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Achieving the Urban Tree Trifecta: Scenario Modelling for Salubrious, Resilient, and Diverse Urban Forests in Densifying Cities

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Abstract. Background: Urban forests can provide nature-based solutions (NBS) to complex climate-change challenges via the provision of ecosystem services such as shade and cooling that offset increased risks of chronic diseases and excess mortality. They also confer indirect health benefits by providing regulating ecosystem services that can facilitate climate-change mitigation efforts: increased shade can encourage shifts to lower-carbon transportation methods such as walking and cycling, for example. However, in order to ensure that urban forests are both resilient to threats and confer the maximum possible benefits, we must be able to project decades into the future in order to understand the implications of current urban forestry decisions. Methods: This study outlines a framework for creating urban-forest scenario models and reports the results of a case study conducted to highlight the ways in which decisions made at each stage of the scenario-development process impact its outcomes and application. Our case study focused on a neighbourhood in Vancouver, Canada, that is simultaneously undergoing urban densification and aiming to significantly increase canopy cover by 2050. Three distinct aims were identified for the case study: maximizing public-health benefits, selecting climate-resilient tree species, and integrating planting across public and private lands to advance diversity. To achieve these aims, baseline information on the neighbourhood's existing tree network was collected, entered into GIS software, and delineated based on a set of pre-identified characteristics. Next, a list of climate-adapted species was developed. This climate-adapted species list was then virtually "planted" across the neighbourhood, using a combination of machine-based and manual planting techniques. Finally, the resulting scenario model was quantitatively assessed to understand its composition and impacts. Results: Our study demonstrates that a salubrious, resilient, and diverse urban forest can be created via a strategic program that complements extant trees in the public domain with planting programs along blue-green streets and on private property. Conclusions: Achieving the urban tree trifecta will require collaboration among municipal departments and the development of a range of public and private initiatives, but it has the potential to maximize nature-based solutions in cities facing rapid shifts due to densification and climate change.

Keywords. Biodiversity; Modelling; Nature-Based Solutions; Scenario Planning; Urban Forest.

INTRODUCTION

The critical role natural ecosystems play within urban environments has been increasingly acknowledged in both research and policy over the past 4 decades. Human dependence on forests and biodiversity is highlighted in the United Nations' Sustainable Development Goal 15 (United Nations 2022), recognized as a pillar of health-promoting environments by the World Health Organization (World Health Organization 2017), and embedded into municipal sustainability plans such as the "One New York" plan in New York City (City of New York 2015), Vancouver's "Urban Forest Strategy" (Vancouver Board of Parks and Recreation 2018), and the "First Step" urban forest management plan in Los Angeles (City of Los Angeles 2018). Indeed, natural landscapes are now being touted for their potential to provide nature-based solutions (NBS) to the complex set of challenges arising from climate change, whether social, economic, or ecological (European Commission 2015).

Urban forests are increasingly recognized as being salubrious (health-giving) for urban residents. Looking specifically at the urban forest as a form of nature, the range of benefits for both physical and mental health is robust. With respect to physical health outcomes, the presence of 10 street trees per block in

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Toronto, Canada had the same impact on overall health improvements as an additional $10,000 in yearly household income (Kardan et al. 2015). Likewise, individuals living in areas with the highest tree density within 1 kilometer of their homes in New York City were 23% more likely to report very good or excellent health in comparison to residents of areas with the lowest tree density (Reid et al. 2018). In terms of psychological health, the evidence is even more robust. Greater street tree density was linked to significant reductions in depressive symptoms among residents of socioeconomically deprived neighbourhoods across the Netherlands (Gubbels et al. 2016) and to reduced rates of antidepressant prescriptions among lower-socioeconomic status individuals residing in Leipzig, Germany (Marselle et al. 2020). More complex assessments of urban forests also demonstrate benefits. A recent evaluation of the 3-30-300 rule for urban forestry carried out in Barcelona, Spain found that individuals who could see at least 3 trees from their windows, had 30% canopy cover surrounding their homes (as assessed via a measure of residential surrounding greenness), and were within 300 meters of a park or other greenspace were 69% less likely to have visited a psychiatrist or psychologist over the prior year (Tonne et al. 2021).

Healthy urban forests also indirectly benefit human health by serving as a solution in climate-change resilience efforts. Resilient urban forests seek to reduce the harms to humans associated with high greenhouse gas (GHG) emissions (European Commission 2015) and to increase capacity to help cities recover from disturbances related to climate change (Huff et al. 2020). A systematic analysis of existing reviews that have examined the potential of various urban natural environments to serve as NBS found robust evidence for the substantial cooling effect of urban greenery, offsetting the increased risks of heat stress, chronic -disease exacerbation, and excess mortality in increasingly hot cities (van den Bosch and Sang 2017). Additional insights come from modelling efforts: a comprehensive urban greening scenario that integrated a 30% increase in street trees along with green roofs and vegetated impervious surfaces (such as carparks) across greater Manchester in the United Kingdom linked this "deep green" development with a reduction of 3 to 4.9 °C in surface temperatures, even in the context a high-emissions future (Carter et al. 2015).

Mitigation strategies are just as crucial as adaptation solutions, because they aim to stave off the most drastic harms of climate change by reducing greenhouse gas emissions or increasing carbon storage (European Commission 2015). One such strategy is urban densification, which has been linked to improvements in building energy efficiency and population-level shifts to lower-emissions transportation methods—such as walking, cycling, and the use of public transit—both of which can reduce per capita greenhouse gas emissions (Tonne et al. 2021). Conversely, more dispersed community designs have been linked to significantly larger GHG emissions, due both to a greater reliance on private-vehicle travel over larger distances (Ewing and Hamidi 2015) and to a higher amount of per-capita infrastructure, such as single-family homes rather than multi-unit dwellings (Norman et al. 2006; Hamidi et al. 2015). How urban forests perform with increased density is not well understood (Haaland and van den Bosch 2015). In terms of urban forest health, urban densification can also lead to a lack of permeable surfaces, insufficient soil volume to grow healthy trees, and less space for large patches of urban greenspace.

At the same time, many urban-planning policies that seek to increase density may threaten existing urban forests. In already developed urban cores, these threats occur in 2 principal areas. First, as lots that once held single-family homes or low-rise multi-unit dwellings are redeveloped into larger multi-unit developments, existing private trees are often cleared for the larger required footprint. Numerous cities have tree protection ordinances (TPOs) in place that regulate the replacement of lost trees, governing issues such as the size and species of replacement trees, which trees are subject to replacement, and how these rules are enforced (Lavy and Hagelman 2019). However, delving into the TPO for Vancouver, Canada demonstrates a number of factors that may result in replacement trees that provide fewer ecosystem services than the original components of the urban forest. In Vancouver, these issues include the following: (1) the rule applies to trees of at least 20 cm in diameter at removal, but replacements need only be 6 cm at the time of planting; (2) tree species are required to be selected "for disease resistance and hardiness" but not to be chosen with a changing climate in mind; and (3) the requirement as a whole can be met in lieu by paying a relatively small fee (City of Vancouver 2022a). In addition, even carefully selected and well-cared-for

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trees face additional pressures as their surrounding environments densify, including soil compaction due to land development, solid impediments to root proliferation (such as building foundations and roads), and toxic levels of heavy metals deposited in soil from high levels of vehicular traffic (Day et al. 2010).

