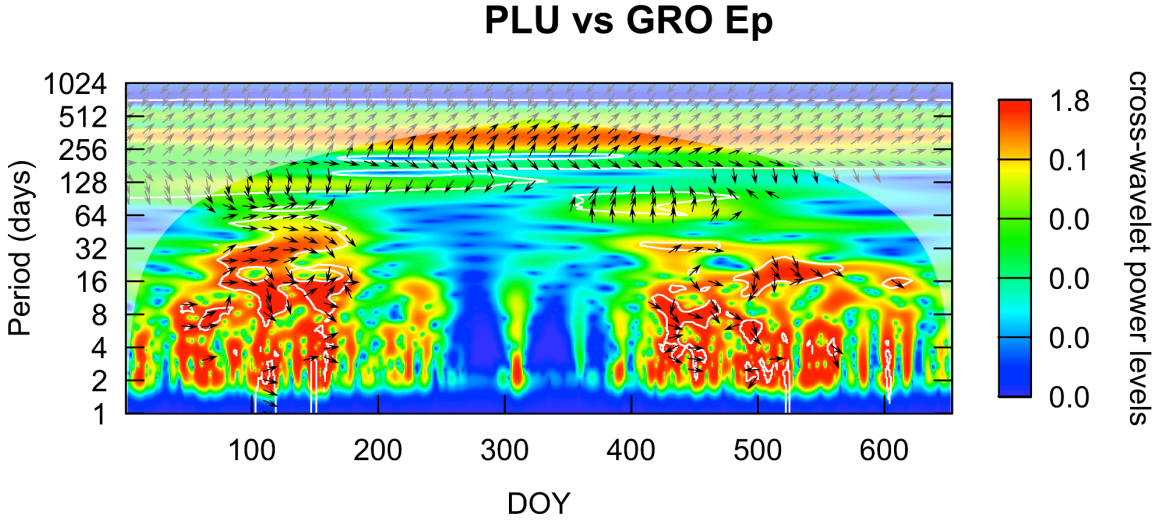


Figure S12: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Eugenia pruinosa.* This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

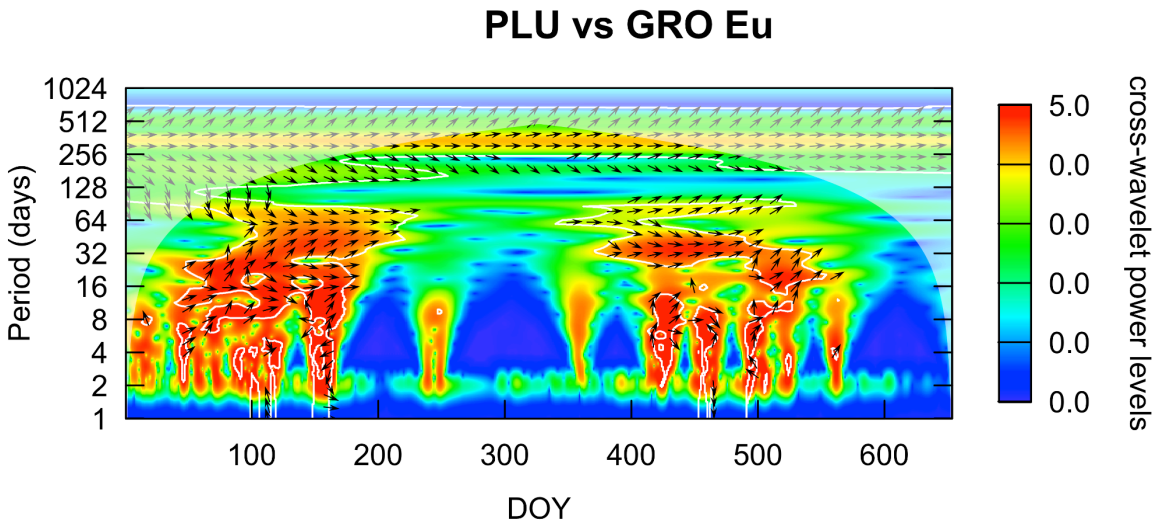


Figure S13: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for *Eugenia uniflora.* This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

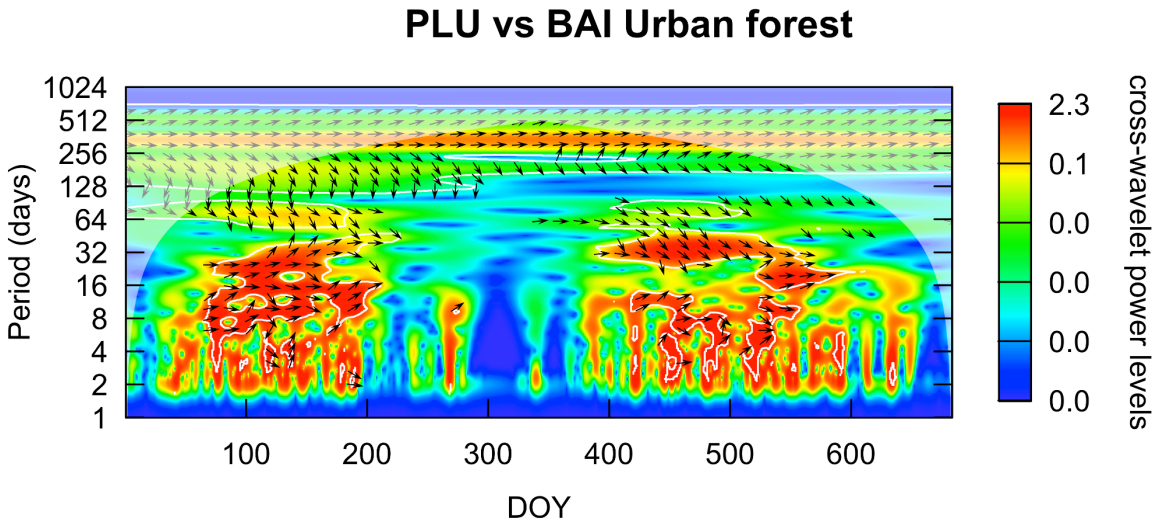


Figure S14: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for all species of the urban park. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

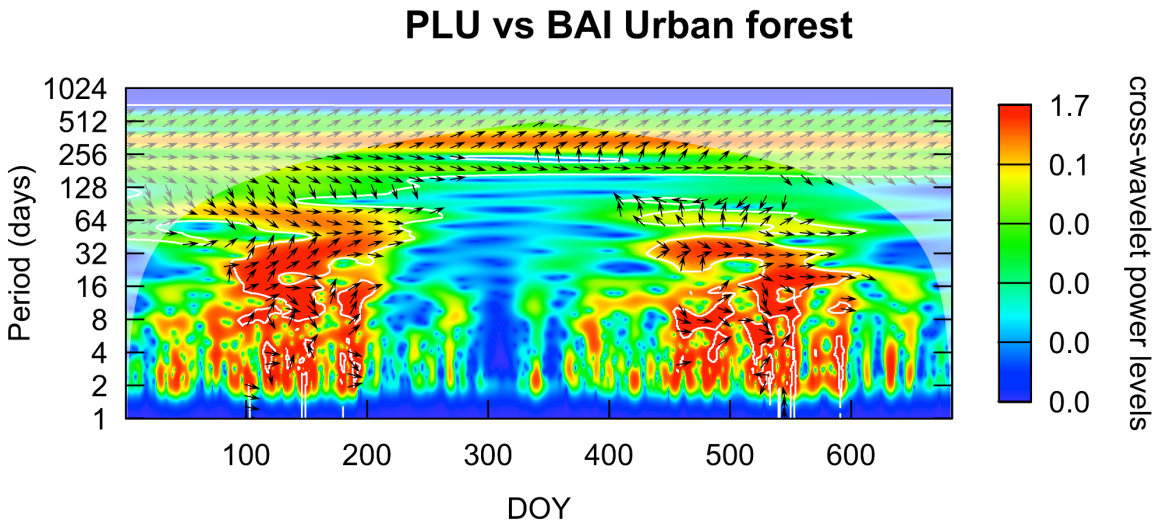


Figure S15: Cross-wavelet analysis of precipitation (PLU) and growth (GRO) for all species of the urban forest. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

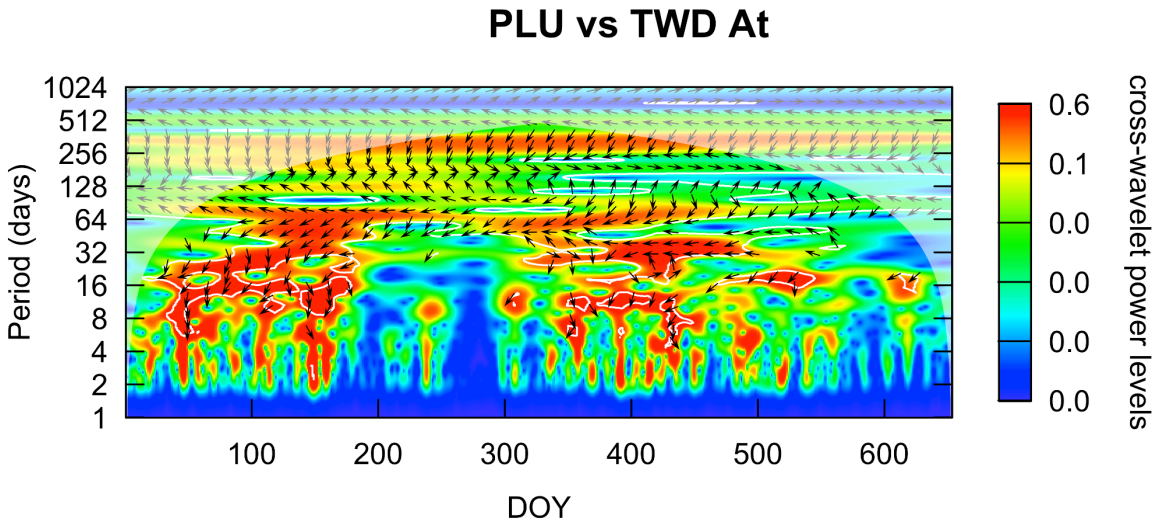


Figure S16: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Alchornea triplinervia*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

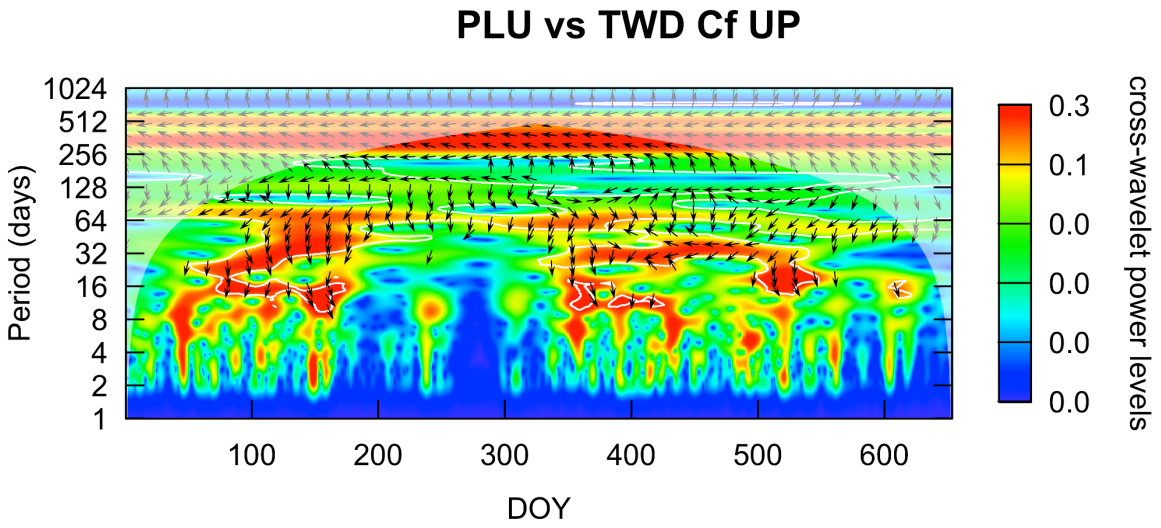


Figure S17: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Cedrela fissilis* of the urban park (UP). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

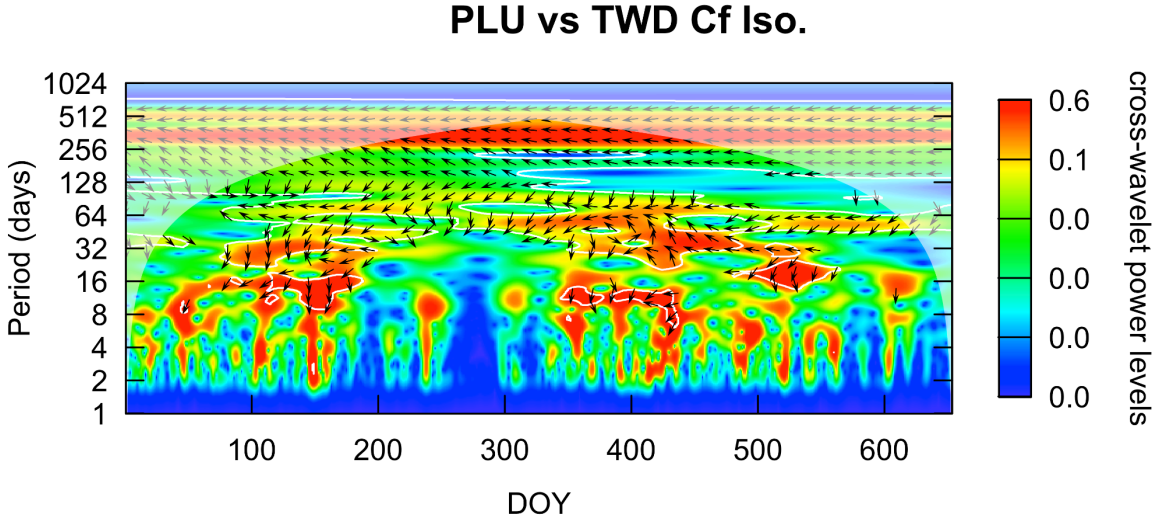


Figure S18: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Cedrela fissilis* isolatedof the urban park (UP). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

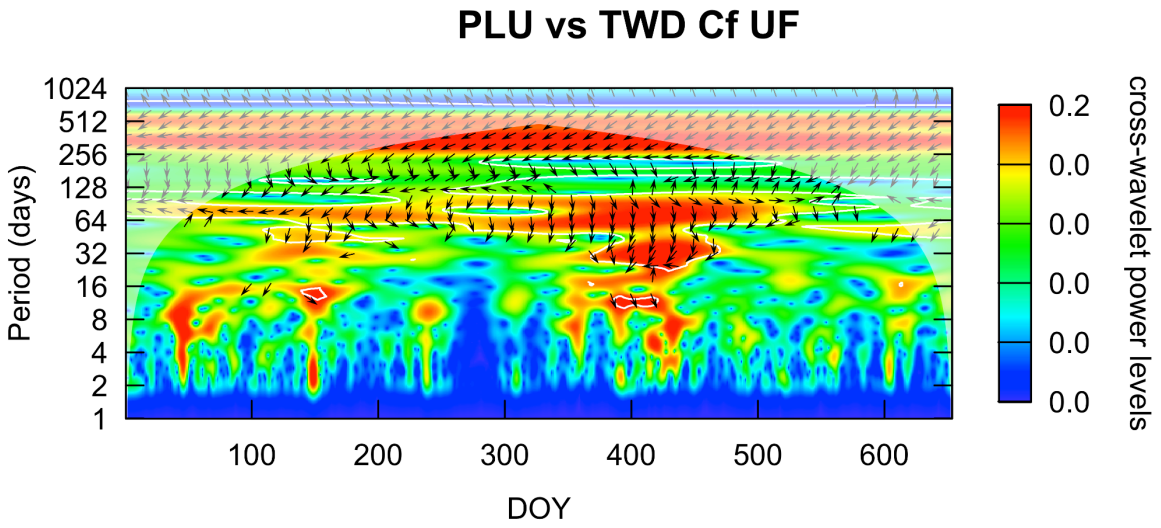


Figure S19: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Cedrela fissilis* of the urban forest (UF). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

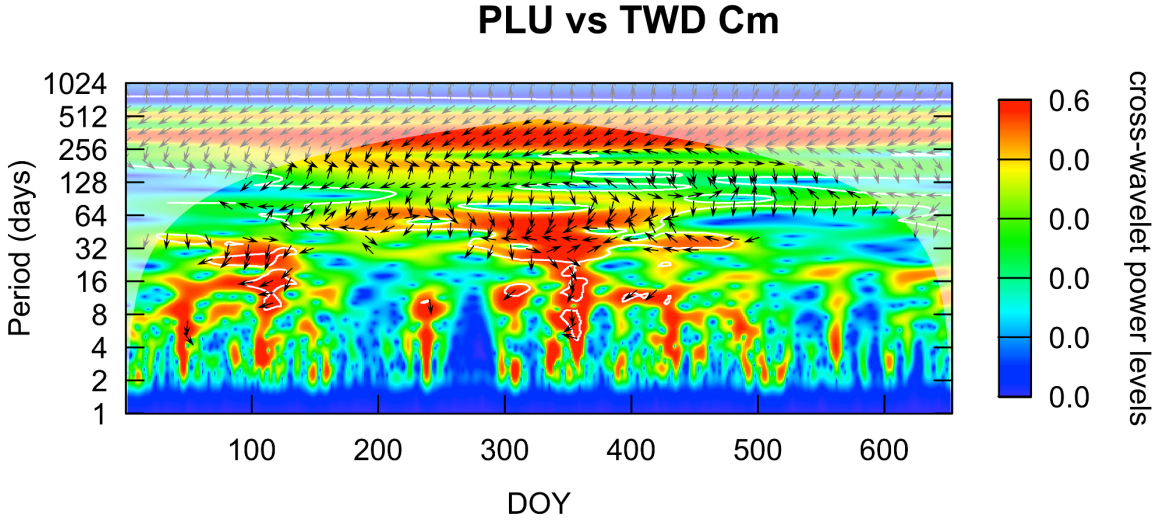


Figure S20: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Cryptocaria mandiocanna*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

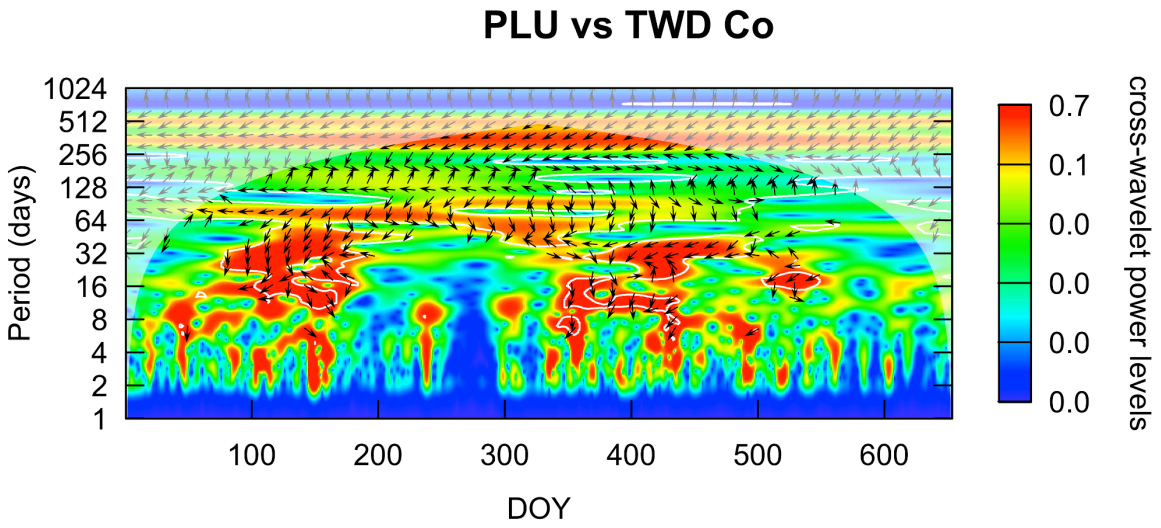


Figure S21: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Cupania oblongifolia*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

