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Architecture as Habitat: Enhancing Urban Ecosystem Services Using Building Envelopes

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Abstract

The practice of reconciliation ecology in urban environments relies heavily on urban green space as the primary source of vegetated habitat in cities. However, most cities lack the quantity, connectivity, and accessibility of green space needed to provide essential ecosystem services for the health, well-being, and resilience of human and non-human species. In reaction to urban densification and the increasing frequency and severity of climate change impacts, this study argues that architecture could strategically provide vegetated habitats to supplement existing urban green space and provide refuges for non-human species during extreme disturbances. A spatial analysis was conducted to test the performance of the existing green space network against targets for human well-being and Indigenous avifauna habitat needs in a 1.93 km^2 neighborhood in Wellington, Aotearoa New Zealand, during normal conditions and flooding. The results showed an insufficient quantity and connectivity of green space during both normal conditions and flooding to meet the habitat needs of Indigenous avifauna. Though the per capita green space and accessibility targets for human well-being are met under normal conditions, there is insufficient green space to meet those targets during flooding. During normal conditions, 9% of the roofs in the neighborhood need to be converted to green roofs to achieve the targets for both human well-being and Indigenous avifauna. The amount increases to 17% if the targets are to be maintained during flooding. At least 3% of the roofs need to function as small and medium-sized habitat patches in key locations to increase the existing green space network's connectivity. The study concludes that though ground-level green space is limited, with regenerative architecture strategies and supporting governance policy, the surplus of existing roofs could be used to increase urban habitat provision, thereby enhancing the health and resilience of humans and Indigenous avifauna in cities.

Keywords

Urban green space; habitat provision; ecosystem services; climate change mitigation; green roofs; regenerative architecture; green infrastructure; urban biodiversity; well-being

1. Introduction

The habitat loss and degradation that results from rapid and increasing urbanization is a primary threat to global biodiversity [1]. The fields of conservation biology and restoration ecology strive to protect habitats from human disturbance and restore them for biodiversity. Though these approaches are critically important, they do not address landscapes that have no habitat worth conserving and are too modified to restore. Reconciliation ecology argues for preserving global biodiversity by sharing human-modified landscapes, like cities, with other species [2]. The primary way people currently practice reconciliation ecology and provide habitat for other species in our cities is through urban green spaces [3]. Green spaces are critical pieces of urban green infrastructure [4, 5] that improve urban environmental quality and human health and reduce the burden on existing grey infrastructure, such as stormwater drains [6-9]. By providing vegetated habitat [2, 10, 11], they positively contribute to ecosystem services, such as climate regulation, purification, species maintenance, and provide opportunities for people to connect with nature [12-19]. Though the habitats may be highly modified, urban green spaces containing some of the Indigenous habitat characteristics can be considered analogous habitats for some species and can facilitate their survival in the novel ecosystems of cities [20]. Despite being important sites for biodiversity and human well-being [21-24], several issues limit the habitats urban green space can provide; thereby, limiting the supply of urban ecosystem services.

Cities are dominated by hard surfaces and contain minimal vegetation relative to the pre-development land cover [25, 26]. Reliance on green spaces as the primary providers of diverse, vegetated habitats in large built areas is problematic because their land cover in cities is often less than what is needed to support healthy ecosystems, resulting in species decline and reduced ecosystem services [10, 15, 27]. Habitat fragmentation makes the movement or dispersal of many species and individuals between habitat patches more difficult [28, 29]. Isolation can negatively impact the genetic, individual, and community health of biodiversity within habitat patches, and therefore the ecosystems as a whole [30]. Human health and well-being are also impacted by the amount, proximity, and perceived biodiversity of urban green space [31-33]. Increasing population, density, land value, and development pressure put existing green spaces at risk and decreases the likelihood of additional new green spaces being constructed [6]. As cities grow and densify, the demand for ecosystem services will also grow while urban green space reduces in total quantity and per capita quantity, exacerbating the negative impacts cities have on local and regional ecosystems [34]. In addition, the loss of urban biodiversity will reduce residents' ability to connect with nature, which may, in turn, lessen their awareness about the importance of nature and biodiversity conservation [8].

As climate change progresses, the negative impacts of sea-level rise, floods, drought, and extreme temperatures will degrade and reduce the habitat urban green spaces provide; thereby, reducing the biodiversity they sustain [22]. Addressing climate change through the lens of reconciliation ecology means ensuring a supply of habitat during times of stress so that species are not forced to shift their natural ranges and occupy novel geographic areas [3]. A study conducted by Berdejo-Espinola et al. [35] demonstrated the importance of accessible green spaces for humans to engage in nature-based coping mechanisms during times of stress. In the face of an increasing frequency and severity of natural disasters due to climate change, providing diverse, connected, and accessible habitats in cities are vital to the health and resilience of human and non-human species in urban environments [36].

Given the inadequate provision of existing urban green space in most cities and the numerous risks that may reduce it further, urban green infrastructure cannot only rely on green spaces to supply the critical habitat needed to sustain healthy ecosystems and human well-being in urban environments. Most buildings tend to negatively impact ecosystems and provide minimal ecosystem services [16], but research has identified that habitat provision is one of the ecosystem services most applicable to the built environment [34]. Though the current habitat analogs supplied by most buildings are limited [37, 38], there is more opportunity for architecture to supply vegetated habitats and be part of urban green infrastructure. Regenerative architecture strategies, such as green roofs, can provide food and shelter for non-human species, purify the air, moderate temperature, manage stormwater, absorb noise, and confer well-being benefits to humans [39-41]. Green roofs can also sequester carbon and improve the thermal performance of buildings, thereby reducing carbon emissions and decreasing the built environment's contribution to climate change [42]. Elevated habitats can provide opportunities for species to retreat from unfavorable ground-level conditions, such as flooding, which will be critical for species survival and adaptation to changing climates [4, 5]. The three-dimensional nature of the built environment may limit the types of appropriate plant assemblages, and some species will not be able to adapt to urban environments or coexist in close proximity with people [43, 44]. However, strategic implementation of green roofs still offers great potential to increase the amount of vegetated habitat in our cities [45-47].

In the green infrastructure literature, with a few notable exceptions [48, 49], there remains a focus and reliance on green spaces to supply urban ecosystem services and a lack of consideration of their contribution to biodiversity [50]. Though regenerative architecture strategies, such as green roofs, are already in use, there are gaps in the literature and design practice around their implementation at an infrastructural level. Installing a green roof and enhancing the ecosystem services of one building may be enough to confer well-being benefits to humans but, to truly put the principles of reconciliation ecology into practice, a more ubiquitous and strategic implementation of them will be required. This research investigates how to increase the quantity and connectivity of urban vegetated habitats using existing building roofs. The urban environment is the fastest growing habitat typology globally [51]; therefore, answering this question is critical to preserving and increasing habitat in urban environments for the health, well-being, and resiliency of humans and non-human species.

