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Perspective

Native Trees as a Provider of Vital Urban Ecosystem Services in Urbanizing New Zealand: Status Quo, Challenges and Prospects

Jihwi Jang [1] and Su-Young Woo [2,*]

[1] School of Biological Sciences, University of Canterbury, Christchurch 8041, New Zealand; jihwi.jang@pg.canterbury.ac.nz
[2] Urban Environment and Plant Sciences Laboratory, Department of Environmental Horticulture, University of Seoul, Seoul 02504, Korea
* Correspondence: wsy@uos.ac.kr; Tel.: +82-2-6490-2691

Abstract: In New Zealand, over 87% of the population currently resides in cities. Urban trees can face a myriad of complex challenges including loss of green space, public health issues, and harm to the existence of urban dwellers and trees, along with domestic greenhouse gas (GHG) and air pollutant emissions. Despite New Zealand being a biodiversity hotspot in terms of natural environments, there is a lack of knowledge about native tree species' regulating service (i.e., tree development and eco-physiological responses to low air quality, GHG, rising air temperatures, and drought) and how they grow in built-up environments such as cities. Therefore, we argue for the value of these native species in terms of ecosystem services and insist that they need to be viewed in relation to how they will respond to urban abiotic extremes and climate change. We propose to diversify planted forests for several reasons: (1) to improve awareness of the benefits of diverse planted urban forests; (2) to foster native tree research in urban environments, finding new keystone species; and (3) to improve the evidence of urban ecosystem resilience based on New Zealand native trees' regulating services. This article aims to re-evaluate our understanding of whether New Zealand's native trees can deal with environmental stress conditions similarly to more commonly planted alien species.

Keywords: tree diversity; ecosystem resilience; native tree; urban environment; urbanization

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1. Introduction

1.1. Effects of Urbanization on Tree Growth and Development

Urbanization is a worldwide phenomenon and a key driver of environmental degradation and climate change [1,2]. An urban environment can generally be defined as an area containing an aggregation of infrastructure, buildings, and open spaces that provide for the urban community's socio-economic functions [3]. Currently, over half of the global human population lives in urban and metropolitan areas [4], and this proportion is expected to increase to 70% by 2050 [5].

Trees in urban areas can suffer from chronic abiotic stresses, such as changes in the growing season and circadian rhythm due to urban thermal discomfort, disorders caused by air pollution, and droughts, which are typically enhanced by increasing urbanization [6]. The drastic changes in the urban landscape and environment have negatively affected urban tree and ecosystem health as many plant species have been moved from their provenance to cities (i.e., new environment) [7]. For instance, soil moisture, atmospheric temperature, relative humidity (RH), and vapor pressure deficit (VPD) are often less favorable for urban trees than for their rural environmental counterparts. This is because they result in different tree growth rates (i.e., slower or faster), lower density root systems, and higher leaf temperature, showing different relative tree growth rates until final tree development [8,9]. Another environmental feature for an urban area is a specific airborne chemical composition produced by emissions from traffic, households, and industries, which results in higher CO_2 concentration and more air pollution, raising the atmospheric temperature through GHG. Hence, urban trees growing in built-up areas are subjected to a microenvironment characterized by higher pollution and GHG emission levels due to traffic volume, additional soil drought, and contamination by the input of heavy metals or high salinity [10], as well as a restricted area for root extension which in turn decreases water availability (i.e., cover plate of a tree disc, tree pit covers, and road pavement) [11,12].

This article examined case studies currently used for carbon sequestration and air pollutant removal of urban trees native to New Zealand and compiled currently available results in New Zealand native trees in cities. However, the currently available results are related to alien tree studies and a large degree of uncertainty due to the limitation of applied studies on New Zealand native trees. For a better understanding of New Zealand native trees for urban ecosystem services, it is proposed that planted forests should be diversified for several reasons in this paper: (1) to improve awareness of the benefits of diverse planted urban forests; (2) to foster native tree research in urban environments, finding new keystone species; and (3) to improve the evidence of urban ecosystem resilience based on New Zealand native trees' regulating services. This article aims to re-evaluate our understanding of whether New Zealand's native trees can deal with environmental stress conditions similarly to the more commonly planted alien species. We compiled 146 publications that reported existing data, literature, and opinion on urban forestry and ecology. This perspective article explored and discussed whether New Zealand native trees can provide urban ecosystem services and confirmed that the existing literature can support the advantages of having native trees in cities.

1.2. The Decline of Native Forests after Human Settlement in New Zealand

As shown in Figure 1, the decline of New Zealand's native forests began with the arrival of Māori pioneers in AD 1000, who began deforestation for land-use conversion [13–16]. With the arrival and establishment of the first European settlers around 1840, more natural forests were lost as more towns were developed and agricultural activity increased. By 2000, nationally forest cover in New Zealand had been reduced to only 25% of its pre-settlement level ([15,17]; see Figure 1A). The decline of native trees has also been consistent with urban sprawl and the urbanization trend of New Zealand chronologically by the early 20th century (1920s) ([18]; see Figure 1B). Currently, many introduced species (approximately 2264 species: 30 mammals, 34 birds, and 2200 plants), including in urban areas, are reported in New Zealand [19].