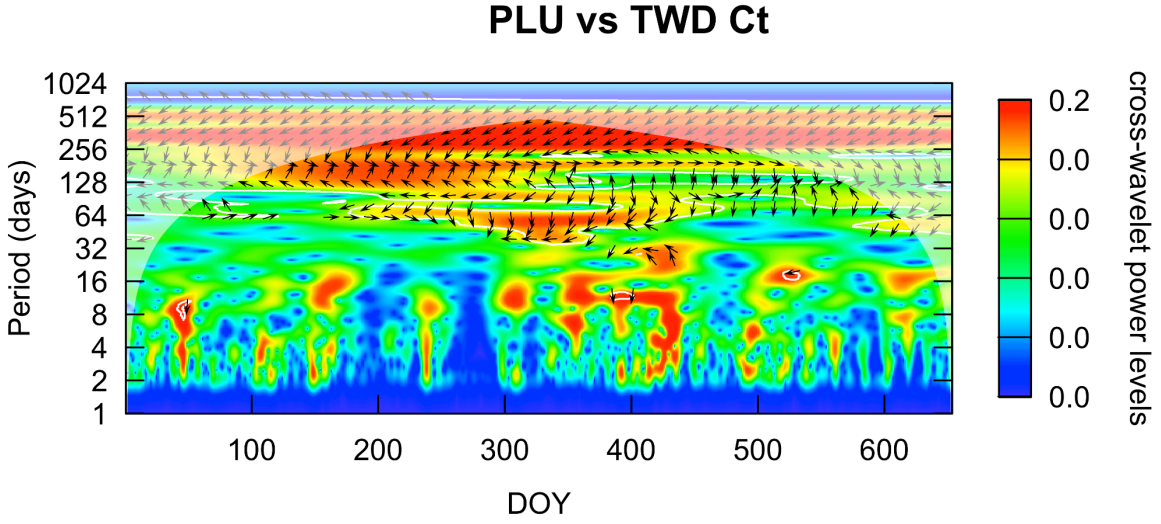


Figure S22: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Centrolobium tomentosum*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

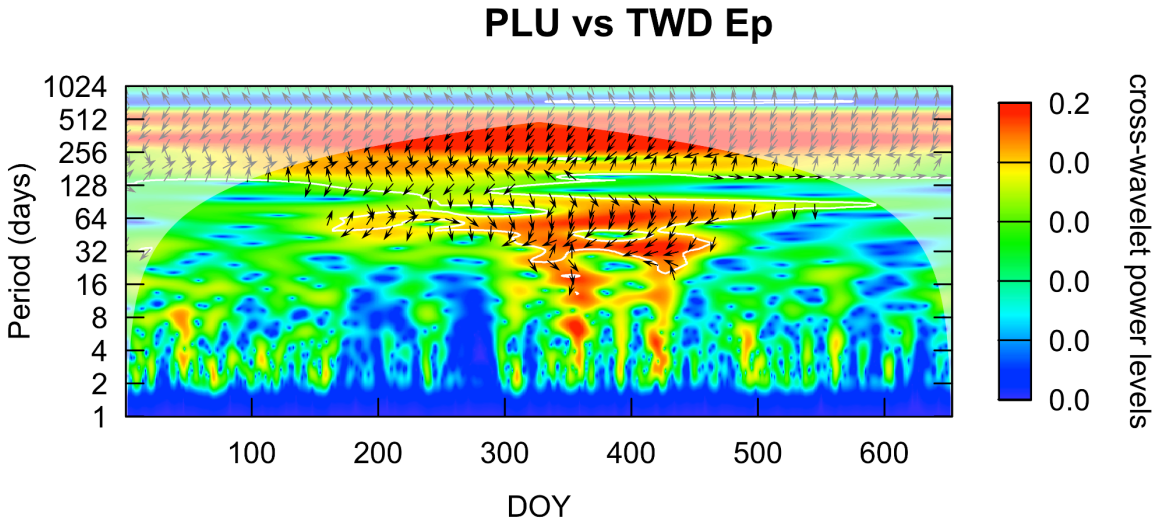


Figure S23: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Eugenia pruinosa*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

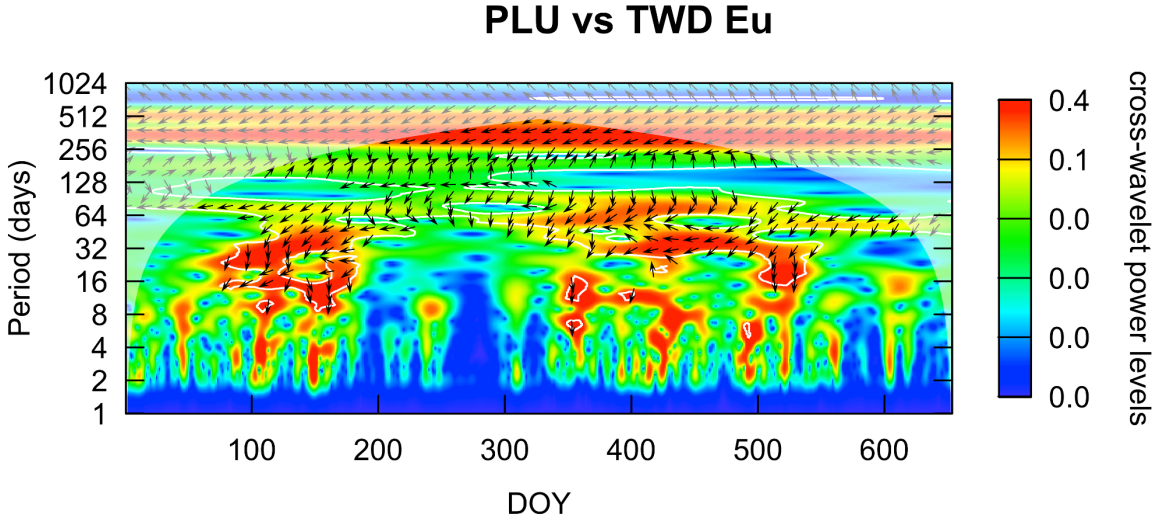


Figure S24: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for *Eugenia uniflora*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

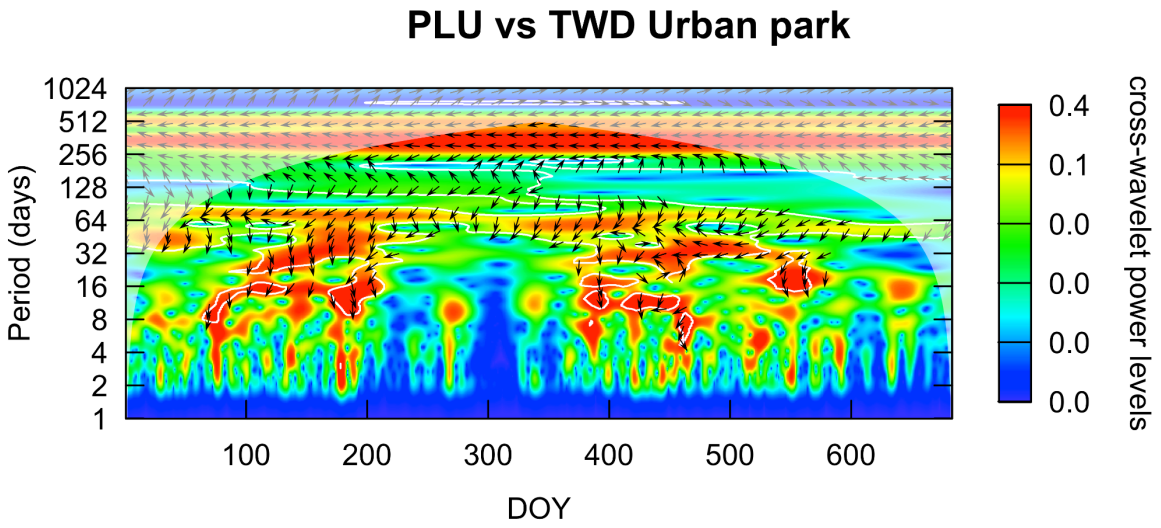


Figure S25: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for all species of the urban park. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

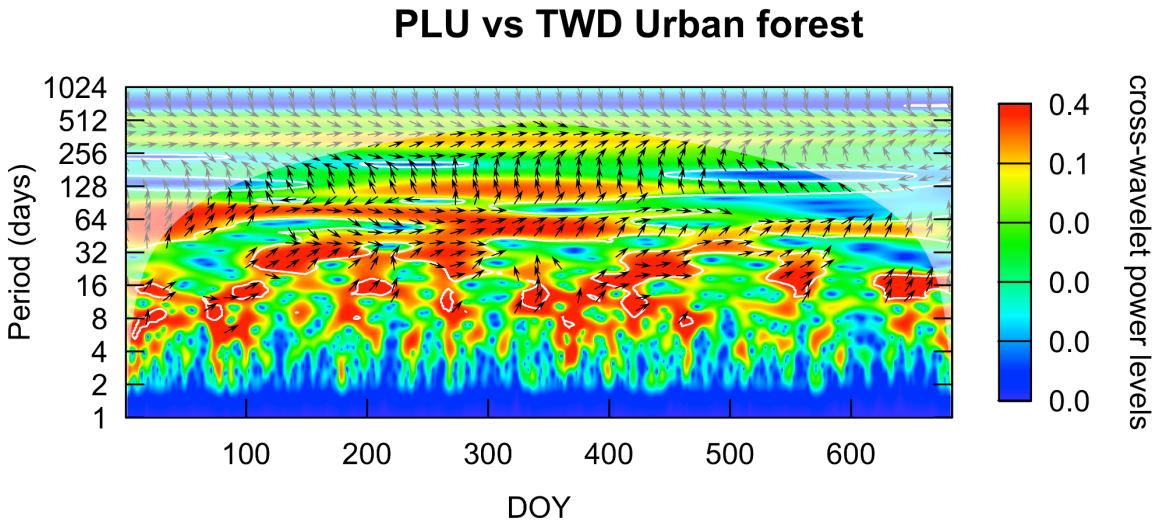


Figure S26: Cross-wavelet analysis of precipitation (PLU) and tree water deficit (TWD) for all species of the urban forest. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

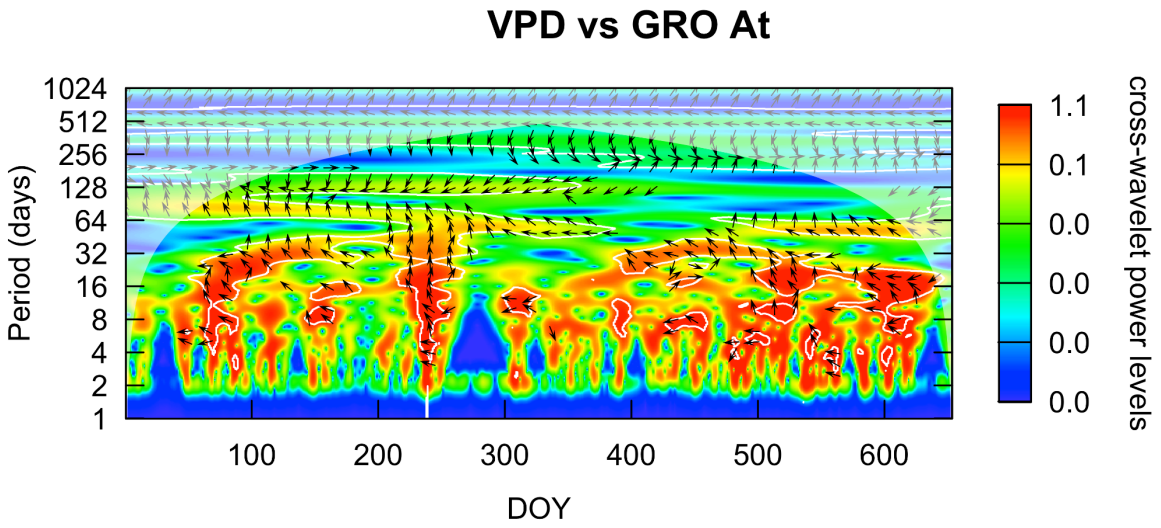


Figure S27: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Alchornea triplinervia*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

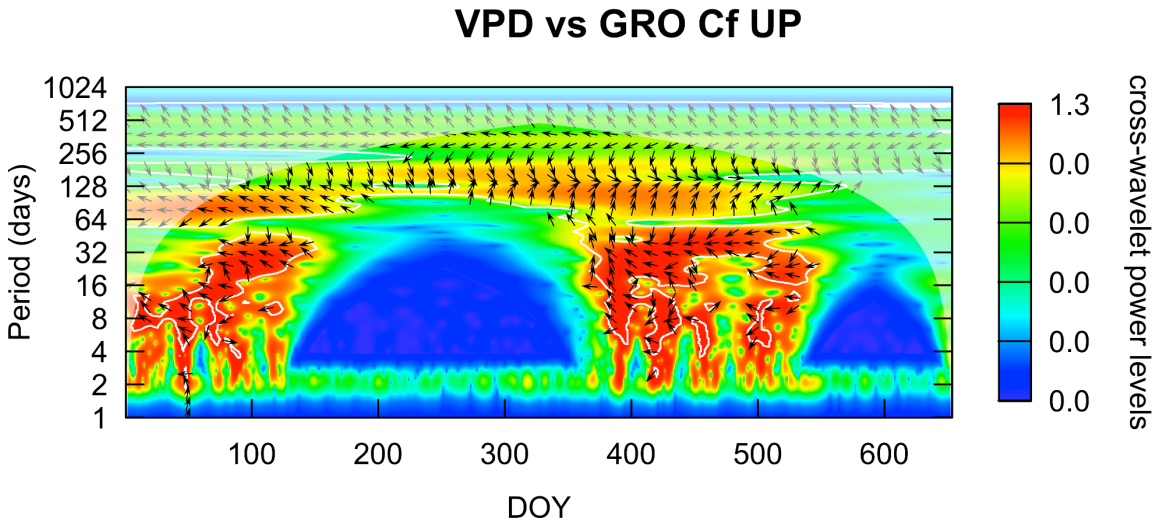


Figure S28: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Cedrela fissilis* of the urban park (UP). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

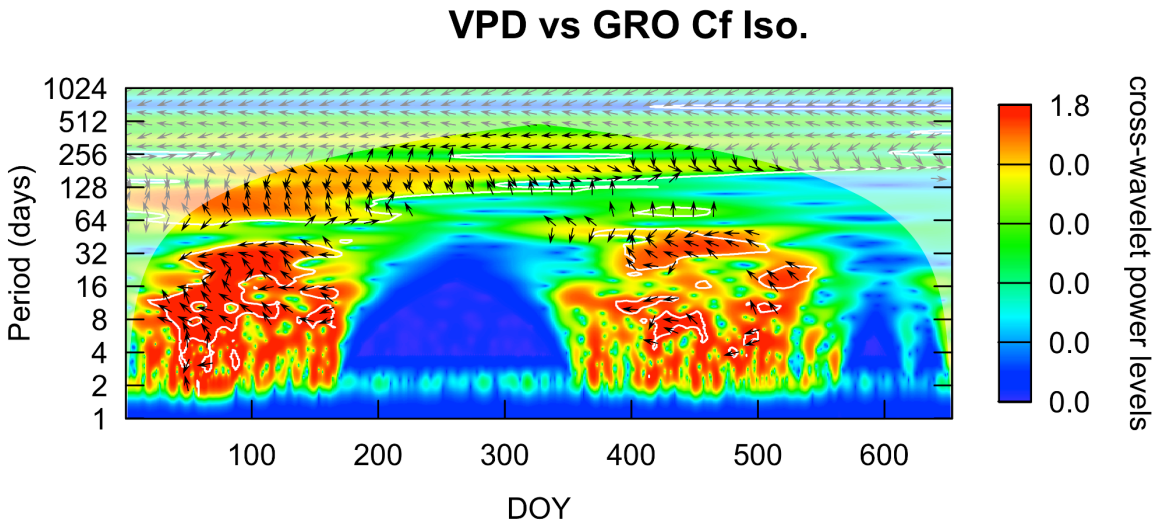


Figure S29: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Cedrela fissilis isolated* of the urban park (UP). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

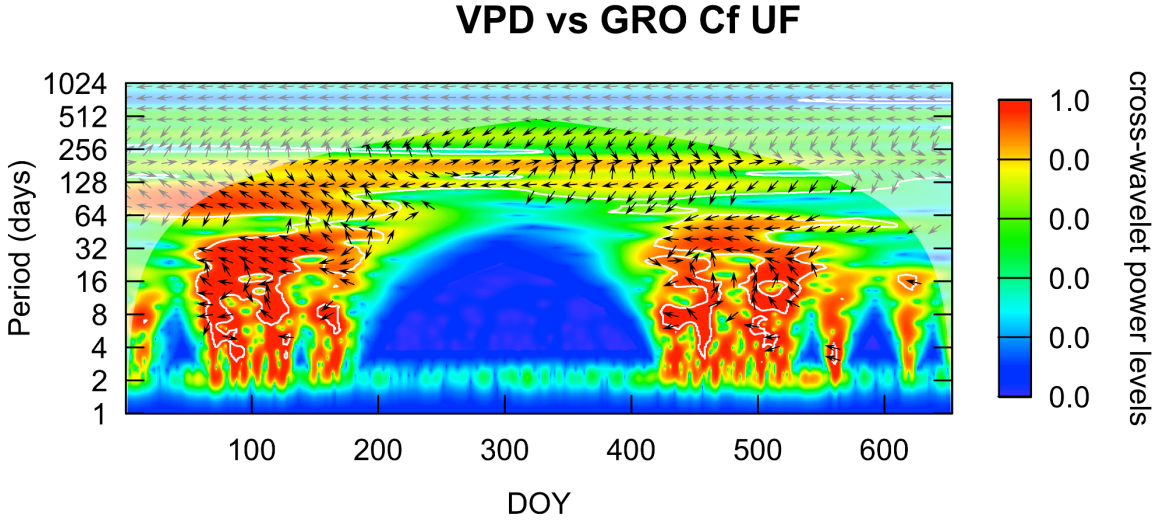


Figure S30: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Cedrela fissilis* of the urban forest (UF). This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