Finally, many of the direct, short-term effects of climate change pose perils to tree health as well as human health. One recognized way to help address future unknown disturbances is to carefully and strategically increase the diversity of the tree population in terms of age, size, and species (Morgenroth et al. 2016). In British Columbia (BC), Canada, which includes the site of the current case study, recent years have been marked by a number of climate-related disasters, including devastating wildfires, a record-breaking heat dome, and severe flooding (Crawford 2022). Across coastal areas of the region, such floods are projected to become more common in the future, with simulation models indicating that the atmospheric rivers responsible for extreme precipitation will become 50% more frequent under projected warming scenarios (Espinoza et al. 2018). In addition to this increase in precipitation in the wet season, models indicate significantly less precipitation during the dry season, with the length of dry spells expected to increase by 22% over the historical average by the 2050s (Metro Vancouver 2016). Each of these climate-related disasters can negatively impact the urban forest. Wildfires can result in increased air pollution that can reduce the rate of photosynthesis or increase susceptibility to microbial and entomological stressors (Depietri et al. 2012). Heatwaves lead to crown dieback and mortality among both native and exotic species (Marchin et al. 2022). Flooding reduces nutrient availability in the soil (Depietri et al. 2012).

In order to develop and manage urban forests that are resilient in the face of these threats while providing the full range of nature-based solutions to nearby residents, we must be able to project into the future. In this way, we can understand precisely what climatic conditions the urban forest will face over the coming decades, select the tree species that will be able to thrive under these conditions, and detail the full range of ecosystem services that will be provided as a result. The overarching objective of this study is to outline a framework for creating future urban-forest scenario models by clarifying the impact of each stage of the scenario-development process on a model's outputs and applicability to policy decisions. We report the results of a case study in a neighbourhood in Vancouver, Canada with both low building density and low canopy cover in 2020, envisioning a future for the area in which both of these attributes would shift substantially by 2050. In addition to these overall criteria, the future scenario sought to model, and thereby investigate, the implications of 3 additional planning decisions that reflect policy priorities in the region: (1) designing the urban forest in a manner that would achieve greater public-health benefits via the integration of "blue-green streets" as a specific form of NBS; (2) prioritizing the inclusion of tree species that would be maximally resilient under a changing climate; and (3) integrating planting programs into the existing network of trees on both public and private property to ensure the highest possible diversity across the urban forest. This study was designed as a complement to Czekajlo et al. (in press), which offers a comprehensive description of the underlying scenario-development methodology, by elucidating the effects of embedding specific policy priorities.

MATERIALS AND METHODS

The City of Vancouver's Urban Forestry and Sustainability Planning

Located in southwestern British Columbia, Vancouver is Canada's third largest municipality (following Toronto and Montreal) and has the highest population density of any Canadian municipality according to the 2021 Census, at 5,750 people per square kilometer (City of Vancouver 2022b). The city's population increased by 4.9% between 2016 and 2021 to a total of 622,248 residents, comprising a quarter of the population of the broader metropolitan region and accounting for 17% of the region's growth over this time period (City of Vancouver 2022b). Within the city, growth rates and population density vary widely, with some neighbourhoods reporting a population increase of nearly a quarter across the 5 years in between censuses and others remaining essentially flat. The downtown core reported the highest population density of any location in Canada, at 18,837 people per square kilometer compared to Toronto's figure of 16,608 and Montreal's of 8,367 (City of Vancouver 2022b). This pattern of urban densification is expected to continue over the coming decades, with the region projected to grow by nearly 1.5 million residents by 2050 (Metro Vancouver 2022).

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Despite this densification, the city has managed to maintain its relatively high level of urban greenness (Czekajlo et al. 2020; Lantz et al. 2021), in part due to the Greenest City 2020 Action Plan, which set numerous goals for increasing access to nature compared to the 2010 baseline (City of Vancouver 2015). Specific aims included ensuring all residents live within a 5-minute walk of a park, greenway, or other greenspace; planting a total of 150,000 new trees over the course of the decade; and increasing tree canopy cover to a total of 22% by 2050 (City of Vancouver 2015). This final goal was successfully reached a full 3 decades early, with the city calculating a citywide canopy cover of 22% in 2020 (Vancouver Board of Parks and Recreation 2020). Having met this goal, at the end of 2020, the Vancouver Board of Parks and Recreation then set a citywide target of reaching 30% tree canopy cover by the year 2050—while also seeking to advance equity by focusing on canopy-deficient neighbourhoods; increase connectivity between trees and other forms of greenspace, such as parks; and support the city's broader climate-change mitigation efforts (Vancouver Board of Parks and Recreation 2020).

Scenario Setting

To develop a granular understanding at a small scale, modelling scenarios were built in a proxy area (or "sandbox") of 1,600 m by 1,600 m in size. The sandbox was created by piecing together 16 smaller, manageable urban blocks (400 m by 400 m in size), generated and arranged in previous research (Lu et al. 2021; Lu et al. 2023). The relevant characteristics incorporated into the model were based on a neighbourhood in southeastern Vancouver that had less than 10% canopy cover at the study's 2020 baseline. In addition to being in need of a significant planting effort to meet the city's 2050 canopy cover goal, the area is expected to rapidly densify, with its population growing by roughly a third between 2020 and 2050 based on mid-point provincial projections with input from local planners (more details in Lu et al. 2021; Lu et al. 2023; Czekajlo et al. in press).

Data on the neighbourhood's built environment were derived from a range of sources, including Metro Vancouver, a regional governing body that is responsible for planning for urban growth and maintaining and developing parklands across the region (Metro Vancouver 2022); BC Assessment, which assesses and documents property information from across the province (BC Assessment 2022); and the Pacific Institute for Climate Solutions' Energy Efficiency in the Built Environment project, which modelled the effects of a range of policy solutions to climate change (Salter et al. 2020; Lu et al. 2023). Integrating these data, the sandbox was populated with a total of 15,164 residents in 2020, predominately living in single-family homes (75% of the parcel area). Other residence types and land uses were relatively uncommon at baseline, with 4% of parcels in the area consisting of multi-unit dwellings, 6% commercial properties, 1% mixed-use, 1% civic, and 8% parks or greenspace. Additional details regarding the sandbox inputs are provided in Czekajlo et al. (in press).