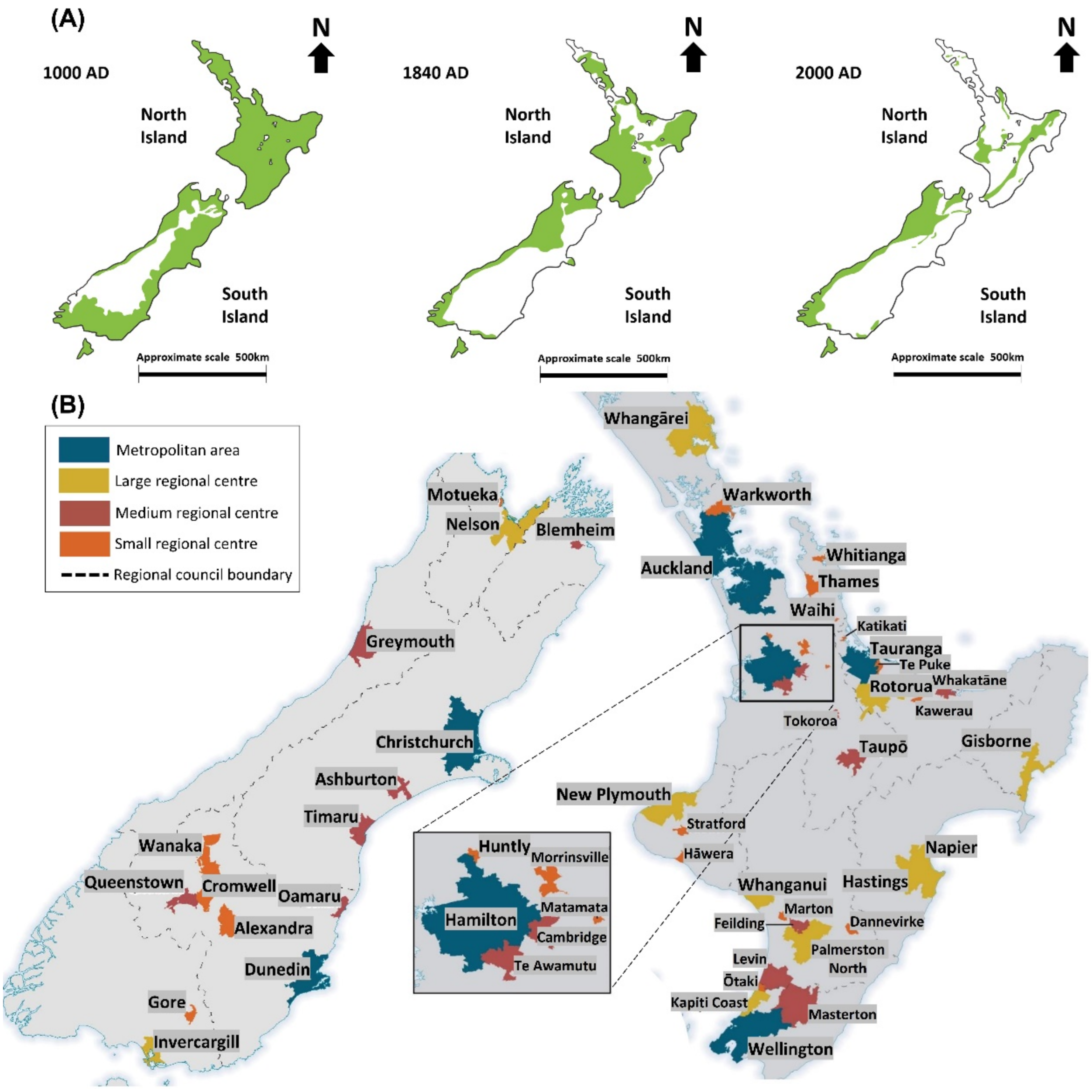

Figure 1. (**A**) Changes in native tree/forest coverage (green color) over time in New Zealand, adapted from Stevens et al. [15] and Nomura et al. [20]; (**B**) functional urban areas by type, New Zealand [21].

With agriculture, dairy farming, and township settlement, forestry activities (i.e., establishing plantation forests, logging, and timber yield) have contributed to the decline of native forests [22–24]. As a result of these activities, many native New Zealand tree species that were once common are now classified as threatened or protected in both rural and urban areas [25,26]. However, New Zealand is currently host to a wide range of alien species, defined as species non-native to New Zealand [24–30]. Since the 1990s, alien (non-native) tree species have had a significantly higher afforestation rates than native species in New Zealand [31,32]. Historically, the use of alien tree species, such as *Quercus* spp. and *Fraxinus* spp., has been preferred in urban green spaces and for garden planning [33,34]. The invasion of alien species in New Zealand cities has contributed to a severe decline in native clusters (indigenous trees clusters) over time [27–29]. In Hamilton, currently the fourth largest and second fastest-growing city in New Zealand, the distribution of native trees in the city is only 2.1%, which is the lowest among New Zealand's six main cities—namely, Auckland, Wellington, Christchurch, Hamilton, Tauranga, and Dunedin [18]. The remnants or patches of native dominated vegetation in each of the cities are very small (2.1–8.9% in the urban boundary) [18,19] and most native trees, except for nature heritage parks in cities, have been planted through urban restoration projects since the 1990s [19]. Although the resilience and flexibility of all trees to abiotic stress caused by human settlement and urbanization require further study, the physiological adaptation of urban trees that are native to New Zealand has been investigated less (especially in urban settings) than that of species indigenous to other countries, such as Central Europe [6,35,36], North America [37], East Asia [38], and Australia [39]. Since the 2000s, urban restoration, including native tree planting in cities, has continued to grow in New Zealand, but relevant research effort is required to overcome a lack of interdisciplinary breadth (i.e., environmental science, plant physiology and biochemistry, forest science, and urban ecology) [19].

2. Urbanization in New Zealand, Its Consequences, and the Role of Tree Diversity

2.1. Urbanization and CO_2 Emission Rate Increment in New Zealand

In the case of New Zealand, as much as 87% of the population currently reside in urban environments and cities [40], and urbanization is increasing especially in the Auckland region, reaching suburban areas such as Tauranga and Hamilton [41]. Urbanization is a strong influencer of population growth (including internal and international migration), building and infrastructure construction, and the spreading of residential areas and fragmentation of urban forests [41,42]. Half of New Zealand's population is expected to live in the Auckland metropolitan area by 2050, and the country's population is expected to reach 8 million by 2073 [41]. New Zealand is heading toward the upper end of urbanization, defined as rapid population growth with new infrastructure, based on Auckland [43]. In total, 76.5% of New Zealanders reside on the country's North Island, which has four major cities: Auckland, Wellington, Hamilton, and Tauranga [44].