Urbanization, densification, and climate change have and will reduce the habitat provision and other ecosystem services supplied by urban green space, leaving little room for non-human species in cities. While cities may be in short supply of available, ground-level habitat, there is an abundance of underutilized building surfaces that could provide a solution. An urban-scale plan is required to provide and connect existing green space habitats via green roofs to increase ecosystem services at both the urban and architectural scales and foster more stable and resilient ecosystems. The objectives of this study are to test the performance of the existing green space in a city (Wellington, Aotearoa New Zealand) against targets for urban habitat provision and determine the amount and location of green roofs required to supplement and enhance the existing green space.

2. Materials and Methods

2.1 Case Study Location Description

Site and species specificity are important for research related to biodiversity and ecosystem services [52]; therefore, the city of Wellington, Aotearoa New Zealand, was selected for this research. Wellington is a temperate island coastal city in the South Pacific with a population of 216,505 [53]. Wellington is a member of the international Biophilic Cities Network (a group of cities working towards the vision of natureful urban environments) [54], and it has a high proportion of visible green space due to its hilly topography [55]. On average, central Wellington has approximately 20 m^2 of urban green space per person [56]. This is partly due to the constraints of topography on development and the preservation of the Town Belt (a series of interconnected green spaces) and key Indigenous habitat reserves, such as the large urban fenced predator-free habitat named Zealandia [57]. However, Wellington is facing challenges similar to many cities worldwide, namely increasing densification, population growth, and climate change, which will increase the demand and pressure on the city's existing green spaces [58].

The central business district neighborhood of Te Aro (1.93 km^2) was selected for the case study as it has the lowest provision of urban green space in central Wellington and is predicted to densify and increase in population by 31% over the next 20 years [56, 59]. Te Aro sits in a low-lying valley between steep hills to the east and west and is bordered by the harbor on the north side. Its location and high proportion of impervious surfaces make it vulnerable to flooding during heavy rain events. As climate change progresses, a 10% rainfall increase (15% in winter) in the Wellington region, in addition to sea-level rise and increased storm intensity, will exacerbate this vulnerability and result in more flooding [60]. More frequent and severe floods may reduce and degrade the existing green spaces in the neighborhood, negatively impacting the ecosystem services they can provide. Redundancy is an essential feature of ecosystem resilience [61]; therefore, it is important that there are habitats to sustain urban biodiversity during both normal conditions and flooding.

In addition to humans, Indigenous avifauna are active users of Aotearoa New Zealand's urban environment and are the primary species of interest for this study. Due to the island nation's long separation from other landmasses, a high proportion of its Indigenous avifauna are endemic and are therefore a high priority for conservation given the ongoing threats of habitat loss and predation [62]. While conferring well-being benefits to humans through their presence and song, Indigenous avifauna are also seed dispersers and play a key role in local ecosystems [36, 63]. Conservation strategies to protect Indigenous avifauna in urban environments, such as Indigenous forest regeneration and introduced non-native pest control, are already underway in Wellington [64, 65]. While urban green spaces and other vegetated habitats, such as green roofs, cannot replace pristine natural habitats, increasing the amount of connected habitat would enable Indigenous avifauna to more easily survive and disperse across the dense urban landscape.

2.2 Performance Target Setting

A literature review was conducted to establish performance targets for the quantity and connectivity of habitat provision in Aotearoa New Zealand urban environments for both human well-being and Indigenous avifauna habitat needs. The performance targets used for this study are listed in Table 1.

Table 1 Habitat provision performance targets for an urban New Zealand context.

Targets	Quantity	Connectivity/Accessibility
Indigenous Avifauna	10% habitat coverage	>62,500 m^2 large habitat patch 5 km apart >16,000 m^2 medium habitat patch 1 km apart 100-16,000 m^2 small habitat patch 0.2 km apart
Humans	9 m^2 green space per capita	5-minute walk (<400 m) from home or work

An ecosystem services analysis of the pre-development ecosystem suggests a habitat provision target of 100% [10]; however, other research in Aotearoa New Zealand, has recommended a minimum target of 10% Indigenous habitat coverage within urban areas to stop Indigenous biodiversity decline [66-70]. This is a more achievable initial goal given that Wellington only has 2% Indigenous cover, which drops to nearly 0% in Te Aro [63, 71]. Therefore, in the context of this research, existing and future green space planting strategies will need to include more Indigenous species in addition to achieving the other performance targets listed in Table 1 [55, 66]. The location of habitat patches must also be carefully considered to counteract some of the adverse outcomes of isolated patches, increase Indigenous avifauna and seed dispersal across the urban landscape, and contribute to the regeneration of Indigenous habitat [57]. While there are several articles discussing habitat connectivity in Aotearoa New Zealand urban environments, many of them rely on green spaces and green strips associated with roadways to increase habitat connectivity [56, 70]; therefore, their applications to an urban habitat provision strategy that uses buildings are limited. However, Meurk and Hall [72] proposed a patch pattern for modified landscapes (including urban environments) that would improve the health and functionality of Indigenous Aotearoa New Zealand ecosystems and can be adapted to include buildings. The pattern was composed of large habitat patches (62,500 m^2) spaced 5 km apart, medium habitat patches (16,000 m^2) spaced 1 km apart, and small habitat patches (100 m^2) spaced 200 m apart [72]. Patches less than 100 m^2 were not included in the patch pattern. Though buildings may not be able to supply large, Indigenous habitats, they may be able to provide the recommended small and medium-size habitat patches and function as important stepping stones for the propagation and dispersal of several species of Indigenous flora and avifauna to larger habitats in or around the urban environment [13].

A minimum urban green space per capita target of 9 m^2 has been recommended by the World Health Organization (WHO) for human well-being in urban environments [73]. In Te Aro specifically, population estimates from Forecast id. were used to calculate the urban green space per capita for the current population (2021) and the forecasted population (2043) [53]. Surveys suggest that the ideal distance of urban green space for regular use is a five-minute walk from residents' homes or workplaces [74, 75].

2.3 Spatial Analysis

Based on the research of Blaschke et al. [56], which identified and mapped green spaces in central Wellington, an updated map of the existing provision of urban green space, including parks and roadside greenery, was created using satellite imagery [76] and site visits to confirm the locations and sizes (Figure 1). The green space areas were then calculated using AutoCad to determine the percentage of green space coverage in Te Aro. The green spaces were then classified as large (>62,500 m^2), medium (>16,000 m^2), or small (100-16,000 m^2) habitat patches based on the Meurk and Hall [72] habitat patch matrix. Patches less than 100 m^2 were not included in the matrix and, therefore, were not included in the habitat connectivity calculations.

