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An evidence-based protocol for developing lists for tree planting

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Abstract

Tree planting is increasingly being promoted for urban greening, carbon sequestration, and to enhance biodiversity. However, poorly planned and executed tree-planting schemes can inadvertently contribute to biological invasions which often have detrimental effects on local ecosystems, economies, and human well-being. Therefore, sustainable, rigorous, repeatable and transparent species selection strategies need to be employed to maximise ecosystem benefits.

Using the Polyphagous Shot Hole Borer (PSHB, *Euwallacea fornicatus*) invasion in South Africa as a case study, we used a multi-criterion approach, incorporating national lists of regulated invasive plant species, records of their invasiveness in other regions, and data on PSHB susceptibility to develop a strategic decision protocol for identifying tree taxa that can be safely considered in planting schemes. Using a recently published national planted tree inventory, we apply this protocol to the City of Cape Town, South Africa, a metropolitan municipality experiencing widespread tree and PSHB invasions.

Among the 445 planted tree taxa evaluated in Cape Town, 85 are regulated nationally as invasive species (and so must not be used), while 49 are deemed suitable candidates for planting initiatives (i.e., a safe list).

This protocol provides evidence-based guidance for tree planting to mitigate the risk of tree invasions and to reduce the spread and impact of associated pests and pathogens. It can provide support for environmental planners and managers in making informed decisions to safeguard ecosystems and optimise ecosystem services. This protocol is replicable and adaptable for use in other regions and offers a robust model for sustainable planting, restoration planning, and invasive species management.

Keywords: biological invasions, ecosystem services, green infrastructure, pest management, treescapes, tree invasions, tree planting, urban greening

Introduction

Tree planting initiatives have gained widespread attention as a nature-based solution to global environmental challenges, including urban greening, carbon sequestration, biodiversity conservation, and climate-change mitigation (Roy et al. 2012, Bastin et al. 2019, Seddon et al. 2020). Across the world, governments, non-profit organisations, and communities are investing in large-scale tree-planting programs to restore ecosystems, improve air and water quality, and create green spaces that benefit both human health and wildlife (e.g., Bonn Challenge, the Great Green Wall Initiative, Trillion Trees Campaign). Many of these tree-planting programs focus on rapid planting efforts to meet ambitious planting targets, often overlooking major ecosystem impacts (Bond et al. 2019) and other critical considerations such as appropriate species selection, site suitability, and the potential risks of future pest and pathogen invasions (Brancalion et al. 2020, Holl and Brancalion 2020).

As tree-planting initiatives gain momentum – often with considerable financial, political and societal support - there is growing concern that poorly planned and executed efforts will inadvertently introduce new biological invasions or exacerbate existing ones (Brundu and Richardson 2016, Blanchard et al. 2017). Such invasions, often facilitated by the planting of non-native tree species, can have devastating effects on ecosystems, economies, and human health (Richardson and Rejmánek 2011). The planting of native species, if done without regard to local pest dynamics, can also provide suitable hosts for invasive pests and pathogens (Paap et al. 2018). In some cases, the very trees intended to enhance biodiversity and provide ecosystem services can become vectors for pest proliferation, undermining the long-term goals of the initiative. These oversights can lead to reduced biodiversity, and compromised ecosystem services, creating the need for costly management interventions (Holl and Brancalion 2020).

South Africa has a long history of tree introductions, beginning with European colonisation in the mid-17th century (Poynton 1984, Richardson et al. 2003). The motivations for tree-planting have evolved over time – from meeting basic needs such as food, fuel, shade, and soil stabilisation to later bolstering the forestry sector and improving agricultural systems (Richardson et al. 2003), and, more recently, enhancing urban environments (Potgieter et al. 2022). Despite the benefits of tree-planting, this practice has generated considerable controversy. For instance, many planted non-native tree species introduced for cultivation have become invasive, spreading beyond cultivation areas and causing major negative impacts (van Wilgen et al. 2022). A substantial invasion debt has accumulated, as many species have yet to fully realize their invasive potential or cause maximum impact (Rouget et al. 2016). Shifting environmental and socio-political conditions are influencing tree-planting policies and practices in South Africa. Rapid urbanisation is driving the development of new and expanding urban ecosystems, and efforts to retrofit existing cities to enhance sustainability and liveability (van Staden and Stofberg 2021). Increasing tree cover has been deemed a key component of strategies to build resilience against global change.

The growing globalisation of trade, increased movement of people and goods, and changing climate patterns have contributed to a dramatic increase in the spread of pests and pathogens around the world (Hulme 2009, Raum et al. 2023). One of the most recent examples is the polyphagous shot hole borer (PSHB, *Euwallacea fornicatus*), an invasive ambrosia beetle, native to South-east Asia, that has caused widespread damage around the world (Stouthamer et al. 2017, Van Rooyen et al. 2021). PSHB, along with its symbiotic fungus *Neocosmospora euwallaceae* L. Lombard & Crous, 2019 (previously *Fusarium euwallaceae*), infests hundreds of taxonomically diverse tree species, leading to significant tree mortality in both urban and natural environments (Freeman et al. 2016, Townsend et al. 2025). Invasive species like PSHB thrive in urban landscapes, where a high density of susceptible host trees, coupled with human-mediated movement, accelerate the invasion process (Raum et al. 2023, Paap et al. 2020, Potgieter et al. 2024).

Although South Africa has faced extensive challenges from invasive species, particularly trees (van Wilgen et al. 2020, 2022), the country has until now avoided large-scale ecological disruptions from tree disease epidemics – though this is changing (Wilson et al. 2020). The PSHB infestation in South Africa is part of a broader pattern where hundreds of tree species, many of which are critical for ecosystem services, are increasingly vulnerable to pests and pathogens (Paap et al. 2017, Raffa et al. 2023). This alarming trend underscores the importance of developing proactive measures to mitigate the risk of biological invasions in tree-planting efforts. While tree-planting remains a valuable strategy for conservation and climate change mitigation, there is a pressing need to shift from *ad hoc* species selection to more strategic and evidence-based approaches that consider ecological risks.

Specifically, in the case of the PSHB infestation in South Africa, resulting urban tree mortality necessitates rigorous and transparent guidelines for replacement plantings that do not exacerbate plant invasions in South Africa. Brundu et al. (2020) provide global guidelines for the sustainable use of non-native trees, outlining the precautions that should be taken when introducing and planting non-native trees. Their guidelines include eight key recommendations, including prioritising native or non-invasive non-native species, complying with regulations, assessing invasion risks under global change scenarios, implementing tailored silvicultural practices, and promoting early detection, stakeholder engagement, and international collaboration. These guidelines aim to support sustainable forestry, biodiversity conservation, and global environmental objectives. Further, Kumschick et al. (2024) outline considerations for developing and implementing a safe list for non-native taxa including criteria for risk assessments, stakeholder involvement, and regulatory mechanisms to ensure effective application.

Our goal is to operationalise these guidelines into a strategic protocol for tree selection that mitigates the invasion risk of both the planted trees and their associated pests and pathogens, using the PSHB invasion in South Africa as a case study.