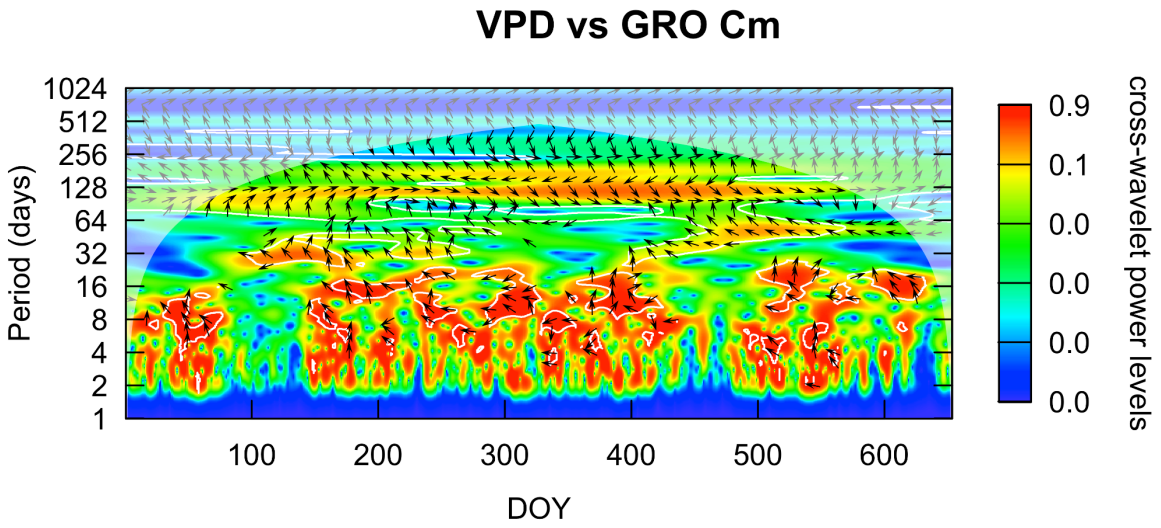


Figure S31: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Cryptocaria mandiocanna*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

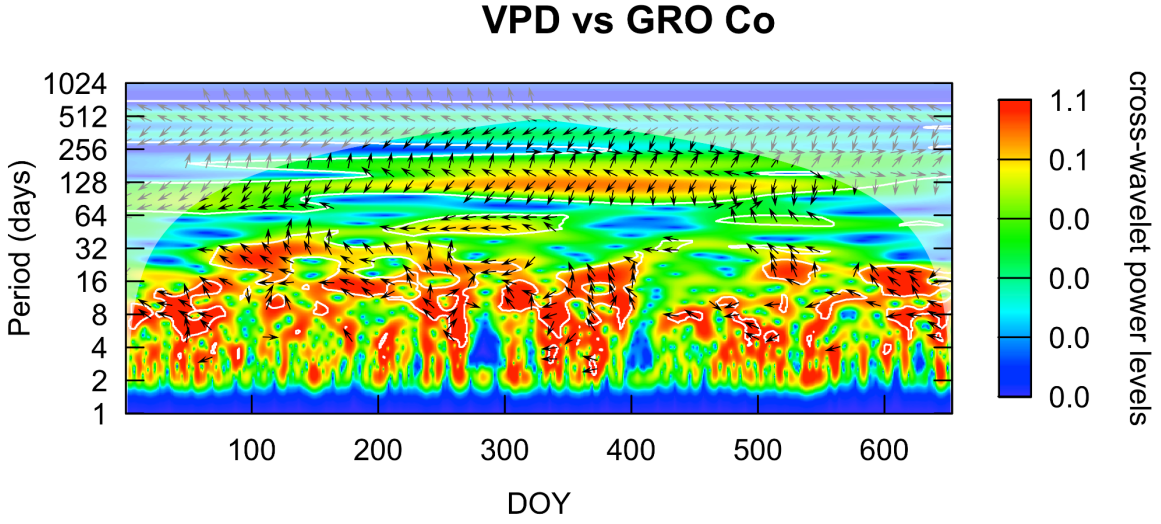


Figure S31: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Cupania oblongifolia*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

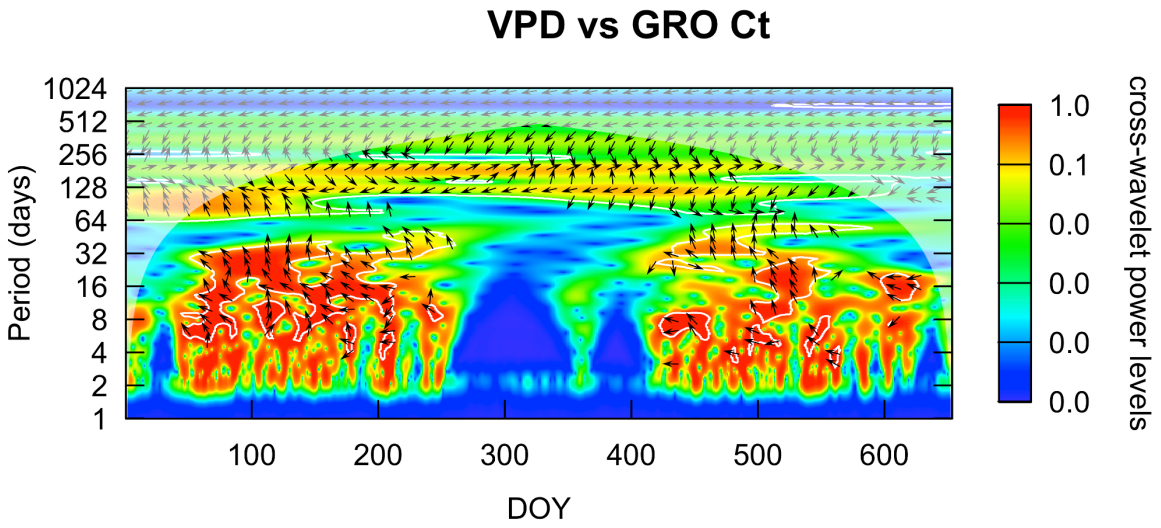


Figure S32: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Centrolobium tomentosum*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

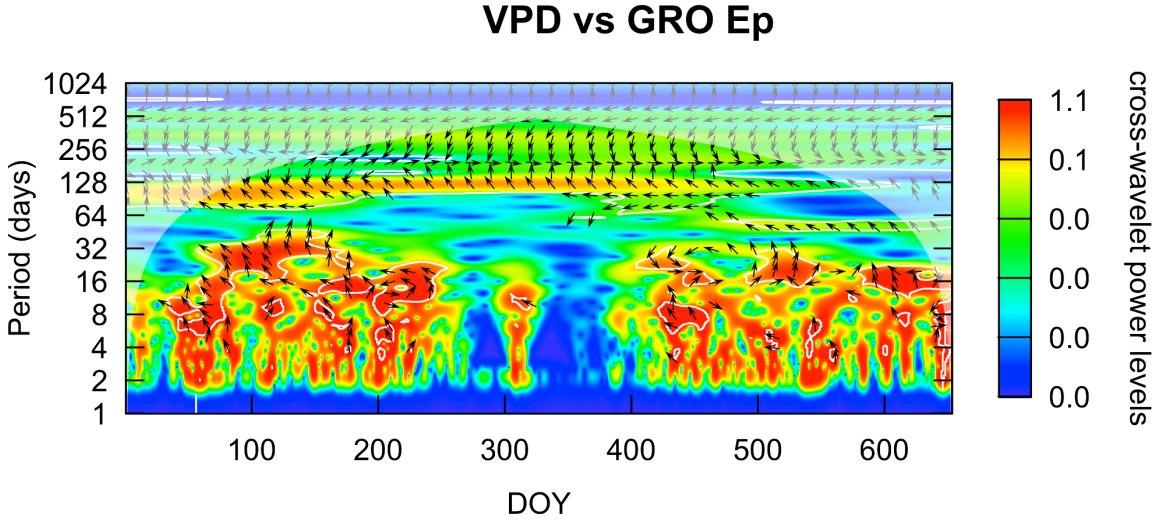


Figure S33: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Eugenia pruinosa*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

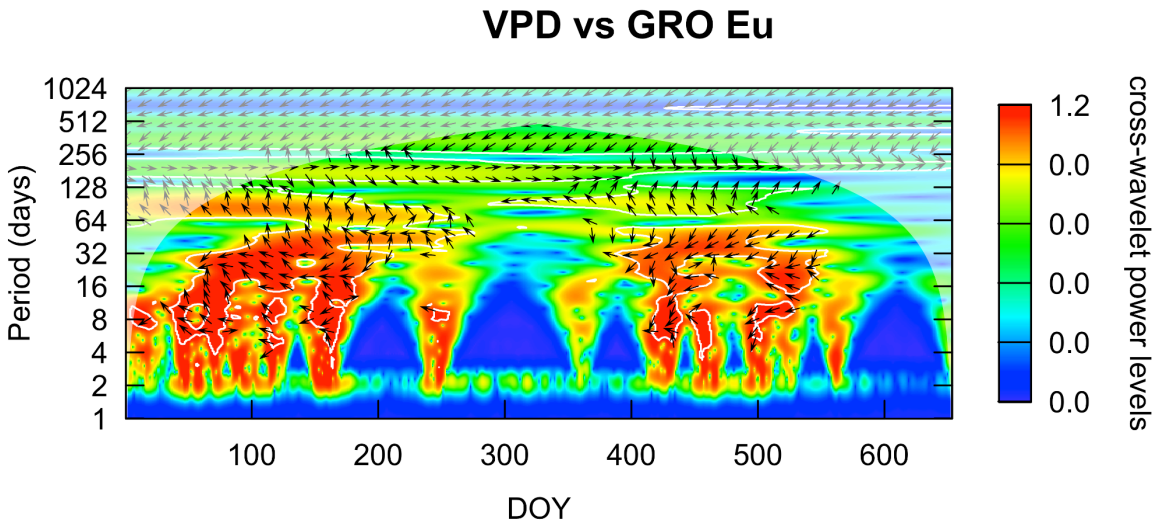


Figure S34: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for *Eugenia uniflora*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

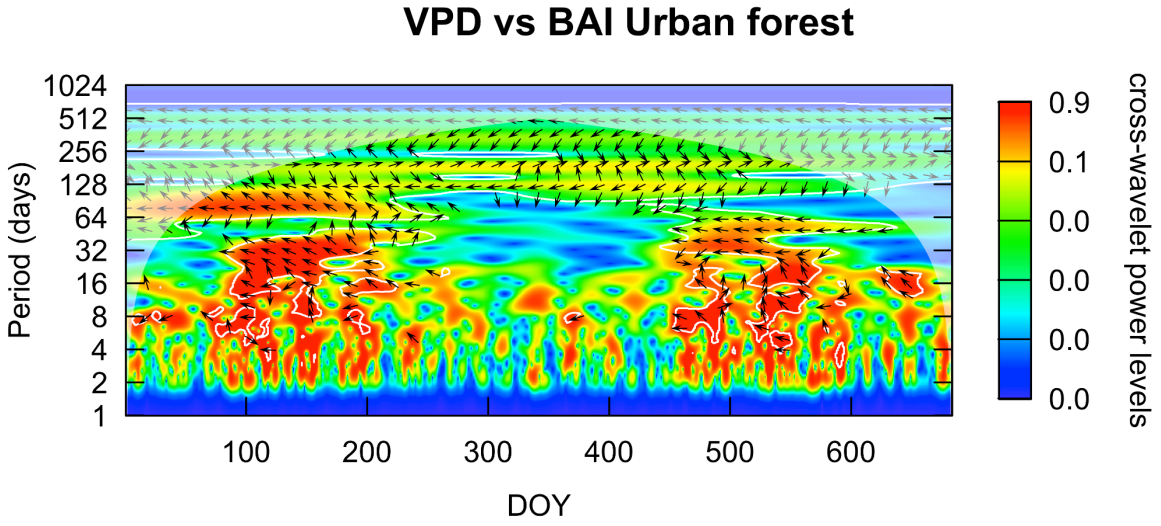


Figure S35: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for all the species of the urban forest. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

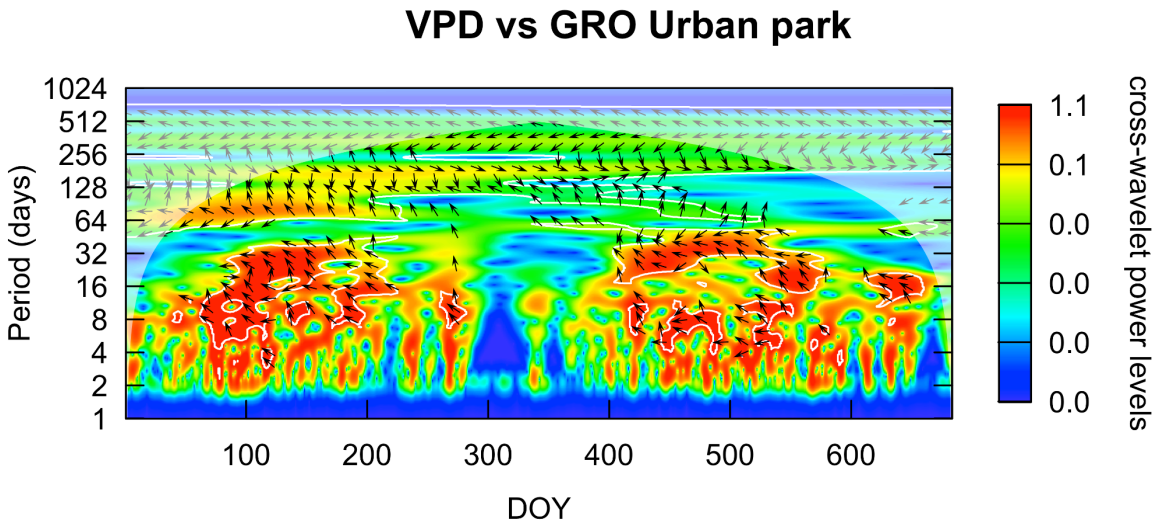


Figure S36: Cross-wavelet analysis of vapor pressure deficit (VPD) and growth (GRO) for all the species of the urban park. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

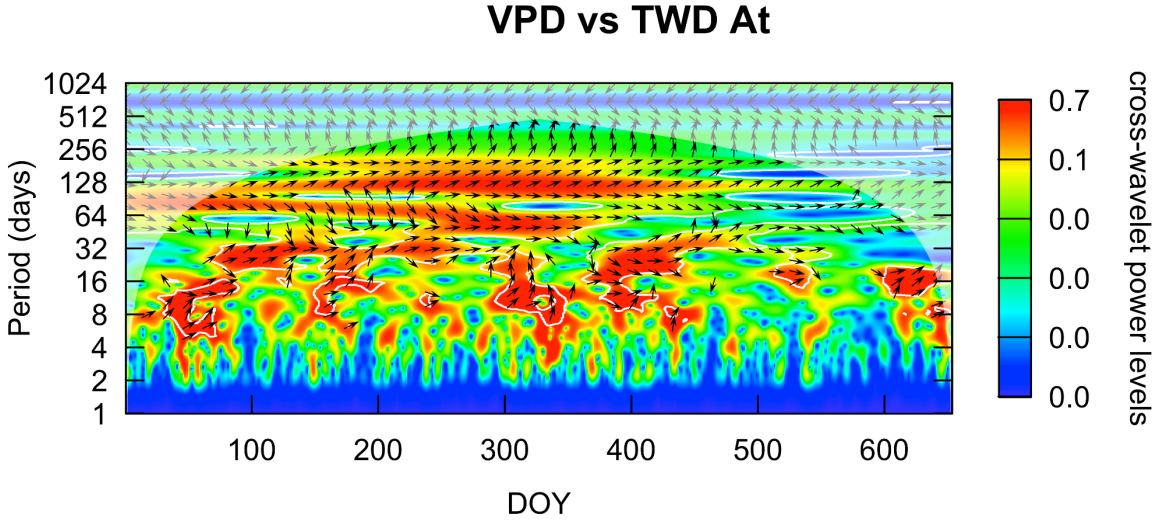


Figure S37: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Alchornea triplinervia*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

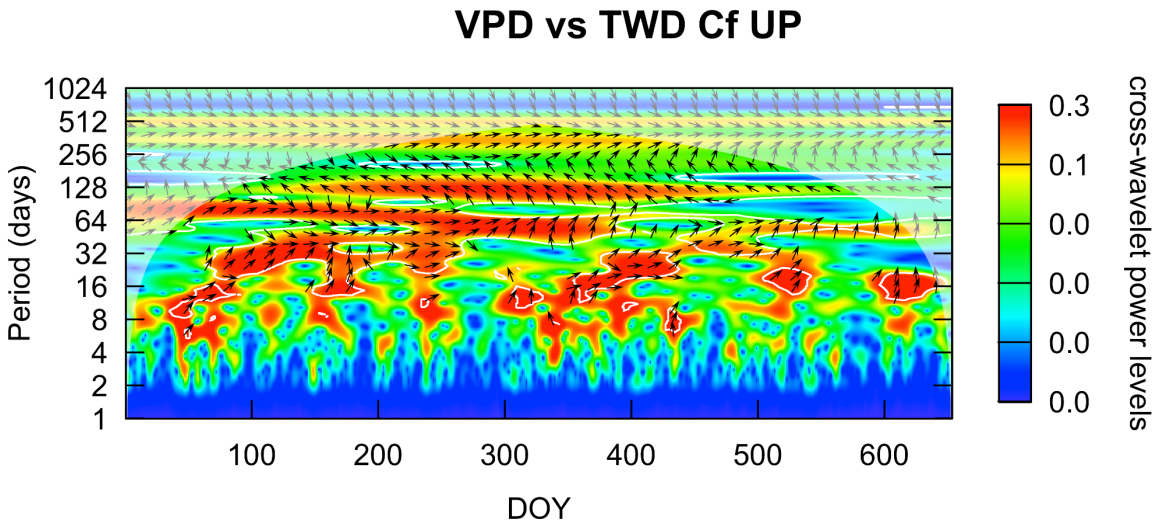


Figure S38: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Cedrela fissilis* of the urban park. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

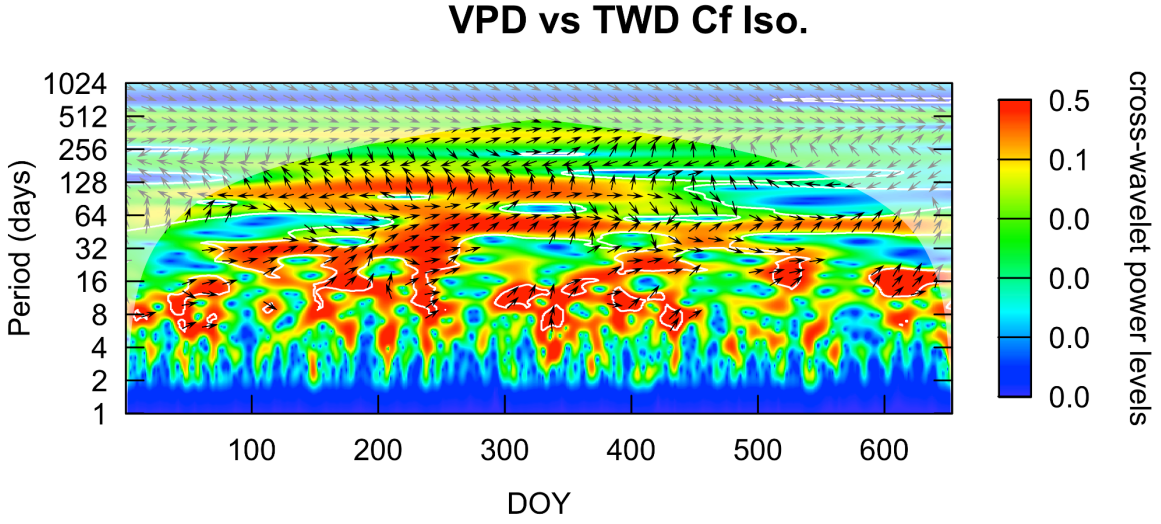


Figure S39: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Cedrela fissilis isolated* of the urban park. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