Anthropogenic impacts are likely to accelerate abrupt changes in tree growth conditions (i.e., atmospheric temperature, humidity, CO_2 concentration, air quality, and drought extent) in cities. Even though New Zealand has among the highest air quality in the world [45], the amount of domestic anthropogenic greenhouse gas (GHG) emissions has increased over time. This increase in GHG emissions (mainly CO_2, SF_6, and HFCs) is highly related to urbanization in New Zealand [46,47]. However, since the adoption of the Climate Change Response (Zero-Carbon) Amendment Act 2019 of New Zealand, it is expected that New Zealand's government will focus on the reduction of GHG emissions [46].

The GHG inventory report of New Zealand's government largely attributed the increases in GHGs to the energy/transport sectors, determining that these sectors are responsible for 38.2% of the net increase in CO_2 emissions since 1990. In addition, land use, land-use change, and forestry activities (LULUCF) have not shown a decreased rate (i.e., carbon sequestration process in plants and soils) against the build-up of atmospheric CO_2 over time (+7203.3 Kt(CO_2) increment between 1990 and 2017) ([46]; see Appendix A). Approximately 20% of New Zealand's annual energy consumption is from road transportation in urban areas [48], and the emission rate from road transportation steadily grew during the last two decades with an increased rate of private vehicle ownership [49]. Consequently, 47% of New Zealand's total domestic CO_2 emissions come from the road transportation sector and these emissions have tripled over the past three decades [50].

2.2. High Private Vehicle Usage and Deterioration Extent in New Zealand

Over time, road transportation and the use of fossil fuel-dependent vehicles have dramatically increased. They are consistent with the 2020 population growth rate per year (2.1–2.8%). Although Auckland has 52.4 km of bicycle routes [51], private vehicle usage is still the most common form of daily transport [41,52]. In Christchurch, the second most populated city in New Zealand [53], the proportion of CO_2 emissions from vehicles has increased over the last two decades [48]. The use of private vehicles is very dominant in Christchurch, being used for the daily commute by 84% of commuters, which is similar to Auckland (85%). However, the proportion of public transportation use in many cities is still low (2–8%), except for Wellington (21%) ([52]; see Appendix B). This dominance of private vehicles is likely to affect New Zealand's urban environment and contribute to global climate change (GCC), especially as the population growth rate of Christchurch has been 13.5% for five years since 2013 [52], and therefore, the population is predicted to continue to rise.

The deterioration of private vehicles is likely to have a profound effect on New Zealand's GHG emissions. The average age of New Zealand's vehicle fleet is estimated at 14.2 years [54], which is older than that of most OECD countries; the average private vehicle ages in USA, Canada, and Australia are lower than 12 years [55]. Between 2000 and 2017, the proportion of vehicles over 15 years old in New Zealand increased from 24.5% to 42.3% [55,56], and this trend is likely to continue [55]. In addition, over the last 15 years, the proportion of 0–4-year-old vehicles remained under 20% [55,56]. Kjellström and Mercado [57] reported that the average age of vehicles is an important indicator of urban environmental health; old vehicles are likely to be less energy efficient than newer vehicles, have lower fuel efficiency, and their exhaust fumes have stronger links to GHG emissions in cities, including CO_2, CO, NO, NO_2, and particulate matter of less than 10 or 2.5 μm (PM_{10} and $PM_{2.5}$, respectively) [58]. In the case of Auckland, the concentration of multiple air pollutants ($PM_{2.5}$, black carbon (BC), and NO_2) is highly related to a high density of vehicular traffic, showing 2.5-fold ($PM_{2.5}$) and 2.9-fold (NO_2) higher concentrations in the city center (central business district) than other suburban areas in Auckland [59]. Consequently, it might affect human health and tree disservices issues to urban dwellers (87% of New Zealand population). Therefore, it is important to find proper urban tree species among various genetic diversity pools for effective GHG mitigation and air pollutant removal in the changing environment of New Zealand cities.

2.3. The Role of Tree Diversity in Ecosystem Resilience

Ecosystem services are the varied benefits to people provided by the natural environment and healthy ecosystems [60,61]. Ecosystem resilience can generally be defined as the ability to absorb disturbance and provide a stable condition for the ecosystem without loss of ecological function or ecosystem service [62]. Therefore, understanding the role of species diversity of native trees in ecosystem resilience can be vital for strategic ecosystem management tactics to combat anthropogenic disturbances, because it supports functional diversity based on species interaction under interwoven abiotic factors [63]. As a sufficient level of species diversity affects the maintenance of resilience-based management [64], native species can constitute an important proportion of resilience. Species richness is empirical evidence of plant biodiversity [65] and can contribute to effective ecosystem resilience [66]. Species diversity can improve ecosystem stability and act as an environmental buffer [66]. Moreover, increased diversity of trees in an ecosystem can mitigate the disturbance of carbon cycling through trees' species-specific eco-physiological functions and different spreading extent of root systems [67]. Thus, understanding tree diversity is important for climate change regulations [63]. One example of the vital role of native species in imparting resilience is that they attract more pollinator species than alien species [68]. The flowering and fruit production of trees are significantly increased when the monotonous alien proportion decreases [68]. In addition, native trees provide diverse faunal biodiversity habitats [69–71].