Scenario Aims

Each of the 4 modelling scenarios focused on expanding the urban forest to contribute to the City of Vancouver's 2050 goal of 30% canopy cover (Vancouver Board of Parks and Recreation 2020), but they incorporated slightly different criteria to reach this outcome. The scenario that formed the focus of the current study—referred to as "scenario 4" in Czekajlo et al. (in press)—prioritized planting new trees to create "blue-green streets" as a specific form of green infrastructure. Based upon the City of Vancouver's definition, such blue-green streets integrate green features (including trees and other "park-like elements") in a manner that also supports hydrological (or blue) functions, thereby helping to achieve the city's goal of increasing access to nature while also providing essential regulating ecosystem services, such as flood management and improved water quality (City of Vancouver [date unknown]). These blue-green streets comprised 2 thoroughfares within the sandbox for which the planting programs were specified to be resilient to the increased heatwave-associated drought and flooding expected in the region. In addition to meeting these resiliency criteria, larger trees were preselected as the preferential option, in part due to their increased ability to shade the higher volume of pedestrian and cycling traffic planned for these routes. Finally, the scenario embedded Santamour's 30-20-10 guidelines for diversity: planting no more than 30% of any family of trees, no more than 20% of any genus, and no more than 10% of any single species (Santamour 1990). All in all, scenario 4 (S4) aimed to achieve the urban tree trifecta: identifying resilient

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species, selecting new trees that complement the existing urban forest to maximize diversity, and placing trees in locations that provide the greatest range of ecosystem services to a densifying community.

Scenario Data Sources and Inputs

In order to model future diversity of both tree sizes and species, current and accurate inventories of public and private trees were integrated with freely available and climatically-relevant tree databases. Size (both in terms of height and canopy spread) and approximate location for trees in the baseline (2020) sandbox model were acquired from LiDAR data collected in 2013, made available freely through the City of Vancouver's Open Data Portal (City of Vancouver 2013). Baseline species' information for street trees on public lands were available from the continuously updated City of Vancouver street tree inventory (Vancouver Board of Parks and Recreation 2018). However, these details had to be developed via a multistep process for trees located within parks and on private property due to data unavailability. Missing species information was supplied using a species list derived via a novel remote identification protocol that integrated Google Street View imagery.

This step took advantage of the predominance of single-family homes that abut laneways in the neighbourhood, which allowed us to visually analyze images of backyards captured along these laneways and determine the species of any trees they contained. After creating 100 sample plots of 405 m^2 in size randomly distributed throughout the neighbourhood, following sample-plot size guidelines outlined by Nowak et al. (2008), Google Street View was used to virtually determine the species of all identifiable trees within each plot (or the genus if the species was not identifiable). We were fortunate that Google Street View regularly scans this neighbourhood, and we were able to ensure that all images used were captured at the same time. The proportions of tree species found within these sample plots were then extrapolated to cover the entire sandbox area.

With these data in hand regarding the current urban forest composition, we integrated prior work conducted on behalf of Metro Vancouver that used projections of the region's future climate to create a list of tree species that are likely to maintain vitality under projected conditions (Metro Vancouver 2019a, 2019b). We used this list as the initial basis for selecting tree species that could be planted to complement the existing urban forest, further refining the selection by accounting for size and species diversity. With respect to the latter quality, the inventory of existing trees highlighted that species from both the *Acer* and *Prunus* genera were over-represented in the study area, so they were subsequently excluded from the final planting list.

Scenario Development and Assessment

The final phase of the scenario modelling process was simulating and assessing the impact of the planting process in the year 2050. Figure 1 outlines the

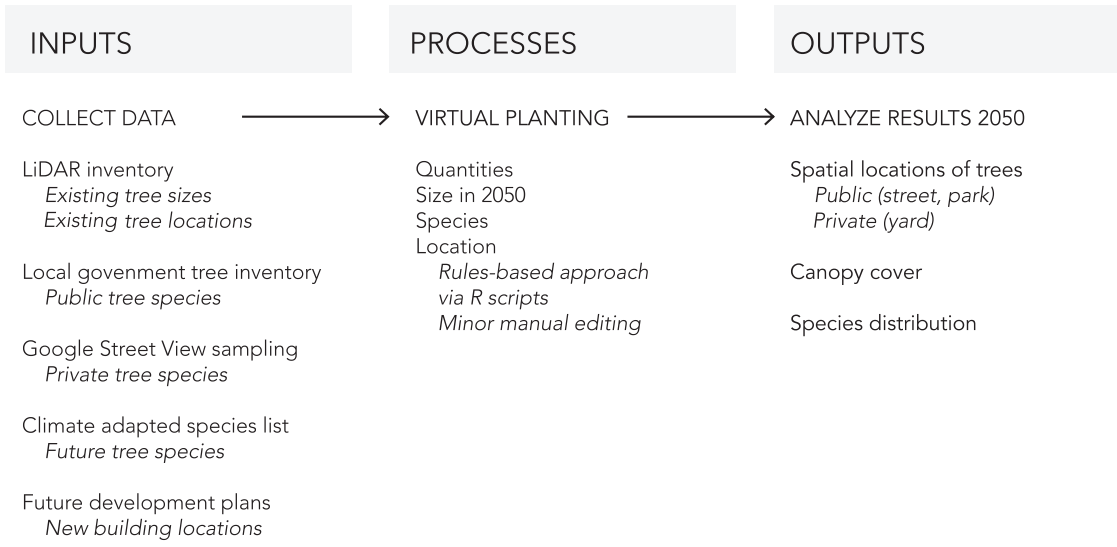

Figure 1. Outline of process used to develop future scenario models.

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inputs, processes, and outputs used to create, run, and analyze the scenario models. Scenario data assignment and model development were conducted systematically using a rules-based approach via R scripts (R Core Development Team 2017), including the following packages: ggplot2 (Wickham 2016), tidyverse (Wickham et al. 2019), rgdal (Bivand et al. 2022), raster (Hijmans et al. 2015), and sf (Pebesma et al. 2022). Additionally, some minor manual editing was performed using ArcGIS Pro (Version 2.9.2). Inputs used to create the 2050 scenario models included information about which trees were directly sourced from the baseline 2020 model (i.e. "existing" trees). Trees that were not selected for the 2050 models due to pre-determined mortality rates, based on rates provided by Hilbert et al. (2019) and species prioritization rules, were removed and considered "aged out". For replacement and additional trees that were new in the 2050 models, quantities were determined through analysis of available spaces in the neighbourhood. Representative species were selected across small, medium, and large categories from the climate-adapted tree species list (Metro Vancouver 2019a), ensuring that diverse families and genera were represented. In alignment with the blue-green streets concept, trees that are known to tolerate the conditions in stormwater swales were prioritized. Trees from each size category were then selected for a site based on the location of the planting area. For example, we "planted" new trees to reach a goal of 2 trees per parcel in private yards, selecting small and medium species in recognition of the fact that most yards are unable to accommodate large trees.