Wellington City Council has created a series of interactive maps based on research conducted by the National Institute of Water and Atmospheric Research (NIWA) on risk exposure in low-lying coastal areas in Aotearoa New Zealand [77]. The Flood Hazard Areas map shows the area of Te Aro at risk of a 1% Annual Exceedance Probability (AEP) flood, meaning that for any given year, there is a 1% chance of a flood of a given magnitude occurring [78]. For the Sea-Level Rise and Storm Surge Water Depth maps, a sea-level rise value of 1 m was selected as it was the highest value in both map settings that was within the 0.3 - 1.3 m range of sea-level rise deemed likely to occur before 2100 [79,80]. This enabled the visualization of the compounding effects of sea-level rise and storm surges. Images from these maps were overlaid on the map of existing Te Aro green space under normal conditions to calculate the habitat patches impacted during flooding and the distances between the remaining unflooded habitat patches.

A third spatial analysis was completed to calculate the percentage of roof coverage in Te Aro and quantify the opportunity for buildings to supplement the habitat provided by existing urban green spaces. Satellite images [76], combined with site visits and the use of Google Maps to confirm roof locations and sizes, were used to calculate roof areas in AutoCad and measure distances to determine key green roof locations to achieve the habitat connectivity targets.

3. Results

3.1 Performance During Normal Conditions

A total green space area of 128,317 m^2 was calculated for Te Aro, which is 7% of the total area of the neighborhood (Table 2). Comparing the existing green space during normal conditions against the performance targets for Indigenous avifauna showed that the current habitat provision is below the habitat quantity and connectivity targets. An additional 64,805 m^2 of urban green space is required to meet the 10% habitat coverage target, with anything above this aiding in regeneration rather than just conservation of existing ecosystem function. Classifying green space by habitat patch size revealed that Te Aro has no green spaces of large habitat patch size (62,500 m^2), though there are large habitat patches (the Town Belt to the east and west, and Zealandia to the east) within 5 km of its boundary. There is only one medium habitat patch (>16,000 m^2), with the majority of green spaces falling in the small habitat patch category (100-16,000 m^2). The spatial analysis of the connectivity of the small habitat patches revealed five areas (totaling 3% of the neighborhood) that are isolated from other small habitat patches. Four of the five areas sit centrally in the neighborhood because a higher proportion of Te Aro's small habitat patches are near the neighborhood's boundary or in adjacent neighborhoods (Figure 1). A larger area of Te Aro (totaling 42% of the neighborhood) is isolated from the only medium habitat patch. Outside of the Te Aro boundary, two sports fields are of medium habitat patch size and within a 1 km range; however, given that they are primarily grass and frequently disturbed by sporting events, they are unlikely to function as proper stepping stone habitats. Therefore, the existing green space in Te Aro falls below both the quantity and connectivity habitat provision targets for Indigenous avifauna during normal conditions.

Table 2 Te Aro habitat provision during normal conditions compared to performance targets. The total Te Aro neighborhood area is 1,931,216 m^2.

Species	Quantity		Connectivity/Accessibility	
	Existing	Target	Existing	Target
Indigenous Avifauna	7% habitat coverage (128,317 m^2)	10% habitat coverage (193,122 m^2)	3% (55,983 m^2) isolated from other small habitat patches 42% (819,469 m^2) isolated from other medium habitat patches	>62,500 m^2 large habitat patch 5 km apart >16,000 m^2 medium habitat patch 1 km apart 100-16,000 m^2 small habitat patch 0.2 km apart
Humans	10 m^2 per capita (2021 population of 13,102) 7 m^2 per capita (2043 population of 17,176)	9 m^2 green space per capita	No area in Te Aro further than a 5-minute walk from green space	5-minute walk (<400 m) from home or work

Figure 1 Existing green spaces cover 7% of Te Aro during normal conditions. Most green spaces are of small patch size (orange), with only one medium sized-patch (yellow). The orange and yellow dotted lines indicate areas isolated from other habitat patches, which can negatively impact the ability of Indigenous avifauna to access different habitats and disperse across the neighborhood. The base satellite image is from Landcare Research [76].

Comparing the existing green space during normal conditions against the performance targets for human well-being showed that the current habitat provision achieves the green space quantity and accessibility targets for the current population. Though the urban green space in Te Aro is predominantly located around the edges of the neighborhood, the spatial analysis revealed that there is some type of green space within a five-minute walk (400 m) from anywhere in the neighborhood [75]. The green space per capita value for Te Aro during normal conditions is 10 m^2. While this is above the WHO minimum target, there is little buffer for any decrease or degradation in the existing green space provision. With population growth alone, the neighborhood's per capita green space value will decrease to 7 m^2 by 2043. Meeting the minimum target for the future population (in 2043) requires an additional 26,267 m^2 of urban green space and would increase Te Aro's total green space coverage to 8%. These findings indicate that ground-level urban green space is sufficient to meet the minimum green space per capita target for the current population; however, it will be insufficient to meet the needs of the future population as the neighborhood densifies.

3.2 Performance During Flooding

A total of 39% of Te Aro is at risk of flooding due to sea-level rise, storm surge, and increased rainfall, with rainfall being the largest contributor to increased flooding frequency and severity

(Table 3) [78-80]. Up to 44% of Te Aro's green space could be inundated during these events, reducing the habitat provision in the neighborhood to 4% until the floodwaters recede or longer depending on the level of damage. Comparing the existing green space during flooding against the performance targets for Indigenous avifauna showed that the current habitat provision is below the habitat quantity and connectivity targets. During flooding events, there would be no medium habitat patches and fewer small habitat patches available. Reduced available habitat increases the area isolated from other small habitat patches to 24% and makes all of Te Aro isolated from medium habitat patches. Therefore, the current quantity and connectivity of existing urban green space in Te Aro are insufficient to meet the habitat needs of the Indigenous avifauna during flooding (Figure 2).

Table 3 Te Aro habitat provision during flooding compared to performance targets. The total Te Aro neighborhood area is 1,931,216 m^2.

Species	Quantity		Connectivity/Accessibility	
	Existing	Target	Existing	Target
Indigenous Avifauna	4% habitat coverage (70,574 m^2)	10% habitat coverage (193,122 m^2)	24% (458,181 m^2) isolated from other small habitat patches 100% (1,931,216 m^2) isolated from other medium habitat patches	>62,500 m^2 large habitat patch 5 km apart >16,000 m^2 medium habitat patch 1 km apart 100-16,000 m^2 small habitat patch 0.2 km apart
Humans	6 m^2 per capita (2021 population of 13,102) 4 m^2 per capita (2043 population of 17,176)	9 m^2 green space per capita	No area in Te Aro further than a 5-minute walk from green space	5-minute walk (<400 m) from home or work, though other accessibility barriers likely.