Tree species diversity in cities can provide a characterized tree population for improved species structure, function, and value [72]. However, native trees tend to be underutilized in cities [73,74]. Relying excessively on a small number of species threatens urban forest resilience and reduces ecosystem services [75]. Urban tree species are generally removed and/or replanted once they are regarded as having disservice and/or no use in urban forest management [2,76]. Complex interactions between biotic and abiotic factors can affect species imbalances and/or deletions in resilience [77]. Hence, it is important to conduct strategic management of urban ecosystems and vegetation to create a sustainable urban forest that is resilient to environmental disturbances (e.g., fragmentation and imbalances caused by invasive species) [78].

During the last five years, in the Auckland area, there was a net increase of 226 ha in tree canopy cover in built-up areas, 46 ha in urban parkland/open space, and 4 ha in transport infrastructure. However, owing to limited information on the effectiveness of native trees in urban ecosystems and environmental services in New Zealand, there remains an imbalance between alien and native species in this new tree canopy cover, possibly hindering the long-term environmental, cultural, and socioeconomic impacts on urban areas [71].

Planting alien trees in cities can be suitable for environmental regulating, different cultural or heritage purposes, and ecosystem services in some cases, especially for deciduous trees required to enlarge the canopy, or to establish community orchards [65]. Previous studies have noted that alien species on diversity can foster soil nutrients by increasing nitrogen cycling and the composition of soil microbial communities [79]. However, alien species can affect local native plant communities and diversity by minimizing species richness [80] and by affecting pollinators and soil carbon-degrading enzymes of native species [81,82]. In addition, native trees might provide better ecosystem services (with beneficial environmental regulating services) than alien trees in cities. Rahman et al. [2] reported that Central European native tree species planted in cities showed better regulating services (i.e., cooling effect) with 2.8 °C air temperature reduction (ΔAT) and higher transpiration rate than that of alien tree species in a case study of an urban area in Munich, Germany. Many urban trees (alien and native) have differing wood anatomies that highly affect trees' strategies under urban environmental stress such as drought and urban heat island (UHI). Moser-Reischl et al. [83] reported that diffuse-porous and anisohydric trees have a higher cooling effect with high canopy-scale transportation rates amid thermal discomforts in cities, whereas ring-porous and isohydric trees provide higher water potential with high survival rate (low maintenance) by affecting urban hydrology over time. Sonti et al. [37] reported that North American native trees planted in cities showed higher or equivalent stress tolerances with alien trees (i.e., increased air temperature stress, air pollution, and drought) by showing higher chlorophyll fluorescence parameters (e.g., F_v/F_m) than those of alien trees in cities (case studies of New York, NY; Philadelphia, PA; Baltimore, MD). Therefore, it is likely important to find native trees' characteristics (e.g., benefits on regulating services) [37,83], control the number of alien species, and reject uniformity [68]. According to previous studies, however, species diversity showed positive or negative impacts on ecosystem resilience to environmental stresses in many case studies. For instance, Mulder et al. [84] and Steiner et al. [85] reported that diversity enhances plant communities with species interactions by reducing drought impact. However, Wardle et al. [86], Griffiths et al. [87], and Caldeira et al. [88] reported that species diversity did not affect ecosystem resilience, resistance, or mitigating effects on drought. Hence, further studies of the impact of tree diversity on ecosystem resilience to abiotic stressors in urban areas are required.

3. Lower Proportion of Native Trees That Live in New Zealand's Cities

In this article, we define urban forest as a collection of trees that grow in a city and/or town that encompasses green space in a developed (built-up) area, yards and corridors, and park/roadside trees [89]. New Zealand's urban forests are dominated by alien tree species [90]. There are no well-documented reports on whether trees native to New Zealand have prominent ecosystem functions and increase resilience to abiotic stressors in the city. Because of their well-known benefits (environmental regulating services, e.g., carbon storage and air pollutant removal) [91], alien trees are often planted in urban forests and streets, leading to an imbalance in the ratio between alien and native tree species particularly in Auckland [92] and Christchurch [34]. Despite Christchurch being named the "garden city" of New Zealand (due to an urban botanic garden area and the number of urban parks), native species vegetation, clusters, and forests have become increasingly fragmented and insignificant in size [24,34], with the trend being toward small numbers of alien species, leading to a small genetic pool of native trees [34,90]. There are several reasons for the unequal distribution of tree cover across the region in New Zealand cities, such as land ownership (public/private greenspace), land use (urban/industrial/agricultural), geography, and natural heritage for legal protection. For instance, except for natural heritage sites in urban areas and some public/private green spaces, mostly alien species have planted and grown with higher coverages in the cities [90]. Historically, the types of tree planting and development, street trees, and urban vegetation are influenced by municipal urban planning manuals, funding resources, available space, urban dwellers' species preferences, practitioners' preferences based on alien species well known for their environmental regulating services and physiological functions for tree planting rather than genetic diversity, cultural services, and provenance [2,92–94]. Consequently, alien tree species (mainly *Betula pendula*, *Fraxinus ornus*, *Quercus palustris*, *Prunus yedoensis*, *Liquidambar styraciflua*, and *Quercus robur*) have become more dominant than native trees (mainly *Plagianthus regius*, *Sophora tetraptera*, *Cordyline australis*, and *Sophora microphylla*) in parklands and on streets in Christchurch [34,95]. Previous case studies of other countries' cities reported that increasing tree diversity and enlarging green spaces through planting native trees may increase physiological resistance to environmental stressors (regulating service), including those caused by urbanization [91,93] with the fulfillment of cultural services (i.e., cultural identity (e.g., Māori culture, local history) and aesthetic inspiration in New Zealand cities). This means that high genetic diversity with native trees might improve ecosystem resilience to miscellaneous abiotic extremes in cities. Native species can, therefore, constitute an important proportion of resilience [94].