Identifying tree taxa suitable for planting

We present a workflow that outlines the key steps needed to identify tree taxa suitable for planting (Fig. 1). In our example, we focus on trees suitable for planting in Cape Town, South Africa considering the devastating impacts of PSHB on urban forests in the county (de Wit et al. 2022). The process begins by compiling an initial list of candidate tree taxa, followed by defining the filtering and inclusion criteria. Relevant taxa lists are then collated for each criterion and cross-referenced with the suitable tree taxa list. A decision protocol is subsequently applied, resulting in a final set of recommended species for planting.

Step 1. All tree taxa

The first step involves compiling a comprehensive list of all tree taxa relevant to the study region. Data can be sourced from global and regional biodiversity databases such as the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/), GlobalTreeSearch (https://tools.bgci.org/global_tree_search.php), iNaturalist (for cultivated records, https://www.inaturalist.org/), and national botanical databases. Gardening books, nursery catalogues (especially those specialising on trees) and arboreta, and arborists and tree enthusiasts can also be consulted. Collaboration with local botanical gardens, forestry departments, and research institutions can ensure the list is exhaustive and regionally appropriate. To maintain taxonomic accuracy, taxa names should be cross-checked against standardized taxonomic references such as the World Checklist of Vascular Plants (Govaerts et al. 2024). This process ensures consistency in species identification.

Step 2. Tree taxa safe for planting

Once the full taxa list is established, a subset of tree taxa deemed safe for planting can be identified. This selection can be based on ecological, economic, and social criteria to ensure that the recommended taxa support biodiversity and ecosystem services while minimising risks associated with invasiveness and pest susceptibility. For this study, we used the national planted tree inventory for South Africa, which comprises over 35,000 records of the 805 tree taxa currently planted across the country (hereinafter referred to as the "tree inventory"; Richardson and Potgieter 2024). Only tree taxa already present in South Africa were considered for planting to avoid promoting new introductions, which would be subject to prolonged risk assessments under national regulations. Introducing new species carries inherent ecological risks, including unforeseen invasion potential, and requires rigorous screening before approval. Therefore, the protocol focuses on evaluating and selecting among the existing tree taxa to ensure responsible planting decisions that align with national biosecurity policies and sustainable urban greening initiatives.

Step 3. Filtering and inclusion criteria

To assess the potential risks associated with tree-planting, a set of filtering and inclusion criteria was established. These criteria encompassed key risk factors associated with both tree invasiveness and susceptibility to PSHB. In this study, the first criterion focused on the invasion status of tree taxa, identifying those taxa listed under South Africa's National Environmental Management: Biodiversity Act 10 of 2004 Alien and Invasive Species Regulations [NEM:BA A&IS Regulations, these were most recently updated in 2020, for details see Wilson & Kumschick (2024)]. However, official lists might not capture emerging or localised invasions, especially in regions with infrequently updated invasive species lists.

To address this, collaboration with local practitioners can help identify incipient invasions and ensure planting decisions reflect the most current on-the-ground knowledge.

The second criterion considered PSHB host status, distinguishing between *Neocosmospora*-colonised, competent, and kill-competent hosts (Townsend et al. 2025). *Neocosmospora*-colonised hosts are those in which fungal transmission from PSHB is possible, but which do not support beetle reproduction. Competent hosts are those in which the beetle successfully establishes a natal gallery and produces offspring. Kill-competent hosts included those tree taxa where at least one individual has been documented as succumbing to the combined effects of the beetle and *N. euwallaceae* infestations. To implement these criteria, multiple data sources were consulted.

Step 4. Criterion data sources

With the criteria established, the next step involves collating taxa lists for each criterion. We used 1) the NEM:BA A&IS Lists of 2020 (Wilson 2024) to determine the regulatory status and legal implications for each taxon, 2) the biogeographical status (native or non-native) using the categorisation of Richardson and Potgieter (2024), 3) the Global Naturalised Alien Flora (GloNAF, updated following van Kleunen et al. 2019) to determine whether each taxon is naturalised in and/or outside of South Africa, 4) the PSHB global host list (DPIRD 2024), which was compiled and validated using molecular records confirming PSHB identity from multiple sources, and 5) Lynch et al. (2025) to determine the host status of each tree taxon. We also identified taxa potentially susceptible to PSHB infestation by evaluating whether they belong to the same genus as confirmed PSHB hosts, given the increased likelihood of susceptibility among closely related species (Lynch et al. 2025). To account for differing *Neocosmospora* susceptibilities within genera, taxa with unknown statuses were conservatively assigned the highest known risk level among their congeners. This precautionary approach ensured that potential risks were not underestimated and allowed for a more conservative assessment of host susceptibility.

Step 5. Cross-referencing data sources with taxa list

To systematically evaluate the suitability of tree taxa for planting initiatives, we cross-referenced our curated list of suitable tree taxa (i.e., the tree inventory taxa list) with multiple key data sources (described above). This process involved extracting and assigning critical attributes to each taxon, including its listing in the NEM:BA A&IS Regulations, biogeographical status, invasion status, and PSHB host status. This approach ensured that each taxon was evaluated using multiple, independent criteria, allowing for a robust and evidence-based classification of tree species in relation to both invasion potential and susceptibility to PSHB.

Step 6. Application of decision protocol

We developed a multi-criterion, evidence-based decision protocol that provides targeted recommendations for guiding tree-planting initiatives using national invasive species regulatory lists, records of invasiveness in other regions, and known PSHB host data (Fig. 2). The protocol emphasises the exclusion of tree taxa regulated under national legislation, with high invasion potential, and known susceptibility to PSHB from tree-planting programs, thereby reducing the likelihood of further biological invasions. The protocol consists of eight recommendations that each consider issues of tree-planting, tree removal, and tree monitoring. Should there be any uncertainty regarding decisions, the global data sources highlighted in the previous section should be consulted, or any region-specific data sources relevant to the local context.

We applied this protocol to the City of Cape Town Metropolitan Municipality. The city has the most comprehensive planted tree data coverage of any municipality in South Africa (Richardson and Potgieter 2024) and has also recently experienced PSHB invasions (first detected in 2019) with over 10,000 trees infested and ~4000 already removed from public land due to PSHB infestation (City of Cape Town Invasive Species Unit pers comm, Fig. 3a). The city has a relatively low tree canopy cover at just six percent (City of Cape Town 2021), and this is likely to decrease further due to urban expansion, tree removals for infrastructure development, the impacts of climate change, and pest-pathogen infestations. By aligning with global frameworks such as the United Nations Sustainable Development Goals (United Nations 2015), and initiatives like the New Urban Agenda (United Nations 2017), and the Global Covenant of Mayors for Climate and Energy (GCoM 2022), Cape Town has committed to developing policies that aim to augment its green infrastructure to meet these international targets while ensuring a healthier, more liveable future for its residents. Our decision tool can provide evidence-based guidance for identifying tree taxa that, based on current data, can be safely considered in planting schemes.