To efficiently run the scenarios, all trees were "planted" in the modelled environment during the year 2020 so they would be of exactly the same age 3 decades later. Data on species' average 30-year growth curves were unavailable or inconsistent across the range of online plant guides and databases appropriate for the study area's climatic region, which included those produced by Oregon State University (OSU), the University of British Columbia (UBC), and the University of Florida (Breen 2022; University of Florida 2022; UBC Botanic Garden 2022). The OSU data provided the greatest extent of coverage about mature tree height for the species included on our planting list, however, so those details were used to estimate each planted tree's height following 30 years of growth (estimated as 80% of mature height). Data on trees not included in the OSU database were collected from Kwantlen Polytechnic University (Kwantlen Polytechnic University 2015), Missouri Botanical Gardens (Missouri Botanical Gardens [date unknown]), and Plants For A Future (Plants for a Future [date unknown]). Because only mature tree heights were consistently provided within the consulted online plant databases, 30-year canopy spread (i.e., diameter) was estimated as 45% of average mature tree height. Details about growing trees of each species to 30-year sizes for this project, and further information about scenario data and models, are provided in Czekajlo et al. (in press).

RESULTS

The results of the virtual planting process carried out for our case study offer indications of the potential of the urban-forest scenario modelling process to inform the development of salubrious, resilient, and diverse urban forests in the context of a changing climate and densifying populations. Table 1 lists the top 15 species planted across public and private settings, demonstrating significant differences in the composition of these 2 components of the overall urban forest. Most notable is the absence of coniferous trees as common planting choices in the public realm, and their relative abundance in the private realm, with only *Prunus* found as a top planting choice in both.

This distinction in planted species between the public and private realms is particularly important in light of a separate finding from the case study: resilience and diversity require an increasing reliance on trees planted on private property in order to achieve a substantial increase in canopy cover. At our study's baseline, the total canopy cover within the sandbox was 6.6%, with 74% of this coverage coming from publicly maintained trees and 26% from private trees. By 2050, the canopy cover had grown substantially to 15.6% (which was just over half of the scenario's stated aim of 30%) and the tree ownership ratio had shifted dramatically: 57% of coverage was now provided by private trees.

This change in tree ownership was accompanied by a shift in the average size of trees, both with respect to height and crown radius. In the baseline tree inventory, tall trees (those greater than 15 m) comprised 25% of the canopy, but this fell to 15% of the canopy in 2050, due primarily to the replacement of fully mature trees (at least 50 years old) with the

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Table 1. Genus, species, and common name of most-common trees planted at baseline.

Private		
Genus	**Species**	**Common name**
Thuja	*Thuja occidentalis*	Arborvitae
Thuja	*Thuja plicata*	Western red cedar
Prunus	*Prunus* spp.	Plum/cherry
Acer	*Acer palmatum*	Japanese maple
Ficus	*Ficus carica*	Brown Turkey fig
Trachycarpus	*Trachycarpus fortunei*	Windmill palm
Pseudotsuga	*Pseudotsuga menziesii*	Douglas fir
Thuja	*Thuja* spp.	Cedar—unknown
Pinus	*Pinus mugo*	Mugo pine
Chamaecyparis	*Chamaecyparis pisifera*	Sawara cypress
Pinus	*Pinus nigra*	Black pine
Cedrus	*Cedrus atlantica*	Atlas cedar
Cercidiphyllum	*Cercidiphyllum japonicum*	Katsura
Magnolia	*Magnolia grandiflora*	Southern magnolia
Malus	*Malus* spp.	Apple
Public		
Genus	**Species**	**Common name**
Prunus	*Prunus serrulata* ‘Kwanzan’	Japanese cherry or Kwanzan cherry
Carpinus	*Carpinus betulus* ‘Fastigiata’	Erect European hornbeam
Prunus	*Prunus cerasifera*	Purple-leaf cherry plum
Prunus	*Prunus serrulata* ‘Ukon’	Ukon flowering cherry
Acer	*Acer platanoides*	Norway maple
Prunus	*Prunus cerasifera* ‘Nigra’	Black cherry plum
Gleditsia	*Gleditsia triacanthos*	Honey locust
Acer	*Acer* × *freemanii* ‘Armstrong’	Armstrong Freeman maple
Fraxinus	*Fraxinus americana*	European ash
Liquidambar	*Liquidambar styraciflua*	Sweet gum
Fraxinus	*Fraxinus ornus*	Manna ash
Pyrus	*Pyrus calleryana*	Chanticleer pear
Sorbus	*Sorbus aucuparia*	Whitebeam
Carpinus	*Carpinus caroliniana*	American hornbeam
Fraxinus	*Fraxinus pennsylvanica*	American ash

moderately mature trees planted in the scenario (Czekajlo et al. in press). When sizing was standardized, the difference in canopy size was found to be associated with the chosen species, with most climate-adapted species tending to be smaller overall. In addition, there was a wider range of tree heights at baseline than in 2050, due to the greater variation in mature height than that seen at 30 years following planting. Conversely, crown radii were grouped more distinctly at 30 years, with a skew toward the lower end of the range and very few trees found in the higher end. Figure 2 captures the changes in the composition of the urban forest between baseline and 2050, with statistics on the distribution of public versus private

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trees, as well as the relative size of trees with respect to height and crown radius.

Looking next at the resilience of the future urban forest in our case study, we found that a relatively large proportion of the trees planted at baseline would not be resilient to the shifting climate, as indicated by the color coding in Figure 3. The extent of this issue is greater for the trees planted in the public realm than in the private realm, primarily due to the predominance of new plantings of private trees, for which the list of climate-resilient species developed by Metro Vancouver was used to guide the selection.

Finally, with respect to diversity, our case study indicated that a high level of diversity could be achieved via a strategic planting program. Even staying within the confines of the much smaller set of trees known to be climate-resilient, the implementation of a rule precluding both *Acer* spp. and *Prunus* spp. resulted in a significant decrease in the predominance of the families *Sapindaceae* and *Rosaceae* respectively, allowing us to fulfill the 30-20-10 planting rule in 2050, as depicted in Figure 4.

DISCUSSION

Our results demonstrate that scenario modelling can play an important role in developing evidence-based plans for developing resilient and diverse urban forests in densifying cities such as the study setting of Vancouver, Canada. We purposively selected a neighbourhood that is anticipated to undergo rapid densification over the coming decades and then developed a case study to achieve 3 distinct aims: (1) maximizing public-health benefits; (2) selecting tree species best suited to thrive in a changing climate; and (3) creating a holistic urban forest that integrates both public and private plantings to promote diversity. Using this approach, this study clarified the path toward achieving the urban tree trifecta, with lessons that can be applied by urban foresters and their municipal partners to increase canopy cover while advancing equity.