Native trees in cities are generally planted in private greenspaces, where they have moderate to high canopy cover rates but offer a low level of protection to biotic/abiotic stressors and management [94]. Many native tree species are statistically highly distributed across housing estates with a high New Zealand Social Deprivation Index (NZDep) [92]. Huang [92] reported that alien street trees were higher in species richness (75.76% of total species) and abundance (68.51% of total individuals) than native trees in many urban forests and street trees in Auckland. A previous study in Christchurch also found that 84.1% of street trees were alien species, and found a similar array of alien street tree species in Auckland (i.e., *Acer* spp., *Betula* spp., *Quercus* spp., *Prunus* spp., *Ulmus* spp., and *Fraxinus* spp.) Recent data also show that tree cover canopy of all the land in Christchurch is 15.59%, and alien street trees are more dominant than native tree species in Christchurch ([33,34,96,97]; see Table 1).

Table 1. List of the main street trees of Christchurch and planting status in 2020 [33,34,96–98].

Species	Common Name	Provenance	Species Abundance ††
Betula pendula	Silver birch	Europe	4642
Fraxinus ornus	Manna ash	southern Europe, southwestern Asia	4384
Quercus palustris	Swamp Spanish oak	United States	4241
Plagianthus regius †	Lowland ribbonwood	New Zealand	3340
Prunus yedoensis	Yoshino Cherry	Japan	2722
Liquidambar styraciflua	Sweetgum	North America, Asia	2594
Sophora tetraptera †	Large-leaved Kōwhai	New Zealand	2472
Cordyline australis †	New Zealand cabbage tree	New Zealand	2411
Sophora microphylla †	Kōwhai	New Zealand	2291
Quercus robur	English oak	Britain	2242
Sum of main trees			31,339
Others (mixed with small numbers of numerous alien species)			81,547
Total (total abundance of street trees)			112,886

† native tree species; †† number of trees.

4. Current Roles and Further Research Direction for Urban Ecosystem Services Provided by New Zealand Native Trees

4.1. Definition of Ecosystem Service in New Zealand

Urban forests have a history of providing ecosystem services (i.e., cultural, provisioning, supporting, and regulating services) and increasing resilience to abiotic stresses in cities and can help to mitigate GHG emissions and GCC caused by urbanization, road transport, and prolonged exhaust exposure [89,99,100]. The planting and management of trees in urban forests offer effective ecosystem services [101] (e.g., pleasing esthetic values [102], shade/shelter functions against thermal disservices [2], and cooling effects [6]). New Zealand focuses on six major ecosystem services (benefits) for forestry: (1) carbon storage, (2) soil erosion control, (3) biodiversity for threatened species, (4) water purification, (5) provision of agroforestry/understory crops, and (6) recreation [103]. However, there are certain ecosystem services that are more likely to affect urban dwellers in New Zealand's cities, that present many opportunities to support ecosystem services in urban areas, which is not possible in rural landscapes [60]. Meurk et al. [61] reported that ecosystem services in New Zealand's urban areas can be classified as (1) provisioning services, (2) environmental regulating services, and (3) cultural services. They noted that regulating services have more direct benefits for human health, well-being, and environmental rehabilitation for urban dwellers.

For urban ecosystem services, such as the conversion of land use and biodiversity conservation, tree species selection can substantially contribute to developing biosphere reserves. Urban forests have a wide spectrum of environmental ecosystem services, such as air, water, soil, and climate regulation, as well as ecological habitat quality through the function of various tree species and their assemblage [104]. Trees are crucial for carbon reduction and GHG elimination in cities as part of New Zealand's Zero-Carbon Act (Climate Change Response Act) in the post-Paris Agreement era [46,105]. Under Article 7 of the Rio Earth Summit ratified in 1992, New Zealand is required to submit an annual inventory of GHG emissions to the UNFCCC [106]. With these regulating services, planting native trees in cities can also contribute to diversity conservation and educating society about native species (e.g., cultural and supporting services). Clarkson [107] reported that native tree species such as *Cordyline*, *Sophora*, and *Carex* can be important for the restoration of native vegetation in New Zealand's urban areas. However, there is less understanding of native trees in New Zealand's cities than in cities of other countries [108], as there is less preference for native trees [70,109,110]. Therefore, developing an understanding of native trees for suitable species selection and utilization is likely to contribute to improved urban ecology and urban ecosystem services provision.

4.2. Urban Trees' General Environmental Regulating Service: Carbon Sequestration

Proper tree species selection and management contribute to carbon storage and act as urban ecosystem services. Various perspectives and approaches to species selection for urban ecosystem services have been proposed to reduce GHG emissions in many cities [99]. For instance, in an urban forestry context, "carbon-neutral carbon commonly involves measuring carbon emissions through emission reduction actions and carbon offsets" [111]. Moreover, urban forests can contribute to carbon neutrality and sequestration through urban tree management with updated tree inventories [72]. In addition, carbon management and urban ecosystem service functions are strongly influenced by the level of urbanization, knowledge of carbon sequestration management, and education levels, such as management skills and environmental awareness, and familiarity with the ecosystem services and carbon storage functions of urban trees [100]. For example, Akbari et al. [112] reported that atmospheric temperature reduction by vegetation in cities has an equivalent effect of 7 kg of total CO_2 emission reduction. Urban areas can contribute to long-term carbon storage for carbon emission mitigation through absorbing CO_2 with urban trees and forest resources through alternative methods such as chemical carbon substitution [2,43,113]. Forests are non-artificial terrestrial carbon sinks that account for approximately 45% of global land surface [114,115]. Moreover, forests account for 80% of the global above ground and 40% of the global below-ground carbon storage in terrestrial ecosystems [116]. During the last two decades, the carbon sink in temperate forests increased by more than 10%. However, the carbon sink of tropical forests decreased and that of boreal forests showed insignificant changes [114]. The decrease in tropical forests was driven by decreases in tree size, shifts in tree species distribution, and elevated tree respiration rates under high temperatures due to GCC [117,118]. Conversely, in boreal forests, the significant change was due to vulnerability to GCC and the very low nutrient-absorption ability of trees [119]. New Zealand belongs to the temperate region, except for some subtropical parts of North Island [120]. Therefore, focusing on the role of temperate forest trees and urban forests in GHG mitigation is important for New Zealand.