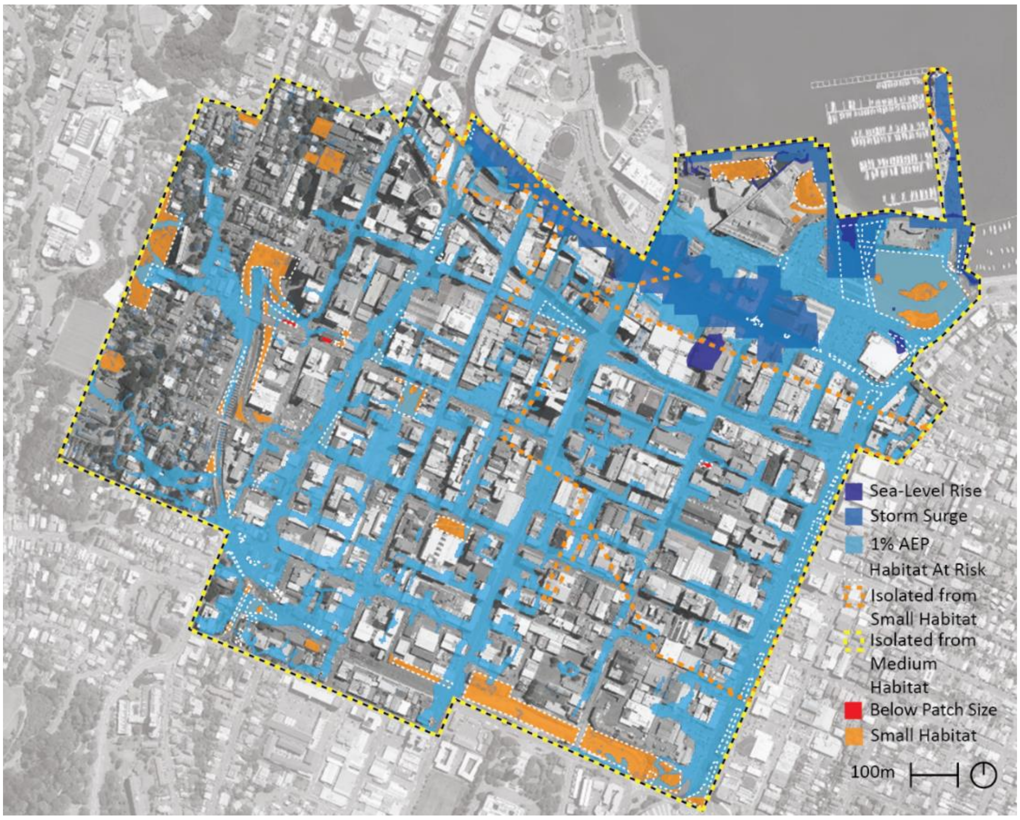

Figure 2 Urban green space coverage is reduced to 4% of Te Aro during flooding. There are no unflooded medium habitat patches and fewer small habitat patches (orange) available compared to normal conditions. The orange and yellow dotted lines indicate areas isolated from other habitat patches. Reduced habitat quantity and connectivity negatively impact Indigenous avifauna's ability to retreat from unfavorable conditions and live in the neighborhood. Sea-level rise, storm surge, and 1% AEP overlays are based on the Wellington City Council interactive climate change maps [78-80]. Base satellite image from Landcare Research [76].

Comparing the existing green space during normal conditions against the performance targets for human well-being showed that the current habitat provision fails to achieve the per capita green space target. The green space per capita value for Te Aro during flooding is 6 m^2 and, with the anticipated 2043 population, this will be reduced to 4 m^2 green space per capita during flooding. Distance calculations from the spatial analysis showed that there remained some type of green space within a five-minute walk (400m) from anywhere in the neighborhood; however, a visual assessment of the flooding map indicates that accessibility would be reduced by floodwater blocking roads and pathways used to access nearby green spaces. Therefore, these findings suggest that ground-level urban green space is insufficient to meet the minimum green space per capita target for the current and future populations during increasingly frequent and severe flooding events.

3.3 Roof Area in Te Aro

In total, roofs cover 37% of Te Aro. Based on the performance targets for Indigenous avifauna, achieving 10% habitat coverage during normal conditions, 9% of Te Aro's roofs need to be converted to green roofs. The roof area needed increases to 17% if the target is to be maintained during flooding and provide habitat redundancy to enhance ecosystem resilience [61]. One strategically located cluster of roofs (at least 16,000 m^2 of roof area) needs to be converted to green roofs to achieve the connectivity targets for medium-sized habitat patches during normal conditions and flooding. Five small habitat patches (at least 100 m^2 each) strategically located are needed to meet the connectivity targets during normal conditions. An additional two small habitat patches are required to maintain the target during flooding (Table 4). Figure 3 shows the sizes and key locations of the roofs required (at least 3% of the Te Aro roof area) to achieve the habitat connectivity targets for Indigenous avifauna during normal conditions and flooding and enhance the performance of the existing urban green space network. The remaining green roofs to be converted to achieve the habitat coverage target may be more flexibly distributed throughout the neighborhood as needed based on other factors, such as building height, typology or thermal performance [81].