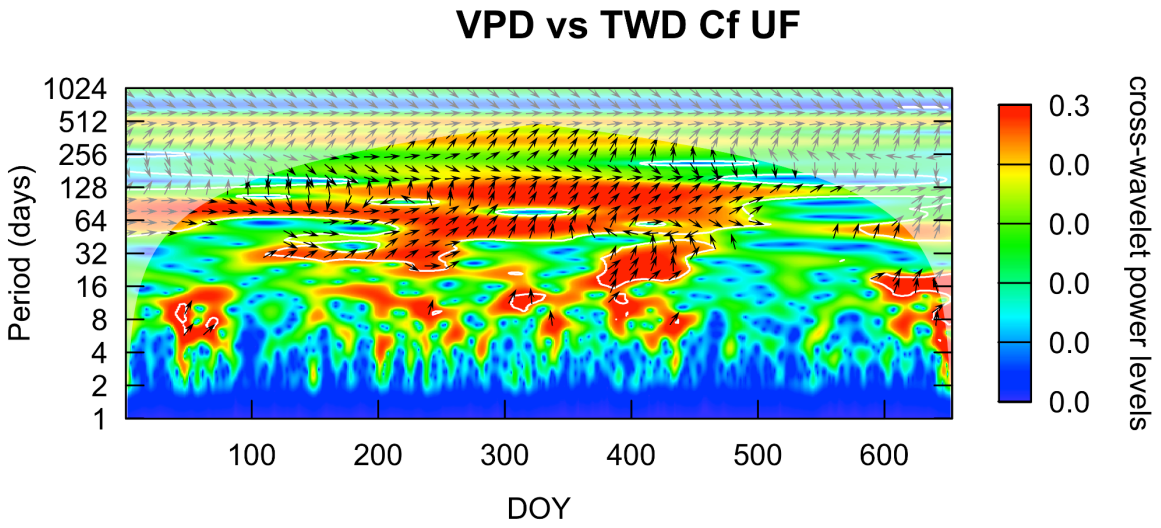


Figure S40: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Cedrela fissilis* of the urban forest. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

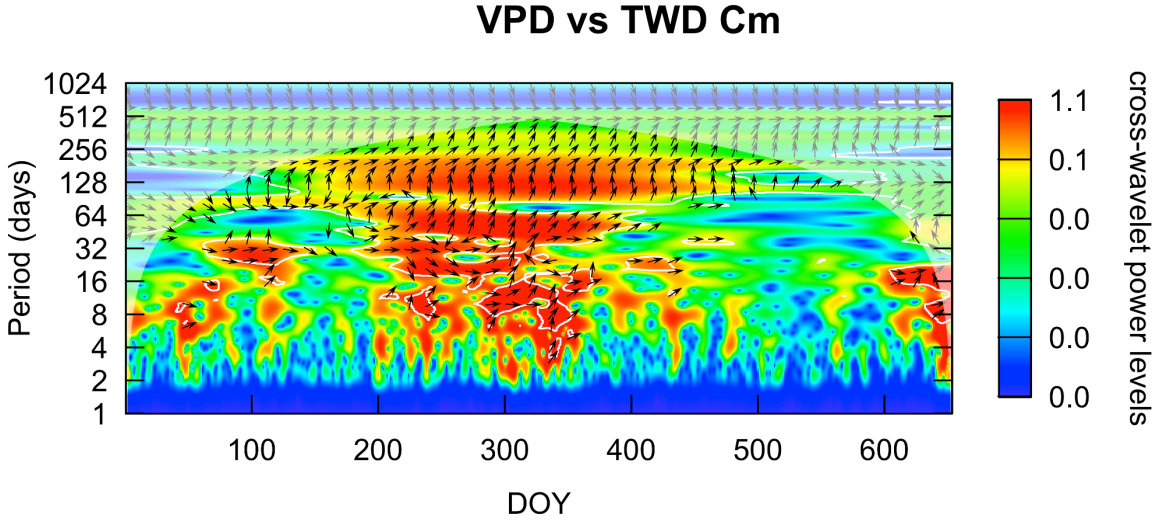


Figure S41: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Cryptocaria mandiocanna*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

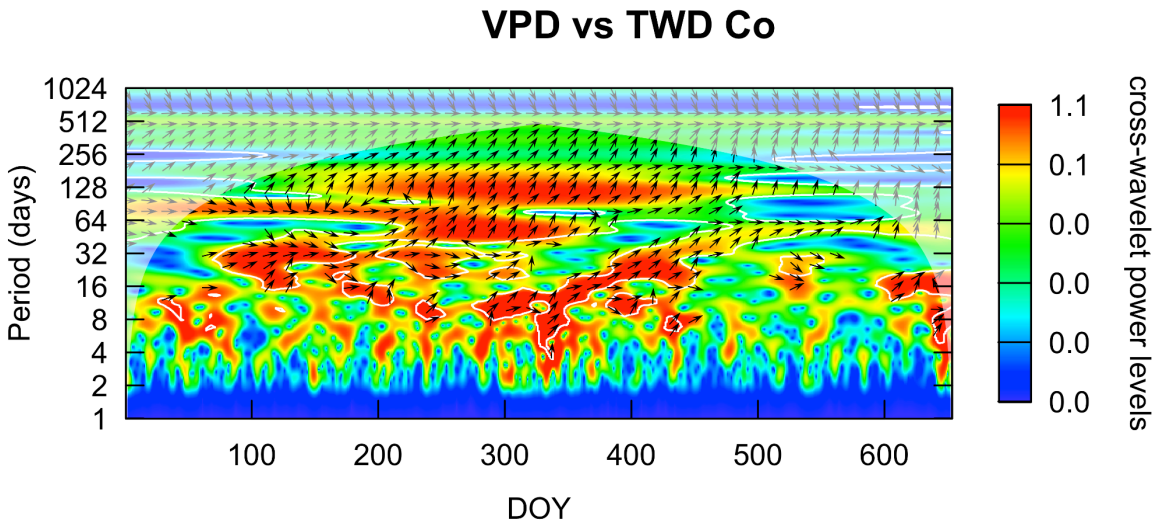


Figure S42: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Cupania oblongifola*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

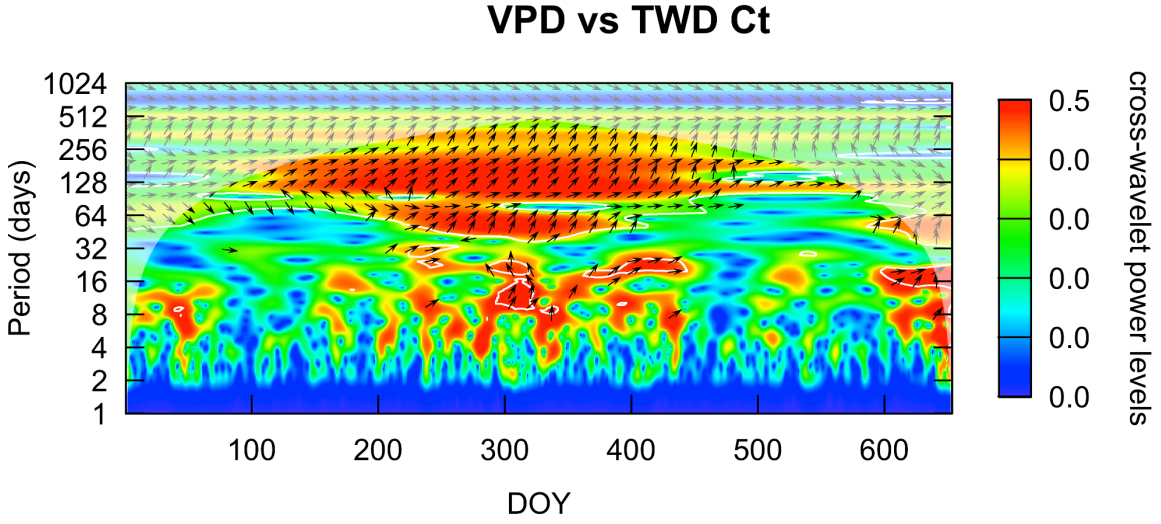


Figure S43: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Centrolobium tomentosum*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

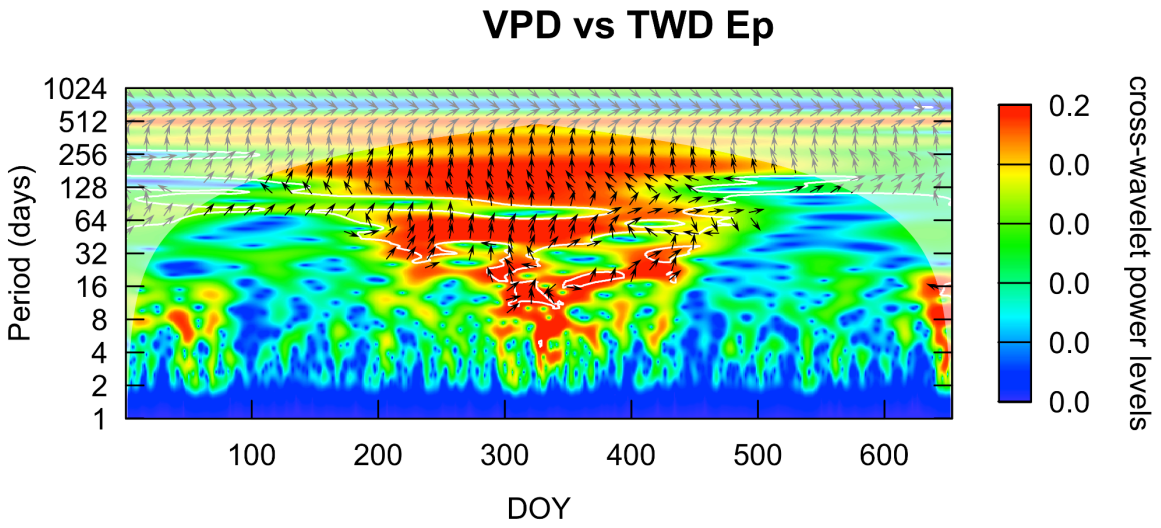


Figure S44: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Eugenia pruinosa*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

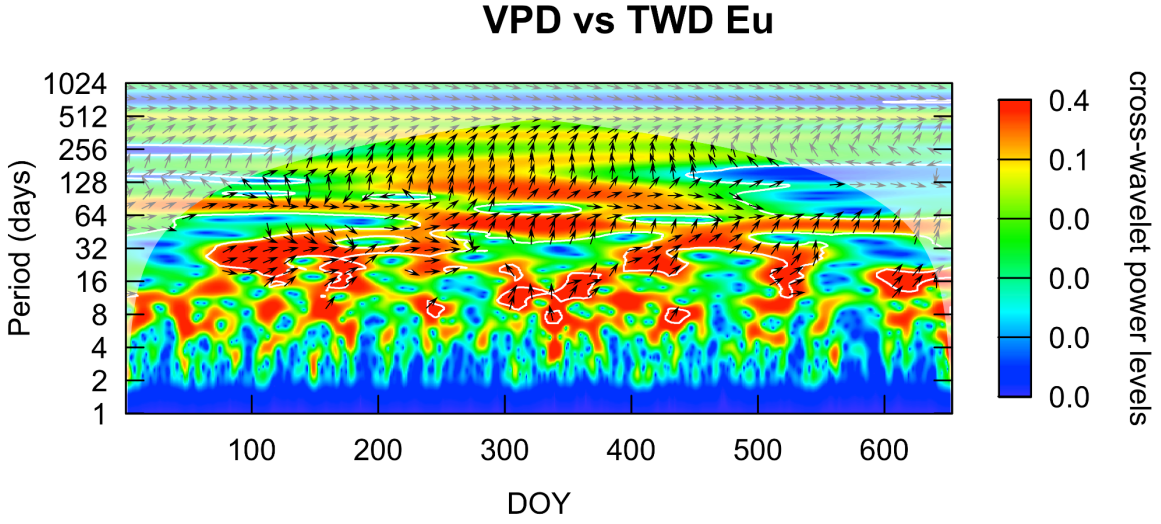


Figure S45: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for *Eugenia uniflora*. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

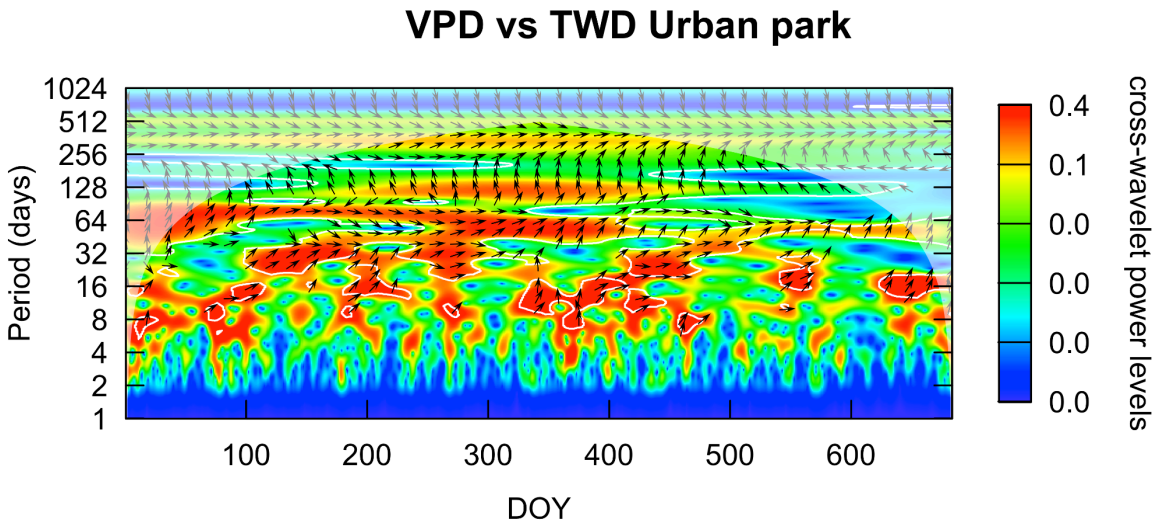


Figure S46: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for all the species of the urban park. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

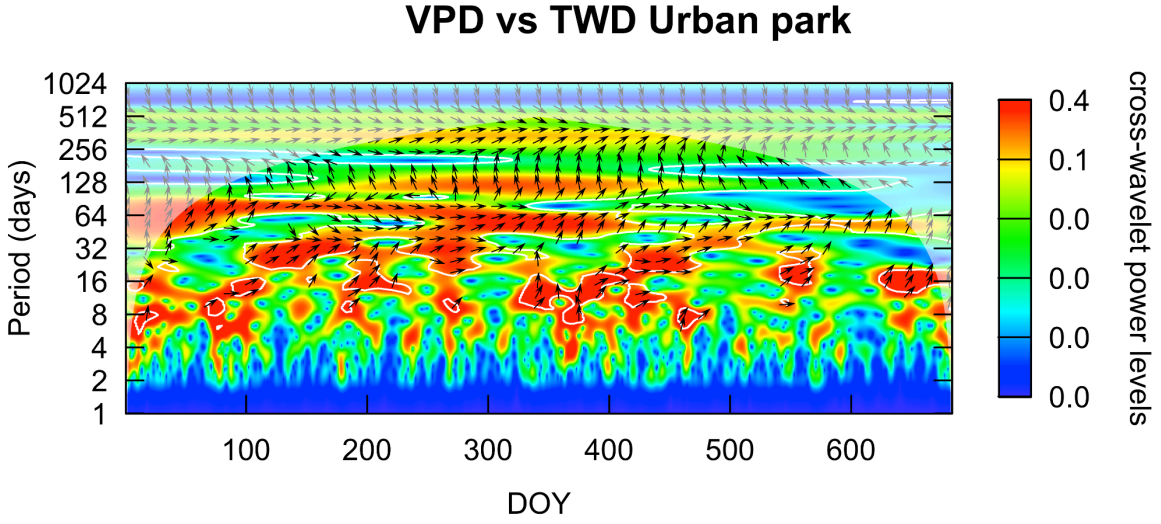


Figure S47: Cross-wavelet analysis of vapor pressure deficit (VPD) and tree water deficit (TWD) for all the species of the urban forest. This panel illustrates the coherence and phase relationship between and growth over the study period. Regions of significant coherence are demonstrated in red, and arrows indicate the phase relationship (e.g., right-pointing for in-phase, down-pointing for precipitation leading growth). Where edge effects are significant, is delimited by a white line. DOY= day of the year.

3. Chapter 3

How urban tree species modulate non-structural carbohydrates to support growth and cope with water stress?

In collaboration with: Augusto Akio Lucchezi Miyahara, Denzel Porto Silva, Larissa Souza, Marisa Domingos, Adriana Grandis, Marcos Buckeridge, Giuliano Maselli Locosselli

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4.1 Abstract

The tolerance of tree species to heterogeneous environmental conditions in cities is a growing priority in urban forestry worldwide. Trees are known to rely on non-structural carbohydrates (NSCs) to support seasonal growth and cope with stress, but the use of NSCs by urban trees is still largely unknown. Here, we evaluated NSC fractions (glucose, fructose, sucrose, raffinose, and starch) in the stems of seven native tree species in São Paulo, Brazil. We sampled quarterly, for two years, in an urban park and urban forest and assessed how trees cope NSC and growth and tree water deficit, monitored using high-resolution dendrometers. Results revealed consistent seasonal patterns of NSC fractions among species and sites, indicating a seemingly convergent NSC use strategy. Nonetheless, the absolute investment in different fractions was species-specific, evidencing distinct strategies in the NSC allocation. Deciduous species tend to invest more in sucrose and starch compared to brevidecidous / evergreen species. The results also show that trees couple NSC and growth, as for the significant correlations between sucrose or glucose, and growth rate. Yet there is no significant association between stem water deficit and NSC, suggesting a decoupling between NSC and water stress, at least under this study constellation. The fact that the observed patterns are more evident in the segments closest to the cambium suggests a NSC compartmentalization in the studied species. These findings advance our understanding of NSC allocation in urban trees, potentially informing management strategies for resilient urban forests.

Keywords: non-structural carbon; urban trees; urban parks; nsc seasonality; nsc dynamics; sapwood nsc.

4.2 Introduction

Urban trees resilience to the heterogenous environmental conditions in cities is a growing priority in urban forestry worldwide. Urban agendas acknowledge the need for a healthy and functional tree canopy cover to promote ecosystem services in cities as a measure of mitigation and adaptation to climate change (Zaeropur et al. 2025; Ettinger et al. 2024). Nonetheless, heterogeneous urban conditions push the limits of tree species' biotic and abiotic optimum conditions to support growth and reproduction (Kumar 2025). This fast-paced change is expected to threaten up to 70% of urban tree species globally by 2050 (Esperon-Rodrigues et al 2022). The pursuit of diverse urban forests is thought as the most efficient measure to reduce the vulnerability of urban forests, in all its forms (Huff et al. 2020; Roebuck et al. 2022), now and into the future. This assumption stems from the common belief that diversity begets resilience in urban forests (Paquette et al. 2021; Xing et al. 2025), based on the fact that combining species-specific traits and phenological, hydraulic, and growth strategies can result in a wide array of responses to environmental conditions (Silva Luz et al. 2024). However, emerging research challenges this assumption indicating that diversity of species strategies may not necessarily translate into improved resilience (Candido et al under review).