The importance of forest conservation in global efforts to fight climate change was recognized by Article 5 of the Paris Agreement, on Forests, which endorsed the role forests play in mitigating GHG emissions [115]. Unlike natural forest (non-urban forest), urban forests generally include green space/infrastructure and roadside trees located within or close to cities, namely population centers of building aggregation, such as commercial, residential, and industrial areas [89,121,122]. Therefore, scientists are debating how to use native trees as "green infrastructure for climate change adaptation" and for mitigation in an urban forestry context [69,107] to try to ameliorate environmental problems that threaten ecosystems and human health [107,123]. There are also discussions about the role of urban forests in ecosystem services for urban dwellers in the post-COVID-19 era [124]. Social restrictions and changes in lifestyle paradigms may fundamentally alter the relationship between urban dwellers and urban green spaces [125]. Hence, it is crucial to study and determine the roles of native trees in tackling current challenges such as climate change, water scarcity, after-effects of COVID-19, and plant biodiversity loss [109,123]. Each tree species has different climate change-adaptation strategies and responds with different mechanisms and/or resistances to these changes [126,127].

4.3. Unexploited Potential of Native Trees' Regulating Service in New Zealand's Cities

Past studies have demonstrated that trees native to New Zealand (see Appendix C for pictures of a sample of common native trees) are valuable for urban ecosystem services. By adopting selective native tree planting, afforestation in built-up environments might have similar effects as those of natural native forests on carbon storage potential and absorption rates in New Zealand [128–130].

Huang [92] reported that the mean diameter growth rate of abundant street trees managed by the city council in Auckland was 13.54 $\pm$ 1.04 mm y^{-1}. Even though the average growth rate of native trees (9.59 $\pm$ 4.76 mm y^{-1}) is slower than alien trees (13.15 $\pm$ 7.08 mm y^{-1}) in urban areas, several scientists have suggested that Auckland's urban forests/street trees composed of native trees have equivalent or better climate change mitigation potential than alien trees and can support enhanced provision of ecosystem services through eco-assessment and carbon sequestration [131–133]. By studying the carbon sequestration potential of native trees, Carswell et al. [134] found that the sequestration rate of Kānuka (*Kunzea ericoides*) was approximately 2.3 MgC ha^{-1} y^{-1} (slower sequestration rate than average of alien trees through comparison study). In addition, Schwendenmann and Mitchell [133] reported that the carbon sequestration values of native trees ranged from 69.8 to 290.9 kgC, with carbon concentration values of 44.9–49.6%. This is based on a case study of native tree species widely planted in Auckland for urban revegetation and restoration project fulfilment: Kānuka, Karaka (New Zealand laurel; *Corynocarpus laevigatus*), Lemonwood (Tarata; *Pittosporum eugenioides*), and Kōhūhū (*Pittosporum tenuifolium*). Compared with the sequestration rate of New Zealand's common alien tree *Pinus radiata* (8 MgC ha^{-1} y^{-1}) and the common trees of U.S. cities (2.8 MgC ha^{-1} y^{-1}) (Nowak et al., 2013, as cited in [133]), the average value of these four native trees in urban areas (2.1 MgC ha^{-1} y^{-1}) was significantly lower (Maclaren 2000, as cited in [133]). Nevertheless, Carswell et al. [134] stated that native trees have significant potential to mitigate

GHG emissions, providing that they have success in long-term woody succession. They reported that Kānuka and red beech (*Nothofagus fusca*) showed notable carbon storage potential after 50 years of succession with values of 148 ± 13 MgC ha^{-1} 50 $years^{-1}$ and 145 ± 19 MgC ha^{-1} 50 $years^{-1}$ with biodiversity fulfilment, respectively.

Marden et al. [130] reported that the eight most distributed native trees in New Zealand are conifers—Matai (*Prumnopitys taxifolia*), Kauri (*Agathis australis*), Miro (*Prumnopitys ferruginea*), Totara (*Podocarpus totara*), Kahikatea (*Dacrycarpus dacrydioides*), and Rimu (*Dacrydium cupressinum*)—and broadleaved species: Tītoki (*Alectryon excelsus*) and Puriri (*Vitex lucens*). Native conifers collectively contribute 90% of New Zealand's total live-plant carbon by volume, with the softwoods Rimu, Totara, Miro, and Kahikatea being the most abundant species (Peltzer and Payton, 2006, as cited in [130]). Among them, only Tītoki and Totara trees are relatively dominant in proportion to the Auckland urban area [131]. However, the potential for carbon storage and sequestration of large native trees is scarcely reported in urban areas.

