Reducing street parking can free up large areas for urban nature

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Abstract

Nature-based solutions (NBS) are increasingly recognised as a means to address critical urban sustainability problems such as heatwaves, flooding and biodiversity loss. Accordingly, cities around the world have committed to ambitious targets for urban greening. Meeting these targets will require large areas of land to be converted from existing uses to green space. However, finding this land is difficult in established urban areas, where space is already strongly contested. Here we show an approach by which cities can make substantial progress towards a range of sustainability targets: by converting redundant street parking into biodiverse green space. Significant areas of public land in dense cities are currently allocated to street parking, while off-street parking garages in urban areas are typically abundant and have high rates of vacancy. We demonstrate that vacancy in off-street garages is so substantial that up to half of street parking in our case study municipality (The City of Melbourne, Australia) could be accommodated in garages within 200 m, freeing up large areas for conversion to green space. Our modelling shows this would have significant benefits in terms of tree canopy cover, stormwater treatment and ecological connectivity in the city. These benefits would represent strong progress towards – and even meet – a number of the city's ambitious NBS targets. As many cities allocate extensive areas to both street parking and off-street garages, this approach to freeing up space for nature in cities is widely applicable. Our findings indicate this is a practical means for municipalities with the required political will and public support to deliver their sustainability goals.

Introduction

Nature-based solutions (NBS) have great potential to provide ecosystem services in cities. They can help reduce the impacts of climate change, enhance biodiversity, and maintain the liveability of highly urbanised areas[1–4]. This potential is reflected in the rapid increase of ambitious municipal NBS strategies[5–7]. For many cities, the challenge is now to deliver these plans; to do this, they must retrofit NBS at scale into established urban environments, where public space is often strongly contested[8,9].

The urgent, large-scale delivery of urban NBS is important in the context of several global policy drivers. These range from high-level commitments such as the Sustainable Development Goals (SDGs)[10,11], to reducing the impacts of more frequent and severe heatwaves and flooding as cities face climate change[12,13]. Cities also have an important role to play in conserving biodiversity[14,15] and remedying past environmental injustices that have produced inequitable access to ecosystem services[16]. Most recently, in the wake of the COVID-19 pandemic, the notion of a 'green recovery' supported by NBS delivery has been advanced both within academia[17] and by powerful international institutions including the OECD, EU, and UNEP[18–20].

However, while delivery of NBS at a large scale is crucial, it remains largely unrealised[21–24]; optimistic NBS discourses seldom acknowledge the degree of land use change necessary to deliver effective solutions in urban areas. For example, in the city of Melbourne, Australia, the Elizabeth Street Catchment (watershed) faces extreme flood risk. Because over 80% of the catchment surface is impermeable (i.e. covered in concrete, asphalt, or buildings)[25], heavy rains can quickly exceed the capacity of the city's engineered drainage systems. The city's flood management strategy includes a target that 65ha of public land in this small urban catchment is de-paved or made permeable by 2030[25]. This is a significant area; nearly three times the size of the largest park in the catchment (Carlton Gardens, 25ha).

Melbourne's target for de-paving joins a growing list of ambitious NBS strategies; Paris aims to have 50% permeable vegetated cover by 2030[26], and Los Angeles' 'Green New Deal' includes a target to plant 90,000 new trees in less than two years[27]. Many cities will need to retrofit hundreds or thousands of hectares of land to make space for greenery in coming years if they are to realise their vision of NBS and meet their sustainability goals. However, urban land is expensive, and subject to numerous competing land uses, particularly in dense residential and commercial areas[9,28]. The scale of land use change necessary will require cities to target existing land uses that can be systematically replaced with green space. Any urban land use changes require consideration of the practical trade-offs, and so identifying the most viable opportunities for large-scale, systematic change is an essential prerequisite for cities hoping to meet targets for NBS delivery. Our study focuses on one promising trade-off: the conversion of street parking into biodiverse green space.

We focus on streetscapes because they cover very large areas of land in cities[9]. For example, streets cover 26% of all land in the city centres of Melbourne and Sydney, and over 30% in London, Barcelona and New York[29]. A substantial portion of this land is typically allocated to on-street parking; 21% in Melbourne[30] and 28% in Vienna[9]. An abundance of off-street (i.e. garage) parking space in built-up areas means that some of this streetscape allocation may be redundant. In many cities, this abundance is the result of urban planning regulations, requiring decades of commercial and residential development to provide generous off-street parking [31,32]. Even after relaxing these requirements, Melbourne's central municipality has over four million square metres of parking garages, covering an area more than triple the size of the city's central business district[33] .

High vacancy rates in off-street parking areas are typical in many cities[34–36], with a substantial portion of street parking used by residents with access to garages[37]. Central city garages also have low utilisation rates; even before the Covid-19 pandemic of 2020-21, apartment parking in central Melbourne had a considerable vacancy rate (26-41%)[33]. This extent of underutilisation is significant considering that the municipality has 49,500 off-street residential parking spaces, more than double the on-street allocation of 23,500 spaces[33].

Consolidation of on-street car parking into nearby garages with redundant capacity represents a considerable untapped opportunity to systematically free up street space for NBS [38]. This could be achieved through existing, proven parking management mechanisms, such as the use of centralised car parking facilities (common in Germany[35] and Japan[39,40]), or peer-to-peer parking apps which operate similarly to AirBNB or Uber[41,42].

Here, we explore this opportunity in a case study from Melbourne, Australia. We focus on the 'City of Melbourne' municipality, which covers the central business district and innermost suburbs (population approximately 170,000) within a metropolis of five million people. Rapid recent development in the central city has placed significant pressure on its existing urban forest[43,44]. The city also faces heatwaves[45,46], flooding[25] and water quality problems in the adjoining bay[47].

First, we identify and map on-street parking spaces that are candidates for reallocation because of their proximity to under-utilised off-street parking. Different assumptions about which on-street parking spaces can be reallocated underpin twelve scenarios that vary according to the type of destination garages (using commercial parking only, non-commercial parking only, or both), assumed levels of vacancy in destination garages (high or low), and the maximum distance between the on-street and off-street carparks (100m and 200m). The scenarios identify thousands of redundant parking spaces. All scenarios retain significant areas of on-street parking, recognising that some spaces are not redundant, and provision of disability and delivery parking will remain important in streetscapes.

Next, we model a range of sustainability benefits delivered by replacing the redundant on-street parking with biodiverse green space. Our models based on a modular green space design we prepared for this study (Figure 1), which was informed by the principles of both Water and Biodiversity Sensitive Urban Design (WSUD & BSUD)[48,49].