Records within the City of Cape Town Metropolitan municipal boundary were extracted from our suitable tree taxa list to create a dataset of 445 planted tree taxa for the city. We applied our decision protocol to these taxa and categorised them from high to low likelihood of PSHB infestation and invasion of the tree taxon itself. Targeted recommendations associated with each category were also provided.

Step 7. Taxa suitable for planting

This process yielded a list of tree taxa not currently listed as invasive under national legislation, not known to be naturalised in South Africa or elsewhere, and no known susceptibility to PSHB. These taxa can therefore currently be recommended as suitable for planting in the city.

Developing a tree planting strategy for the City of Cape Town

Decision protocol

Tree taxa listed under the NEM:BA A&IS Regulations must not be planted unless a permit or exemption has been granted by the relevant environmental authority (recommendation A, Fig. 3b). Unauthorised planting can result in legal consequences and contribute to socio-ecological and economic impacts and conflicts. If a permit or exemption is granted, plantings should be recorded and reported to facilitate regulatory compliance, carefully monitored to prevent unintended spread, and measures taken to reduce the likelihood of spread.

Kill-competent host trees that are naturalised in or outside of the country should not be considered for planting (recommendation B, Fig. 3c). Their susceptibility to PSHB means they can serve as breeding reservoirs, amplifying PSHB populations (Townsend et al. 2025). As naturalised taxa, these trees can spread in and around the planting site leading to ecological and socio-economic impacts, including loss of biodiversity, and costly control efforts (Richardson and Rejmánek 2011). If the planting site is in or close to a PSHB-infested and/or ecologically sensitive area such as a protected area, riparian zone or wetland, removing trees of the same species is recommended, and all trees in and around the planting site should be monitored for early signs of PSHB infestation and naturalisation of the tree taxon. This approach can reduce beetle numbers and the likelihood of further naturalisation. Planting of native kill-competent host trees, especially in PSHB-infested areas, and competent host trees that are naturalised in or outside of the country is also not recommended and alternative tree taxa should be considered (recommendation C). The above-mentioned tree removal and monitoring recommendations also apply.

Planting of native competent host trees, and taxa in the same genus as competent host trees that are naturalised in or outside of the country, especially in PSHB-infested areas, is not recommended and alternative tree taxa should be considered (recommendation D). Taxa in the same genus as competent hosts are more likely to be susceptible to PSHB than more distantly related taxa, either due to shared physiological traits or the possibility of the beetle adapting to utilize the tree over time (Lynch et al. 2025). If planting of such trees is carried out, these, and all trees in and around the planting site, should be monitored for signs of naturalisation and PSHB infestation.

Large-scale planting (many trees planted over a large area) of native taxa in the same genus as competent host trees, especially in PSHB-infested areas, and *Neocosmospora*-colonised host trees that are naturalised in or outside of the country is also not recommended and alternative tree taxa should be considered (recommendation E). Where a tree taxon is a native *Neocosmospora*-colonised host tree, large-scale planting should still be avoided in heavily infested areas, but it can be planted more broadly, including in areas with some PSHB presence, provided the trees are regularly monitored for signs of PSHB infestation (recommendation F). Large-scale planting of taxa in the same genus as *Neocosmospora*-colonised host trees that are also naturalised in or outside of the country should be avoided in ecologically sensitive areas (recommendation F).

Native taxa in the same genus as *Neocosmospora*-colonised host trees can be considered safe for planting, provided that the planted trees are monitored for signs of PSHB infestation in known infestation zones (recommendation G). Large-scale planting of taxa that are not known hosts or closely related to any hosts, but that are naturalised in or outside of the country should be avoided (recommendation G). Taxa that are not known hosts with no evidence of naturalisation can be considered safe for planting and should be monitored for signs of PSHB infestation if planted in known infestation zones (recommendation H, Fig. 3d).

In cases where the planting site is in or close to an ecologically sensitive area, removing trees that are naturalised in or outside of the country is recommended where feasible, and the planting site should be monitored for signs of naturalisation of the tree taxon. In cases where PSHB infestations persist, maintaining detailed records of affected tree locations, host species, and management interventions will provide valuable data to refine control strategies and improve long-term invasion management efforts.

For areas outside of PSHB-infested or ecologically sensitive zones, tree-planting should prioritize taxa that are not known PSHB hosts and have no evidence of naturalisation (recommendation H). Additionally, taxa in the same genus as *Neocosmospora*-colonized hosts can be considered safe for planting, provided regular monitoring is conducted in regions where PSHB infestations may emerge (recommendation G). While large-scale planting of taxa that are not known PSHB hosts but are naturalised in or outside of the country should be avoided due to their potential invasion risk (recommendation G), selective planting of such species may be permissible in controlled urban settings where their spread can be managed. However, these trees should be monitored to detect any signs of naturalisation or pest susceptibility.

City of Cape Town

We applied the decision protocol to the City of Cape Town. The assessment categorized 445 planted tree taxa based on their invasion status and PSHB host status (see Potgieter 2025 for the full dataset). Among the assessed taxa, 85 species are currently regulated under NEM:BA A&IS and should not be planted. Two taxa were identified as kill-competent hosts, both of which are non-native and naturalised. Competent hosts included 64 taxa which are predominantly non-native and naturalised. Additionally, 79 taxa share a genus with a competent host, while 71 taxa are *Neocosmospora*-colonized hosts. While 117 taxa are not known to be PSHB hosts in the city, 66 of these were non-native and naturalised and are not recommended for planting. The most suitable options for planting included 13 non-native species that have not naturalised and 38 native species (recommendation H, Table 2), which pose minimal invasion risk while supporting ecosystem resilience.

Key considerations for safe tree-planting

Our tree selection protocol incorporates invasive species regulations, global invasion records, and pest-host interactions, and ensures that tree-planting schemes do not inadvertently facilitate biological invasions or exacerbate pest outbreaks. This protocol helps operationalise global guidelines into region-specific guidance by providing decision-makers with an evidence-based tool to minimize ecological and economic risks while promoting sustainable and resilient tree-planting practices in the face of global change.

When recommending a list of tree taxa suitable for planting, additional ecological and biogeographical factors must be carefully considered to ensure responsible species selection. Below, we discuss some of these key factors including: determinants of invasion (such as species traits, propagule pressure, and environmental conditions) that can contribute to the spread and establishment of non-native tree taxa; relevant regulations and risk analyses, outlining legal frameworks and scientific approaches used to assess and mitigate invasion risks; tree management practices such as community engagement, biodiversity-based planting and inequities in tree distribution; and monitoring, emphasising long-term surveillance, early detection of invasive behaviour, and adaptive management strategies to ensure sustainable urban greening efforts.