Nīkau (*Rhopalostylis sapida*) and Pōhutukawa (*Metrosideros excelsa*) are the most common native tree species in New Zealand cities. In particular, Pōhutukawa is the most numerous street tree in the Wellington urban area, and it has the highest air pollutant (PM_{10} and O_3) removal efficiency (75 g (PM_{10}) $tree^{-1}$ y^{-1}, 61 g (O_3) $tree^{-1}$ y^{-1}) in the Auckland urban area [132]. Dale [131] investigated the carbon sequestration potential of seven native species (Nīkau, Pōhutukawa, Northern rata, Pōhutukawa × Northern rata hybrid, Taraire, Puriri, and Karaka) in the Wynyard Quarter area, Auckland, and estimated the total tree carbon storage potential for the sample street trees to be 1.5 MgC y^{-1}, which is equivalent to the carbon emissions from driving 30,000 km in a private vehicle (57 tree samples of 7 native species). Dale [131] also reported that Pōhutukawa trees had the highest average storage potential (0.099–0.11 MgC $tree^{-1}$ y^{-1}) due to higher wood density and tree maturity. In addition, in a case study of the Wynyard Quarter area, Findlay [132] determined Nīkau and Pōhutukawa as having the highest carbon removal efficiencies with higher canopy values and biomass. These findings can have significant implications for the debate over diversity needs and ecosystem services along with environmental acclimation through the provenance of trees in cities, but more information is still required (i.e., carbon storage, physiological responses, and long-term assessment) for various types of native tree species in urban settings.

4.4. Further Research Direction of Urban Ecosystem Services in New Zealand

Most studies on tree responses in urban areas to GCC have focused on species alien to New Zealand, and there is a lack of knowledge regarding how native urban trees will respond to the changing climate in New Zealand's cities. The annual precipitation in New Zealand is predicted to be strongly affected by changing patterns of evaporation, which are influenced by higher surface temperatures [135]. Moreover, intensification of the El Niño cycle is likely to enhance the regularity, severity, and duration of droughts in New Zealand [136,137]. Indeed, recent New Zealand climate change projections indicate that droughts are likely to increase in both intensity and duration in many cities on the North Island [138]. Currently, drought in New Zealand is not a serious issue, despite a drought occurring in Huapai, Auckland during the summer season of 2013. During this drought, the soil volumetric moisture content was recorded in the range of 29–51% at 10 cm depth, compared with 43–60% in 2012 [139]. The threat of drought leading to urban water shortages has been raised as a severe issue on the Kapiti Coast and in Wellington. This is because climate change can lower the water level and yield of the Waikanae River, leading to water shortage in surrounding urban areas that rely on the river for water [140,141]. More frequent drought events are therefore likely to lead to water shortages from the river to the built-up environment in the Kapiti Coast/Wellington and Wairarapa regions. In the Auckland and Northland regions, the frequency and intensity of El Niño events are associated with periods of drought [138]. Changes in the physiological responses and carbon and nitrogen budgets of New Zealand native trees in response to climatic conditions, such as drought, higher temperatures, and elevated CO_2, especially in urban environments, have seldom been explored in New Zealand [95]. There is also very little information available on fluxes of nutrients (e.g., carbon allocation) in New Zealand's native trees [139]. Consequently, there is a poor understanding of native tree growth and responses in New Zealand, as most research and management in New Zealand urban forestry has focused on alien tree species [95,107].

Species diversity contributes to a better provision of urban ecosystem services [142]. It affects ecosystem resilience in terms of urban forest protection from pests and plant diseases, climate change, warmer (higher) temperatures, and abiotic extremes [142,143]. Therefore, tree diversity is an important buffer against catastrophic tree loss in managed forests, including urban forests [144]. Generally, monocultures are more vulnerable to biotic and/or abiotic stressors [75,144]. Urban forests with low tree diversity and biotic homogenization may be vulnerable to ecological disturbances and are at greater risk from local/regional climate changes [145]. Therefore, it is necessary to confirm whether these findings are consistent with the large body of evidence that shows that most urban trees grow better with a diverse mixture of species rather than in a monoculture or with less diversity.

5. Conclusions

Urban trees grow under extreme/harsh/difficult and complex conditions. There has been continuous debate and controversy regarding whether native trees are resilient to urban abiotic stresses and should be planted in cities instead of alien trees [70,107,109,110]. In the case study that explored the carbon sequestration potential of native trees growing in an Auckland urban park, the potential sequestration of native trees was estimated to be in the range of 69.8–290.9 kgC, with a carbon concentration of 44.9–49.6%. Even if these carbon sequestration rates are lower than those of alien trees such as *Pinus radiata*, New Zealand native trees may have significant potential in mitigating GHGs if they are competitive in long-term woody succession.

The stress resistance of native tree species in New Zealand cities to GCC and air pollution has received less attention [47,95,108]. This is due to the relatively short history of anthropogenic environmental changes in the growth of trees in urban settings. Therefore, further investigations are needed on the growth and physiological changes in response to future GCC projections, including high temperatures, elevated O_3, $PM_{2.5}$, and CO_2 levels, and increased drought severity. Previous studies have considered the effects of individual components of GCC on tree species. However, few studies have assessed the interactive effects of stress factors, such as higher temperatures, drought stress, and elevated CO_2 [146]. Therefore, these must be assessed together more in future studies. In particular, intensive tree physiological studies during drought and the combined effects of more than two factors on species tolerance to GCC will aid in proper tree species selection and environmental policy in New Zealand's cities. Research on the adaptability to urban abiotic extreme conditions would improve the current poor understanding of native trees' responses in the urban areas of New Zealand. Therefore, it is necessary to pay attention to the role of native trees in cities to develop novel ideas that can positively affect New Zealand's climate policy in the post-Paris Agreement era.

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Appendix A

Table A1. New Zealand's CO_2 emissions by sector between 1990 and 2017.

Sectors	Kt (CO_2)-Equivalent		Change from 1990 (Kt (CO_2)-Equivalent)	Change from 1990 (%)
	1990	2017		
Energy and road transport	23,785.7	32,876.6	+9090.9	+38.2
Industrial processes and product use	3579.9	4968.6	+1388.7	+38.8
Agriculture	34,257.2	38,880.7	+4623.5	+13.5
Waste	4041.9	4124.7	+82.9	+2.1
Gross (excluding LULUCF †)	65,668.3	80,853.5	+15,185.2	+23.1
LULUCF	−31,161.8	−23,958.4	+7203.3	+23.1
Net (including LULUCF)	34,506.5	56,895.0	+22,388.5	+64.9

Source: MfE [46]. † LULUCF refers to land use, land-use change, and forestry sector under the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol.