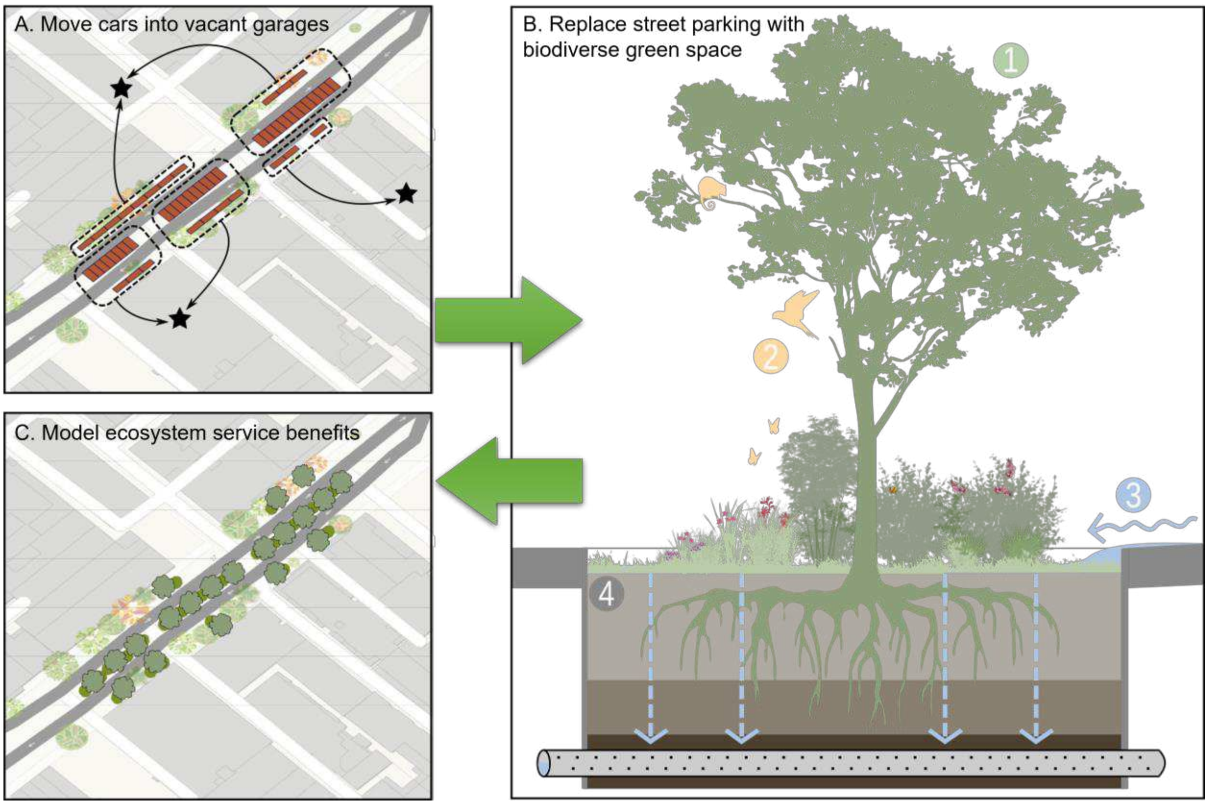


Figure 1 - Summary of the process used to estimate the benefits of replacing redundant on-street carparking with biodiverse green space. A: On-street car parks close to parking garages with vacancy are identified and reallocated. B: Redundant street parking is replaced by biodiverse green space, as per the schematic design shown, which integrates a street tree (1), habitat resources such as understorey plants (2), stormwater infiltration using a sunken 'raingarden' design (3), and effectively de-paves the area of the parking space (4). C: Benefits of this change in land use across the City of Melbourne are estimated in terms of tree canopy, ecological connectivity, interception and treatment of stormwater flows, and total area of impermeable asphalt removed (de-paved).

We find that the modelled benefits of converting redundant parking into biodiverse green space would result in substantial progress towards a number of the city's published urban sustainability targets, and could meet targets outright in some cases. Our findings emphasise that large-scale delivery of NBS is possible through systematic land use change in streetscapes, if political and public support is sufficient to align with sustainability goals.

Results

This study considers the reallocation of a portion of the City of Melbourne's 23,500 street parking spaces into vacant space in the 193,500 garage spaces within the municipality. We tested a range of parking consolidation approaches and vacancy levels across twelve scenarios. We present headline findings here, showing the range of results. Detailed results are supplied at Supplementary 1.

There is substantial opportunity to convert parking into biodiverse green space in every scenario modelled (Figure 2A; Supplementary 1). We identified between 3,146 and 11,668 redundant on-street spaces, depending on input assumptions. 11,668 spaces represent 47% of the 24,745 total on-street spaces in the city, which cover approximately 50ha.

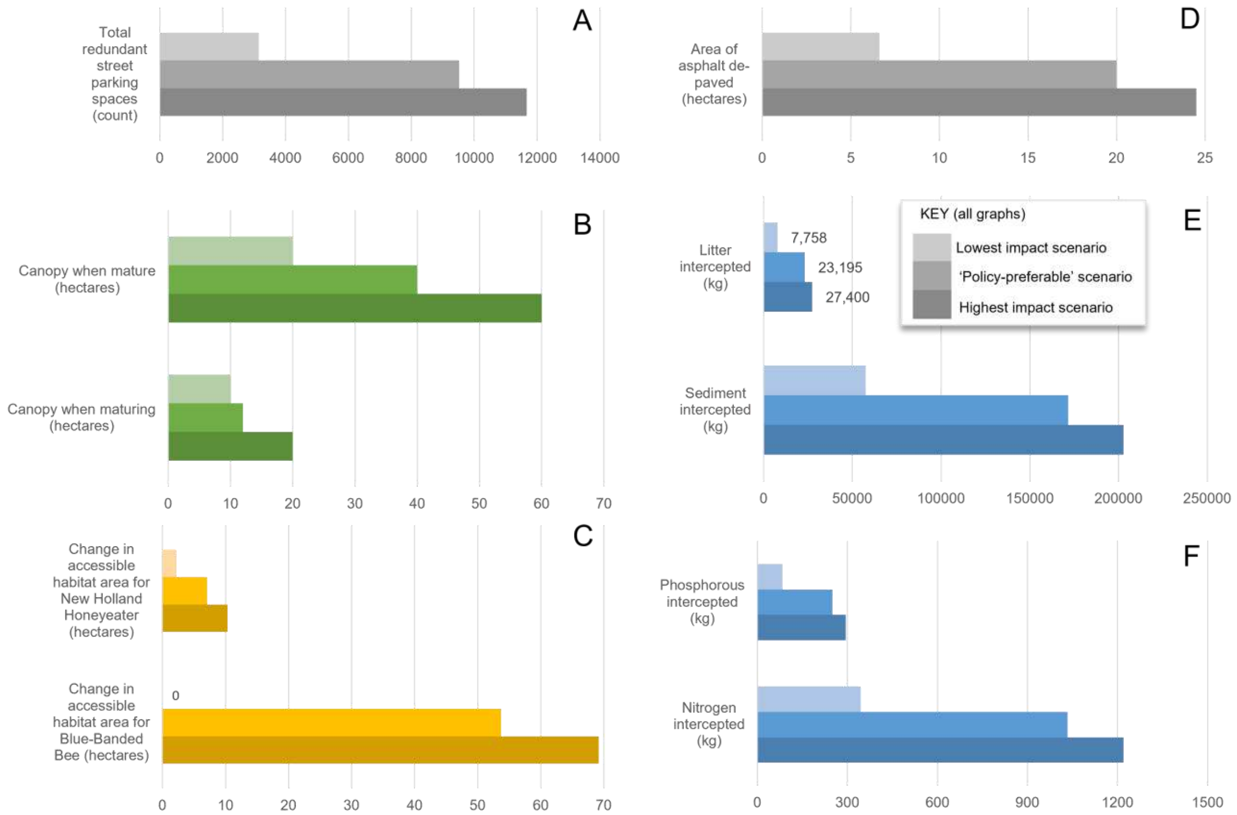


Figure 2 – Summary of results. Highest and lowest results are included to show the range identified in our twelve scenarios. We include a full table of results at Supplementary 1. The lowest impact scenario used commercial parking only, assumed low vacancy (up to 30%), and a 100m maximum distance between the street parking and the destination garage. The highest impact scenario used all types of garage parking, assuming higher vacancy (up to 70%), with a 200m maximum distance. We also show a scenario that we speculate to be 'policy preferable' because it delivers promising results, while assuming only low vacancy across all types of parking, and used a 200m maximum distance; this is included to represent a beneficial and attainable result.

Tree Canopy Cover

We estimated an increase of between 31 and 59ha of tree canopy cover expansion generated by trees at maturity, with 11 to 22ha provided in intermediate years as trees mature (Figure 2B). This is a considerable contribution to the city's 254ha of existing public-realm tree canopy[50], particularly considering the twelve tree species selected (detailed in Methods) were chosen primarily to support habitat outcomes over canopy cover optimisation.

Ecological Connectivity

Ecological connectivity improved substantially as the converted parking spaces created key habitat stepping-stones and reduced the effect of fragmentation for two focal animal species (Blue-banded Bee, *Amegilla spp*. and New Holland honeyeater, *Phylidonyris novaehollandiae*). Figure 3 shows a typical improvement in connectivity under a higher-impact scenario. Connectivity improvements were observed for the New Holland honeyeater, but the Blue-banded Bee showed the greatest improvements (Figure 2C).