Looking first at the public-health benefits of the scenario via the lens of the urban forest as a form of nature-based solutions (NBS), our model was successful at advancing this component by more than doubling canopy cover (from 6.6% at baseline to

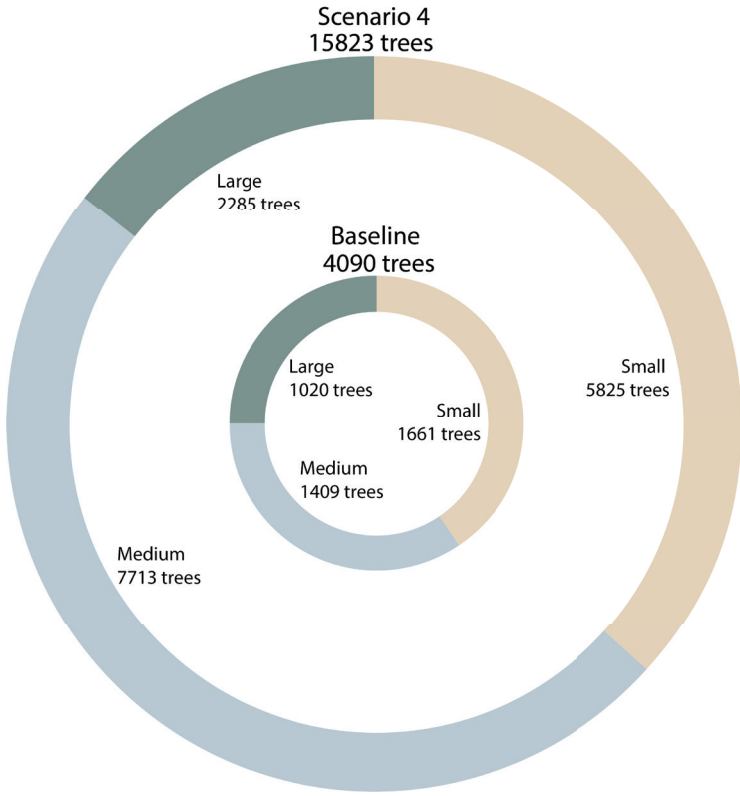

Figure 2. Urban forest composition comparison between baseline and Scenario 4. Tree sizes are based on mature tree height and include small (< 10 m), medium (10 to 15 m), and large (> 15 m) groupings.

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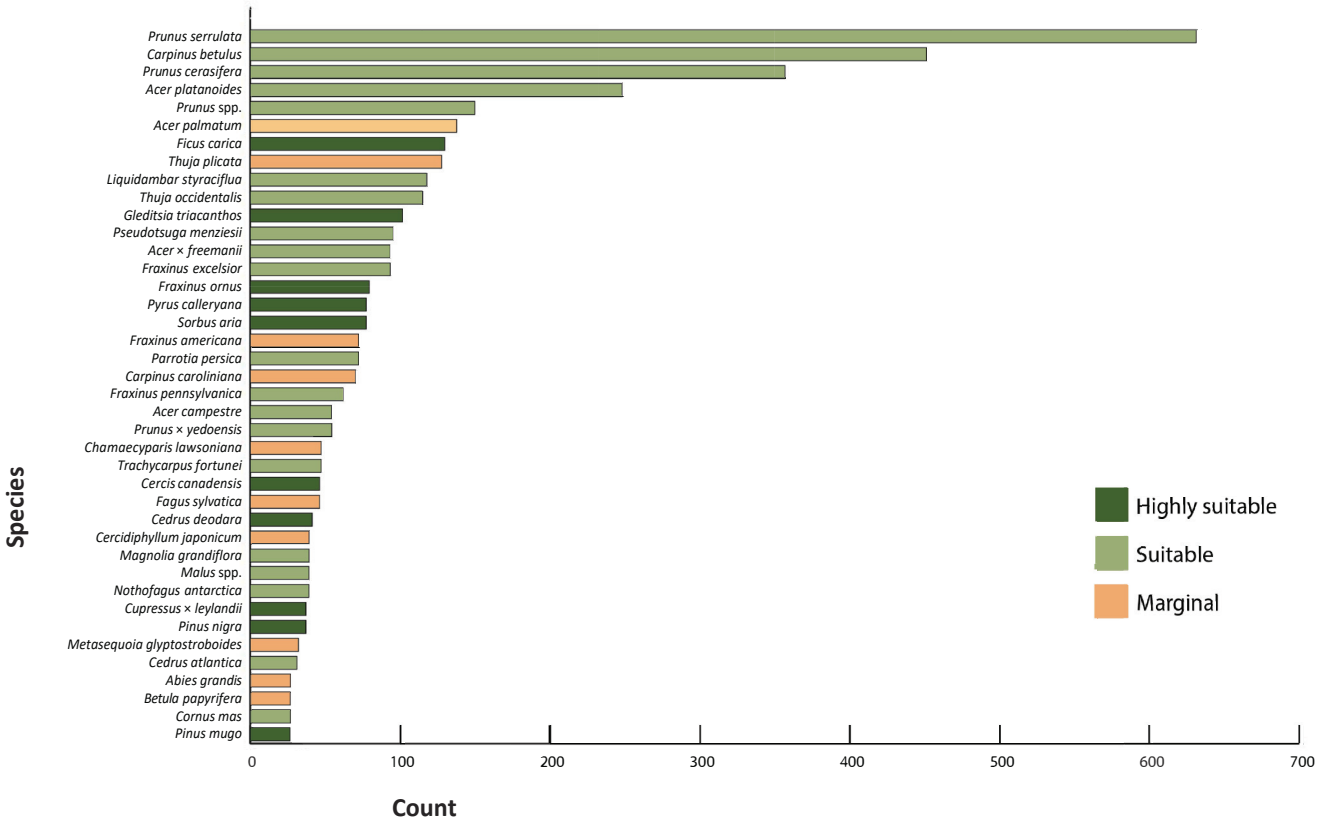

Figure 3. Resilience of commonly planted trees on public and private property.

15.6% in 2050) and by creating "blue-green streets" that may provide multiple benefits, including outdoor shading and cooling (Yu et al. 2020; Jiang et al. 2021; Qiu et al. 2023). A greater amount of canopy cover both reduces average temperatures and increases the availability of shade, which is particularly important in cities such as Vancouver that are predicted to experience more frequent heatwaves in a changing climate. The health benefits of an expansive urban forest during heatwaves were demonstrated in a study conducted by the British Columbia Centre for Disease Control in Vancouver, which reported that individuals who died during the city's 2021 heatwave were more likely to live in areas of higher building density and lower surrounding greenness (Henderson et al. 2022). Ensuring that tree canopy cover is incorporated in a manner that creates an inviting environment for physically active modes of transportation such as walking and cycling, which is precisely what our model's blue-green streets provide, is embedded in Vancouver's regional growth strategy specifically to "to promote positive mental and physical health" (Metro Vancouver 2022).