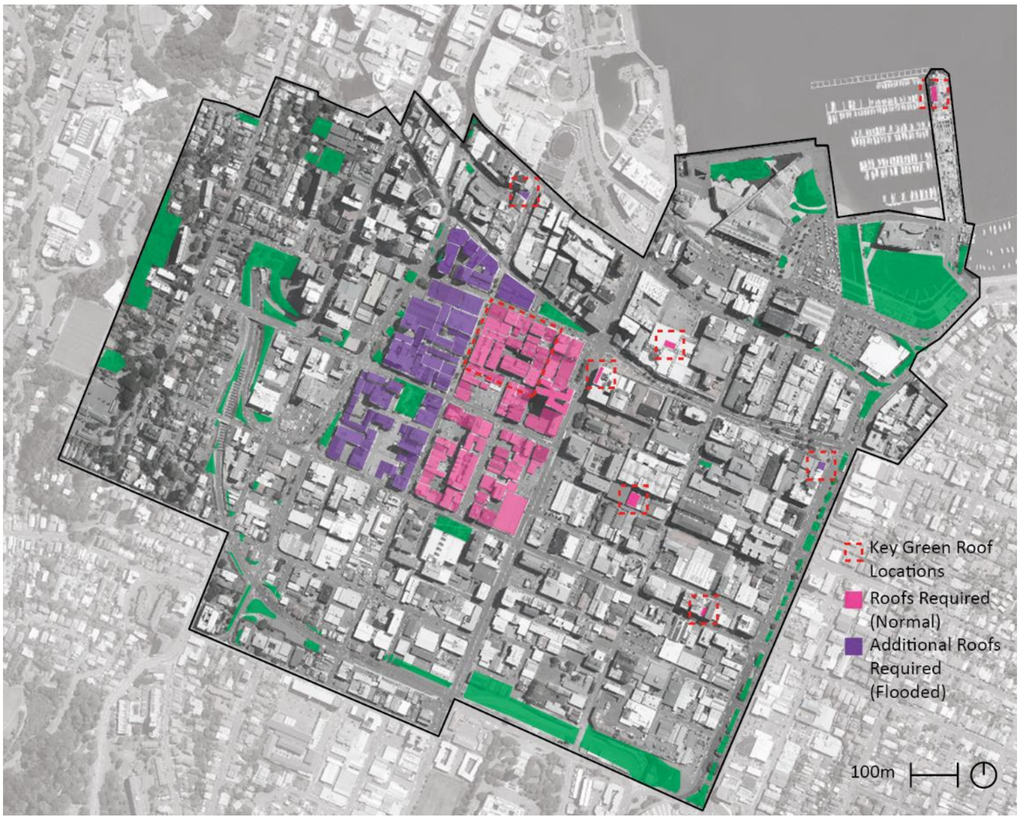

Figure 3 During normal conditions, 9% of Te Aro's roof area needs to be converted to green roofs, with an additional 8% required during flooding to meet all of the performance targets for both humans and Indigenous avifauna during normal conditions and flooding. At least 3% of the roofs need to function as small and medium-sized habitat patches in the key locations identified. Non-residential buildings with roof heights of less than 60 m were prioritized for conversion to minimize the negative effects of building height on roof habitats [81]. Given that non-residential buildings, in particular, are major contributors to greenhouse gas emissions within the built environment [82], the carbon sequestration and climate regulation functions of green roofs could counteract some of the negative environmental impacts of the buildings [83]. Base satellite image from Landcare Research [76].

Table 4 The green roof area needed to supplement existing green space and meet performance targets in Te Aro. The total roof area in Te Aro is 728,472 m^2.

Condition	Species	Quantity	Connectivity/Accessibility
Normal	Indigenous Avifauna	64,805 m^2 needed (9% of roofs)	Five 100 m^2 patches strategically located (less than 1% of roofs) One 16,000 m^2 patch strategically located (2% of roofs)
	Humans	0 m^2 needed (2021) (0% of roofs) 26,267 m2 needed (2043) (4% of roofs)	0 m^2 needed (0% of roofs)
Flooding	Indigenous Avifauna	122,547 m^2 needed (17% of roofs)	Seven 100 m^2 patches strategically located needed (less than 1% of roofs) One 16,000 m^2 patch strategically located needed (2% of roofs)
	Humans	47,344 m^2 needed (2021) (7% of roofs) 84,010 m^2 needed (2043) (11% of roofs)	0 m^2 needed (0% of roofs)

Based on the performance targets for human well-being, the roof area required is less than that of Indigenous avifauna, with only 7% and 11%, respectively, of roofs needing to be converted to green roofs during normal conditions and flooding. However, in order for these green roofs to contribute to human well-being, they must be accessible. Due to Wellington's hilly topography, adding green roofs to Te Aro's low and medium-rise buildings could provide additional visible contact to nature for people in neighboring high-rise buildings and those on the hills surrounding the valley. Nevertheless, these findings show a surplus of roof area available to supply the habitat needed to meet the quantity, connectivity, and accessibility targets for humans and Indigenous avifauna.

4. Discussion

Spatial analyses, like the one conducted in this study, are necessary to identify the number and locations of buildings required to supplement existing green space, increase habitat connectivity, and enhance ecosystem services. Though previous research on stepping stones in Wellington focused on ground-level habitat, the findings of this research suggest that there is a surplus of roofs in Te Aro that could be converted to green roofs to increase urban habitat provision in Wellington. Buildings are an underutilized green infrastructure resource for reconciliation ecology but, with more implementation and innovation in green roofs and other regenerative architecture strategies, they could positively contribute to urban avifauna health and human well-being [28, 84].

In order to increase Indigenous avifauna populations and not just stop their decline, urban habitat provision will need to go beyond the minimum target. Though 10% habitat coverage is the minimum target for an urban New Zealand context, other international research argues for higher minimums [85, 86]. While ambitious, higher habitat provision targets could be achieved using buildings as the foundation for habitat. If all of the roofs in the neighborhood were converted to green roofs, 44% of Te Aro would be covered with vegetated habitat. If Wellington's human residents are to better co-exist with Indigenous avifauna populations, there needs to be enough habitat for Indigenous avifauna to feed, nest, and take shelter in the city and not just in the larger natural habitats surrounding it. Though some of the urban green spaces in Te Aro are of a sufficient habitat patch size, many of them contain hard surfaces, large swathes of grass, and exotic vegetation. The lack of Indigenous plant diversity and habitat heterogeneity reduces their value to Indigenous avifauna [20, 56]. In order to function optimally as stepping stone habitats within the neighborhood and between larger patches of vegetation outside the study area, new green space planting strategies and green roofs that provide analogous Indigenous habitats will be required [55, 87]. Some conflicts may arise between the green space needs of humans for recreation and outdoor sports versus the needs of Indigenous avifauna for Indigenous habitat. Creating analogous Indigenous habitats for Indigenous avifauna on roofs may be one way to increase habitat provision while not reducing the availability of green space for physical activity for humans. Conducting thorough ecosystem services analyses for urban green spaces can optimize the trade-offs required for different ecosystem services and species [67]. Reducing the isolation of habitats on top of roofs depends on how they are positioned in the existing green space network and how they connect to the ground. Adding green walls to buildings with green roofs can increase the amount of habitat available and the connectivity to other ground-level habitats [37, 88]. Rooftop stepping stones may be sufficient for some Indigenous avifauna, but other Aotearoa New Zealand species who cannot disperse as easily across the urban landscape (such as lizards) would benefit from the addition of green corridors and green wall connections to green roofs [17].

While Te Aro achieves the 9 m^2 minimum green space per capita target, the WHO has also set an ideal target of 50 m^2 green space per capita for human well-being in urban environments [73]. With the anticipated population growth and additional 3,000 dwellings to be built in Te Aro by 2043 [53], it will be near impossible to maintain the minimum per capita green space target, let alone achieve the ideal target (an additional 730,483 m^2 of green space), without making use of buildings. Though avifauna can easily access green roofs, using green roofs to contribute to the per capita green space target would require that they be made accessible to people. However, due to the private ownership of green roofs, their accessibility will likely be more limited than public urban green space. In addition to connecting green roofs to ground-level habitat, green walls could also provide visible contact to nature for people in neighboring buildings and those walking through the city, particularly from green walls installed near sidewalks [89, 90]. More opportunities for people to view and engage with nature can increase the well-being of those visiting and living in the city [91-93] and potentially inspire more interest in biodiversity conservation [94].