There are many traits that can be measured to assess the potential resilience of trees and their performance in the urban environment (Silva Luz et al. 2024). The strategic allocation and mobilization of non-structural carbohydrates (NSC) is one of these traits (D'Andrea et al. 2021; Piper & Paula, 2020) known to support growth and decouple the responses of trees to adverse conditions (Locosselli & Buckeridge 2017). They represent up to 19% of the stem dry biomass and are an important source of carbon and energy for plants (Ramirez et al. 2024; Piper & Paula, 2020). Plants produce glucose, through the photosynthesis, as the substrate for primary and secondary metabolism in leaves, or it can be transported via phloem as sucrose, a glucose and fructose disaccharide (Locosselli & Buckeridge, 2017; Hartmann & Trumbore, 2016). In the stem, which is the largest absolute NSC pool in trees (Ramirez et al. 2024), sucrose is them hydrolysed to support base metabolism, osmotic balance, and cell-wall synthesis during cell division and expansion for growth. Oligosaccharides like raffinose offer additional transport functions and protect cells against abiotic stresses (Hartmann et al., 2018). Glucose is further available for the synthesis of starch, the most stable and longstanding reserve form, which sustains metabolism during nighttime, dormant periods, or prolonged stress (Davidson et al. 2021). Thus, the NSC support tree growth, survival, and recovery from stress (Nawaz et al. 2025; Reed & Hood,

2024). For example, in urban trees the NSC helps to cope with pruning, not depleting carbohydrates but adjusting the photosynthetic rates for resilient species (Ramirez et al. 2018, Ramirez et al. 2017). Urban trees can also prioritise the accumulation of NSC over diameter or height grown (Ramirez et al. 2021, Pruning et al. 2017) when facing defoliation, root pruning or stem girdling, but can reduce sugar concentration when facing light pollution or when in street-side locations (Czaja et al. 2022, Wang et al. 2022). The NSC dynamics can be highly specie-specific (Czaja et al. 2022).

Despite their recognized importance, significant knowledge gaps persist in understanding NSC dynamics (Hartmann et al., 2018; Furze et al. 2020; Ramirez et al. 2024). The complexity of understanding the NSC dynamics arise from their intricate seasonal cycles of allocation and mobilization between source and sink tissues (Furze et al. 2018; Tixier et al. 2020; Guo et al 2025). These seasonal cycles are tightly coupled to the vegetative phenology that determines the balance between source and sink. According to the literature, NSC reserves decline during the spring to support leaf flush, onset of growth and eventual flower bud. Following fruit senescence and leaf abscission during the autumn, trees replenish their NSC reservoirs to cope with the winter imbalance between source and demands (Tixier et al. 2020). These reserves are critical for the maintenance respiration during cambium dormancy, and are remobilised to support budding and initial growth in the spring (Tixier et al. 2019). However, these patterns vary among functional groups. For instance, evergreen species tend to have higher concentrations of NSC, while deciduous species depend more heavily on accumulating reserves during the growing season (Guo et al. 2025). The knowledge about the seasonality of urban trees is limited, as most studies focus on natural forests and only examine total NSC, without assessing individual sugars or starches (Zhang et al. 2018, Ramirez et al. 2018).

The relationship between growth and NSC storage in trees reflects a trade-off between carbon allocation for tissue expansion and reserve formation. The consistent negative association between NSC concentrations diameter growth, suggesting a conservative strategy of prioritising reserves formation over immediate growth under carbon-limiting conditions (Ramirez et al. 2021). This preferential allocation to carbon reserves ensures the maintenance of essential physiological functions, such as respiration, hydraulic integrity, and osmotic adjustment, which are fundamental for medium- and long-term resilience (Ramirez et al. 2021). Still, interspecific differences, such as between deciduous and evergreen species, and the heterogeneity of sugar and starch dynamics, remain critical gaps in understanding the mechanisms that regulate growth and storage

particularly under stress (Furze et al. 2019).

The interactions between NSC reserves and stress, particularly water stress, are key determinants of tree survival and performance. Initial studies attributed drought-induced growth reduction primarily to limited carbon assimilation (Lloret et al. 2018). However, recent evidence suggests that growth is not only restricted by carbon supply, but rather by limitations in its use due to reduced cell turgor and lower sink activity (Potkay et al. 2022; Trugman & Anderegg, 2025). Under these conditions, the accumulation of soluble sugars favours osmotic adjustment, maintenance of metabolism and eventually the reversal of embolisms in the xylem (Tomasella et al. 2020; Souden et al. 2020). Furthermore, the mobilization of NSC during water stress does not follow a universal pattern, since tolerant species tend to increase NSC concentration, while susceptible species often reduce it (Signori-Müller et al. 2021). In urban environments, the NSC dynamics of trees can vary significantly due to the stresses associated (Wang et al. 2023). The mobilization of NSC during water stress is particularly substantial in branches and stems, being more sensitive to reserve depletion (Wang & Wang, 2025). Elucidating these nuanced NSC processes is therefore fundamental for uncovering the plant's responses and NSC during growth and changes in environmental conditions.

Integrating high-resolution dendrometer data, phenology, and biochemical analyses of non-structural carbohydrates offers a promising method to clarify trees' growth and their responses to stress (Moser-Reischl et al. 2019; Tixier et al. 2020; Adikurnia & Rathgeber, 2025). Despite substantial advances in knowledge about NSC, significant gaps remain in understanding its dynamics in stem wood, in the individual characterisation of sugars, particularly in urban tree species, which are crucial for the provision of ecosystem services in urban areas. In this context, this study evaluated the concentration of different NSC fractions (glucose, fructose, sucrose, raffinose, and starch) in the stems of seven tropical species growing in two green areas in the city of São Paulo, Brazil, and how NSC cope with growth and water stress. Specifically, we tested if: (i) NSC concentrations decrease in the begging of the growth and increase after growth; (ii) NSC concentrations are lower in a dense forest; (iii) evergreen species have higher concentrations of NSC (iv) NSCs are directly associated with growth rate and water stress conditions; (v) there is compartmentalisation in the dynamics of NSC use within active sapwood.

4.3 Material and methods

4.3.1 Study site

The study took place in the municipality of São Paulo (Figure 1), southeastern Brazil. It encompasses approximately 1,521 km² and hosts about 12 million inhabitants, reaching 21 million over the Metropolitan Area (IBGE, 2024). The climate is humid subtropical, marked by hot, rainy summers and mild, drier winters. Average annual rainfall is around 1,600 mm, mostly concentrated during the wet season from October and March, and the mean annual temperature ranges from 19–22 °C (Obregon et al. 2014). The city lies in the domain of the Atlantic Rainforest biome (Arantes et al. 2021).

In this study, we monitored trees in two contrasting urban forests: the Ibirapuera Park, a 158.50 hectares public park established in 1954 and designed for recreational purposes with mixed vegetation cover, from lawns to planted forest stands, and the Fontes do Ipiranga State Park (PEFI), established in 1969 (Barros et al., 2002; Prefeitura Municipal de São Paulo, 2025), consisting of a 526.38 hectares remnant of native Atlantic Rainforest (see Fig 1). Together, these two parks represent approximately 5% of the green areas within the municipality of São Paulo. For the sake of understanding, these parks will be hereafter referred to as an urban park and an urban forest in the study, respectively.

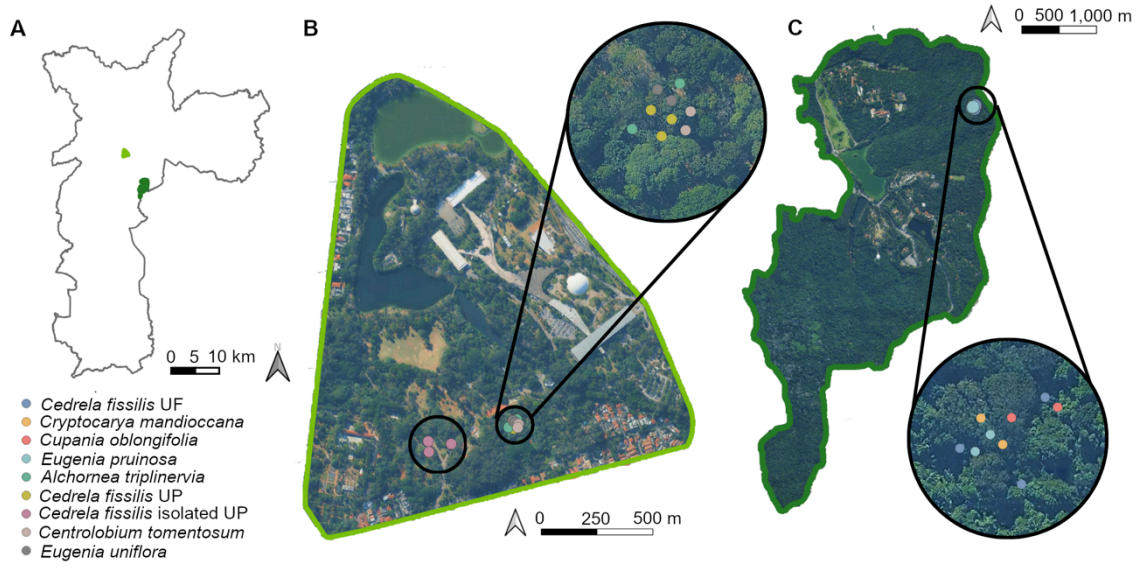


Figure 1. The two study sites in the city of São Paulo, Brazil (A). The urban park is a 158 hectares mixed vegetation area in which trees of four were monitored in a planted forest stand, together with trees growing in isolation (B). The urban forest is a 526 hectares remant of the Atlantic Rainforest where four tree species were monitored for two years (C).

4.3.2 Species selection

Native tree species were selected among the dominant ones at each study site (da Silva Filho & Tosetti, 2010; Tanus et al., 2012; Avolio et al. 2019; Vellend et al. 2007; Pau & Dee, 2016). Because of the different species composition between the sites, we selected three particular species to each site, and one common species to allow some level of comparability between sites (Table 1). We also tried to include a wide array of species ecological strategies according to their shade tolerance and phenology, to provide nuanced insights into the NSC dynamics in the trees. Based on these criteria, we selected *Centrolobium tomentosum* Guill. ex Benth., *Alchornea triplinervia* (Spreng.) Müll. Arg., and *Eugenia uniflora* L. in the urban park; and *Cupania oblongifolia* Mart., *Eugenia pruinosa* D. Legrand, and *Cryptocarya mandioccana* Meisn in the urban forest. *Cedrela fissilis* Vell. was included as the common species between the two sites. We sampled all trees in the urban forest and a planted woodland in the urban park. For *C. fissilis*, we sampled one additional set of isolated trees in the urban park to represent to some extent the heterogeneous vegetation of the park.

Table 1: Species characteristcs. (DBH) Diameter at breast height. *Lorenzi, 2000; Kondrat et al. 2020; Barretto e Catharino, 2015.

Specie	Family	Site	n	Mean DBH (cm)	Light tolerance	Phenology
Eugenia uniflora	Myrtaceae	UP	2	19.5 ± 1.6	Shadow tolerant*	Brevi-deciduous
Alchornea triplinervia	Euphorbiaceae	UP	2	68.5 ± 10.7	Shadow intolerant*	Brevi-deciduous
Centrolobium tomentosum	Fabaceae	UP	2	42.0 ± 7.7	Shadow tolerant*	Deciduous
Cedrela fissilis	Meliaceae	UP	3	50.3 ± 4.5	Shadow intolerant*	Deciduous
Cedrela fissilis isolated	Meliaceae	UP	3	31.9 ± 2.5	Shadow intolerant*	Deciduous
Cedrela fissilis	Meliaceae	UF	3	56.0 ± 3.1	Shadow intolerant*	Deciduous
Eugenia pruinosa	Myrtaceae	UF	2	23.1 ± 2.4	Shadow tolerant*	Evergreen
Cryptocarya mandioccana	Lauraceae	UF	2	24.7 ± 0.6	Shadow tolerant*	Evergreen
Cupania oblongifolia	Sapindaceae	UF	2	28.1 ± 5.0	Shadow intolerant*	Brevi-deciduous

4.3.3. Non-structural carbohydrates

To quantify the non-structural carbohydrates in the stem of the trees, we collected samples of the sapwood every three months (Figure 2) in each specimen using a 5mm increment borer (Haglof). We collected 5cm long samples to include the entire width of the sapwood, a length that proved enough for this purpose. Samples were taken at opposite sides of the trunk to avoid any bias from local wound healing, first following the cardinal points, starting at the south, and going around the trunk clockwise. We stored the samples below 0˚C in the field and then in ultra-freezers at -80° C to prevent any degradation of the non-structural carbohydrates. We took the first sample in August 2021 up to June 2023, from dormant period to dormant period, covering two growing seasons (Figure 2). All the samples were analysed for soluble sugars and starch.

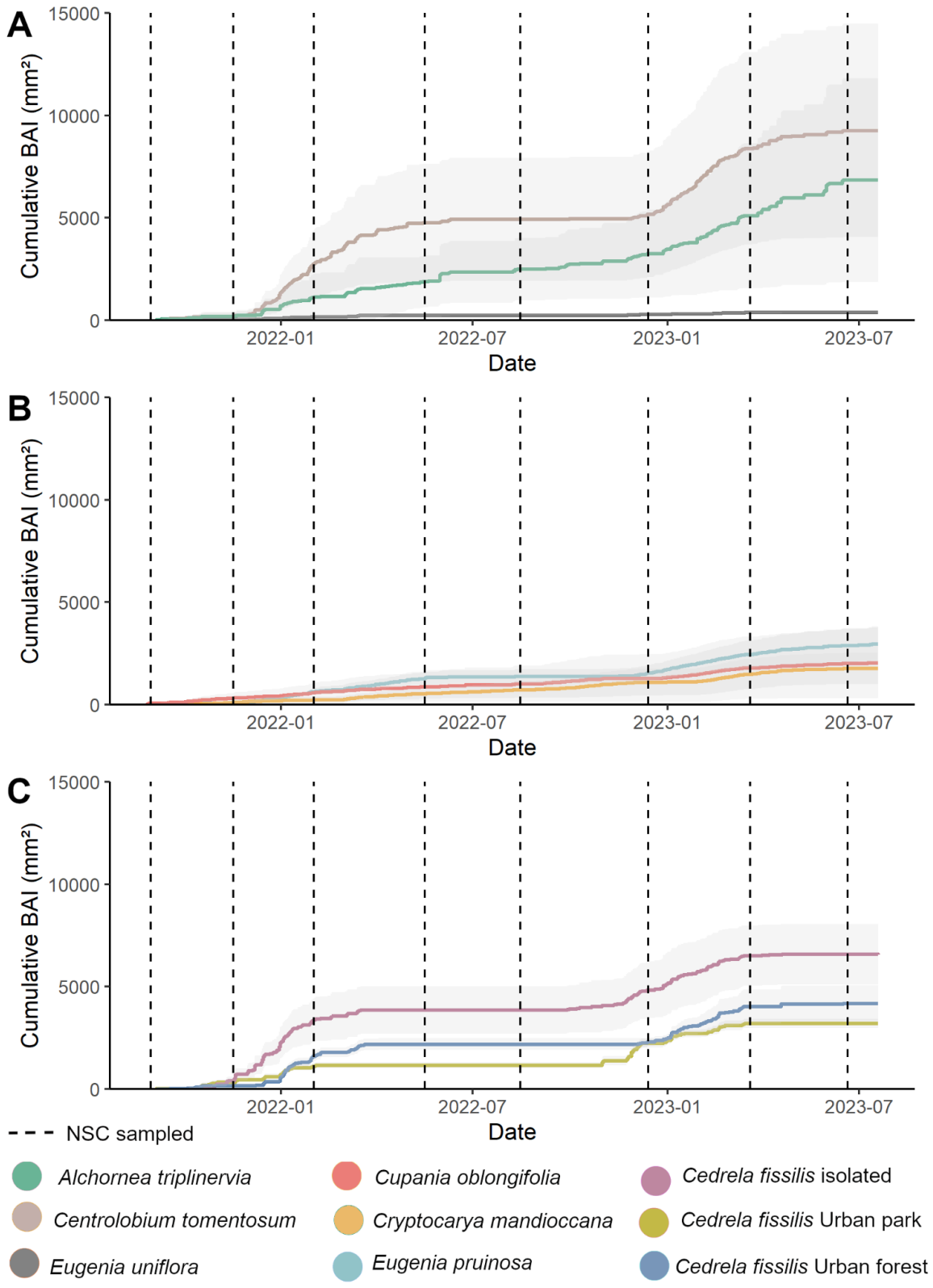


Figure 2. Growth patterns represented by cumulative BAI (basal area increment) for the analysed species and non-structural carbon sample collection dates represented by the vertical dashed lines. A) trees from the urban park (*Alchoernea triplinervia*, *Centrolobium tomentosum*, *Eugenia uniflora*), B) trees from the urban forest (*Cupanea oblongifolia*, *Cryptocarya mandioccana*, *Eugenia pruinosa*), C) *Cedrela fissilis* collected in the urban park and urban forest.

To quantify NSC, the samples were freeze-dried overnight and the sapwood was sectioned into three equal parts of 1 cm starting at the xylem limit close to the cambium (Fig 2). We grounded the samples in a ball mill (Tissuelyser) and weighed 10mg of the dry mass of each sample for the subsequent analyses. For the extraction of soluble sugars (glucose, fructose, sucrose and raffinose), we ran four extractions in 1.5mL of 80% (v/v) ethanol at 80°C, each lasting 20 minutes, and centrifuged the samples at 13,000 rpm for 10 minutes to isolate the supernatant containing the soluble sugars. Following, we dried the supernatant in a vacuum condenser (SpeedVac) (ThermoScientific Savant SC 250 EXP), resuspended it in 1mL of water and 1mL of chloroform and centrifuged at 13,000 rpm for 10 minutes. We isolated the supernatant containing the soluble sugars and analysed by ion exchange chromatography with pulse 6 amperometric detector (HPAEC-PAD) on a Dionex system (ICS 3000) using a CarboPac PA1 column eluted with 150 µM sodium hydroxide in a 27-minute isocratic run (Pagliuso et al. 2022).

For the starch extraction, we dried the pellet left from the soluble sugar's extraction in a dry oven at 50°C for one day. We then carried out the starch extraction by inserting 0.5 ml of α-amylase enzyme diluted in MOPS buffer (120 U/mL) into each sample under 75°C in a water bath twice for 30 minutes. Then, we added 0.5 mL of amyloglucosidase enzyme diluted in sodium acetate buffer (30 U/mL) and subjected it to 50°C in a water bath twice for 30 minutes, and stopped the reactions by freezing the samples (Amaral et al. 2007). For starch dosage and quantification, we isolated the supernatant by centrifugation and dosed the starch from 10 to 50 µL of supernatant (depending on the species and/or sample) and diluted it in 50 µL deionised water. After this step, we added 250 µL of GODPOD (Glucose PAP liqueform) incubated the samples for 15 minutes at 30°C. The free glucose content was determined in spectrophotometry coupled to an ELISA microplate reader at a wavelength of 490 nm. We built the standard curve with glucose at varying concentrations from 0.02 to 0.2 $mg.mL^{-1}$.

4.3.4 Growth and Tree Water Deficit Monitoring

We installed high-resolution DRL26C band dendrometers (EMS-Brno), which measure changes in trunk diameter at 1 µm on an hourly basis. The dendrometer data allows to assess the growth rate derived from any sustained increases in trunk diameter, as well as the as Tree Water Deficit (TWD) derived from stem shrinkage due to variations in water content. We processed the dendrometer data in R (R, 2024) using the dendRoAnalyst package (Aryal et al. 2020), which helped to identify occasional data gaps and calculate both

effective growth rate (GRO) and TWD. This analytical approach enabled a precise separation of growth dynamics from hydraulic responses to environmental conditions. Based on the dendrometers' results, we defined periods within the dormant and growing seasons to precisely assign the growth stages at the moment of NSC sampling. We defined five phases, namely: dormancy before (DB), early growth (EG), growth (GR), late growth (LG), and dormancy after (DA), according to Figure 2.