These streets also respond to calls in the literature to fully integrate urban-forest planning into the broader socio-ecological system of cities, paying careful attention to the intersection between NBS and other forms of infrastructure, and ensuring that trees are integrated in a way that provides ecosystem services both within individual neighbourhoods and across cities (Hansen et al. 2022).

The selection of trees is as vital as their placement in order for the urban forest as a whole to be resilient to the impacts of climate change. Urban forests possess the potential to mitigate the worst outcomes of climate change if they can thrive under rapidly, and often dramatically, changing conditions (Depietri et al. 2012), but climate change can lead to a reduction in both the level and range of ecosystem services provided if resiliency is not taken into account (Runting et al. 2017). Recognizing the importance of street trees to mitigation, numerous cities have made tree-planting

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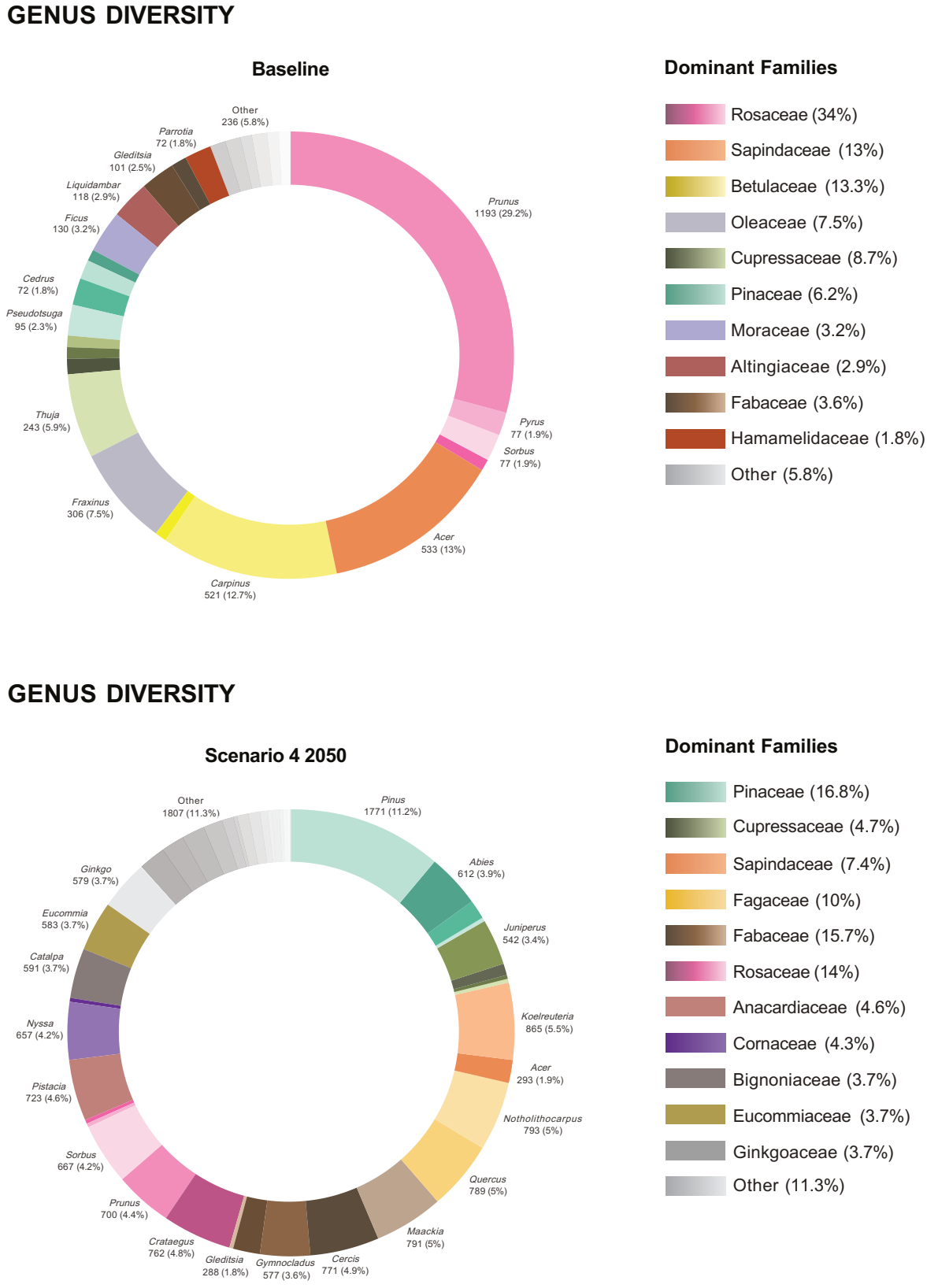

Figure 4. Urban forest family and genus diversity at baseline and 2050. Genus totals do not add to 100% because not all genus are listed in the diagram for legibility reasons.

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programs a cornerstone of their sustainability plans (City of Los Angeles 2018; City of New York 2015; Vancouver Board of Parks and Recreation 2018). However, less attention has been paid to the management costs that are required to address issues of long-term vitality among newly planted trees (Roman et al. 2021). Our case study identified a greater lack of resiliency among public trees than private trees due to the impact of historical planting decisions, making adequate planning and funding for the maintenance of the existing urban forest an essential complement to tree-planting programs.

Similarly, the lack of diversity in the baseline urban forest, which was primarily composed of public trees, calls attention to a challenge that is common to numerous locations beyond Vancouver: few species currently planted are on the "highly suitable" list for Metro Vancouver, as demonstrated by the findings captured in Figure 2. These findings make it clear that some species of trees should be put on a pause list for planting, both because of their unsuitability in projected future climates and because they have been planted in such large numbers over prior decades, resulting in a less diverse urban forest that is more vulnerable to the effects of urbanization and to climate-related disasters such as droughts, flooding, and pest outbreaks.

Promoting high biodiversity in urban ecosystems is a cornerstone of preserving global biodiversity (Alvey 2006), and there is significant evidence that urban landscapes can achieve high biodiversity (Ordóñez and Duinker 2012; Sushinsky et al. 2012). Tratalos et al. (2007) argue that higher-density nodes in large areas of greenspace create a complex form that improves biodiversity, if designed well. In a modelling study comparing compact and sprawling development patterns, researchers found that compact developments had comparatively low ecological impact, but that this "depends crucially on maintaining high-quality interstitial greenspaces between high density developments" (Sushinsky et al. 2012, p. 407).