Appendix B

Table A2. Comparison of the 'means of transportation for daily commute' among New Zealand's six biggest cities [43,44,52].

Private Vehicle Fleet Usage			Region	2020 Population Growth Rate (%)	
City (Population in 2020)	Percentage (%)	Rank			
Tauranga (136,700)	91	1	Bay of Plenty	2.8	
Hamilton (160,900)	87	2	Northland	2.6	
Auckland (1,571,700)	85	3	Waikato	2.3	
Christchurch (369,000)	84	4	Auckland	2.2	
Dunedin (126,300)	82	5	Canterbury †	2.2	
Wellington (202,700) ††	54	6	National wide	2.1	
Bus/Train Usage			**Walk**		
City	**Percentage (%)**	**Rank**	**City**	**Percentage (%)**	**Rank**
Wellington	21	1	Wellington	21	1
Auckland	8	2	Dunedin	12	2
Christchurch	4	3	Hamilton	7	3
Hamilton	3	4	Christchurch	5	4
Dunedin	3	5	Auckland	5	5
Tauranga	2	6	Tauranga	4	6

† Selwyn's growth rate is 5.2%, which means the largest net internal migration, followed by Tauranga city and Waikato. †† This value has excluded the population of Upper Hutt and Lower Hutt.

Appendix C

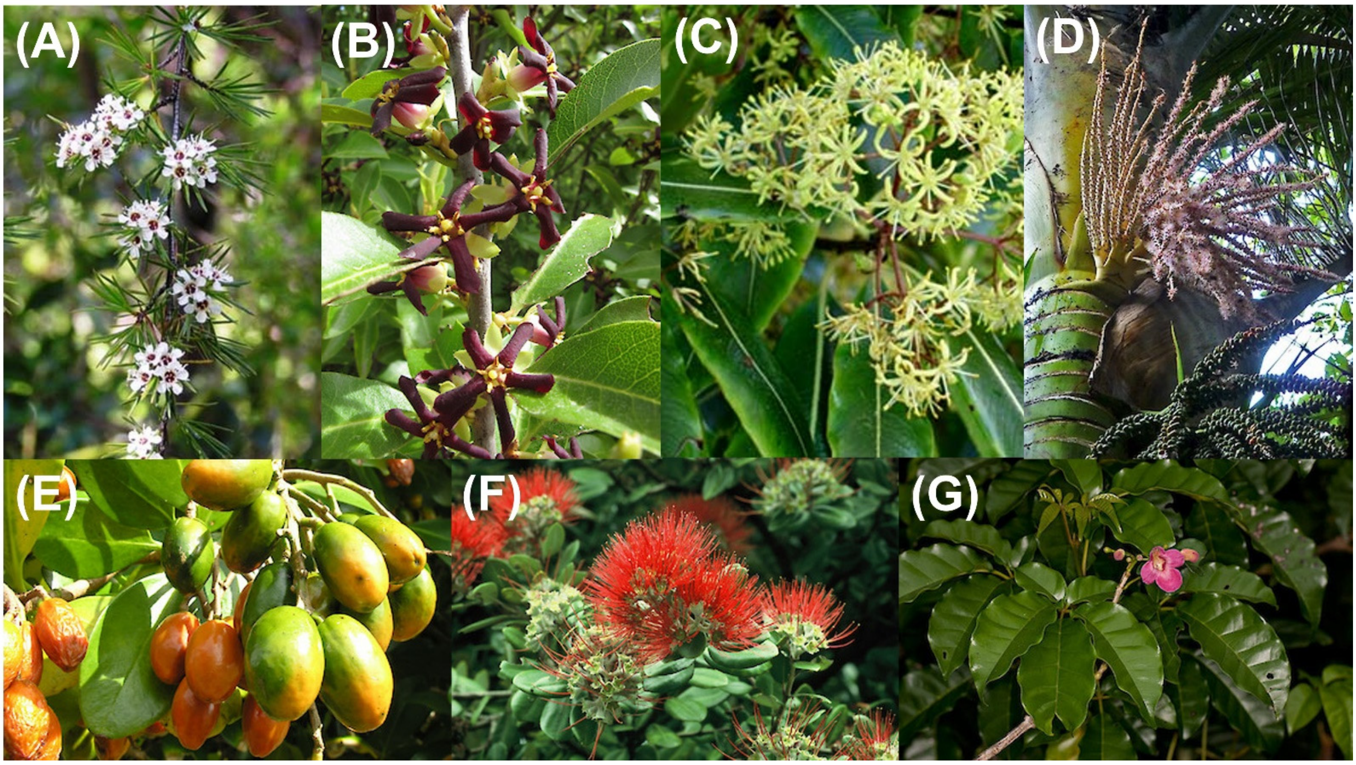

Figure A1. Sample pictures of New Zealand native trees grown and investigated environmental regulating services in domestic cities. (**A**) Kānuka (**B**) Kōhūhū (**C**) Lemonwood (Tarata) (**D**) Nīkau (**E**) Karaka (**F**) Pōhutukawa (**G**) Puriri (Retrieved from New Zealand Plant Conservation Network (NZPCN), 2021). Image credit by Mike Wilcox (Kānuka), John Barkla (Kōhūhū), Peter J. de Lange (Lemonwood), Colin C. Ogle (Nīkau), Simon Walls (Karaka), Gillian M. Crowcroft (Pōhutukawa), and John E. Braggins (Puriri), CC BY 4.0 [147].

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