*Figure 1 - Ecological connectivity improvements for the blue-banded bee (*Amegilla spp.*) in Melbourne, showing how fragmented habitat patches (coloured differently) become more connected within the landscape (coloured the same). This effect was much more marked in scenarios where parking spaces were moved 200m instead of 100m. Supplementary Materials 2 supplies detailed connectivity values recorded for each parking scenario, along with the corresponding mean connected area size and number in relation to the total area of habitat available in each scenario.*

De-paving

The large amounts of redundant parking identified in the spatial scenarios represent an opportunity to remove a substantial area of asphalt (Figure 2D). In total, 6.6-24.5ha of parking could be de-paved. This equates to an area of permeable, biodiverse green space between approximately 1.5 and 6 city blocks. Of this total area (municipality-wide), between 2.7 to 7.7ha of de-paving opportunities exist within the flood-prone Elizabeth Street Catchment at the centre of Melbourne.

Stormwater

The proposed raingarden design showed notable results in interception of stormwater. Our modelling indicates these would capture up to 27 tons of gross pollutants (litter) and 202 tons of sediment (Figure 2E), as well as hundreds of kilograms of nutrient pollutants phosphorus and nitrogen (Figure 2F). As we demonstrate in the following section, the quantities intercepted are significant when compared to policy targets.

Policy impact

To present this study's results in terms of the challenges cities seek to address using NBS, where possible, we compared our results to quantitative targets already established by City of Melbourne. We found that this single strategy could meet sediment and phosphorus interception targets identified by the city (Figure 4). The changes would also represent a large contribution to the city's ambitious '40% by 2040' target for tree canopy cover on public land, delivering up to a third of the required change. The 2.7 to 7.7ha of de-paving delivered in the flood-prone Elizabeth Street Catchment at the heart of the municipality represents between 4% and 12% of the 65ha target for de-paving in this area, highlighting the need for complementary measures such as rooftop greening, permeable sidewalks and other de-paving solutions.

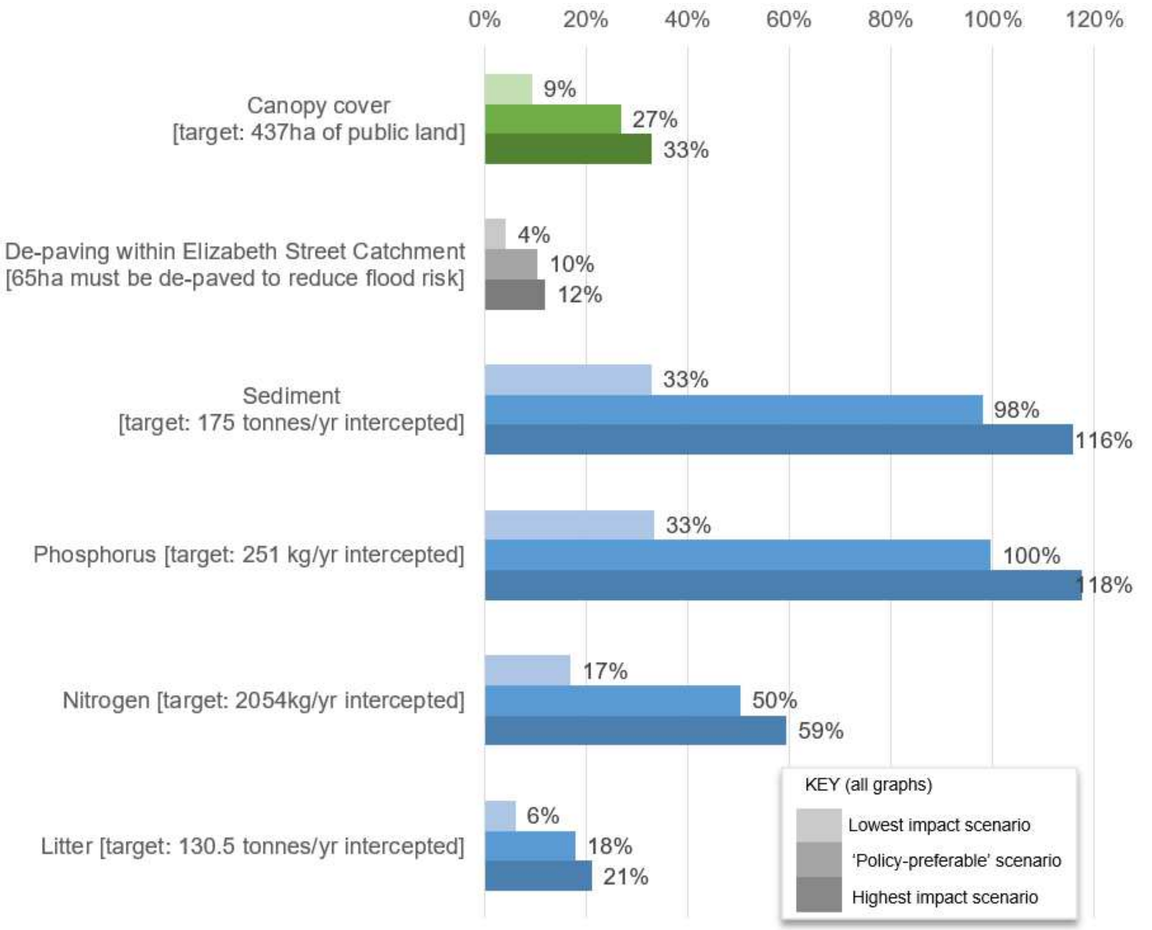


Figure 4: Summary of policy impacts of parking replacement, showing the impact of each scenario as a proportion of the total change required to deliver the relevant sustainability target. The canopy target is from the City of Melbourne Urban Forest Strategy[51]. The de-paving target is from the Elizabeth Street Catchment Strategy, which covers a highly urbanised, flood-prone watershed within the central city[25]. Sediment, Litter and Phosphorus targets are articulated in the city's 2009 Total Watermark strategy[52]. The Nitrogen target is from a 2014 iteration of the same strategy[53]. Figure 4 does not show quantitative progress towards an ecological connectivity target; the city's biodiversity strategy simply seeks an improvement in connectivity overall by 2027[54]. Our modelling indicates that this is possible under most scenarios (Figure 2C).

Discussion

We examined the extent to which redundant street parking may be converted to biodiverse green space, quantifying the impacts of this change in terms of tree canopy, de-paving impervious surfaces, stormwater treatment and ecological connectivity. Our results indicate that this single land use reallocation tactic could deliver substantial, integrated outcomes for urban sustainability.

This set of findings is of international relevance. Streetscapes form between a quarter and a third of all the land in cities[29], and street parking in turn constitutes around a quarter of that space[9]. This translates to huge areas of public land. At the same time, due to common planning rules requiring generous parking provision in new builds, many cities have created extensive areas of garage space as they developed[31,37,55]. This effectively duplicates street parking. As cities around the world plan NBS delivery to address critical challenges such as climate adaptation and COVID-19 recovery, this redundant parking is an important area of opportunity in dense urban areas. This is significant both because space for NBS is especially difficult to find in these areas[9], and because the inner city tends to be particularly susceptible to heat island effects[45] and flooding[56] due to extensive asphalt and concrete cover.

Our study highlights how a systematic reallocation of space in streetscapes can produce benefits at the scale that is required for cities to genuinely tackle significant urban sustainability challenges. The thousands of redundant car parking spaces in central Melbourne's streets represent an opportunity to replace up to 24 hectares of asphalt with biodiverse green space in the city's densest neighbourhoods. This would generate 31-59 hectares of new tree canopy cover, delivering up to a third of the city's ambitious 2040 canopy target[51]. This is valuable from a heat mitigation perspective, as even small tree canopy patches have been demonstrated to significantly decrease extreme heat[57]. Results for stormwater treatment are also very promising, showing this approach can meet (and in some cases exceed) targets for sediment and nutrient pollutants, both of which are classic challenges in urban watersheds[58]. Our approach has promising biodiversity benefits, primarily by creating 'stepping stones' that link habitat patches for urban species, especially bees. As found in other connectivity studies, even small fragments of habitat can have a positive impact on mobility, particularly for species that may need to rest while dispersing[59–66].