Vegetation can slow surface water flooding and reduce the pressures on stormwater management drainage systems, which will become more important as rainfall and storm severity and frequency increase in Wellington [42, 95]. In Te Aro, there is a clear case for additional green infrastructure to manage current and future flooding, which negatively impacts the ability of urban green spaces to consistently and reliably provide habitat and other ecosystem services. In addition to absorbing and slowing surface water runoff, green roofs can provide habitat redundancy during flood events, providing species with opportunities to retreat from the unfavorable conditions in other ground-level habitats [61]. Green roofs and other habitat installations, such as artificial or modified shading, humidifying, and sheltering structures, as well as those suitable to support breeding in target species, can be important tools to help humans and non-human species adapt to climate change impacts in urban environments by providing microhabitat refuges and reducing stress [3, 93]. The process for mapping flooding impacts on existing green space conducted in this study is one way to identify which species or ecosystem services need to be prioritized in key locations. This process is particularly important in areas where other regenerative architecture strategies, such as solar panels, may compete for space [34]. In the case of Te Aro, this may relate to balancing how much roof space is used for water tanks or pipes versus habitat. Other climate change impacts on the habitat provision performance of existing urban green spaces in Wellington, such as temperature rise, extreme winds, and species range shifts, were not included in this study but should be investigated and considered in holistic and resilient green infrastructure planning [96].

5. Conclusions

Protected areas of more pristine, Indigenous habitat remain crucial to biodiversity conservation efforts as there are limitations to the types of habitats and species architecture can support. However, though they are not often considered in conservation strategies, cities have an important role to play as living laboratories for creating novel habitat analogs that can support a diverse range of species and provide opportunities for people to connect with flora and fauna in their neighborhoods. Interdisciplinary collaboration and leadership will be necessary to draw upon the expertise of many fields of study [9]. Ecological reconciliation in urban environments will rely on national and local governments and policymakers creating spatial plans, building policies, and incentives that support and catalyze the construction of urban green infrastructure that includes regenerative architecture. It will also require building owners, designers, ecologists, and local organizations to cooperate and foster Indigenous habitats and habitat analogs on their properties and in their communities [41]. While green roofs and walls are not the only way to practice reconciliation ecology, they are a way to use and improve the resources and three-dimensional infrastructure cities already contain. The Te Aro neighborhood, for example, could achieve the habitat provision it needs to support humans and Indigenous avifauna during normal conditions and flooding by converting 17% of its roof area to green roofs. Using architecture to add more habitat and green infrastructure to cities can enhance the current provision of urban ecosystem services, ensure they are maintained or restored quickly during disturbances, and safeguard a supply for the future, resulting in more resilient cities and ecosystems [5].

Author Contributions

All authors contributed to the conceptual development of the study. M. MacKinnon conducted the spatial analysis and prepared the initial draft of the manuscript, which was reviewed and edited by M. Pedersen Zari and D.K. Brown.

Competing Interests

The authors have declared that no competing interests exist.

References

1. Shwartz A, Turbé A, Julliard R, Simon L, Prévot A. Outstanding challenges for urban conservation research and action. Glob Environ Change. 2014; 28: 39-49.
2. Rosenzweig M. Win-win Ecology: How the earth's species can survive in the midst of human enterprise. Oxford: Oxford University Press; 2003.
3. Cannizzo Z, Dixon S, Griffen B. An anthropogenic habitat within a suboptimal colonized ecosystem provides improved conditions for a range-shifting species. Ecol Evol. 2018; 8: 1521-1533.
4. Collins R, Schaafsma M, Hudson M. The value of green walls to urban biodiversity. Land Use Policy. 2017; 64; 114-123.
5. Salata S. Ecologically-compatible urban planning designing a healthier environment. Bingley: Emerald Publishing; 2019.
6. Vargas-Hernández J, Pallagst K, Zdunek-Wielgołaska J. Urban green spaces as a component of an ecosystem. In: Handbook of engaged sustainability. New York: Springer International Publishing; 2018. pp.885-916.
7. Tzoulas K, Korpela K, Venn S, Yli-Pelkonen V, Kaźmierczak A, Niemela J, et al. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. Landsc Urban Plan. 2007; 81: 167-178.
8. Botzat A, Fischer L, Kowarik I. Unexploited opportunities in understanding liveable and biodiverse cities. A review on urban biodiversity perception and valuation. Glob Environ Change. 2016; 39: 220-233.
9. Steiner F. Frontiers in urban ecological design and planning research. Landsc Urban Plan. 2014; 125: 304-311.
10. Zari M. Devising urban biodiversity habitat provision goals: Ecosystem services analysis. Forests. 2019; 10: 391.
11. McKinney M. Urbanization, biodiversity, and conservation. BioScience. 2002; 52: 883-890.
12. Mao Q, Wang L, Guo Q, Li Y, Liu M, Xu G. Evaluating cultural ecosystem services of urban residential green spaces from the perspective of residents' satisfaction with green space. Front Public Health. 2020; 8: 226.
13. Gharibi S, Shayesteh K, Attaeian B. Interconnected ecological network design using lcp algorithm and cohesion index in urban scale. Urban Ecosyst. 2021; 24: 153-163.
14. Gill S, Handley J, Ennos A, Pauleit S. Adapting cities for climate change: The role of the green infrastructure. Built Environ. 2007; 33: 115-133.
15. Alberti M. Advances in urban ecology: Integrating humans and ecological processes in urban ecosystems. New York: Springer; 2008.
16. Zari M. Understanding and designing nature experiences in cities: A framework for biophilic urbanism. Cities & Health. 2019; 1-12.
17. Meurk C, Blaschke P, Simcock R. Ecosystem services in New Zealand cities. In: Ecosystem services in New Zealand: Conditions and trends. 1st ed. Lincoln: Manaaki Whenua Press; 2013. pp.254-273.
18. Dadvand P, Bartoll X, Basagaña X, Dalmau-Bueno A, Martinez D, Ambros A, et al. Green spaces and general health: Roles of mental health status, social support, and physical activity. Environ Int. 2016; 91: 161-167.