4.3.5 Data analysis

Initially, we evaluated the seasonal variability of NSC concentrations for each species in each site, growth stages, in the three different positions within the sapwood by calculating the average values for all individuals in the two years of monitoring. because of the observed similarities in NSC concentration trends, we tested the differences in average sugar concentrations for all species in each growth stage, by the position in the sapwood, using Kruskall-Wallis test and the post-hoc Dunn test, for the lack of normality and homoscedasticity in the data. We further delved into the species variability of NSC, we used principal component analyses (PCA) to understand the linear association among the vectors representing the variability of soluble sugars and starch, and to investigate how species cluster in terms of NSC variability along the entire study period. For this last analysis, we used the 95% confidence interval ellipses in the PCA.

In addition, correlation analyses were conducted to examine the relationship between sugar concentration at different positions in the sapwood and growth variables and total water deficit (TWD) using the dendRoAnalyst package (Aryal et al. 2020). All statistical tests were considered significant at a 95% confidence level ($p < 0.05$). All statistical analyses were conducted in R (R Core Team, 2024).

4.4 Results

The results indicate a substantial contribution of starch to the trunk NSC pool, for all species, reaching up to 125 µg mg^{-1} DW. It is followed by sucrose, glucose, and fructose, reaching up to 22 µg mg^{-1} DW, 17 µg mg^{-1} DW, respectively (Figuere 3). Rafnose is the lowest concentration soluble sugar in the xylem, reaching up to 2.5 µg mg^{-1} DW. The concentration of these soluble sugars tends to vary seasonally in the tree species in both sites.

Overall, the combined glucose and fructose pools show a decreasing trend from the period before the onset of the growth (DB, dormancy before), along the growing season (EG, early growth; GR, growth; LG, late growth), to the period right after the end of the growing season. This is the exactly opposite trend observed for sucrose that tends to increase from the beginning to the end of the growing season. Despite this overall trend in the NSC concentrations, species tend to exhibit individual nuances within the growing season, following two patterns, namely, a decrease in sucrose in the early growth (e.g *C. mandiocana*, *C. tomentosum*), or an increase in it (e.g. *E. pruinosa* and *E. uniflora*). Rafnose follows a similar pattern, with an increasing concentration trend from the beginning to the end of the growing season. Whereas the concentration of starch does not seem to follow a clear pattern shared by all studied species. The observational patterns are clearer in the first centimetre of the sapwood, closer to the cambium, where the concentration of NSC tends to be higher, for most species, and gradually decreases towards the third centimetre.

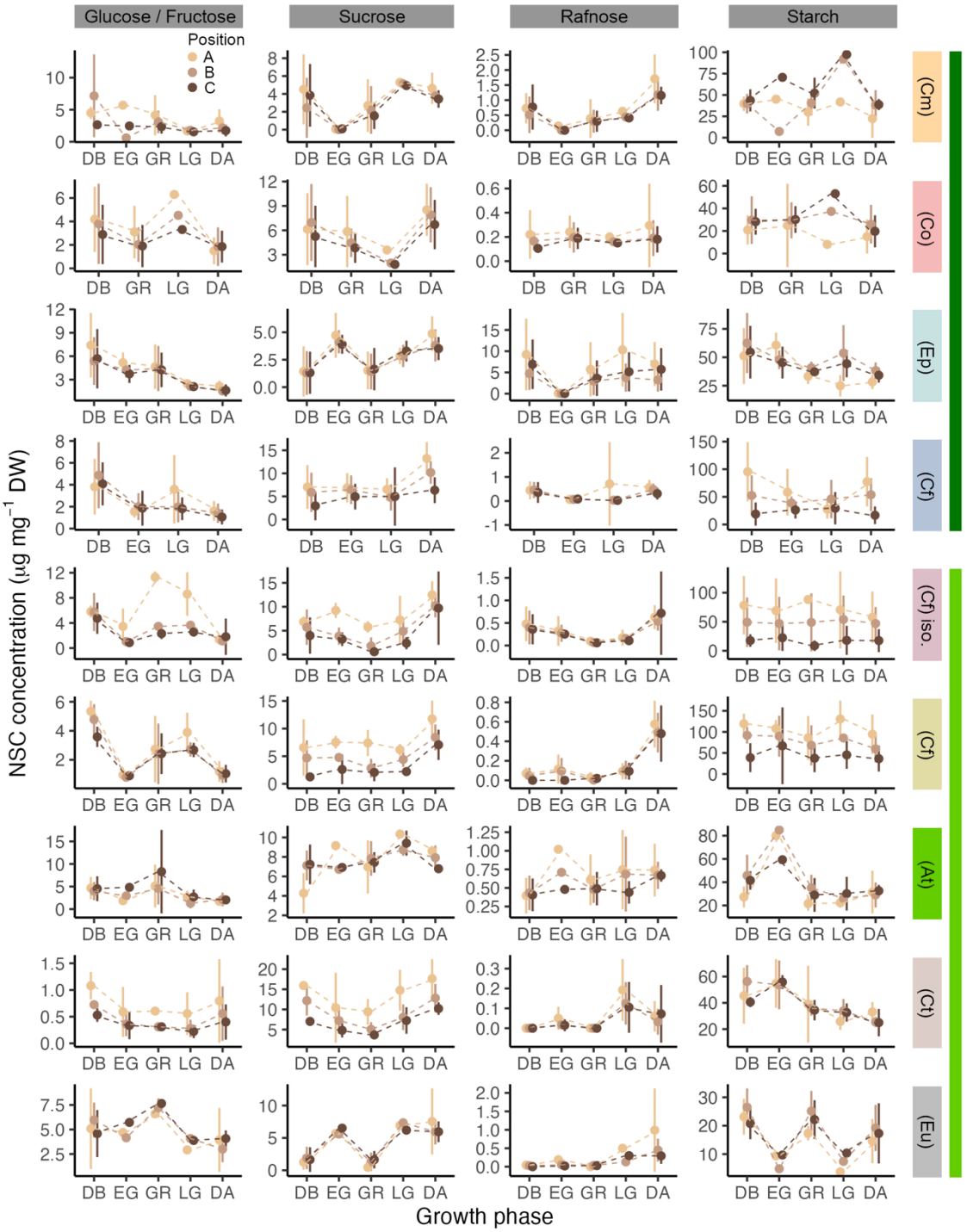


Figure 3. Non-structural carbon concentration for different species according to position A, B and C of the sapwood and growth phases. DB = dormancy before, EG = early growth, GR = growth, LG = late growth and DA = dormancy after; Cm= *C. mandioccana*, Co= *C. oblongifolia*, Ep= *E. pruinosa*, Cf= *C. fissilis*, Cf iso.= *C. fissilis* isolated, At= *A. triplinervia*, Ct= *C. tomentosum*, Eu= *E. uniflora*. Dark green indicates urban forest species and light green indicates species located in the urban park. The positions in the sapwood are: salmon = position A, green = position B, blue = position C.

These seasonal patterns were statistically confirmed at the site level (Figure 4). The concentration of the glucose and fructose combined pools, due to similar metabolic roles, confirms the statistically different concentrations before and during the growing season in comparison with the concentrations after the end of the growing season. Nonetheless, only the trees from the urban park displayed a reduction in the glucose plus fructose

concentrations during the early growth, followed by a replenishment of the pools during the middle of the growing season. The opposite trend is confirmed at the site level for sucrose, which displays statistically higher concentration during the end of the growing season and subsequent dormant period in both sites. A similar trend is observed for raffinose. For glucose plus fructose, sucrose and raffinose, seasonal trends are stronger in the first two sapwood segments (positions A and B), compared to the third segment (position C), where just few statistical differences have been observed. In contrast, the seasonal variation of starch at population level is more subtle particularly in the urban park, where concentrations are not statistically different among any of the growing phases.

The concentrations of the NSC between sites are mostly consistent among the growth phases between sites, with only minor particular differences. For instance, the urban park trees display a statistically significant lower concentration of glucose/fructose during the early growth, whereas the concentration of sucrose is higher during the late growth, compared to the urban forest trees. Likewise, concentrations of raffinose are also higher in the urban forests during the middle of the growing season for all three positions in the sapwood.

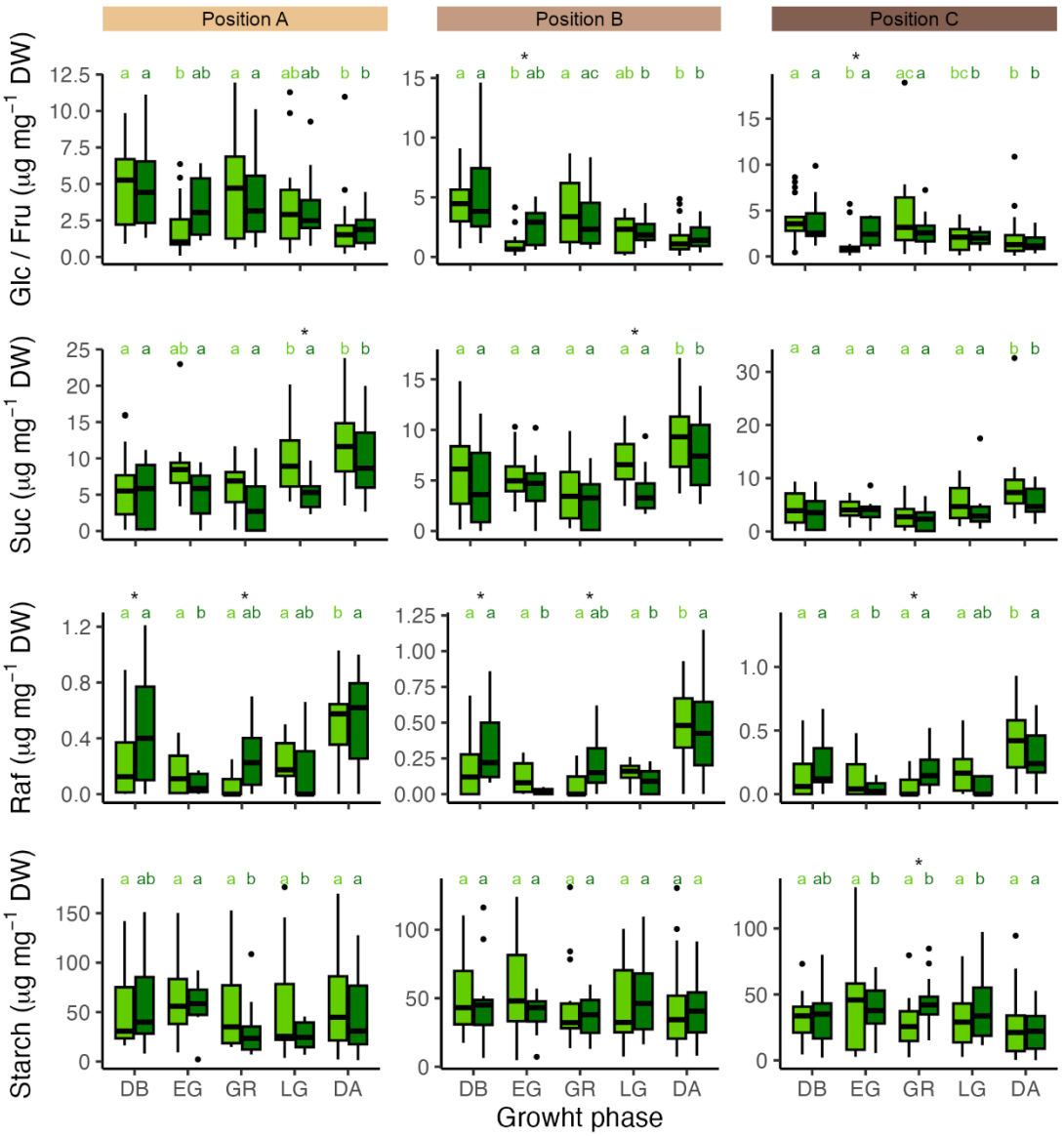


Figure 4. Boxplots displaying the distribution of the measured concentrations of NSC along the five growth phases (e.g., DB = dormancy before, EG = early growth, GR = growth, LG = late growth and DA = dormancy after), in each one of the three positions in the sapwood (Position A = first centimetre after the cambium, Position B = second centimetre, and Position C = third centimetre). Different letters indicate statistically significant differences among the growth phase in each site, either the urban park (light grey) or urban forest (dark grey), based on the Kruskal-Wali's test and the ad-hoc Dunn test. The black asterisk indicates a statistically difference between sites for the NSC concentrations in the growth phase. Both for $\alpha = 0.05$.

The principal component analysis (PCA) revealed that the first and second principal components explain between 62.88% and 68.10% of the NSC variability in the studied species. It also reveals three cluster of species in the first segment of the sapwood (position A, Figure 5). The first component is mostly characterising the glucose and fructose variability, whereas the second component is mostly representing the variability in starch. All three *C. fissilis* populations together with C. tomentosum tend to have higher concentrations of sucrose and starch, whereas all other species tend to have lower concentrations of sucrose and starch, but higher concentrations of Rafinose. In addition, *C.* tomentosum tend to have lower concentrations of glucose and fructose compared to all other studied tree species. The observed differences in NSC are not as evident in the other two

positions in the sapwood, since all species cluster together. For all sapwood segments, glucose and fructose shows a very strong association. In contrast, starch positively associated with sucrose in the first sapwood segment (position A), and negatively associated with raffinose, but these associations invert in the second and third sapwood segments (positions B and C).

The observed variability in NSC pools both at the site and species level is associated to some extent to the average growth rate of these trees (Figure 6). The combined glucose and fructose pool is negatively associated with growth only at the sapwood position B and positively associated with sucrose at all positions in the sapwood. On one extreme of these linear relationships, the evergreen and understory *E. uniflora* trees display the slowest growth rate and the highest concentration of glucose and fructose, and lowest concentration of sucrose. *C. mandiocana* follows as an evergreen but canopy species that ranks in second place as a slow-growing species with high concentrations of glucose and fructose and low concentrations of sucrose. On the other extreme of the statistically significant linear relationships, *C. tomentosum* and all *C. fissilis* populations, as deciduous and canopy species, display the highest growth rates, lowest concentrations of glucose and fructose and highest concentrations of sucrose. Despite the statistically significant associations between NSC and growth, there are no significant relationship between any NSC and tree water deficit as measured by the dendrometer along the two years of monitoring (Figure 7).

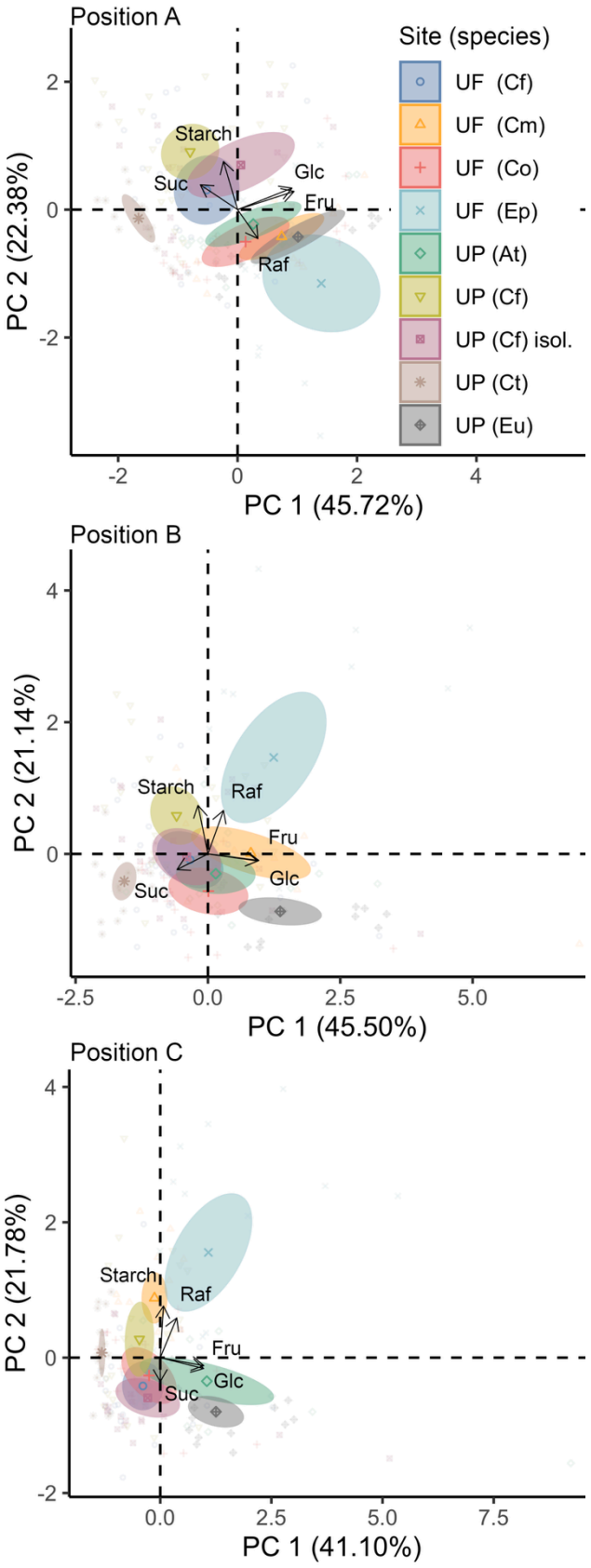


Figure 5. Principal Component Analysis (PCA) based on the concentrations of NSCs (glucose/fructose, sucrose, raffinose, and starch) in different tree species. The graph shows the distribution of samples in the first two principal components (PC1 and PC2), which explain 47.5% and 22.4% of the total variance, respectively. Vectors indicate the contribution and direction of the original variables to the principal components. Close clusters suggest similarity in the chemical profile between species or phases. Here we present a PCA for positions A, B, and C.

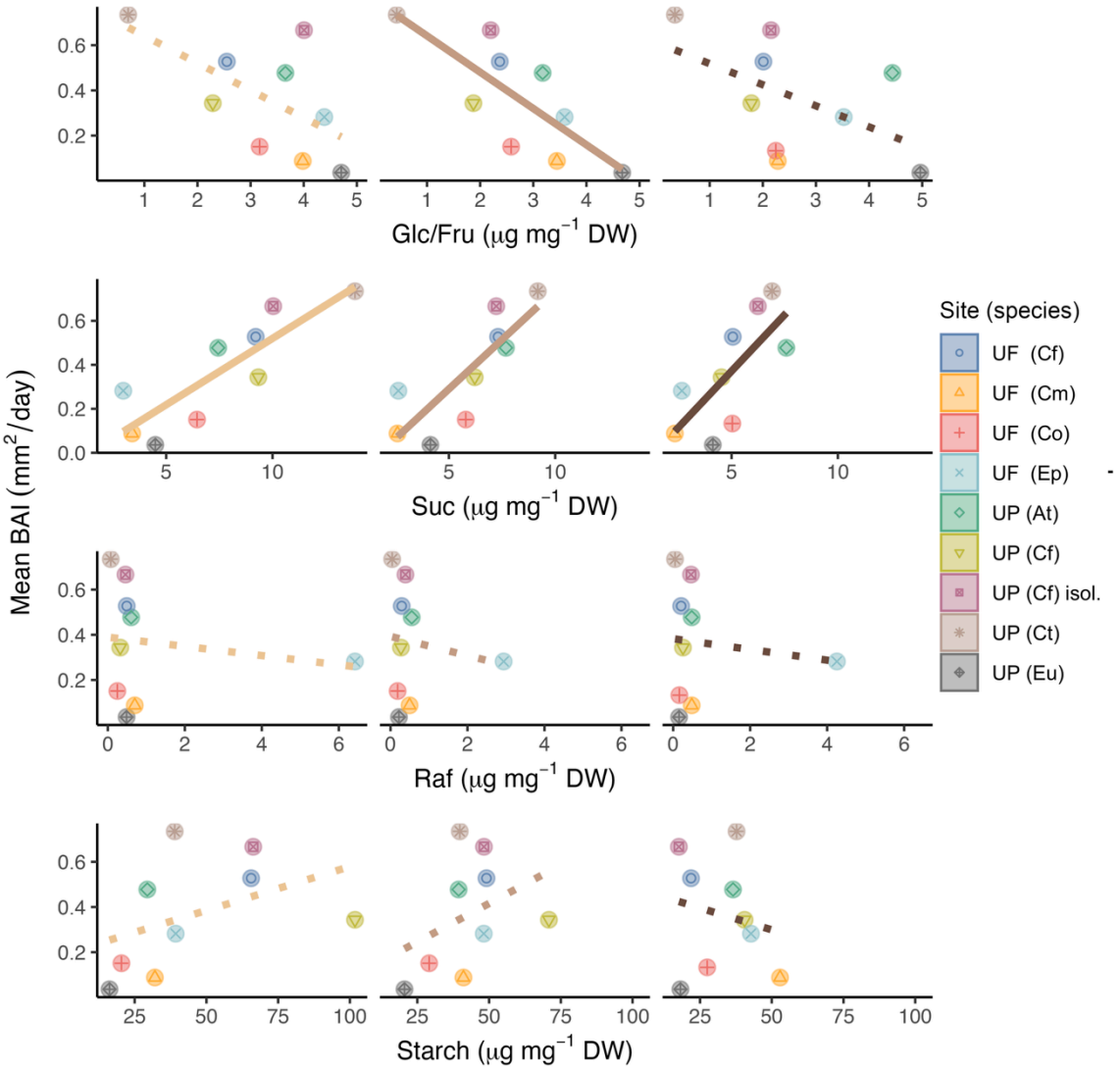


Figure 6. Linear relationship between the average NSC concentrations and the average BAI (mm²/hr) over 20 days before the NSC sampling. Straight lines indicate statistically significant association ($\alpha = 0.05$), and dotted lines non-signification association. The linear relationships were tested for the three positions within the sapwood: closest to the cambium (light brown), 2cm from the cambium (brown), and 3cm from the cambium (dark brown). Each point in the scatterplots represent the average values for each population, specimens in each site.