Determinants of invasion

The likelihood of a species becoming invasive is shaped by how long it has been present in a region (residence time), the number of propagules introduced (propagule pressure), the configuration of plantings, and the ability of the species to establish under local climatic conditions (Wilson et al. 2007, Pyšek et al. 2009, Donaldson et al. 2014). When selecting tree species for planting, it is critical to evaluate invasion histories from regions with similar climates to the study region, as species that have naturalised or become invasive in these regions can exhibit similar trends locally (Kinlock et al. 2022). For example, Mediterranean-climate regions such as Australia and California, USA, provide useful comparisons for assessing potential invaders in the Cape Floristic Region of South Africa, while subtropical areas such as Florida offer insights into risks for parts of South Africa's east coast (Thuiller et al. 2005, Richardson and Thuiller 2007). The inclusion of climatic compatibility models in decision tools can further refine predictions of which taxa are likely to spread beyond intended planting zones (Petitpierre et al. 2012).

When selecting tree species for planting, it is critical to consider traits linked to increased invasiveness, as these characteristics can enhance a species' ability to establish, spread, and compete with native vegetation (van Kleunen et al. 2010). High seed production increases propagule pressure, ensuring that a species can rapidly colonize new areas, especially if seeds are viable for extended periods or germinate under a wide range of conditions (Lockwood et al. 2005). Long-distance dispersal mechanisms, such as wind-dispersed seeds (e.g., pines) or seeds carried by animals (e.g., fleshy fruits consumed by birds), enable species to escape from cultivation to invade natural ecosystems (Aronson et al. 2007). Clonal reproduction, where trees propagate vegetatively through root suckers or resprouting, allows for rapid spread even in the absence of seed-based reproduction, making control efforts particularly challenging (Klimešová and Martínková 2022). Taxa with strong resprouting ability after disturbance—whether from fire, cutting, or drought—can also outcompete native species and dominate landscapes, altering ecosystem dynamics. Given that tree-planting initiatives often aim to enhance biodiversity, ecosystem services, and climate resilience, it is essential to select species that provide these benefits without posing a risk of invasion. Failure to account for these invasion-linked traits can lead to unintended ecological consequences, including biodiversity loss, altered fire regimes, and water resource depletion (Richardson and Pyšek 2012, Rejmánek and Richardson 2013).

Although native tree species are often favoured in planting schemes due to their ecological benefits, factors such as habitat disturbance can allow certain native trees to expand beyond their natural range, sometimes resulting in negative economic and socio-ecological impacts (Nelufule et al. 2022). For example, the native tree *Dais cotinifolia* can be safely recommended for planting (Table 2) but naturalised populations have been reported (Baard et al. 2014). Large-scale planting of such taxa should be carefully considered.

Regulations and risk analyses

The Risk Analysis for Alien Taxa (RAAT) framework provides a structured, evidence-based approach to assessing the invasion risk of tree taxa before their introduction or widespread planting (Kumschick et al. 2020). It was developed specifically to assist South African decision-makers (and so it aligns with the NEM:BA A&IS Regulations) but the principles are general. This framework can help to identify taxa that pose ecological, economic, or social threats, ensuring that tree-planting initiatives do not inadvertently facilitate biological invasions. By evaluating key factors such as species' invasion history, ecological traits, climatic compatibility, and potential pathways of spread, RAAT helps decision-makers determine whether a tree taxon is low-risk, requires further risk mitigation, or should be restricted entirely. Given the increasing concern over tree invasions and pest-host dynamics, particularly with PSHB, referring to RAAT or other risk analysis frameworks is crucial in guiding planting decisions that minimize long-term risks.

The NEM:BA A&IS Regulations categorize species based on their invasion risk at a national level; however, in some cases (48 out of 365 terrestrial or freshwater plant taxa listed on continental South Africa) these listings differ by province (although this could be deprecated in future in favour of provincial ordinances, cf. Wilson & Kumschick, 2024). A tree species listed as invasive in one region might not be regulated in another, complicating national tree-planting decisions. For instance, certain *Acacia* and *Eucalyptus* species are considered invasive in parts of South Africa but remain widely used in forestry or urban greening elsewhere. These regional classifications should be considered to ensure that trees regulated in any part of the country are scrutinized before being included in planting schemes. Additionally, the NEM:BA A&IS Regulations include provision for a list of prohibited taxa, comprising species not yet present in South Africa that may not be imported due to their high invasion risk (a prohibited list was included in the 2014 and 2016, but not the 2020 versions). These regulations underscore the need for a cautious, regionally informed approach when selecting tree species for planting.

Given the variation in species regulations and invasion risks across different regions, the most appropriate spatial scale for applying this protocol is at the provincial or municipal level. Assessments at these finer spatial scales allow for more precise management decisions that align with specific environmental conditions, regulatory frameworks, and socio-economic needs. This localised approach can also foster collaboration between key stakeholders, facilitate integration with urban greening programs, biodiversity conservation plans, and climate resilience strategies tailored to local conditions, and ensure that species assessments account for critical site-specific factors such as climate, soil conditions, and propagule pressure from surrounding landscapes (see Supplementary File 1 for additional site-specific criteria *to* consider when selecting tree taxa for planting).

Pest-pathogen and tree management practices

Effective management of pest-pathogen invasions requires an integrated approach that combines scientific research, biodiversity-based planting strategies, tree health promotion, public awareness, and pest management interventions (Paap et al. 2022).

Sous-Silva et al. (2023) highlight the need for tree-planting initiatives to move beyond numeric targets and align with long-term forest management objectives. They propose seven principles to enhance success, including integrating initiatives with clear goals, engaging communities, prioritising canopy cover over tree numbers, ensuring post-planting care, monitoring tree losses and gains, promoting species and structural diversity, and addressing inequities in tree distribution. These principles aim to maximize the ecological and social benefits of urban forests. By integrating these strategies, decision-makers can improve the long-term sustainability of urban and natural tree populations while mitigating the ecological and economic impacts of pests/pathogens and tree invasions.

Carnegie and Grant (2025) highlight the critical role of social licence in the success of urban biosecurity responses to invasive tree pests. They emphasize that eradication efforts, such as tree removal or pesticide applications, often face public resistance due to diverse stakeholder values associated with urban trees. The review identifies key actions to improve the social acceptability of control measures, including early stakeholder engagement, trust-building, participatory decision-making, and effective communication about the ecological and economic risks of pest incursions. By proactively addressing social concerns, biosecurity agencies can enhance public support for necessary interventions, ultimately increasing the likelihood of successful pest eradication.

Our decision protocol aligns with these principles by incorporating an evidence-based assessment to promote tree taxa selection by minimizing future conflicts between biosecurity actions and urban tree management. By prioritising non-invasive and non-host taxa, the protocol reduces the need for reactive interventions, such as tree removal, that could otherwise trigger public opposition. Moreover, the recommendation to monitor plantings for signs of infestation supports early detection, a key factor in both biosecurity success and stakeholder trust (Liebhold et al. 2012). Integrating social licence considerations into tree selection and biosecurity planning can thus enhance both ecological resilience and public cooperation in managing invasive tree pests like PSHB.