Our integrated focus on canopy, biodiversity and stormwater is rare, both in the literature and practice, where single NBS functions such as stormwater tend to dominate program logic[67,68]. However, our approach quantifies only a few of the many important benefits that would be delivered by a large-scale greening of our streetscapes. Green space encourages greater physical activity[69] and is associated with lower rates of obesity[70]. Access to green space can reduce loneliness[71], and tree canopy is associated with a range of mental health benefits[72] and may reduce dementia risk[73]. Intangible NBS benefits like aesthetic appeal and socio-cultural values have also been quantified and found important for residents[74]. We also do not directly quantify cooling[3,75], air quality improvements[76] or reductions in localised flooding[77,78], nor is job creation through construction and maintenance estimated. The value of urban renewal and local economic stimulus in beleaguered retail streetscapes is of particular interest in the wake of COVID-19 lockdowns, but again this is not modelled. These are all potentially significant benefits, and could be factored into decisions if more comprehensive tools and frameworks for multifunctional NBS are progressed[68,79,80].

In addition to omitting many benefits, it is likely that this study under-estimates the benefits we do quantify due to the conservative assumptions underlying our analysis. For example, a skilled streetscape design team could identify locally-specific opportunities for broader expansions of green space by narrowing a wide traffic lane or footpath, delivering green space well beyond what we modelled. Further, the assumption that no parking space would be removed – only moved – is conservative, as many cities pursue uncompensated removal of street parking as they reconsider the role of streets as public spaces[9], and in response to changing working patterns resulting from pandemic management[81]. For example, Amsterdam is removing 1,500 spaces annually[82], and Paris has pledged to remove half of its 140,000 street spaces[83]. If the City of Melbourne were willing to replace parking at a reduced level – for example, by greening three street parking spaces for every two made available in parking garages – the scale of change would effectively be multiplied by that ratio. Similarly, if a walking distance larger than 200m is assumed in modelling, a higher potential for consolidation of parking might be realised. Further conservative assumptions underlying our modelling of canopy and stormwater benefits are detailed in Methods.

While we have identified a significant spatial potential to deliver NBS in urban streets, doing so will require cities to navigate a sensitive political and social context. The street as a public space is increasingly contested, despite the normalisation of a cultural and legal dominance of the private automobile as a practice and a system[84,85]. Public space allocation in streetscapes is fundamentally political, with competing normative and monetised claims determined by complex governance arrangements. Historically, prevailing approaches have prioritised private car parking and, as a result, the politics of on-street parking remain contentious in many cities, including Melbourne[35,37,86]. Any scale of change to parking arrangements can be subject to fierce opposition, as experienced in many cities that have dared to challenge the dominance of automobility – often with success, but rarely without navigating intense conflict[87]. While the consolidation of parking we propose may trigger this kind of conflict, the trade-off is arguably quite modest; the convenience of parking may be somewhat reduced for drivers (while gaining other advantages from garage parking), this change results in the considerable ecosystem service benefits quantified by our analysis.

In addition to political sensitivities, the costs and practicalities involved in a large-scale conversion of parking to green space must be acknowledged. Enacting thousands of car-park-sized changes to the central city – however modular – will be a substantial effort of financing, coordination, design, engineering, and maintenance. However, none of these costs or practicalities are insurmountable when political will, public support, and sustainability goals align[88], and the modular nature of the NBS proposed means that land use change could be rolled out incrementally over a number of years. Examples of changes at this scale remain rare, but they do exist; for example, New York City greened over 600ha between 2010 and 2020, at a cost of USD?1bn[89]. This highlights the scale of change required; cities will miss the substantial benefits of urban nature-based solutions if we cannot enact land use change at this scale.

Our results are a reminder that cities can deliver highly beneficial NBS at large scale using existing municipal land, if they are able to navigate the politics and practicalities of the required land use changes. Establishing evidence-based narratives of benefit can help ensure that these required costs and trade-offs are recognised as worthwhile – particularly as cities reconsider their priorities in the wake of the COVID-19 pandemic[90]. By quantifying the significant ecosystem service benefits in our case study city, we hope to push the discourse towards a new and positive point of focus: measuring what we stand to gain.

Methodology

Case study

The City of Melbourne municipal area (37.7km²) is an inner-city municipality within a larger metropolitan area (9,992 km²) exposed to several climate adaptation and sustainability challenges, including intense heat and flooding. The city has existing policy commitments to improve biodiversity, canopy and stormwater treatment[51,53,54], as well as having appropriate open data[91] and a demonstrated interest in parking reform.

Our analysis is based on a set of twelve scenarios that estimate and map the amount of existing vacant off-street parking available in a range of building types. In each scenario, we identify on-street spaces within a given distance of the off-street parking garage. When a space is identified as having potential, we assume deployment of a simple green space, which we designed as part of this research. We then employ a range of modelling approaches to estimate ecosystem service benefits from the deployment of these green spaces.

We adopt the relatively conservative assumption of 'no net loss' of parking availability; on-street parking is assumed only to be moved off-street, not removed completely. This approach is deliberately conservative given the intense political contestation of kerbside space[86].

Our analysis progressed in two key phases. In phase one, we used GIS analyses to identify suitable on-street parking spaces for reallocation to green space. In phase 2, we modelled the benefits of converting these spaces in terms of benefits to biodiversity, tree canopy cover and stormwater interception, based on a set of simple, modular planting designs developed to fit the identified spaces.

Phase 1 - Locating parking spaces with high potential for reallocation to NBS

This part of the analysis required us to first establish how many potentially vacant off-street parking spaces exist in residential, commercial and other private garages. With that known, we then used GIS to identify which on-street parking spaces exist within a short walk (100-200m) of these vacant parking spaces, and flag them as potentially redundant parking spaces (i.e. candidates for replacement with biodiverse green space).

1.1 - Quantifying vacancy in off-street garages

We accessed spatial data provided on the City of Melbourne's open data platform detailing location, capacity, and type of off-street parking[91]. The three types of parking mapped were coded 'residential', 'commercial' or 'private'. Residential car parking lots include those in large multi-unit dwellings. Commercial car lots are parking garages that charge a fee, usually on an hourly or daily rate. Private car parking is defined as 'car parking in a non-residential building that is provided for use by staff, customers or visitors'[92].

A key input for our modelling was to develop reasonable estimates of what the vacancy rates in the three types of off-street parking might be.

Residential parking vacancy rates are relatively well-known. Prior to the COVID-19 pandemic, vacancy rates in some types of parking in the City of Melbourne were known to be significant; a study in 2018 found that between 26 and 41% of residential apartment parking spaces are unused [33]. This partly reflects the lower need for car ownership in dense areas with good access to jobs, public transport and services[93]. The use of residential garages as *de facto* storage, with streets used for parking, has been demonstrated in many cities around the world. Another study found that over 50% of residential? off-street parking in Melbourne was used as storage by residents who had access to on-street parking[37]; in Dortmund, Germany, that rate was 12-22%[94]. A study in Los Angeles, USA, measured 75% of residential garages were used as storage[95].

By contrast, commercial and office vacancy rates are often unknown and will remain uncertain for some time in the wake of the pandemic, but we have reason to consider significant drops in demand possible, especially for paid commercial parking. A study commissioned by the City of Melbourne in 2020 found that 41% of office workers were unwilling to return to work in the city, with long commute times cited as a major reason not to return, and instead work from home. On top of this, a vast majority of workers intend to be in the office only some of the time. Perhaps most significantly, only 23% of the workforce intends to be in the office more than three days a week[81]. This evidence is consistent with the finding that many workers found working from home positive[96] and that billions of dollars of lost time was saved by avoided commutes[97]; these findings also underline the possibility that telecommuting may be actively promoted by governments in the wake of the pandemic.

Given commercial parking tends to be relatively expensive, and private employee parking may be in lower demand if office worker visitation drops, we see potential for more flexible demand for commercial parking, with more uncertainty around private (e.g. office) parking rates. Accordingly, our assumptions of commercial vacancies are higher and have more spread (30-70%) than assumptions for the 10-20% private parking (which is most uncertain) and 10-20% residential parking (which has at least some measured vacancy data, 26-41% as noted above[33], but is more difficult to offer to other users). We tested two possible scenarios having lower and higher vacancy rates for each parking type, as summarised in Table 1. Due to the ongoing cycle of COVID-19 variant outbreaks at the time of writing together with volatile petrol prices, future parking and travel patterns may remain essentially unknowable for some time, so we adopted a spread of scenarios to offer a plausible basis for exploring the range of possibilities.