19. Nowak D, Greenfield E, Hoehn R, Lapoint E. Carbon storage and sequestration by trees in urban and community areas of the United States. Environ Pollut. 2013; 178: 229-236.
20. Richardson P, Lundholm J, Larson D. Natural analogues of degraded ecosystems enhance conservation and reconstruction in extreme environments. Ecol Appl. 2010; 20: 728-740.
21. Chang J, Qu Z, Xu R, Pan K, Xu B, Min Y, et al. Assessing the ecosystem services provided by urban green spaces along urban center-edge gradients. Sci Rep. 2017; 7: 11226.
22. Kwon O, Hong I, Yang J, Wohn D, Jung W, Cha M. Urban green space and happiness in developed countries. EPJ Data Sci. 2021; 10; 28.
23. de Vries S, Verheij R, Groenewegen P, Spreeuwenberg P. Natural environments - healthy environments? An exploratory analysis of the relationship between greenspace and health. Environ Plan. 2003; 35: 1717-1731.
24. Gómez-Baggethun E, Barton D. Classifying and valuing ecosystem services for urban planning. Ecol Econ. 2013; 86: 235-245.
25. Potschin M, Haines-Young R, Fish R, Turner R. Routledge handbook of ecosystem services. Abingdon: Routledge; 2016.
26. McKinney M. Effects of urbanization on species richness: A review of plants and animals. Urban Ecosyst. 2008; 11: 161-176.
27. Mcdonald R, Kareiva P, Forman R. The implications of current and future urbanization for global protected areas and biodiversity conservation. Biol Conserv. 2008; 141: 1695-1703.
28. Ignatieva M, Stewart G, Meurk C. Planning and design of ecological networks in urban areas. Landsc Ecol Eng. 2011; 7: 17-25.
29. Ignatieva M. Urban greening manual. In: How to put nature in our neighborhoods: Application of low impact urban design and development (LIUDD) principles, with a biodiversity focus, for New Zealand developers and homeowners. Lincoln: Manaaki Whenua Press; 2008.
30. Williams N, Lundholm J, MacIvor J. Do green roofs help urban biodiversity conservation? J Appl Ecol. 2014; 51: 1643-1649.
31. Garrard G, Williams N, Mata L, Thomas J, Bekessy S. Biodiversity Sensitive Urban Design. Conserv Lett. 2018; 11: e12411.
32. Maas J, Verheij R, Groenewegen P, De Vries S, Spreeuwenberg P. Green space, urbanity, and health: How strong is the relation? J Epidemiol Commun H. 2006; 60: 587-592.
33. Nutsford D, Pearson A, Kingham S. An ecological study investigating the association between access to urban green space and mental health. Public Health. 2013; 127: 1005-1011.
34. Zari M. Biomimetic urban design: Ecosystem service provision of water and energy. Buildings. 2017; 7: 21.
35. Berdejo-Espinola V, Suárez-Castro A, Amano T, Fielding K, Oh R, Fuller RA. Urban green space use during a time of stress: A case study during the COVID-19 pandemic in Brisbane, Australia. People Nat. 2021; 3: 597-609.
36. Aerts R, Honnay O, Van Nieuwenhuyse A. Biodiversity and human health: Mechanisms and evidence of the positive health effects of diversity in nature and green spaces. Br Med Bull. 2018; 127: 5-22.
37. Mayrand F, Clergeau P. Green roofs and green walls for biodiversity conservation: A contribution to urban connectivity? Sustainability. 2018; 10; 985.
38. Faeth S, Bang C, Saari S. Urban biodiversity: Patterns and mechanisms: Urban biodiversity. Ann N Y Acad Sci. 2011; 1223: 69-81.

39. Zari M. The importance of urban biodiversity - an ecosystem services approach. Biodiversity Int J. 2018; 2: 357-360.
40. Baumann N. Ground-nesting birds on green roofs in Switzerland: Preliminary observations. Urban Habitats. 2006; 4: 37-50.
41. Francis R, Lorimer J. Urban reconciliation ecology: The potential of living roofs and walls. J Environ Manage. 2011; 92: 1429-1437.
42. Elmqvist T, Setälä H, Handel S, van der Ploeg S, Aronson J, Blignaut J, et al. Benefits of restoring ecosystem services in urban areas. Curr Opin Environ Sustain. 2015; 14: 101-108.
43. Oberndorfer E, Lundholm J, Bass B, Coffman R, Doshi H, Dunnett N, et al. Green roofs as urban ecosystems: Ecological structures, functions, and services. Bioscience. 2007; 57: 823-833.
44. Soulsbury C, White P. Human-wildlife interactions in urban areas: A review of conflicts, benefits and opportunities. Wildl Res. 2015; 42: 541-553.
45. Chen S, Wang Y, Ni Z, Zhang X, Xia B. Benefits of the ecosystem services provided by urban green infrastructures: Differences between perception and measurements. Urban For Urban Green. 2020; 54: 126774.
46. Krosby M, Tewksbury J, Haddad N, Hoekstra J. Ecological connectivity for a changing climate. Biol Conserv. 2010; 24: 1686-1689.
47. Goddard M, Dougill A, Benton T. Scaling up from gardens: Biodiversity conservation in urban environments. Trends Ecol Evol. 2010; 25: 90-98.
48. Langemeyer J, Wedgwood D, McPhearson T, Baró F, Madsen A, Barton D. Creating urban green infrastructure where it is needed - A spatial ecosystem service-based decision analysis of green roofs in Barcelona. Sci. Total Environ. 2020; 707: 135487.
49. Venter Z, Barton D, Martinez-Izquierdo L, Langemeyer J, Baró F, McPhearson T. Interactive spatial planning of urban green infrastructure - Retrofitting green roofs where ecosystem services are most needed in Oslo. Ecosyst. Services. 2021; 50: 101314.
50. Filazzola A, Shrestha N, MacIvor J, Stanley M. The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta‐analysis. J App Ecol. 2019; 56: 2131-2143.
51. Grimm N, Faeth S, Golubiewski N, Redman C, Wu J, Bai X, Briggs J. Global change and the ecology of cities. Science. 2008; 319: 756-760.
52. Rastandeh A, Zari M, Brown D. Components of landscape pattern and urban biodiversity in an era of climate change: A global survey of expert knowledge. Urban Ecosyst. 2018; 21: 903-920.
53. .id (informed decisions) for Wellington City Council. Population and household forecasts 2013 to 2043. Collingwood: Forecast.id.; 2020 [cited date 2021 July 23]. Available from: https://forecast.idnz.co.nz/wellington/home.
54. Biophilic Cities. Our vision: Connecting cities and nature [Internet]. Charlottesville: School of Architecture University of Virginia Retrieved; unknown [cited date 2021 August 13]. Available from: https://www.biophiliccities.org/our-vision.
55. Rastandeh A, Zari M, Brown D, Vale R. Analysis of landform and land cover: Potentials for urban biodiversity conservation against rising temperatures. Urban Policy Res. 2019; 37: 338-349.
56. Blaschke P, Chapman R, Gyde E, Howden-Chapman P, Ombler J, Zari M, et al. Green space in Wellington's central city: Current provision, and design for future wellbeing. Report for Wellington City Council. Wellington: New Zealand Centre for Sustainable Cities; 2019; 1.