A key consideration in tree selection is prioritising native taxa and promoting diversity to enhance ecosystem resilience and reduce susceptibility to pest-pathogen invasions (Vashist et al. 2025). Monocultures or taxa with similar traits to infested hosts provide little resistance, allowing pest-pathogen populations to persist. A diversity-based planting approach limits host availability, reducing the risk of large-scale pest outbreaks and aligning with broader urban forest resilience principles (Paquette et al. 2021).

Shackleton and Gwedla (2024) explored how colonial and apartheid legacies have shaped urban green infrastructure in South Africa, leading to persistent inequalities in the distribution and composition of urban green spaces. They highlight that wealthier, historically white neighbourhoods retain extensive green spaces dominated by non-native tree species introduced during colonial rule, while lower-income areas, historically designated for marginalized communities, have fewer and lower-quality green spaces. This colonial legacy has not only influenced urban ecology but has also resulted in a significant burden of invasive species management. The study also critiques how public green spaces continue to reflect colonial-era aesthetics and recreational norms, often neglecting African cultural perspectives and contemporary urban needs. The authors advocate for a more inclusive, participatory approach to urban greening that considers local identities, worldviews, and ecological resilience. Our protocol allows for the selection of native tree taxa which can support efforts to break from colonial-era planting practices that have contributed to ongoing ecological and social disparities. Prioritising native species and a diversity-based planting approach can support more ecologically sustainable and socially equitable urban forests. Addressing the historical imbalance in green space distribution, coupled with the proactive selection of appropriate tree taxa, can foster urban landscapes that are both resilient to biological invasions and more reflective of local cultural and environmental priorities.

The importance of governance for improving the sustainability of tree-planting schemes has received increasing attention (Yitbarek et al. 2023). The protocol described here is essential background for both project initiation and planning phases, i.e., guiding the selection of suitable trees.

Monitoring

Establishing a systematic monitoring protocol for trees in regions where pests and pathogens are present or pose a risk of introduction is essential for early detection and effective management (Potgieter et al. 2024). For PSHB, routine visual inspections should be conducted to identify characteristic symptoms of infestation particularly on the trunk and branches, including staining around the entry holes, frass (sawdust-like debris), gumming and discoloration (van Rooyen et al. 2021). These indicators can signal the presence of PSHB before widespread damage occurs. Additionally, incorporating baited traps into monitoring programs can enhance detection efforts and improve response times. Community science initiatives can facilitate broad-scale surveillance, as local stakeholders can assist in reporting early signs of infestation (Potgieter et al. 2024). Collaboration with environmental and forestry agencies to establish a regional monitoring network would further strengthen detection capabilities and ensure the dissemination of best practices for tree management.

Educating residents, landscape managers, and municipal authorities about the risks of planting susceptible or invasive species and the importance of prompt pest reporting can improve surveillance and rapid response efforts. Where susceptible tree species must be retained for cultural, aesthetic, or ecological reasons, an Integrated Pest Management (IPM) approach can be implemented. This may involve regular monitoring, physical control (e.g., removal of infested material), and, where necessary, the careful application of chemical treatments to high-value trees to limit pest-pathogen spread while minimising unintended ecological consequences.

Limitations

Richardson and Potgieter’s (2024) living tree inventory provides a comprehensive list of tree taxa currently planted in South Africa but does not necessarily account for all tree taxa planted in the country. The inventory also does not account for tree taxa that have not yet been trialled for planting. This presents a knowledge gap that could exclude potentially low-risk, suitable species from decision-making simply due to a lack of widespread testing.

While our list of recommended tree taxa provides a valuable guideline for selecting taxa with a lower likelihood of invasion or PSHB susceptibility, its practical implementation is constrained by the availability of these taxa in commercial nurseries. Many nurseries prioritise species based on market demand, aesthetic appeal, and growth characteristics rather than ecological suitability, which can limit access to certain recommended species. To bridge this gap, collaboration between researchers, policymakers, and the horticultural industry is essential to encourage the propagation and distribution of these tree taxa. The list can also serve not only as a decision-support tool for planners but also as a priority list for nurseries. By focusing propagation efforts on taxa identified as low-risk, nurseries can help increase the availability of safe species, support diversification of urban and restoration plantings, and reduce the likelihood of inadvertently introducing invasive or pest-prone species. In this way, the list can guide both short-term planting choices and longer-term changes in nursery production practices toward more ecologically sound options.

It is also important to recognise the dynamic nature of PSHB host susceptibility and the ongoing evolution of suitable host lists. As PSHB is a relatively recent invader in regions like South Africa and Australia, not all tree taxa within these invaded ranges have had equal exposure to the beetle and the fungus *N. euwallaceae*, suggesting a "host debt". The current living tree inventory in South Africa and existing host lists are based on infestations observed since the beetle's arrival. Consequently, tree taxa that are not yet widely planted or that occur in areas not yet significantly invaded might not have been adequately evaluated. As PSHB continues to spread, it is likely to encounter and colonise new tree taxa, leading to further expansion of the known host range. As a result, our present understanding of PSHB hosts represents a temporal snapshot; this is expected to change as the invasion unfolds.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by LJP. The first draft of the manuscript was written by LJP, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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Data availability statement

The final filtered dataset generated and analysed during the study has been archived on Zenodo: https://doi.org/10.5281/zenodo.15259592 (Potgieter 2025).

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Figures

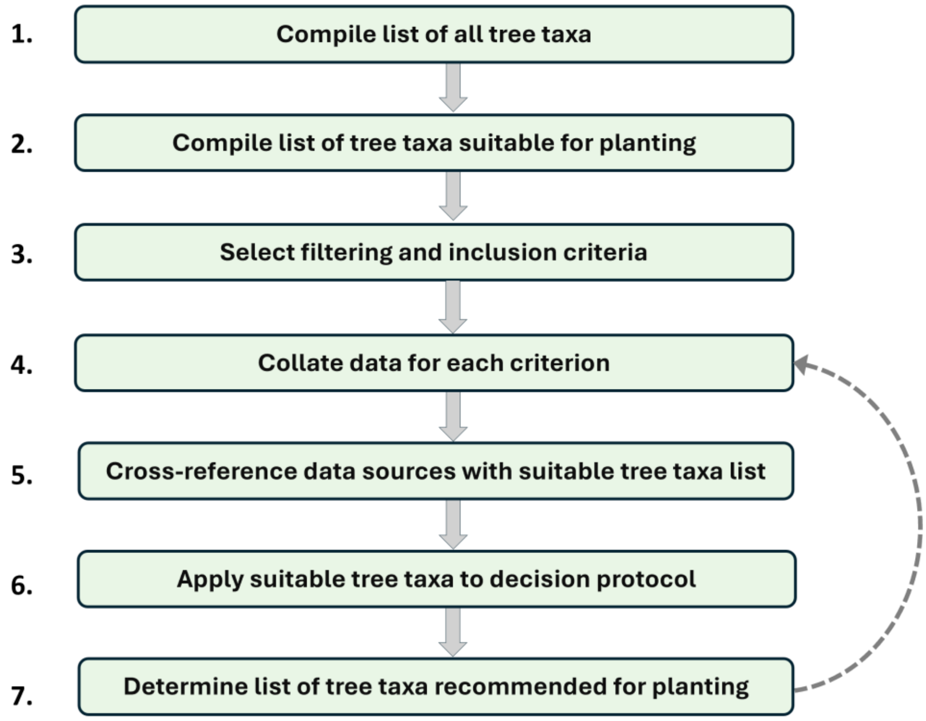

Figure 1. Workflow for identifying tree taxa suitable for planting. The process begins with compiling comprehensive lists of all tree taxa for the study region and those suitable for planting. Filtering and inclusion criteria are then defined, followed by data collation for each criterion. Relevant data sources are cross-referenced with the suitable taxa list, which is subsequently applied to a decision protocol to determine the final set of taxa recommended for planting. The workflow is iterative and adaptive (shown by the dashed arrow), with certain steps subject to ongoing refinement as new data and insights become available.