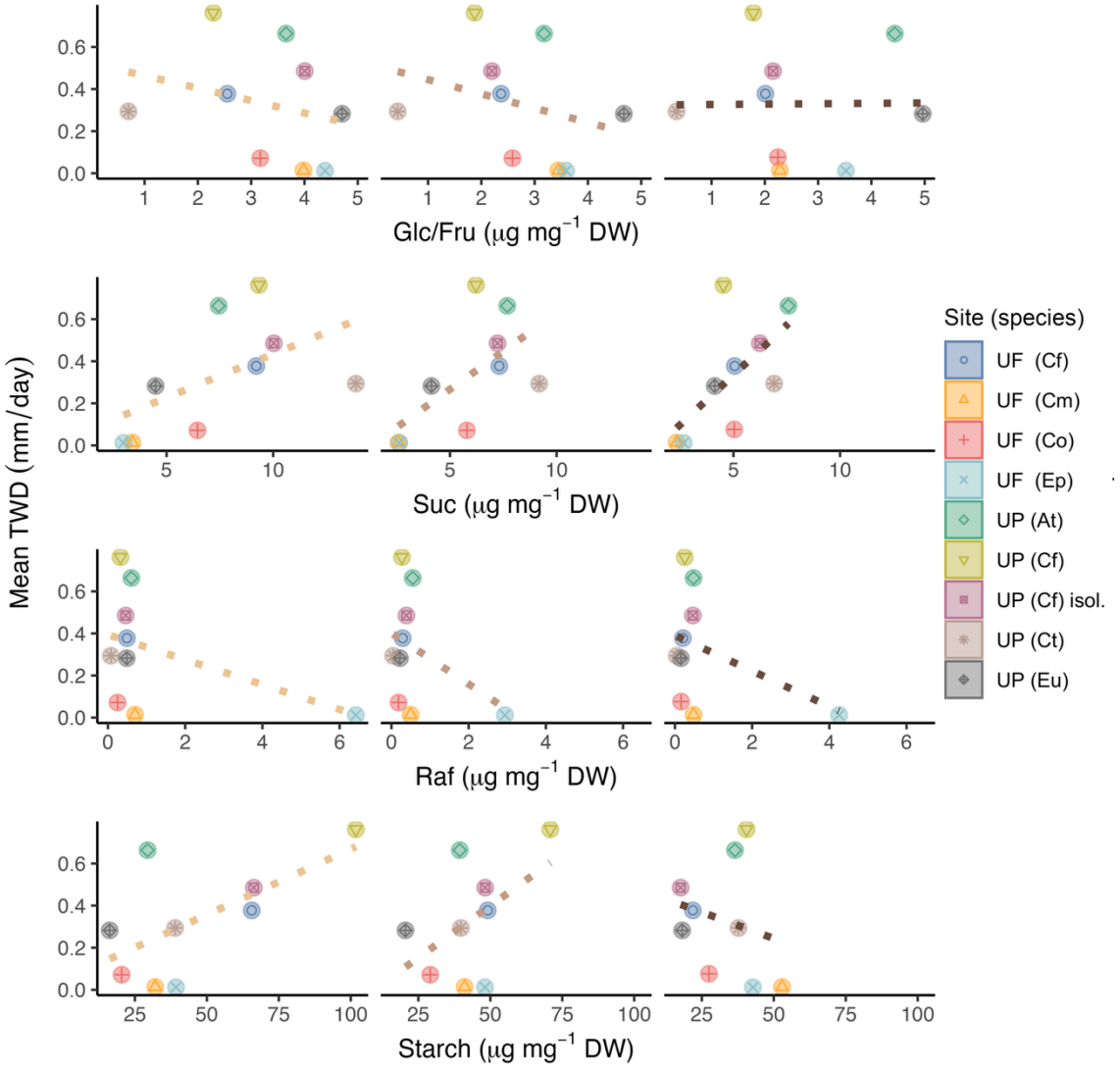


Figure 7. Linear relationship between the average NSC concentrations and the average TWD (mm²/hr) over 20 days before the NSC sampling. Straight lines indicate statistically significant association (α = 0.05), and dotted lines non-signification association. The linear relationships were tested for the three positions within the sapwood: closest to the cambium (light brown), 2cm from the cambium (brown), and 3cm from the cambium (dark brown). Each point in the scatterplots represent the average values for each population, specimens in each site.

4.5 Discussion

4.5.1. NSC seasonal trends

Trees display remarkable convergence in NSC seasonal dynamics, both at species and site levels. The common reduction in glucose and fructose during the active growth phase, followed by an increase in dormancy, suggests that these soluble sugars support cell division and cell-wall synthesis during the growing season, and later support tissue respiration during dormant season (Budzinski et al. 2016; Sami et al. 2019). Although a consistent pattern in this study, other studies have reported alternative pathways such as the seasonal accumulation of sucrose and raffinose at the end of the growing season, as a result

of the degradation of starch into soluble sugars for osmoprotection, during lower temperatures or stressful environment (Richardson et al. 2013; Ashworth et al. 1993).

In contrast, sucrose follows an opposite trend in the studied trees, with a progressive increase throughout the growing season that reinforces its function in the transport of carbon from source to sink, ensuring redistribution and continuous supply to expanding tissues (Jeandet et al. 2022; Dominguez & Niittyla, 2021). This observed pattern is consistently discussed in reviews about carbon transport, where sucrose is highlighted as the predominant form of carbon in transit within plants (Dominguez & Niittyla, 2021; Lemoine, 2000; Aluko et al. 2021). Starch showed relative stability throughout the growing season, suggesting that this carbohydrate plays a role of a long-term reserve not available in response to rapid changes in carbon demand in the wood (Oberhuber et al. 2011; El Zein et al. 2011).

There are, however, nuances, in the seasonal patterns at site level, with significantly lower concentrations of glucose and fructose in the early growth and higher investment in sucrose at the end of the growing season in the urban park. Given the higher temperatures and lower groundwater availability in the urban park compared to the urban forest (Candido et al., *under review*), these nuances point to a higher demand for fast reserves to support early growth under less favourable growth conditions. Followed by a fast replenishment through the transport of sucrose by the end of the growing season (Guo et al. 2025; Signori-Muller et al. 2021; Moser-Reischel et al. 2019). Although the reasoning behind these nuances discussions are well supported by the literature, it remains unconclusive if they can be attributed to site conditions only, or to species composition in each site.

Partially because NSC concentration vary among species functional groups. Contrasting patterns have been observed, for instance the higher investment in starch and sucrose fraction by *C. fissilis* and *C. tomentosum,* whereas *E. uniflora, C. mandiocana, C. oblongifolia*, and *E. pruinose* show lower investment in starch and sucrose and relatively higher investment in rafinose. The investment in glucose and fructose is rather similar in all species, but lower for *C. tomentosum*. This interspecific mosaic is consistent with evidence that the ability to store and remobilise NSC is an ecological trait that varies widely among species according to their strategies, like leaf deciduousness (Piper, 2020; Furze et al. 2018; Furze et al. 2021; Xu et al. 2024). In general, deciduous trees tend to exhibit higher total carbon stores due to the need to sustain spring full crown flush that are mainly carbon sinks until full expansion of the leaf blade. Whereas evergreen species maintain more stable levels and often a higher proportion of soluble sugars throughout the year to support continuous

metabolism and osmoprotective functions (Piper, 2020; Furze et al. 2018; Martínez-Vivalta et al. 2016).

4.5.2. The role of NSC on growth

The role of allocation and mobilization of NSCs to support growth and cope with water stress remains one of the most debated topics in plant ecophysiology (Adams et al., 2013; Galiano et al., 2011; Piper, 2011, Gruber et al., 2012; Jin et al., 2018). In the present study, species phenological and growth strategies seem to be associated with specific soluble sugar pools in the stem. Within the spectrum of fast-growing deciduous species to the slow-growing evergreen species, there is a significant shift in the allocation of NSC from sucrose pools to cope with the high carbon demand during xylogenesis, to glucose and fructose to support metabolism over prolonged periods (Dominguez & Niittylä, 2021). The observed negative correlation between glucose/fructose and growth may be explained by several, non-mutually exclusive mechanisms. First, elevated growth rates may increase metabolic demand, leading to intensified hexose consumption and consequently lower local concentrations. Second, glucose and fructose may act as regulatory or signalling molecules, modulating processes such as cell division and expansion. Third, constraints in sucrose transport and remobilisation may indirectly influence local hexose availability (Hartmann & Trumbore, 2016; Chen et al., 2025). This dissociation between hexoses and growth reinforces that different fractions of NSC play complementary roles: hexoses, acting in local maintenance and osmotic adjustments, and sucrose, more directly linked to biosynthesis and cambial growth (Saddhe et al. 2021; Traversari et al. 2018).

4.5.3. NSC to cope with water stress

It doesn’t come unnoticed the lack of evidence supporting the association between NSC pools and tree water deficit in the present study. This association has been largely reported in the literature, but evidence does not always converge. Some studies report the depletion of reserves during droughts, suggesting NSC consumption for the maintenance of vital functions, particularly of long-term reserves like starch (Adams et al., 2013; Galiano et al., 2011; Piper, 2011). Other studies report the accumulation of NSC under stress, possibly as a surplus of carbon not used in growth (Correia et al., 2018; Crous et al., 2011; Liu et al., 2019). And finally, some have not detected any significant changes in the NSC pools (Gruber et al., 2012; Jin et al., 2018), in line with the results of the present study. These inconsistencies likely emerge from different stress intensity and duration, in addition to

species' phenology and life strategy (Piper & Paula, 2020; Ramirez et al. 2024; Herrera-Ramirez et al. 2023).

In scenarios of urban water deficit, evidence becomes even more complex. Recent studies indicate that, under moderate drought conditions, trees often maintain or even accumulate soluble sugars as an osmotic adjustment mechanism, while starch reserves remain relatively stable (He et al. 2020; Wang et al. 2025). Under severe and prolonged droughts, however, there is progressive starch depletion, compromising long-term resilience (He et al., 2023; Peltier et al., 2025). In this context, the composition of NSCs is decisive for tolerance, since hexoses contribute to osmotic maintenance and stress signalling, while sucrose sustains carbon transport and cambial activity (Saddhe et al. 2021; Afzal et al. 2021).

The observed lack of a significant association between NSC and TWD in the studied tree species in the urban park and urban forest of São Paulo likely could represent a specific strategy of the sampled trees as reported by previous studies. Or, it could indicate that the stress recorded by the dendrometers represent only regular seasonal water stress and not chronic severe water stress that could lead to the mobilization of the NSC pools (Blumstein et al. 2023; Trueba et al. 2024; Li et al. 2018; Signori-Muller et al. 2021).

4.5.4. NSC compartmentalisation in the sapwood

The results of this study not only provide valuable insights into the seasonal dynamics, species-specific strategies, and their association with growth and stress, but also evidence the compartmentalization of the NSC through a functional radial organisation in the sapwood. The radial gradient of NSC concentration in sapwood is well known from the literature, as well as the higher seasonal amplitude in NSC concentrations closer to the cambium (Locosselli and Buckeridge 2018). But no study has shown that the species strategies are mostly expressed by the NSC changes in the first centimetre closer to the cambium. This is in line with evidence that internal reservoirs function as long-term insurance rather than as a source for short-term demands (Sala & Meinzer, 2012; Furze et al 2019, Locosselli and Buckeridge 2018), suggesting fine species-level adjustments possibly linked to their tolerance strategies (Richardson et al. 2015; Fajardo & Piper, 2021; Zhou et al. 2024).

Evidence indicates that, according to the NSC gradient, not all accumulated

non-structural carbohydrates (NSC) are readily accessible due to anatomical compartmentalization. The area closest to the cambium is utilized the most by trees (Arzac et al. 2017; Furze et al. 2020; Blumstein et al. 2023). However, our study revealed that growth is significantly associated only with the combined glucose and fructose pools in the second centimeter from the cambium. This pattern suggests that this middle region of the sapwood may be a key site for rapid hexose consumption, likely to support high rates of local cambial activity. No similar association was observed for sucrose (Lu et al. 2025). This finding implies that glucose and fructose serve as quick reserves that exhibit clear seasonal fluctuations, supporting primary metabolism and tissue construction, primarily associated with position B in the xylem. Additionally, this process is maintained by a constant mobilization of sucrose for carbon transport, bridging carbon sources and sinks.

4.5.5. Implications for urban trees functioning

Our study shows that growth is directly related to NSCs, but TWD is not directly related to NSCs. Since NSCs do not dissociate tree physiology from climatic conditions, all trees tend to respond very similarly to environmental stress, despite differences in their growth strategies. In the urban context, understanding the dynamics of NSCs demonstrates that the assessment of urban tolerance should incorporate physiological indicators, such as NSCs, which provide information on the resilience and functional maintenance of trees in the face of extreme environmental conditions (D'Andrea et al., 2021; He et al., 2020). Second, they emphasize that species selection for urban parks in tropical regions should consider not only phenological and taxonomic diversity, but also carbon storage and mobilization strategies that confer differential tolerance to water stress, ensuring a more robust provision of ecosystem services, even during extreme weather events (Sala & Meinzer, 2012; Saddhe et al., 2021). The tolerance of urban trees is a multifaceted phenomenon, dependent on interactions between species diversity, phenological strategies, growth patterns, and internal carbon physiology (Candido et al., *under review*). In urban contexts, where species coexist with chronic stresses (heat islands, paving, pruning, soil water deficit), recent literature suggests that NSC storage or use strategies can modulate performance and resilience, but also warns of specific knowledge gaps in cities (e.g., lack of seasonal series by organ and radial gradient, and scarcity of individual sugar measurements) (Hartmann & Trumbore, 2016; He & Yan, 2018).

4.6 Conclusion

In summary, this study advances our understanding of NSC reserves dynamics in urban trees. We identified consistent seasonal patterns of soluble sugars across species and sites revealing a convergent strategy in the use of NSC regardless of the species' growth and phenology strategies. In contrast, allocation of carbon to different pools is species-specific. Species clustered into different functional groups based on their phenology - deciduous versus brevidecidous / evergreen species – that occupy opposite ends in the growth / NSC spectrum. The strong relationship between growth and NSC likely buffers trees' growth responses to climate, leading to the expected diversity in climate responses of trees. The lack of a direct association between NSC pools and stem water deficit, as a measure of water stress, suggests that NSC pools cannot decouple tree physiology from water stress, explaining the undesired synchrony in the responses of trees to unfavourable conditions. Finally, this study reveals a clear compartmentalization of the NSC dynamics in the sapwood, adding a spatial dimension to our understanding of carbon storage and mobilization to support tree growth in cities.