This final point also draws attention to the importance of public-private partnerships, especially in light of the shift in trees planted on public property to those on private property that our results demonstrate is essential to achieving anything close to the City of Vancouver's overall canopy coverage aims. Although in the private realm, it's critical that these trees be selected from our list of identified climate-resilient species, which can only be accomplished via a public awareness campaign accompanied by the provision of saplings of these species to private property-holders. Such an effort is already underway in London, England, where the Mayor's Trees for London program is working with a nationwide greenspace advocacy group to provide packs of 50 carefully selected 2-year-old saplings at no cost to organizations such as housing associations and schools, along with a detailed planting guide that covers issues of aftercare and long-term maintenance (The Conservation Volunteers 2022). As the inclusion of aftercare instructions acknowledges, supporting private trees immediately after planting is vitally important, particularly to offset the increased vulnerability of newly planted trees to both drought and flooding. Maintenance issues were also one of the largest concerns expressed by residents who were invited to participate in The Greening of Detroit's street tree-planting program, along with frustrations about the limited opportunities to select trees they found aesthetically pleasing and a good fit for their properties (Carmichael and McDonough 2018). In light of the fact that achieving the diversity aims of our urban tree trifecta will necessarily constrict the types of trees available to plant on private property, this last finding further highlights the importance of both broad-based public education campaigns and more detailed guidance for participating planters.

As with any modelling study, this effort has a number of limitations. Principal among these limitations is the fact that any model is only as robust as its underlying inputs, and our inputs relied on a number of assumptions. These include the extrapolation of baseline species based on what could be visually assessed via Google Street View in a sample of 100 randomly chosen locations across the case study area, rather than an actual inventory of all trees on private property. For future efforts, this limitation could be overcome by the incorporation of a survey sent to neighbourhood residents asking them to count and identify the trees on their property or by the integration of a citizen-science approach in which individuals are trained to conduct ground-truthing of species data by taking photographs of private trees. Alternately, novel machine-learning approaches may successfully detect more than 70% of all public and private trees identified via ground-truthing (Lumnitz et al. 2021), allowing for less time-intensive

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assessments. Other assumptions included the estimated height and crown spread of planted trees following 30 years of growth, for which we integrated mature size data from a reliable database but necessitated a generalized formula to calculate 30-year sizing across all species due to limited and inconsistent existing data and literature. With the increase in open, online tree inventories, future work could incorporate tree allometry and growth measurements, per species and urban environment, for improved model robustness.

For example, incorporating climate impacts such as drought, increases in potential insect and disease infestations, and extreme weather conditions into tree species selection was done through the use of a regional climate-adapted tree species list. Relying on such dated information, even if recently produced, is another limitation. Increasingly, climate impact information is being updated at a rapid pace, and future models could incorporate more recent impact assessments. Robust models also require consideration of cooperation among departments at the municipal and regional levels (i.e., the development of blue-green streets can only be carried out successfully when urban foresters work hand in hand with transportation planners and civil engineers). Although included, this consideration was somewhat limited, focusing primarily on the potential for planted trees to provide sufficient shade along blue-green streets. Other factors to examine would be the potential risks to pedestrians and cyclists associated with falling leaves and branches; conflicts with below and aboveground infrastructure; and the impact of land-use types, such as single-family vs. multi-family housing, on the appropriate selection and maintenance of trees. The current effort was aimed at sparking a conversation with local governments about the potential benefits and limitations of a range of future urban forests with the notion that future iterations would incorporate local governance measures more concretely.

CONCLUSIONS

As the case study described here demonstrates, it is possible to achieve the tree trifecta of a salubrious, resilient, and diverse urban forest even alongside rapid densification and within the constraints imposed by historical planting choices. Reaching this goal will require the creation of strong collaborative relationships between urban-forest managers and a range of other municipal officials, as well as the development of novel public-private partnerships to plant new trees that prioritize both short-term community education and long-term maintenance. In addition, although much of the required effort will take place at the municipal or regional scale, factoring in variation that exists at the neighbourhood, block, or lot level is critical, as is laying out a clear path for reaching the time- and density-based goals common to urban sustainability plans. Different neighbourhoods will have varying extant urban forests, as well as distinct strengths and capabilities in terms of growing their local urban forests. If cities plan urban forests at the neighbourhood scale with the future climate in mind, then species diversity can be tailored appropriately and ecosystem services assessed more accurately. These characteristics must be accounted for to avoid exacerbating existing inequities in canopy coverage that result in a lack of environmental justice from the many ecosystem services the urban forest provides.

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Résumé. Contexte: Les forêts urbaines peuvent fournir des solutions basées sur la nature (SBN) aux défis complexes des changements climatiques via la fourniture de services écosystémiques tels que l'ombrage et le rafraîchissement qui compensent les risques accrus de maladies chroniques et de surmortalité. Elles confèrent également des avantages indirects sur le plan de la santé en fournissant des services écosystémiques de régulation qui peuvent faciliter les efforts d'atténuation des changements climatiques: l'ombrage accru peut ainsi encourager le passage à des méthodes de déplacement à faible émission de carbone, telles que la marche et le vélo, par exemple. Toutefois, afin de s'assurer que les forêts urbaines seront à la fois résilientes aux menaces et qu'elles procureront le maximum de bénéfices, nous devons être en mesure de nous projeter des décennies dans l'avenir afin de comprendre les implications des décisions actuelles en matière de foresterie urbaine. Méthodes: Cette recherche propose un cadre pour la création de modèles de scénarios de forêts urbaines et présente les résultats d'une étude de cas menée afin de mettre en évidence les façons dont les décisions prises à chaque étape du processus de développement des scénarios influencent ses résultats et leur application. Notre étude de cas s'est concentrée sur un quartier de Vancouver, au Canada, qui entreprend en parallèle une densification urbaine et un objectif d'augmentation significative de la canopée végétale d'ici 2050. Trois objectifs distincts ont été identifiés pour l'étude de cas: maximiser les bénéfices pour la santé publique, sélectionner des espèces d'arbres résistantes au climat et intégrer la plantation sur les terrains publics et privés en vue de favoriser la biodiversité. Afin d'atteindre ces objectifs, des informations de base sur la trame d'arbres existants dans le quartier ont été collectées, saisies dans un logiciel SIG et présentées sur la base d'un ensemble de caractéristiques pré-identifiées. Puis une liste d'espèces adaptées au climat a été dressée. Cette liste d'espèces, adaptées au climat, a ensuite été virtuellement "plantée" dans le quartier, en utilisant une combinaison de techniques de plantation mécaniques et manuelles. Enfin, le modèle de scénario résultant a fait l'objet d'une évaluation quantitative afin de comprendre sa composition et ses impacts. Résultats: Notre étude démontre qu'une forêt urbaine saine, résiliente et diversifiée peut être créée grâce à un programme stratégique qui apporte un complément aux arbres existants dans le domaine public par des programmes de plantation le long des rues vertes et sur les propriétés privées. Conclusions: Réussir le tiercé des arbres urbains nécessitera une collaboration entre les services municipaux et le développement d'une série d'initiatives publiques et privées, mais elle a le potentiel de maximiser les solutions basées sur la nature dans les villes confrontées à des changements rapides dus à la densification et aux changements climatiques.