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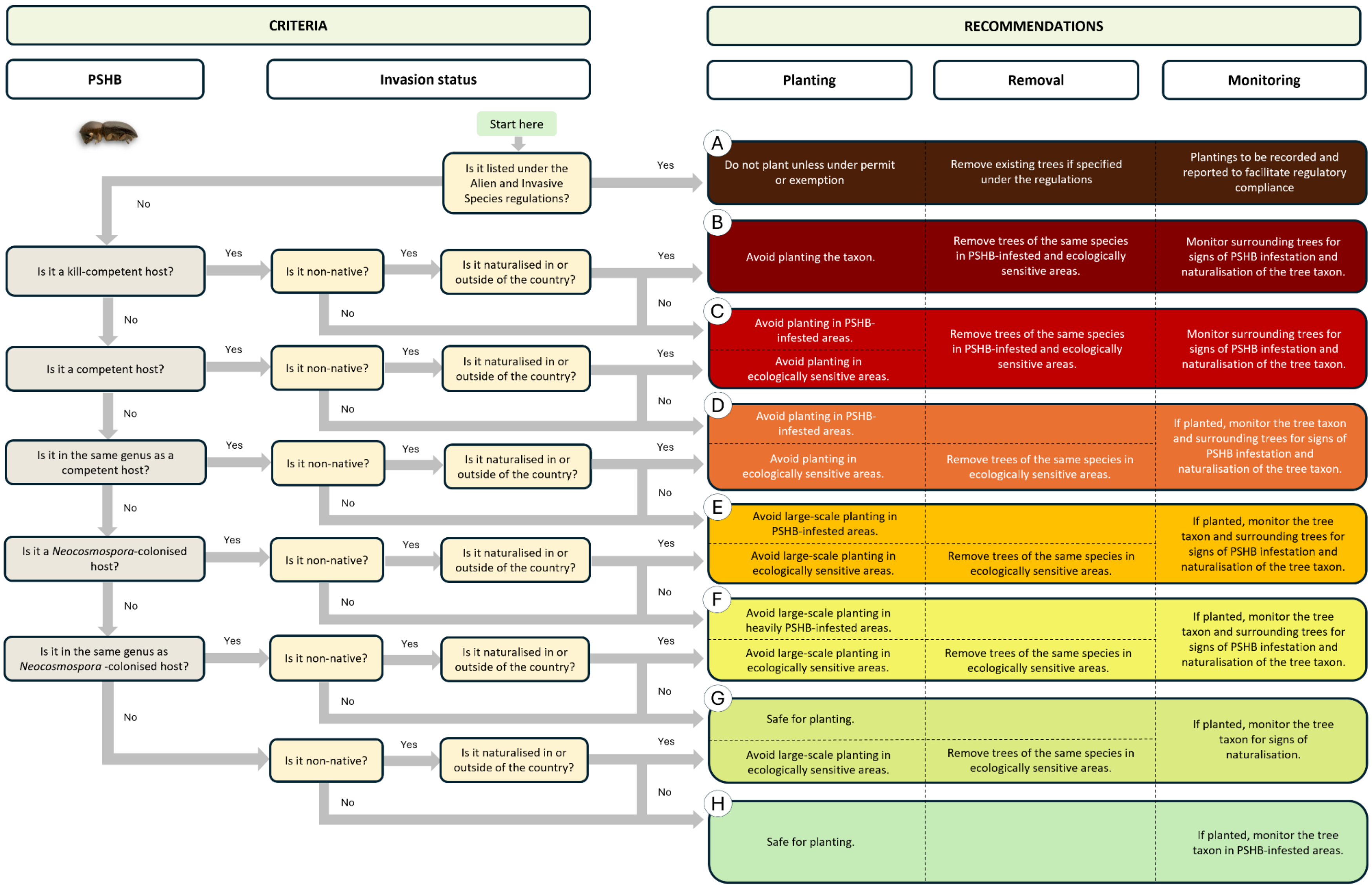

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Figure 2. Decision protocol for tree selection to mitigate the risk of Polyphagous Shot Hole Borer (PSHB, *Euwallacea fornicatus*) infestation and tree invasions. The protocol consists of eight recommendations categorized into three types: tree planting, tree removal, and tree monitoring. These recommendations are further grouped into seven categories, represented by a colour gradient from dark brown to green. Dark red indicates scenarios where planting the tree taxon can result in a high likelihood of both PSHB infestation and invasion of the tree taxon itself, necessitating the exclusion of certain tree taxa from planting initiatives. Progressively lighter shades represent decreasing likelihood of PSHB infestation and/or tree invasion, with green denoting tree taxa posing a low likelihood of PSHB infestation and tree invasion and which are thus suitable for planting. Should there be any uncertainty regarding decisions, the global data sources highlighted in the Methods section (or any region-specific data sources relevant to the local context) should be consulted.

Figure 3. Photo panel including a) Polyphagous Shot Hole Borer (PSHB, *Euwallacea fornicatus*; photo credit: A de Villiers), b) a popular ornamental tree *Metrosideros excelsa* Sol. ex Gaertn. (New Zealand Christmas tree; photo credit: DM Richardson) listed under South Africa's National Environmental Management: Biodiversity Act 10 of 2004 Alien and Invasive Species Regulations, c) signs of PSHB infestation of *Acer negundo* L. (Box elder; photo credit: LJ Potgieter), a kill-competent host, and d) *Dais cotinifolia* L. (Pom Pom tree; photo credit: DM Richardson) currently deemed safe for planting across the City of Cape Town Metropolitan Municipality.

Tables

Table 1. Number of planted tree taxa per recommendation category when applied to the City of Cape Town Metropolitan Municipality (total planted tree taxa = 445). Data from Richardson and Potgieter (2024). For details of the recommendations see Figure 2. Forty-nine tree taxa are deemed safe for planting in the city (Table 2). Regulated as invasive is based on the inclusion of taxa in the National Environmental Management: Biodiversity Act (10 of 2004) Alien & Invasive Species Lists (Wilson 2024). The taxonomic nomenclature follows the World Checklist of Vascular Plants (Govaerts et al. 2024).