Table 1 – Vacancy rates assumed in high and low vacancy scenarios and used when modelling off-street parking availability

	Commercial	**Private and Residential**	**Combined**
'Higher vacancy'	70%	20%	70%/20%
'Lower vacancy'	30%	10%	30%/10%

This set of vacancy assumptions formed an important basis for identifying redundant parking spaces on streets, because it defined the maximum portion of each off-street car park that can be used to 'absorb' on-street parking. Commercial parking was modelled separately in these scenarios both because it has such significant capacity, and is already geared to directly compete with on-street parking (i.e. mechanisms for access, security, pricing is already in place). As private and residential parking both would require changes in order to support a large-scale consolidation of on-street parking, these were modelled in a separate run. Finally, a 'combined' run of the model included all parking types.

1.2 - How many on-street parking spaces correspond with off-street vacancies within a short walk?

We used a GIS technique called 'location-allocation analysis' to identify optimally-placed on-street parking for consolidation into the vacant off-street capacity identified in step 1. This analysis employed two additional datasets from the City of Melbourne Open Data Platform: a map of on-street public parking spaces, and a map of the street network. The analysis was carried out using ESRI ArcMap 10.6, using the Network Analyst package[98]. The location-allocation package, when set to 'maximise capacitated coverage', allocates the closest redundant on-street spaces into the identified vacant capacity until that capacity is filled, thereby producing a dataset which identifies theoretically optimal parking spaces to be moved given the input parameters.

The analysis requires the user to input a maximum distance at which an on-street park would be considered a candidate to be allocated into an off-street carpark. To be conservative, we ran the analysis for distances of 100m and 200m, representing a short walk from the original parking space. Distance is calculated along the street network, not as the crow flies. These distances were selected as being up to half the walking catchment often assumed for public transport stops (400m)[99]. Studies of the distance residents are willing to walk from home to off-street parking are rare, but a study in an area with highly contested parking found that around 90% of residents with cars parked in garages within 200m of home[94]. One limitation of our modelling is that we could not quantify precise access locations (entryways/ramps) into off-street parking, so distances to building centroids were calculated.

In total, we ran twelve versions of this analysis; for each of the six vacancy scenarios in Table 1, we ran the analysis twice, once each for maximum distances between on-street and off-street parking spaces of 100m and 200m.

This analysis assumed that every on-street parking space must be replaced. This is a conservative assumption; for the city's 4,414 parking bays fitted with car occupancy sensors, an occupancy rate of 47.3% was observed prior to the pandemic, with a range of 30-70%[33]. This indicates that a level of spare capacity already exists on the street, even on days with higher demand; accordingly, a 1:1 replacement rate is probably excessive in many locations.

Phase 2 - Modelling benefits

2.1 Developing a design to form the basis of modelling

To model the ecosystem service changes arising from the conversion of street parking to biodiverse green space, we prepared a set of designs to illustrate how land use would change. Our intent was to produce standardised, replicable designs that delivered tree canopy, habitat for wildlife and stormwater interception, while retaining flexibility to satisfy the typical site constraints of urban environments (Table 2). The designs create a foundation for modelling benefits, but are, by necessity, schematic. Refinement of these designs at individual locations by skilled interdisciplinary design teams could further enhance their benefits and contextual fit. This could include responding to location-specific site conditions, or integrating space around redundant parking into the design (e.g. by slightly narrowing the vehicle carriageway, or utilising part of a wide footpath, or proposing to acquire extra parking spaces to deliver a more complete design).

Table 2 - Design objectives and corresponding features

Objective	Design features
Increase canopy	Each design includes one tree. A selection of species of different sizes, forms and growth rates was identified to ensure planting could meet site constraints. A final set of species was selected in collaboration with the ecologists advising on biodiversity aspects of the design. All the species modelled form part of the existing City of Melbourne street tree planting palette.
Improve biodiversity	Designs seek to include botanic diversity and provide habitat for urban wildlife. To guide habitat provision for birds and insects respectively, two iconic target species were selected: the New Holland Honeyeater (*Phylidonyris novaehollandiae*) and Blue-Banded Bee (*Amegilla spp.*). A palette of appropriate tree species was selected, and understorey provision includes a mix of flowering groundcover, taller grasses and mid-storey flowering shrubs to maximise food and resting place resources[49].

To determine likely constraints that parking space conversions may encounter, we used typical site conditions for Melbourne's on-street car parking. Our team reviewed maps of parking types across the study area visited key street segments to note site conditions. We consulted a green infrastructure specialist in a state road agency, as well as specialists in water sensitive urban design, urban ecology, and urban forestry (all of whom are co-authors of this paper) to identify constraints and opportunities (Table 3).

Table 3 - Constraints guiding the design. A number of these are broad remedies that would require site-by-site problem-solving by an appropriately skilled team to deliver.

Constraint identified	Response
Overhead cables	As per EnergySafe Victoria advice[100]: - Include two smaller tree spp. in modelling - Assume tree can be planted and subject to standard maintenance
High-speed roads	As per VicRoads tree policy[101]: - Include subsurface reinforced sleeves for crash barriers (noted as a remedy on roads above 60km/h)
Existing tree canopy	Identify parklets covered by canopy and exclude from canopy modelling (we used 2018 Canopy Polygons provided by the City of Melbourne).
Underground services	Tree planting location is flexible within the ~20sqm footprint. Smaller tree species included in modelled options to minimise root conflicts.
Dining areas	Parking spaces in commercial areas are flagged in our analysis; a dining-oriented design option was modelled for these sites.
Areas unsuitable for seating (e.g. residents may not want seating outside homes on quiet streets)	Design includes subsurface reinforced sleeves so seats and alternative furniture can be used selectively, to meet community preference.
A number of on-street car parking spaces are sited in medians (not kerbside)	A median-specific design was prepared, and assumed for these locations.

Three design variations were necessary to adequately respond to identified site conditions within the municipality. Plan A and Section A show our proposed design option for commercial areas, where on-street seating for dining and/or public use is a priority (Figure 5). This design option still includes a tree, and functions as a raingarden, but a platform and seating are substituted for ground-level understorey planting. Planter boxes still offer some understorey planting area and serve a dual function as traffic barriers.

The design option shown in Plan B and Section B (Figure 5) is the most prevalent type we identified as having potential for conversion, this being a standard kerbside car-park. This design is optimal for all three design goals: it includes a tree, has substantial areas of understorey habitat, and functions as a raingarden. Seating and decking are optional, to allow visual access to the green space without visitors climbing into the raingarden itself.

Plan C and Section C correspond to median car parks (Figure 5). The key differences between this and the other design options is the slightly smaller footprint, and the lack of seating and raingardens. Seating between two lanes of traffic was considered unappealing and likely unsafe. As road surfaces in these areas slope away from the centre towards kerbside gutters, median carparks could not adequately function as raingardens; only rain that falls directly on greened median sites infiltrates. Trees and understorey vegetation are retained.