57. Rastandeh A, Brown D, Zari M. Site selection of urban wildlife sanctuaries for safeguarding indigenous biodiversity against increased predator pressures. Urban For Urban Green. 2018; 32: 21-31.
58. Zari M. Ecosystem services analysis for the design of regenerative built environments. Build Res Inf. 2012; 40: 54-64.
59. Wellington City Council. Long-term Plan 2018-28. Wellington: Wellington City Council; 2018.
60. Pearce P. Wellington region climate change projections and impacts. NIWA Client Report for Greater Wellington Regional Council. Wellington, New Zealand: NIWA; 2017; 1.
61. Zari M. Biomimetic design for climate change adaptation and mitigation. Archit Sci Rev. 2010; 53: 172-183.
62. Parlato, E. H., Armstrong, D. P., Innes, J. G. Traits influencing range contraction in New Zealand's endemic forest birds. Oecologia, 2015; 179: 319-328.
63. Rastandeh A, Zari M. A spatial analysis of land cover patterns and its implications for urban avifauna persistence under climate change. Landsc Ecol. 2018; 33; 455-474.
64. Predator Free Wellington [Internet]. Wellington, New Zealand: PFW; 2021 [cited date 2021 September 21]. Available from: https://www.pfw.org.nz/.
65. Porteous T. Restoration planting: A guide to planning restoration planting projects in the Wellington region. Wellington, New Zealand: GWRC; 2014
66. Clarkson B, Wehi P, Brabyn L. A spatial analysis of indigenous cover patterns and implications for ecological restoration in urban centres, New Zealand. Urban Ecosyst. 2007; 10: 441-457.
67. Zari M. Regenerative urban design and ecosystem biomimicry. Abingdon: Routledge; 2018.
68. Rastandeh A. Urban biodiversity in an era of climate change: Towards an optimised landscape pattern in support of indigenous wildlife species in urban New Zealand. Wellington: Victoria University of Wellington; 2018.
69. Thomson M. Bridging the distance: Accommodating wildlife interaction in an urban setting. Wellington: Victoria University of Wellington; 2020.
70. Clarkson B, Kirby C, Wallace K. Restoration targets for biodiversity depleted environments in New Zealand. Hamilton, New Zealand, The University of Waikato Environmental Research Institute; 2018.
71. Rastandeh A, Zari M, Brown D, Vale R. Utilising exotic flora in support of urban indigenous biodiversity: Lessons for landscape architecture. Landsc Res. 2018; 43: 708-720.
72. Meurk C, Hall G. Options for enhancing forest biodiversity across New Zealand's managed landscapes based on ecosystem modelling and spatial design. N Z J Ecol. 2006; 30: 131-146.
73. World Health Organization. Health indicators of sustainable cities in the context of the Rio+20 UN Conference on Sustainable Development. Geneva: WHO; 2012.
74. World Health Organization (WHO) Regional Office for Europe. Urban green spaces and health. Copenhagen: WHO Regional Office for Europe; 2016.
75. Taylor L, Hochuli D. Creating better cities: How biodiversity and ecosystem functioning enhance urban residents' wellbeing. Urban Ecosyst. 2015; 18: 747-762.
76. Landcare Research. LCDB v5.0 - Land Cover Database version 5.0, Mainland New Zealand online [Internet]. Lincoln: Landcare Research Ltd; 2020 [cited date 2021 July 30]. Available from: https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/.

77. NIWA. National and regional risk exposure in low-lying coastal areas: Areal extent, population, buildings and infrastructure. Wellington: Parliamentary Commissioner for the Environment, 2015; 6.
78. Wellington City Council. Wellington City Council map of flood hazard areas [Internet]. Wellington: Wellington City Council; 2019 [cited date 2021 July 08]. Available from: https://mapping.gw.govt.nz/GW/Floods/.
79. Wellington City Council. Wellington City Council map of storm surge water depth [Internet]. Wellington: Wellington City Council; 2019 [cited date 2021 July 08]. Available from: https://mapping1.gw.govt.nz/GW/SLR/#background-to-topic.
80. Wellington City Council. Wellington City Council map of sea level rise [Internet]. Wellington: Wellington City Council; 2019 [cited date 2021 July 08]. Available from: https://mapping1.gw.govt.nz/GW/SLR/#background-to-topic.
81. Belcher R, Sadanandan K, Goh E, Chan J, Menz S, Schroepfer T. Vegetation on and around large-scale buildings positively influences native tropical bird abundance and bird species richness. Urban Ecosyst. 2019; 22: 213-225.
82. Jagarajan R, Abdullah Mohd Asmoni M, Mohammed A, Jaafar M, Lee Yim Mei J, Baba M. Green retrofitting - A review of current status, implementations and challenges. Renew Sustain Energy Rev. 2017; 67: 1360-1368.
83. Calheiros C, Stefanakis A. Green roofs towards circular and resilient cities. Circular Economy and Sustainability. 2021; 1: 395-411.
84. Akbari H, Shea Rose L, Taha H. Analyzing the land cover of an urban environment using high-resolution orthophotos. Landsc Urban Plann. 2003; 63: 1-14.
85. Garibaldi L, Oddi F, Miguez F, Bartomeus I, Orr M, Jobbágy E et al. Working landscapes need at least 20% native habitat. Conserv Lett. 2021; 14: e12773.
86. Convention on Biological Diversity. Protected areas and other effective area-based conservation measures: Draft recommendation submitted by the Chair [Internet]. Montreal, Canada: CBD; 2018 [cited date 2021 September 21]. Available from: https://www.cbd.int/doc/c/9b1f/759a/dfcee171bd46b06cc91f6a0d/sbstta-22-l-02-en.pdf.
87. Itani M, Al Zein M, Nasralla N, Talhouk SN. Biodiversity conservation in cities: Defining habitat analogues for plant species of conservation interest. PLoSONE. 2020; 15: e0220355.
88. Francis R. Wall ecology: A frontier for urban biodiversity and ecological engineering. Prog Phys Geogr. 2011; 35: 43-63.
89. Coutts C, Hahn M. Green infrastructure, ecosystem services, and human health. Int J Environ Res Public Health. 2015; 12: 9768-9798.
90. Weinmaster M. Are green walls as “green” as they look? An introduction to the various technologies and ecological benefits of green walls. J Green Build. 2009; 4: 3-18.
91. Bosch M, Ode Sang Å. Urban natural environments as nature-based solutions for improved public health - A systematic review of reviews. Environ Res. 2017; 158: 373-384.
92. Blaschke P. Health and wellbeing benefits of conservation in New Zealand. Science for Conservation 321. Wellington: Department of Conservation; 2013; 37.
93. Becker M, Buchholz S. The sand lizard moves downtown - habitat analogues for an endangered species in a metropolitan area. Urban Ecosyst. 2016; 19: 361-372.
94. Aisher A, Damodaran V. Introduction: Human-nature interactions through a multispecies lens. Conserv Soc. 2016; 14:293-304.

95. Lundquist C, Ramsay D, Bell R, Swales A, Kerr S. Predicted impacts of climate change on New Zealand's biodiversity. Pac Conserv Biol. 2011; 17: 179-191.
96. Ministry for the Environment. Climate change projections for New Zealand: Atmosphere projections based on simulations from the IPCC fifth assessment, 2nd Edition; 2018 Sep 1; New Zealand. Wellington: Ministry for the Environment.