Criteria		Number of planted tree taxa	Recommendation	Example tree taxon
PSHB	Invasion status			
	Regulated as invasive	85	A	*Melaleuca viminalis* (Sol. ex Gaertn.) Byrnes
Kill-competent host	Non-native, naturalised	5	B	*Acer negundo* L.
	Non-native	1	C	*Platanus x hispanica* Mill. ex Münchh.
	Native	3	C	N/A
Competent host	Non-native, naturalised	42	C	*Populus simonii* Carrière
	Non-native	3	D	*Platanus* × *hispanica* Münchh.
	Native	13	D	*Erythrina afra* Thunb.
Same genus as a competent host	Non-native, naturalised	41	D	*Syzygium australe* (J.C.Wendl. ex Link) B.Hyland
	Non-native	20	E	*Quercus leucotrichophora* A.Camus
	Native	19	E	*Bauhinia tomentosa* L.

Neocosmospora-colonised host	Non-native, naturalised	43	E	*Celtis sinensis* Pers.
	Non-native	3	F	*Olea europaea* subsp. *europaea*
	Native	22	F	*Ekebergia capensis* Sparrm.
Same genus as a *Neocosmospora*-colonised host	Non-native, naturalised	13	F	*Washingtonia robusta* H.Wendl.
	Non-native	5	G	*Pistacia lentiscus* L.
	Native	11	G	*Schotia afra* Thunb.
Not a known host	Non-native, naturalised	66	G	*Pinus pinea* L.
	Non-native	12	H	*Agathis australis* (D.Don) Lindl.
	Native	38	H	*Curtisia dentata* (Burm.f.) C.A.Sm.

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Table 2. List of tree taxa suitable for planting in the City of Cape Town Metropolitan Municipality, South Africa. These taxa are: not listed under the Alien and Invasive Species Regulations; not known to be naturalised in or outside of South Africa; and are not known Polyphagous Shot Hole Borer hosts, i.e. are 'safe' sensu Kumschick et al. (2024). The taxonomic nomenclature follows the World Checklist of Vascular Plants (Govaerts et al. 2024).

Scientific name	Common name	Family name	Native/Non-native
Agathis australis (D.Don) Lindl.	Kauri	Araucariaceae	Non-native
Aloidendron barberae (Dyer) Klopper & Gideon F.Sm.	Tree Aloe	Asphodelaceae	Native
Aloidendron dichotomum (Masson) Klopper & Gideon F.Sm.	Quiver Tree	Asphodelaceae	Native
Aloidendron pillansii (L.Guthrie) Klopper & Gideon F.Sm.	Giant Quiver Tree	Asphodelaceae	Native
Aloidendron ramosissimum (Pillans) Klopper & Gideon F.Sm.	Maiden's Quiver Tree	Asphodelaceae	Native
Aloidendron tongaense (Van Jaarsv.) Klopper & Gideon F.Sm.	Tonga Tree Aloe	Asphodelaceae	Native
Anthocleista grandiflora Gilg	Forest Big-Leaf	Gentianaceae	Native
Antidesma venosum E.Mey. ex Tul.	Tassel-Berry	Phyllanthaceae	Native
Apodytes dimidiata E.Mey. ex Arn.	White Pear	Metteniusaceae	Native
Araucaria rulei F.Muell.	Rule Araucaria	Araucariaceae	Non-native
Bolusanthus speciosus (Bolus) Harms	Tree Wisteria	Fabaceae	Native
Boscia albitrunca (Burch.) Gilg & Gilg-Ben.	Shepherd's Tree	Capparaceae	Native
Brabejum stellatifolium L.	Wild Almond	Proteaceae	Native
Breonadia salicina (Vahl) Hepper & J.R.I.Wood	Matumi	Rubiaceae	Native
Bridelia micrantha (Hochst.) Baill.	Mitzeeri	Phyllanthaceae	Native
Buckinghamia celsissima F.Muell.	Ivory Curl	Proteaceae	Non-native
Burchellia bubalina (L.f.) Sims	Wild Pomegranate	Rubiaceae	Native
Canthium inerme (L.f.) Kuntze	Turkey-Berry	Rubiaceae	Native
Caryota no Becc.	Giant Fishtail Palm	Arecaceae	Non-native
Chionanthus foveolatus (E.Mey.) Stearn	Pock Ironwood	Oleaceae	Native

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Curtisia dentata (Burm.f.) C.A.Sm.	Assegai	Curtisiaceae	Native
Dacrydium cupressinum Sol. ex G.Forst.	Rimu	Podocarpaceae	Non-native
Dais cotinifolia L.	Pom Pom Tree	Thymelaeaceae	Native
Dodonaea viscosa (L.) Jacq.	Sand Olive	Sapindaceae	Native
Elaeodendron croceum (Thunb.) DC.	Saffronwood	Celastraceae	Native
Euclea natalensis A.DC.	Natal Guarri	Ebenaceae	Native
Euclea racemosa L.	Sea Guarri	Ebenaceae	Native
Euclea undulata Thunb.	Common Guarri	Ebenaceae	Native
Hesperocyparis forbesii (Jeps.) Bartel	Tecate Cypress	Cupressaceae	Non-native
Heteropyxis natalensis Harv.	Lavender Tree	Myrtaceae	Native
Leucadendron argenteum (L.) R.Br.	Silver Tree	Proteaceae	Native
Murraya koenigii (L.) Spreng.	Curry Leaf Tree	Rutaceae	Non-native
Phyllocladus trichomanoides D.Don	Tanekaha	Podocarpaceae	Non-native
Ptaeroxylon obliquum (Thunb.) Radlk.	Sneezewood	Rutaceae	Native
Raphia australis Oberm. & Strey	Kosi Palm	Arecaceae	Native
Rauvolfia afra (Sond.) K.Schum.	Quinine Tree	Apocynaceae	Native
Sabal mexicana Mart.	Mexican Palmetto	Arecaceae	Non-native
Sideroxylon inerme L.	White Milkwood	Sapotaceae	Native
Tarchonanthus camphoratus L.	Camphor Bush	Asteraceae	Native
Tarchonanthus littoralis P.P.J.Herman & D.S.Court	Coast Camphor Bush	Asteraceae	Native
Tarchonanthus trilobus DC.	Mountain Camphor Bush	Asteraceae	Native
Tilia × *europaea* L.	Common Lime	Malvaceae	Native
Volkameria glabra (E.Mey.) Mabb.	Smooth Volkameria	Lamiaceae	Non-native
Warburgia salutaris (G.Bertol.) Chiov.	Pepper-Bark Tree	Canellaceae	Native
Widdringtonia nodiflora (L.) Powrie	Mountain Cypress	Cupressaceae	Native
Widdringtonia schwarzii (Marloth) Mast.	Willowmore Cedar	Cupressaceae	Native

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Widdringtonia cedarbergensis J.A.Marsh.	Clanwilliam Cedar	Cupressaceae	Native
Wollemia nobilis W.G.Jones, K.D.Hill & J.M.Allen	Wollemi Pine	Araucariaceae	Native
× *Hesperotropsis leylandii* (A.B.Jacks. & Dallim.) Garland & G.S.Patterson	Leyland Cypress	Cupressaceae	Non-native

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Supplementary files

Supplementary File 1. Additional site-specific criteria to consider when selecting tree taxa for planting.