RMIT Classification: Trusted

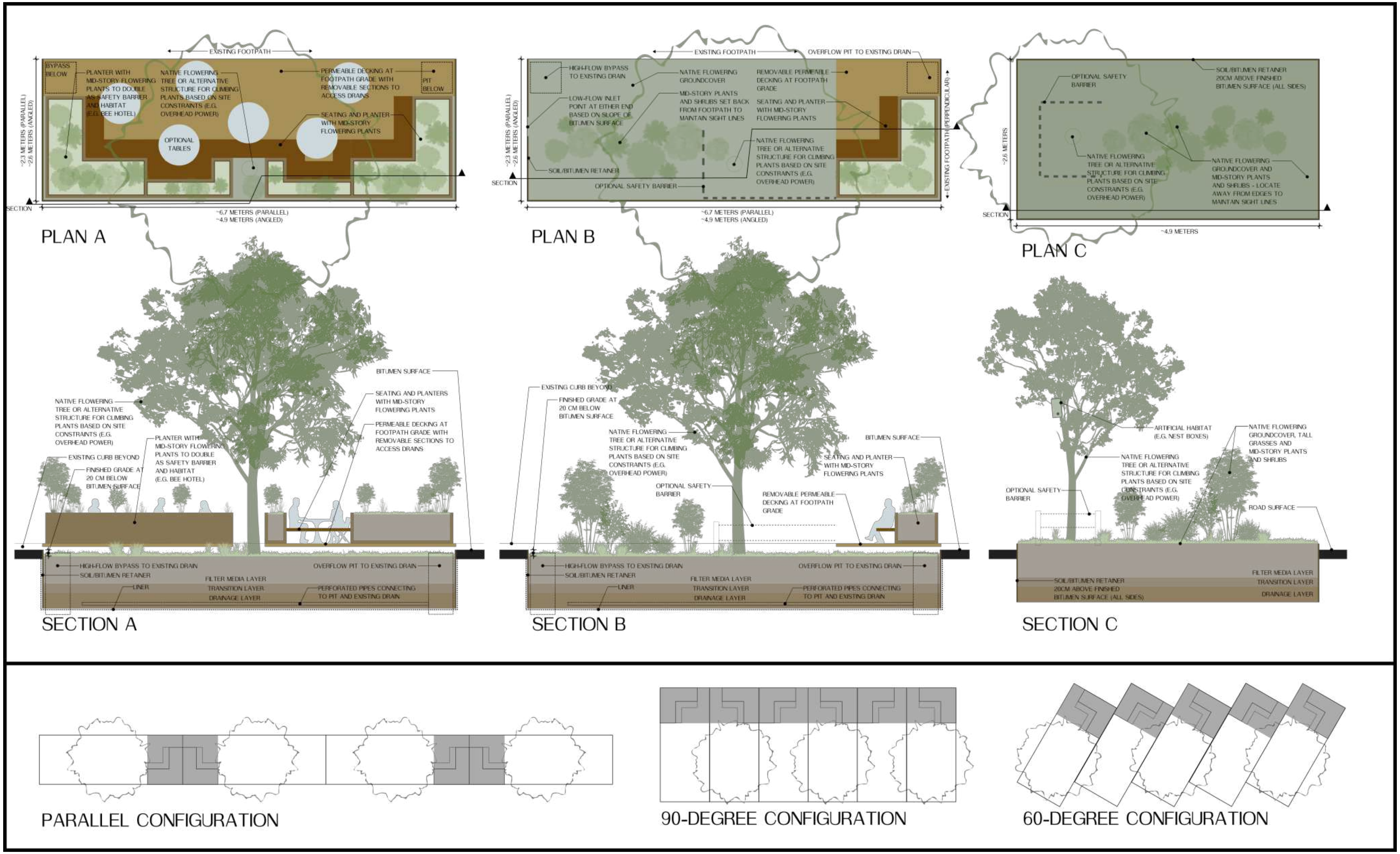


Figure 5 - Schematic designs modelled in this study. These are tailored to replace different kinds of redundant parking. From left to right, (A) replaces kerbside parking in commercial areas, (B) kerbside parking in all other locations and (C) median parking. A range of kerbside alignments can be accommodated, as shown at the bottom of this figure. For clarity, we have omitted the planned subsurface reinforced receiver sleeves for site accessories such as barriers, furniture, and auxiliary structures.

2.2. Estimating ecosystem service benefits

Phase 1 established the number of redundant parking spaces in each scenario. In phase 2, we model the replacement of these spaces with the biodiverse green space shown in Figure 5. Our modelling considers stormwater interception, canopy cover and habitat connectivity.

2.2.1 Modelling canopy cover

A tree allometric analysis was conducted to determine the average diameter at breast height (DBH) and tree crown area for isolated street tree stems planted across the City of Melbourne, drawing on the most recent municipal datasets of tree locations (point data) and tree canopy cover (polygon data)[91]. This involved intersecting tree point data with the canopy/crown polygons in ArcGIS 10.6, and filtering tree stems where there was a clear 1:1 match of a single tree stem location (point) from the inventory to a discrete isolated tree crown polygon from the municipal canopy cover map (i.e., only polygons containing a single tree point were considered to avoid interactive effects on tree architecture and growth due to competition for light and resources).

Out of the 62 tree species found to have at least 25 isolated stems across the study area (9,065 stem total), nine tree species for planting in car spaces were identified. These species i) offer a diverse range of structures and growth rates, ii) are already commonly used by the City of Melbourne, and iii) offer appropriate habitat and resources for the canopy-dwelling target wildlife species, as well as other biodiversity groups.

The selected tree species, all native to Australia, are:

- *Allocasuarina verticillata* – Drooping sheoak
- *Angophora costata* - Smooth-barked apple/Sydney red gum
- *Corymbia maculata* – Spotted gum
- *Eucalyptus camaldulensis* – River red gum
- *Eucalyptus leucoxylon* – Yellow gum
- *Eucalyptus polyanthemos* – Red box
- *Melaleuca styphelioides* – Prickly-leaved tea tree
- *Syzygium smithii* – Lilly pilly
- *Tristaniopsis laurina* – Water gum

Next, linear regression models for each for the selected nine tree species were fitted to measure how the crown area expands as the tree grows (Figure 6). As reliable tree age estimates were not available in this municipal dataset, DBH was used as a proxy for age, consistent with the methods of past studies for estimating growth of urban trees[102]. The use of existing tree data from the City of Melbourne ensures that growth metrics are accurate based on local environmental conditions and horticultural care.

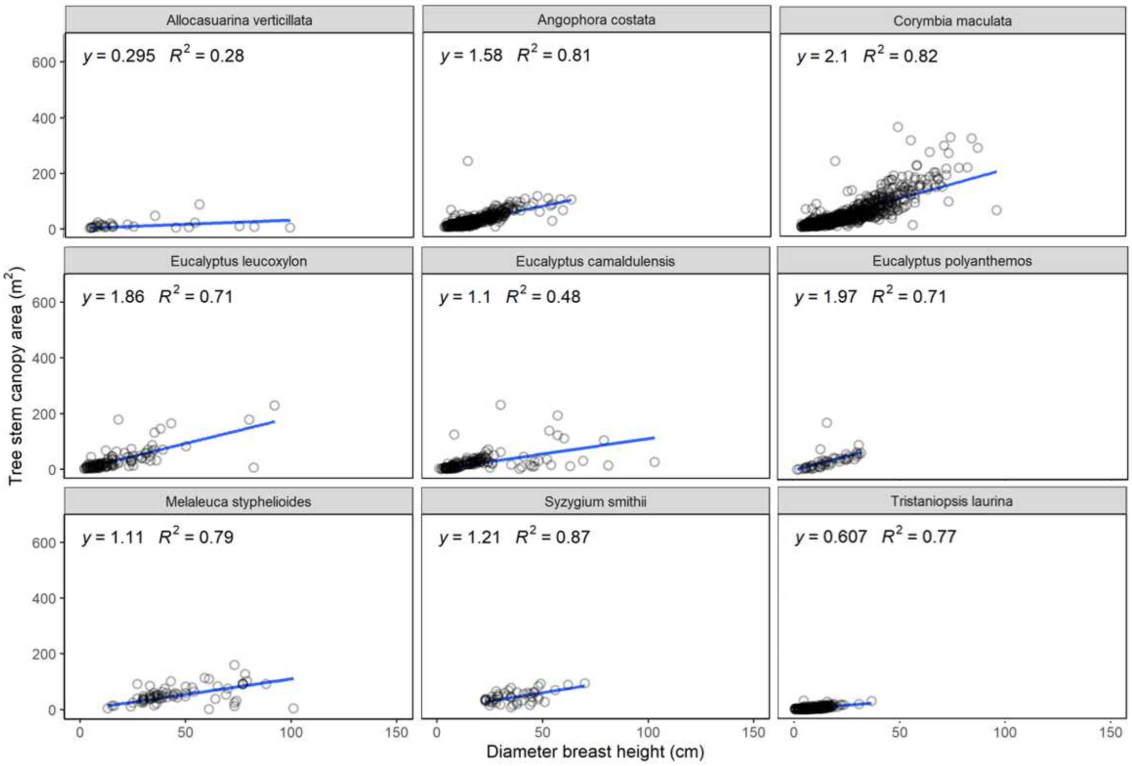


Figure 6 - Relationships between tree DBH and canopy of mature trees in the City of Melbourne.