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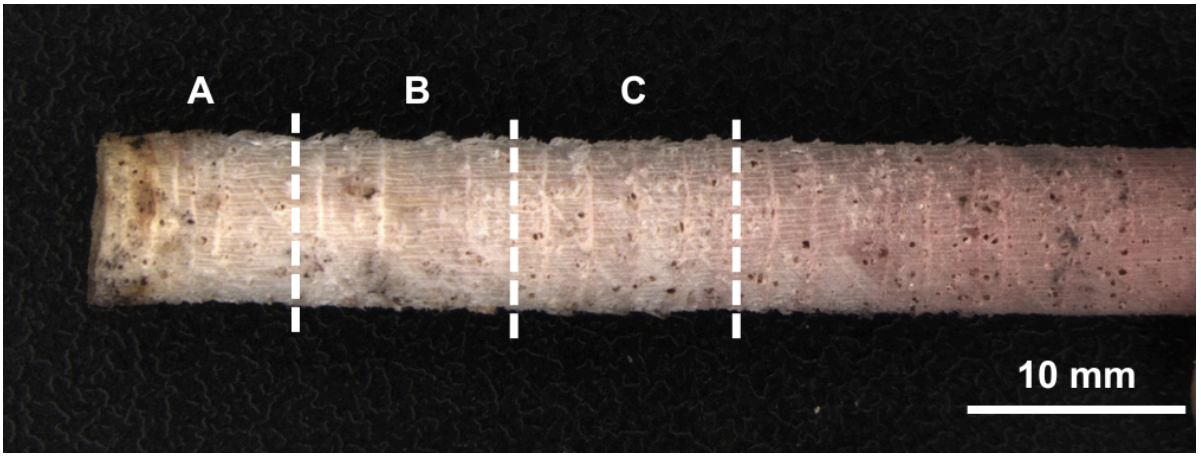
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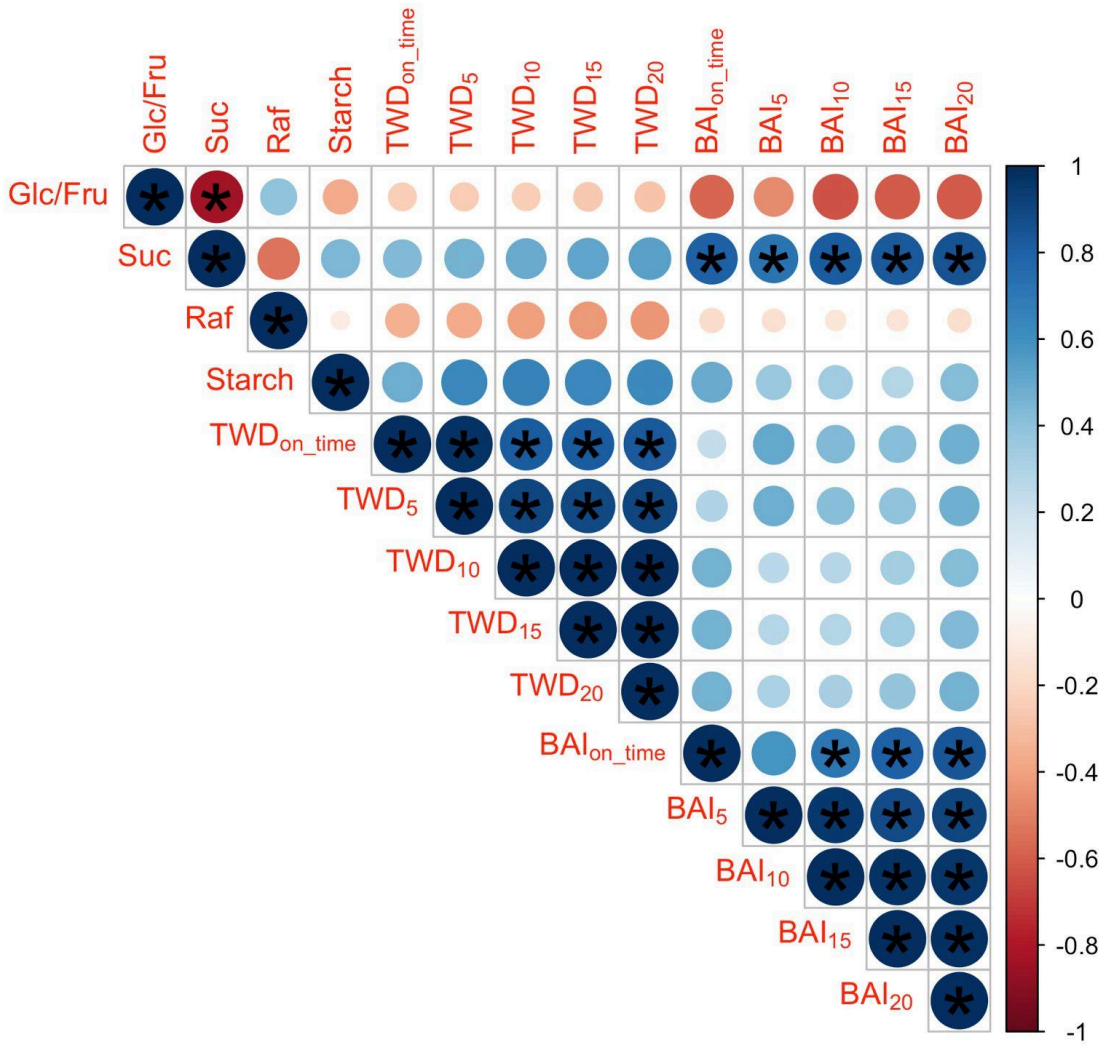
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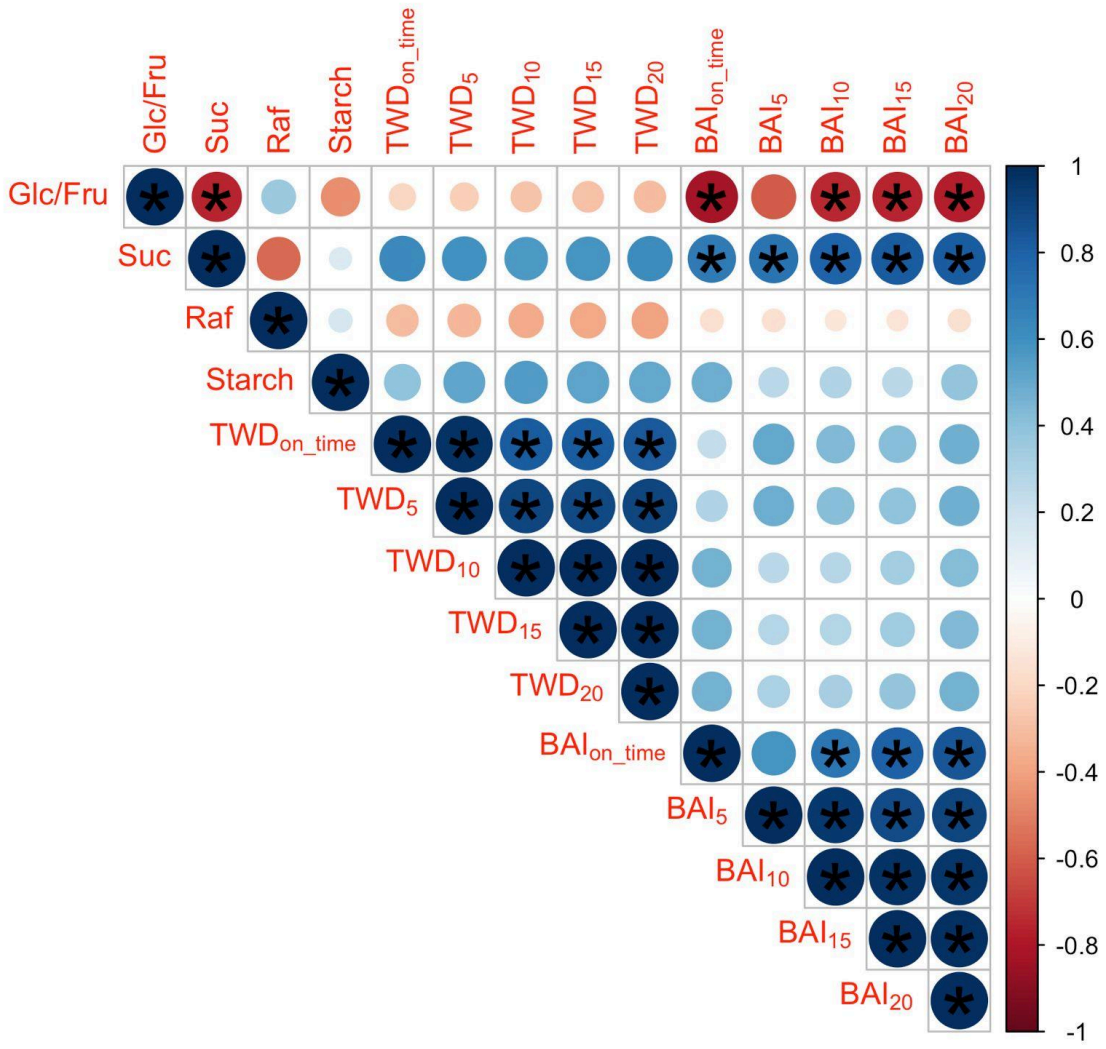
4.8 Supplementary material



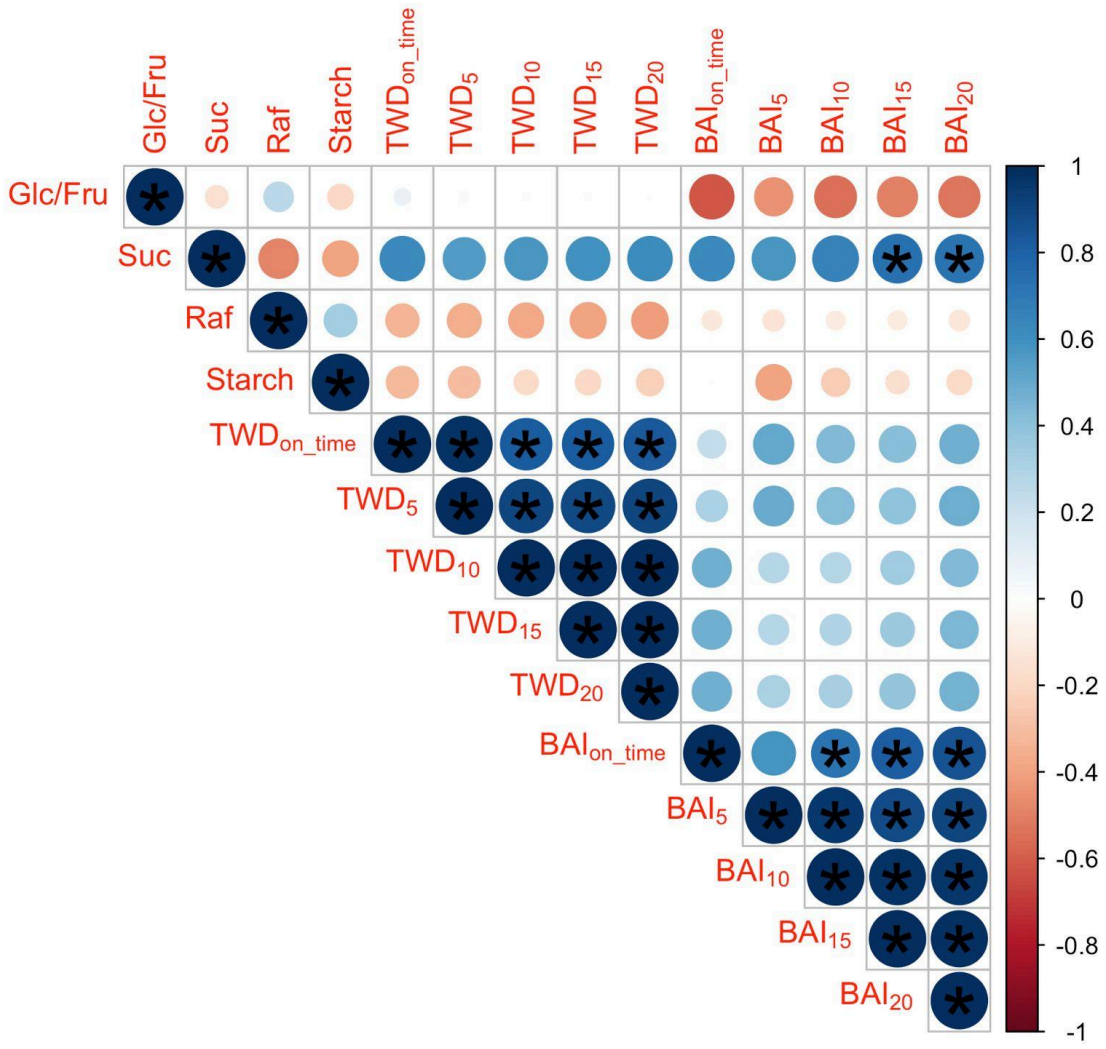
SM Figure 1. *C. fissilis* sample photographed through the stereomicroscope. Part A. Near the cambium; Part B; Median; Part C. Near the limit of sapwood and heartwood.



SM Figure 2. Pearson correlation matrix between NSC and species tree water deficit (TWD) and basal area increment (BAI) for all species from the urban park and urban forest. Correlation coefficients are represented by both the size and color intensity of the squares. All correlations are statistically significant ($p < 0.01$).



SM Figure 3. Pearson correlation matrix between NSC and species tree water deficit (TWD) and basal area increment (BAI) for all species from the urban park and urban forest. Correlation coefficients are represented by both the size and color intensity of the squares. All correlations are statistically significant ($p < 0.01$).



SM Figure 4. Pearson correlation matrix between NSC and species tree water deficit (TWD) and basal area increment (BAI) for all species from the urban park and urban forest. Correlation coefficients are represented by both the size and color intensity of the squares. All correlations are statistically significant ($p < 0.01$).

5. Discussion

The systematic review presented in Chapter one highlighted the need to integrate three central pillars for the selection of tree species in urban environments: ecosystem services, tolerance to stress conditions, and potential disservices. The review demonstrates that the predominant focus of the literature is on ecosystem services, especially the retention of atmospheric pollutants, followed by species resilience, while disservices are still treated marginally. This fragmented approach compromises the construction of frameworks applicable to the reality of cities, especially in subtropical and tropical regions, which, while concentrating the greatest tree biodiversity, are also the most exposed to climatic extremes and intense anthropogenic pressures (Grimm et al., 2008; Vaz Monteiro et al., 2017).

The predominance of studies conducted in temperate regions, except China, which has made significant progress in the functional assessment of urban species (Cai et al. 2019), highlights a critical gap for megadiverse countries in the Global South. In these contexts, dependence on exotic species introduced since the colonial period (Potgieter et al., 2017) has limited the exploitation of the potential of native species, which could offer ecosystem services adapted to local conditions and greater tolerance to the water and heat stress characteristic of tropical cities. Furthermore, the integration of the three pillars remains methodologically challenging. Studies that combine services, tolerance, and disservices tend to rely on secondary data or predictive modelling (Roy et al., 2012; Vieira et al., 2018), which limits the ability to capture the complexity of ecological processes at the urban scale. In this sense, the construction of local and global databases of functional traits of urban trees becomes an essential strategy for advancing the field (Watkins et al., 2021; Tamene et al., 2024). Widely used traits, such as height, DBH, and phenology, offer important starting points, but their relationship with the three pillars is not linear, and it is necessary to understand optimal tree development intervals to maximise benefits and minimise risks (Pretzsch et al., 2017).

Based on this review, it is possible to identify strategic paths to fill gaps and move towards robust species selection frameworks. Among these, the following stand out: (i) expanding studies on disservices, since conflicts with urban infrastructure, allergies, and fall risks have direct impacts on the well-being of populations (Riedman et al., 2022); (ii) fostering international research networks to compare the performance of species under different climatic and urban conditions; and (iii) developing long-term monitoring programmes, which are essential for capturing the dynamics between services, tolerance and

disservices throughout the life cycle of trees (Conway & Vander Vecht, 2015). Thus, the findings in Chapter one emphasise that urban afforestation should not only be planned to maximise immediate benefits, but also to minimise risks and ensure long-term resilience. This approach is particularly urgent in tropical megacities such as São Paulo, where the combination of high biodiversity enables more evidence-based studies.

In Chapter two, we advance our understanding of tree diversity in urban green areas of São Paulo. Although diversity is often conceived as environmental resilience (Isbell et al., 2015; Mori et al., 2013), the results show that this mechanism only materialises when species exhibit complementary physiological responses to environmental stress. In the case studied, even though the native species analysed had different phenology and growth strategies, the homogeneity of their responses to water stress indicates that diversity alone does not guarantee functional resilience. This finding reinforces the risk that distinct species share similar vulnerabilities, limiting the potential to mitigate the effects of climate extremes on urban ecosystem services.

Furthermore, the finding that trees in urban park areas suffer up to 400% more water deficit compared to trees in urban forest fragments reveals how canopy structure and soil characteristics modulate the physiological response of species. These results directly dialogue with the pillars of Chapter 1, especially that of tolerance to urban conditions, demonstrating that stress tolerance does not depend only on diversity itself, but on the interaction between species composition, vegetation structure, and urban microclimate. This perspective has relevant practical implications: public policies that seek to increase tree cover in tropical cities cannot rely solely on species diversity as a criterion for resilience, but must prioritise the selection of species with contrasting and complementary physiological strategies capable of mitigating the effects of extreme weather events (Vannoppen et al., 2020; Anderegg et al., 2019). The second chapter contributes to reducing a key gap identified in the systematic review: the scarcity of empirical evidence on tree species in megadiverse regions of the Global South. Although many species selection frameworks have been developed for temperate climates, the results from São Paulo reveal that ecological functioning in tropical cities obeys its own environmental filters, especially those associated with water stress, which has also been observed in other regions. In this sense, this study was essential not only to fill geographical gaps but also to test the validity and generality of ecological theories applied to urban forests.

In the third chapter, we present an analysis of NSCs that provides a physiological perspective complementary to the findings in chapter two, allowing us to understand the

internal mechanisms that modulate the response of tropical urban trees to climate and water deficit. The results reveal that NSC concentration varies significantly between species, phenological stages, and radial positions in the xylem, especially near the cambium, indicating distinct strategies for storage and mobilization of reserves. But has a common pattern for the NSC dynamics. The active mobilization of glucose and fructose during periods of growth and their accumulation during dormancy show that these fractions are essential to meet immediate metabolic demands, while sucrose and raffinose play strategic roles in transport and osmotic protection (Budzinski et al., 2016; Richardson et al., 2013; Dominguez & Niittyla, 2021). This intra- and interspecific heterogeneity reinforces the idea that functional resilience depends not only on taxonomic diversity but also on complementary physiological responses among species.

The data obtained show that the dynamics of NSCs are related to growth for part of the sapwood, but not to water deficit. The absence of a correlation between NSC and TWD indicates that the availability of reserves does not automatically translate into growth or structural reinforcement of the xylem, corroborating studies that point to a dissociation between soluble carbon metabolism and structural biomass (Gall et al., 2015; Hartmann & Trumbore, 2016). In contrast, the negative relationship between hexoses and growth, especially in the middle region of the xylem (position B), suggests mechanisms of intense metabolic consumption, osmotic adjustments, and regulatory functions that ensure the maintenance of cambium and cell expansion even under water stress (Woodruff et al., 2011; Tomasella et al., 2019). These findings highlight the importance of considering not only the stock of NSCs, but also the biochemical identity of the fractions, their radial distribution, and their interaction with independent structural processes.

Together, the second and third chapter reveals that the lower homogeneity in growth among tree species is likely due to species-specific utilization of NSCs. In contrast, the high synchrony in TWD across trees appears to result from the fact that NSCs are not directly linked to water status. Because NSCs do not decouple tree physiology from climatic conditions, all trees tend to respond in a highly similar manner to environmental stress, despite differences in their growth strategies. In the urban context, understanding the dynamics of NSC demonstrates that the assessment of urban tolerance should incorporate physiological indicators, such as NSCs, which provide information on the resilience and functional maintenance of trees in the face of extreme environmental conditions (D'Andrea et al, 2021; He et al., 2020). Second, they emphasize that the selection of species for urban parks in tropical regions should consider not only phenological and taxonomic diversity, but also carbon storage and mobilization strategies that confer differential tolerance to water

stress, ensuring a more robust provision of ecosystem services even during extreme weather events (Sala & Meinzer, 2012; Saddhe et al., 2021). Finally, this thesis indicates that the tolerance of urban trees is a multifaceted phenomenon, dependent on interactions between species diversity, phenological strategies, growth patterns, and internal carbon physiology. While it demonstrates an advance in the understanding of native species in the São Paulo region for urban afforestation, it can also guide us toward planning denser green areas or areas with more irrigation, and selecting non-dominant species, encouraging us to explore our biodiversity.

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6. Final considerations

This study provides an integrative perspective on the functioning of urban trees, linking growth dynamics, water status, and non-structural carbohydrate (NSC). Our findings highlight that, regardless of urban green cover type, tree growth is consistently influenced by climatic variables, with precipitation acting as the main determinant of growth and vapor pressure deficit controlling tree water deficit. Despite the functional and phenological diversity among species, the observed homogeneous response to climate indicates that common environmental pressures, such as water limitation and evaporative demand, serve as structuring forces in urban environments, while also signaling the vulnerability of urban trees to extreme climate events, which may compromise the provision of ecosystem services.

The analysis of NSC dynamics revealed consistent seasonal patterns of soluble sugars across species and sites, indicating a convergent strategy in NSC utilization, whereas carbon allocation to different pools was highly species-specific. Functional grouping based on phenology (deciduous versus brevidecidous/evergreen) demonstrated that trees occupy opposite ends of the growth/NSC spectrum. The strong association between growth and NSCs likely buffers growth responses to climate variability, but the lack of direct linkage between NSC pools and TWD shows that NSCs cannot decouple tree physiology from water stress, explaining the high synchrony in responses to unfavorable conditions. Moreover, the clear compartmentalization of NSC dynamics in the sapwood adds a spatial dimension to carbon storage and mobilization, enhancing our mechanistic understanding of urban tree physiology.

Taken together, these results underscore the importance of integrating multiple pillars: ecosystem services, tolerance, and disservices into urban tree research. To advance urban forest management and the “right tree in the right place” principle, we recommend expanding studies to underrepresented regions and species, incorporating disservice assessments, establishing long-term monitoring programs, creating global trait databases, and fostering international research networks. Such integrative approaches will improve the selection of resilient species, enhance ecological functioning, and ensure the sustained provision of ecosystem services under changing climatic conditions.