Criteria	Description	Relevant resources
1. Site characteristics and distribution	Environmental factors that influence tree establishment and long-term survival	
1.1 Climatic conditions	Climate-related factors that affect tree health and growth	IPCC Climate Risk Reports, WorldClim Data
1.1.1 Drought risk	Likelihood of prolonged dry periods impacting tree survival	FAO Drought Impact Reports
1.1.2 Heat risk	Risk of high temperatures affecting growth and water demand	NASA Climate Data
1.1.3 Late frost risk	Sensitivity to unexpected frosts that may damage young leaves	USDA Frost Hardiness Guide
1.1.4 Light availability	Shade tolerance and light requirements for optimal growth	Global Forest Watch Canopy Coverage
1.1.5 Plant hardiness zone	Geographic classification of plant tolerance to climatic extremes	USDA Hardiness Zone Map
1.1.6 Soil conditions	Physical and chemical soil properties affecting tree establishment	FAO Soil Atlas
1.1.7 Soil compaction risk	Risk of soil becoming too dense for root penetration	USDA Soil Quality Indicators
1.1.8 Soil depth	Minimum depth required for healthy root growth	FAO Soil Profiles
1.1.9 Soil moisture	Availability of water in the soil profile for tree uptake	Soil Moisture Active Passive (SMAP) Data

1.1.10 Substrate	Type of underlying material affecting root anchorage and nutrient access	FAO Soil Classification
1.1.11 Waterlogging risk	Likelihood of excessive water accumulation impacting roots	Wetland Management Guidelines
1.1.12 pH value	Soil acidity or alkalinity affecting nutrient availability	FAO Soil pH Guidelines
1.2 Distribution	Natural and introduced ranges of tree species	GBIF Species Distribution Data
2. Tree characteristics	Morphological and physiological traits relevant for tree selection	
2.1 Habit	Growth form and structure influencing tree suitability for sites	GlobalTreeSearch Database
2.1.1 Average crown radius	Lateral spread of tree canopy	Urban Forestry Best Practices
2.1.2 Average tree height	Typical mature height of the species	Arboriculture Guidelines
2.1.3 Crown shape	Structural form of the canopy (e.g., round, columnar)	Tree Growth Models
2.1.4 Growth direction	Vertical vs lateral growth patterns	Tree Architecture Studies
2.1.5 Growth speed	Rate at which the species reaches maturity	Forest Growth Projections
2.1.6 Habit	Overall structural form (e.g., single-trunk, multi-stem)	Botanic Gardens Conservation International (BGCI)
2.1.7 Leaf density	Foliage density affecting shade and screening potential	Tree Canopy Cover Research
2.1.8 Maximum tree height	Potential ultimate height under optimal conditions	Tree Biodiversity Databases
2.1.9 Multi-stem development	Propensity to grow with multiple main stems	Silvicultural Guidelines
2.1.10 Near-surface roots	Likelihood of roots causing pavement or infrastructure damage	Urban Tree Risk Assessments
2.2 Leaf	Leaf characteristics influencing ecological and aesthetic value	Tree Physiology Journals
2.2.1 Autumn colouring	Seasonal foliage changes and ornamental value	Horticultural Plant Trials

2.2.2 Foliage	Evergreen vs deciduous nature of leaves	USDA Plant Guide
2.2.3 Foliation	Timing of leaf emergence and duration	Phenology Databases
2.2.4 Leaf shape	Morphological variation in foliage	Botanical Studies
2.3 Flower	Reproductive structures and attractiveness for pollinators	Pollinator Conservation Guides
2.3.1 Flower colour	Visual appeal and biodiversity impact	RHS Plant Selection Guides
2.3.2 Flower ornamental	Aesthetic contribution of flowers	Urban Landscaping References
2.3.3 Flower period	Timing and duration of flowering	Tree Phenology Data
2.3.4 Inflorescence	Arrangement of flowers on a plant	Taxonomy Textbooks
2.3.5 Odor	Presence of scent and its ecological role	Plant Chemical Ecology
2.4 Fruit	Characteristics influencing seed dispersal and wildlife interactions	Agroforestry Systems Research
2.4.1 Fruit colour	Significance for wildlife and ornamental value	Ethnobotanical studies
2.4.2 Fruit ornamental	Decorative appeal of fruit-bearing species	Horticultural reports
2.4.3 Infructescence	Clustering and arrangement of fruit	Forest Reproductive Biology
2.5 Noise suppression	Ability to act as a sound barrier	Urban Green Space Planning
2.6 Screening	Effectiveness in providing visual separation	Landscape Ecology References
2.7 Longevity	Expected lifespan of the species	Tree Aging Studies
2.8 Wind tolerance	Resistance to strong winds and storms	Forestry Wind Damage Reports
2.9 Deciduous/Evergreen	Seasonal leaf retention patterns	Plant Functional Traits Database
2.10 Fire susceptibility	Vulnerability to wildfire damage	Fire Ecology Journals

2.11 Susceptibility to other pests	Risks from insect and pathogen attacks	Forest Health Protection Research
2.12 BVOC emissions	Release of biogenic volatile organic compounds affecting air quality	Atmospheric Chemistry Journals
3. Ecosystem services	Functional benefits provided by trees	Millennium Ecosystem Assessment
3.1 Pollination	Contribution to supporting pollinators	Pollinator Conservation Strategies
3.2 Edibility	Presence of edible fruits, leaves, or seeds	Ethnobotanical Resources
3.3 Medicinal value	Use in traditional or modern medicine	Medicinal Plant Research
3.4 Smoke hardiness	Tolerance to industrial and urban pollutants	Air Pollution and Vegetation Studies
3.5 Honey production	Role as a nectar source for bees	Beekeeping and Forestry Research
3.6 Nitrous and ozone absorption	Capacity to improve air quality	Urban Air Pollution Studies
3.7 Particulate adsorption	Ability to trap dust and pollutants	Urban Greening Research
4. Risks and interferences	Potential negative impacts of tree species	Invasive Species Risk Assessments
4.1 Allergy potential	Pollen and volatile compounds causing allergies	Medical Botany Studies
4.2 Root damage	Risk of roots disrupting infrastructure	Urban Forestry Risk Assessment
4.3 Limb breakage	Structural failure due to wind or disease	Tree Safety Standards
4.4 Toxicity	Harmful compounds in leaves, bark, or fruit	Poisonous Plants Database
4.5 Bark stripping	Removal of bark from a tree’s trunk or branches	Newlands Forest Conservation
5. Required management activities	Maintenance considerations for sustainability	Arboricultural Best Practices

6. Practical considerations	Availability, legal status, and implementation challenges	Nursery Trade Regulations, Invasive species regulations, Conservation Guidelines