With a clear understanding of how canopy cover would increase as our selected tree species matured, we applied these projections to the parking scenarios. For each parking lot that was suitable for tree planting, we assumed one tree was planted, consistent with the designs outlined above (Figure 5). The total canopy cover for each scenario could thus be derived, being the sum of the canopy added by each site.

The overall canopy cover derived in each scenario was calculated by assuming that an equal proportion of each species was planted across the total number of viable parking spaces in each scenario. This meant that any site that received a tree would effectively add the average canopy of the nine species. For all remaining lots, the ninety-fifth percentile of the DBH distribution for each of the nine target species - assumed to be mature individuals – was used in concert with the relative linear model, to calculate the maximum individual tree canopy cover at maturity in each scenario. To get a sense of the development of canopy benefits of each species during tree growth, two intermediate percentiles (25th percentile and 50th percentiles) were also used to model canopy development.

This analysis excluded parking spaces that already had some canopy cover. In each scenario, viable locations with existing tree canopy over parking lot centroids were excluded from the canopy analysis, assuming (conservatively) that trees would not be planted in these lots. This excluded approximately a quarter of all viable parking spaces in each scenario (20-28%). A further conservative assumption was that our trees would follow the growth patterns of existing trees in Melbourne, most of which are planted in standard tree pits; we did not model the significantly enhanced growth outcomes that are possible with passive irrigation[103], which is an important element of our design.

2.2.2. *Modelling increases in ecological connectivity*

The contribution of each parking space conversion scenario to ecological connectivity was measured using the framework detailed by Kirk et al.,2020[62,104]. This geometric measure of ecological connectivity is based on effective mesh size (m_{eff}) which provides an estimate of the area of habitat that can be accessed by an individual organism when dropped at random into the landscape[105,106]. We used a functional connectivity approach[107] to calculate existing ecological connectivity across the City of Melbourne for two target species, the New-Holland honeyeater (*Phylidonyris novaehollandiae*) and Blue-banded bee (*Amegilla spp.*). These species have differing habitat requirements, dispersal ability and barriers to movement. These species were selected as they both use the type of resources that can realistically be provided in a converted parking space but have differing specific habitat requirements and movement capabilities. They also represent two of the key charismatic native species groups found in the City of Melbourne: woodland birds and insect pollinators.

For the existing scenario we mapped current habitat for both species based on vegetation data available on the City of Melbourne open data portal[91] . New-Holland Honeyeater habitat was defined as "all tree canopy and understorey vegetation, plus turf less than 10 m from cover". Roads and railways wider than 15 m and buildings taller than 10 m were considered barriers to movement for New-Holland Honeyeaters, which were assumed to be able to cross gaps in habitat of up to 460m[108]. Blue-banded bee habitat was defined as "all canopy, mid- and understorey vegetation and turf less than 5 m from cover". Roads and railways wider than 10 m were considered barriers to movement for Blue-banded bees, which were assumed to be able to cross gaps in habitat of up to 300m[109]. The movement ability estimates for both target species are conservative as the connectivity model is sensitive to changes in the distance threshold used[62].

To model the effect of parking space conversion on ecological connectivity we assumed that an area of species habitat corresponding to the spatial extent of each parking space would be being added to the landscape. To model this effect we created a new fragmentation layer[105,106] for each parking conversion scenario, as the addition of the parking space habitat patches would change which road segments met the barrier definition for each species (see above paragraph). For each species and each scenario we quantified the area of connected habitat, degree of coherence and increase in connected area compared to the existing landscape in the City of Melbourne (refer to Supplementary 2).

All spatial layers were cleaned, combined and analysed in R 4.0.3 (R Core Team, 2020) using the `sf` spatial analysis package[110].

Modelling increased stormwater interception

To quantify stormwater benefits of these interventions, a set of inputs and assumptions were required. First, a random selection of car parking spaces (a typical car space was identified for each of a sample of seven diverse street typologies) were measured to determine their catchment size, and an average catchment of 395m^2 was established and applied to all spaces in the analysis (consistent with a maximum of one rain garden for every four adjacent parking spaces). Second, as most rooftops drain directly into stormwater drains, no rooftop runoff was assumed; only adjacent roads and footpaths were considered to constitute directly-connected catchment. Third, as the car parks were located in urban areas at the city's centre, we assumed imperviousness to be constant among parking sites.

This catchment figure, alongside the characteristics of the raingarden design , enabled calculations of the stormwater benefits of each raingarden using the industry-standard tool for Australian stormwater management, MUSIC (Model for Urban Stormwater Improvement Conceptualisation) version 6.0[111]. The MUSIC tool requires a range of details on the size of catchment, as well as the water storage capacity, inlet properties, vegetation type and filter media. The inputs to the tool are documented in Supplementary 3.

Importantly, it was recognised that in many cases, redundant on-street car parking spaces occur in groups of adjacent spaces (e.g. a line of kerbside parking). In these cases, it was not reasonable to assume that these groups would have sufficient catchment to model every space as a functioning raingarden. To be conservative, it was assumed that only every fourth parklet in a group would function as a raingarden for the purposes of modelling. The reason for this is that it is inefficient to have a raingarden for a very small catchment area, as there is not enough water to treat. Melbourne Water design guidelines suggest that a rain garden should be 2% of the catchment area (including impervious and pervious surfaces)[112]. As our area is generally 100% impervious asphalt, we have opted for 3.5% of the catchment area ($14m^2/395m^2$). If we were to assume that every second third or second space was a raingarden, the amount of treatment area per catchment area would become unjustifiable.

A total number of raingardens in each scenario was established by adding the number of single raingardens to the 'one-in-four' total of raingardens in grouped locations. Median parking (which does not receive runoff due to road camber) was also excluded. Total stormwater interception benefits were thereby calculated simply by multiplying the individual benefits calculated by the MUSIC model, by the number of viable sites.

A total was derived for each scenario in terms of Total Suspended Solids (kg/yr); Total Phosphorus (kg/yr); Total Nitrogen (kg/yr); and Gross Pollutants (kg/yr).

Declaration of interests

The authors declare no competing interests in relation to the work above.

Data Availability Statement

The data generated by this study is available in full at Supplementary 1.

Author contributions

TC – Writing, Conception of the study, Figures, Location-allocation analysis

SB, GG, RC, AB, LT – Review, Conceptual development

CF – Stormwater analysis

HK – Ecological connectivity analysis, Review, Figures

AO – Canopy analysis, Review, Figures

CV – Design, Review, Figures

References

1. Butt, N. *et al.* Opportunities for biodiversity conservation as cities adapt to climate change. *Geo Geogr. Environ.* **5**, (2018).
2. Norton, B. A. *et al.* Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landsc. Urban Plan.* **134**, 127–138 (2015).
3. Ossola, A. *et al.* Small vegetated patches greatly reduce urban surface temperature during a summer heatwave in Adelaide, Australia. *Landsc. Urban Plan.* **209**, 104046 (2021).
4. Grey, V., Livesley, S. J., Fletcher, T. D. & Szota, C. Tree pits to help mitigate runoff in dense urban areas. *J. Hydrol.* **565**, 400–410 (2018).
5. Davies, C. & Lafortezza, R. Urban green infrastructure in Europe: Is greenspace planning and policy compliant? *Land use policy* **69**, 93–101 (2017).
6. Faivre, N., Fritz, M., Freitas, T., de Boissezon, B. & Vandewoestijne, S. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environ. Res.* **159**, 509–518 (2017).
7. Meerow, S. & Newell, J. P. Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landsc. Urban Plan.* **159**, 62–75 (2017).
8. Cortinovis, C., Olsson, P., Boke-Olén, N. & Hedlund, K. Scaling up nature-based solutions for climate-change adaptation: Potential and benefits in three European cities. *Urban For. Urban Green.* **67**, (2022).
9. Furchtlehner, J., Lehner, D. & Lička, L. Sustainable Streetscapes: Design Approaches and Examples of Viennese Practice. *Sustain.* **14**, (2022).
10. Schmidt, S., Guerrero, P. & Albert, C. Advancing Sustainable Development Goals with localised nature-based solutions: Opportunity spaces in the Lahn river landscape, Germany. *J. Environ. Manage.* **309**, 114696 (2022).
11. Gómez Martín, E., Giordano, R., Pagano, A., van der Keur, P. & Máñez Costa, M. Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. *Sci. Total Environ.* **738**, 139693 (2020).
12. Bush, J. & Doyon, A. Building urban resilience with nature-based solutions: How can urban planning contribute? *Cities* **95**, 102483 (2019).
13. Brink, E. *et al.* Cascades of green: A review of ecosystem-based adaptation in urban areas. *Glob. Environ. Chang.* **36**, 111–123 (2016).
14. Oke, C. *et al.* Cities should respond to the biodiversity extinction crisis. *npj Urban Sustain.* **1**, 9–12 (2021).
15. Ives, C. D. *et al.* Cities are hotspots for threatened species. *Glob. Ecol. Biogeogr.* **25**, 117–126 (2016).
16. Spotswood, E. N. *et al.* Nature inequity and higher COVID-19 case rates in less-green neighbourhoods in the United States. *Nat. Sustain.* **4**, (2021).
17. Moglia, M. *et al.* Accelerating a green recovery of cities: Lessons from a scoping review and a proposal for mission-oriented recovery towards post-pandemic urban resilience. *Dev. Built Environ.* **7**, 100052 (2021).