Zusammenfassung. Hintergrund: Urbane Wälder können naturbasierte Lösungen (NBS) für komplexe Herausforderungen

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des Klimawandels bieten, indem sie Ökosystemleistungen wie Schatten und Kühlung bereitstellen, die das erhöhte Risiko chronischer Krankheiten und erhöhter Sterblichkeit ausgleichen. Sie bieten auch indirekte Vorteile für die Gesundheit, indem sie regulierende Ökosystemleistungen erbringen, die die Bemühungen um eine Abschwächung des Klimawandels erleichtern können: Mehr Schatten kann zum Beispiel den Wechsel zu kohlenstoffärmeren Fortbewegungsmethoden wie Gehen und Radfahren fördern. Um jedoch sicherzustellen, dass städtische Wälder sowohl gegen Bedrohungen resistent sind als auch den größtmöglichen Nutzen bringen, müssen wir in der Lage sein, Jahrzehnte in die Zukunft zu projizieren, um die Auswirkungen aktueller Entscheidungen zur städtischen Forstwirtschaft zu verstehen. Methoden: In dieser Studie wird ein Rahmen für die Erstellung von Szenariomodellen für den städtischen Wald skizziert und über die Ergebnisse einer Fallstudie berichtet, die durchgeführt wurde, um die Art und Weise hervorzuheben, in der Entscheidungen, die in jeder Phase des Szenarioentwicklungsprozesses getroffen werden, dessen Ergebnisse und Anwendung beeinflussen. Unsere Fallstudie konzentrierte sich auf ein Stadtviertel in Vancouver, Kanada, das gleichzeitig eine urbane Verdichtung erfährt und das Ziel verfolgt, den Baumbestand bis 2050 deutlich zu erhöhen. Für die Fallstudie wurden drei verschiedene Ziele festgelegt: Maximierung des Nutzens für die öffentliche Gesundheit, Auswahl klimaresistenter Baumarten und Integration der Bepflanzung öffentlicher und privater Grundstücke zur Förderung der Vielfalt. Um diese Ziele zu erreichen, wurden grundlegende Informationen über das bestehende Baumnetzwerk in der Nachbarschaft gesammelt, in eine GIS-Software eingegeben und auf der Grundlage einer Reihe vorher festgelegter Merkmale abgegrenzt. Anschließend wurde eine Liste von an das Klima angepassten Arten erstellt. Diese Liste klimaangepasster Arten wurde dann mit einer Kombination aus maschinellen und manuellen Pflanztechniken virtuell in der gesamten Nachbarschaft "gepflanzt". Schließlich wurde das resultierende Szenarienmodell quantitativ bewertet, um seine Zusammensetzung und Auswirkungen zu verstehen. Ergebnisse: Unsere Studie zeigt, dass ein gesunder, widerstandsfähiger und vielfältiger Stadtwald durch ein strategisches Programm geschaffen werden kann, das den Baumbestand im öffentlichen Raum durch Pflanzprogramme entlang blau-grüner Straßen und auf Privatgrundstücken ergänzt. Schlussfolgerungen: Das Erreichen der städtischen Baumtrias erfordert die Zusammenarbeit zwischen städtischen Abteilungen und die Entwicklung einer Reihe öffentlicher und privater Initiativen, hat aber das Potenzial, naturbasierte Lösungen in Städten zu maximieren, die sich aufgrund von Verdichtung und Klimawandel raschen Veränderungen gegenübersehen.

Resumen. Antecedentes: Los bosques urbanos pueden proporcionar soluciones basadas en la naturaleza (NBS) a los complejos desafíos del cambio climático a través de la provisión de servicios ecosistémicos como la sombra y el enfriamiento que compensan el aumento de los riesgos de enfermedades crónicas y el exceso de mortalidad. También confieren beneficios indirectos para la salud al proporcionar servicios ecosistémicos reguladores que pueden facilitar los esfuerzos de mitigación del cambio climático: el aumento de la sombra puede alentar cambios a métodos de transporte con menos emisiones de carbono, como caminar y andar en bicicleta, por ejemplo. Sin embargo, para garantizar que los bosques urbanos sean resistentes a las amenazas y confieran los máximos beneficios posibles, debemos ser capaces de proyectar décadas en el futuro para comprender las implicaciones de las decisiones actuales de silvicultura urbana. Métodos: Este estudio describe un marco para crear modelos de escenarios de bosques urbanos e informa los resultados de un estudio de caso realizado para resaltar las formas en que las decisiones tomadas en cada etapa del proceso de desarrollo de escenarios afectan sus resultados y aplicación. Nuestro estudio de caso se centró en un vecindario en Vancouver, Canadá, que está experimentando simultáneamente densificación urbana y con el objetivo de aumentar significativamente la cobertura del dosel para 2050. Se identificaron tres objetivos distintos para el estudio de caso: maximizar los beneficios para la salud pública, seleccionar especies de árboles resistentes al clima e integrar la plantación en tierras públicas y privadas para promover la diversidad. Para lograr estos objetivos, se recopiló información de referencia sobre la red de árboles existente en el vecindario, se ingresó en el software SIG y se delineó en función de un conjunto de características previamente identificadas. A continuación, se desarrolló una lista de especies adaptadas al clima. Esta lista de especies adaptadas al clima se "plantó" virtualmente en todo el vecindario, utilizando una combinación de técnicas de plantación manuales y basadas en máquinas. Finalmente, el modelo de escenario resultante se evaluó cuantitativamente para comprender su composición e impactos. Resultados: Nuestro estudio demuestra que se puede crear un bosque urbano saludable, resistente y diverso a través de un programa estratégico que complemente los árboles existentes en el dominio público con programas de plantación a lo largo de calles azul-verde y en propiedad privada. Conclusiones: Lograr la apuesta por los árboles urbanos requerirá la colaboración entre los departamentos municipales y el desarrollo de una serie de iniciativas públicas y privadas, pero tiene el potencial de maximizar las soluciones basadas en la naturaleza en ciudades que enfrentan cambios rápidos debido a la densificación y el cambio climático.

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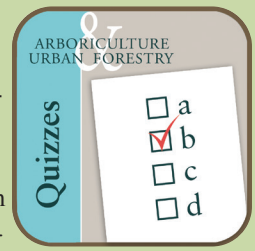

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