18. OECD. Focus on green recovery. https://www.oecd.org/coronavirus/en/themes/green-recovery (2021).

19. European Commission. A European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (2021).

20. UNEP. Smart, Sustainable and Resilient cities: the Power of Nature-based Solutions. https://www.unep.org/resources/report/smart-sustainable-and-resilient-cities-power-nature-based-solutions (2021).

21. Croeser, T. *et al.* Diagnosing delivery capabilities on a large international nature-based solutions project. *npj Urban Sustain.* **1**, (2021).

22. McPhillips, L. E. & Matsler, A. M. Temporal evolution of green stormwater infrastructure strategies in three us cities. *Front. Built Environ.* **4**, 1–14 (2018).

23. Spahr, K. M., Bell, C. D., McCray, J. E. & Hogue, T. S. Greening up stormwater infrastructure: Measuring vegetation to establish context and promote cobenefits in a diverse set of US cities. *Urban For. Urban Green.* **48**, 126548 (2020).

24. Hamel, P. & Tan, L. Blue–Green Infrastructure for Flood and Water Quality Management in Southeast Asia: Evidence and Knowledge Gaps. *Environ. Manage.* 699–718 (2021) doi:10.1007/s00267-021-01467-w.

25. City of Melbourne. *Elizabeth Street Integrated Water Cycle Management Plan*. http://urbanwater.melbourne.vic.gov.au/industry/our-strategies/elizabeth-street-catchment-iwcm-plan/#:~:text=The Elizabeth Street Catchment Integrated,within the municipality of Melbourne. (2015).

26. City of Paris. Urban forests soon on four emblematic sites. https://www.paris.fr/pages/des-forets-urbaines-bientot-sur-quatre-sites-emblematiques-6899/ (2019).

27. City of Los Angeles. L.A.'s Green New Deal: Sustainability Plan 2019. https://plan.lamayor.org/ (2019).

28. Phelan, K., Hurley, J. & Bush, J. Land-Use Planning's Role in Urban Forest Strategies: Recent Local Government Approaches in Australia. *Urban Policy Res.* **37**, 215–226 (2019).

29. UN Habitat. *Streets as Public Spaces and Drivers of Urban Prosperity*. https://unhabitat.org/streets-as-public-spaces-and-drivers-of-urban-prosperity (2013).

30. De Gruyter, C., Zahraee, S. M. & Young, W. *Street space allocation and use in Melbourne's activity centres: Working paper*. https://apo.org.au/sites/default/files/resource-files/2021-09/apo-nid314604.pdf (2021).

31. Shoup, D. C. The trouble with minimum parking requirements. *Transp. Res. Part A Policy Pract.* **33**, 549–574 (1999).

32. Barter, P. A. A parking policy typology for clearer thinking on parking reform. **5934**, (2015).

33. Taylor, E. J. *Transport Strategy Refresh Background Paper: Parking*. https://s3.ap-southeast-2.amazonaws.com/hdp.au.prod.app.com-participate.files/2615/2963/7455/Transport_Strategy_Refresh_-_Background_paper_-_Car_Parking.pdf (2018).

34. Guo, Z. & Schloeter, L. Street Standards as Parking Policy: Rethinking the Provision of Residential Street Parking in American Suburbs. *J. Plan. Educ. Res.* **33**, 456–470 (2013).

35. Taylor, D. E. Free parking for free people: German road laws and rights as constraints on local car parking management. *Transp. Policy* **101**, 23–33 (2021).

36. Pierce, G., Willson, H. & Shoup, D. Optimizing the use of public garages: Pricing parking by demand. *Transp. Policy* **44**, 89–95 (2015).

37. Taylor, E. J. Parking policy: The politics and uneven use of residential parking space in Melbourne. *Land use policy* **91**, 103706 (2020).

38. Rosenblum, J., Hudson, A. W. & Ben-Joseph, E. Parking futures: An international review of trends and speculation. *Land use policy* **91**, 104054 (2020).

39. Clements, R. Parking: an opportunity to deliver sustainable transport. in *Handbook of Sustainable Transport* 280–288 (Edward Elgar Publishing, 2020). doi:10.4337/9781789900477.00041.

40. Barter, P. A. Off-street parking policy surprises in Asian cities. *Cities* **29**, 23–31 (2012).

41. Shao, C., Yang, H., Zhang, Y. & Ke, J. A simple reservation and allocation model of shared parking lots. *Transp. Res. Part C Emerg. Technol.* **71**, 303–312 (2016).

42. Pojani, D. *et al.* Setting the agenda for parking research in other cities. *Park. An Int. Perspect.* 245–260 (2020) doi:10.1016/B978-0-12-815265-2.00014-5.

43. Croeser, T. *et al.* Patterns of tree removal and canopy change on public and private land in the City of Melbourne. *Sustain. Cities Soc.* **56**, (2020).

44. Hurley, J. *et al. Urban Vegetation Cover Change in Melbourne*. https://cur.org.au/cms/wp-content/uploads/2019/07/urban-vegetation-cover-change.pdf (2019).

45. Norton, B. A. *et al.* Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landsc. Urban Plan.* **134**, 127–138 (2015).

46. Hartigan, M., Fitzsimons, J., Grenfell, M. & Kent, T. Developing a metropolitan-wide urban forest strategy for a large, expanding and densifying capital city: Lessons from melbourne, australia. *Land* **10**, (2021).

47. Department of Environment Land Water and Planning. *Port Phillip Bay Environmental Management Plan*. https://www.marineandcoasts.vic.gov.au/coastal-programs/port-phillip-bay (2017).

48. Roy, A. H. *et al.* Impediments and solutions to sustainable, watershed-scale urban stormwater management: Lessons from Australia and the United States. *Environmental Management* vol. 42 344–359 (2008).

49. Garrard, G. E., Williams, N. S. G., Mata, L., Thomas, J. & Bekessy, S. A. Biodiversity Sensitive Urban Design. *Conserv. Lett.* **11**, 1–10 (2018).

50. City of Melbourne. *Annual Report 2020-2021*. https://www.melbourne.vic.gov.au/SiteCollectionDocuments/annual-report-2020-21.pdf (2021).

51. City of Melbourne. *Urban Forest Strategy*. https://www.melbourne.vic.gov.au/community/greening-the-city/urban-forest/Pages/urban-forest-strategy.aspx (2014).

52. City of Melbourne. *Total Watermark*. https://www.clearwatervic.com.au/user-data/resource-files/City-of-Melbourne-Total-Watermark-Strategy.pdf (2009).

53. City of Melbourne. *Total Watermark: City as a Catchment (2014 Update)*. (2014).

54. City of Melbourne. *Nature in the City Strategy*. https://www.melbourne.vic.gov.au/community/greening-the-city/urban-nature/Pages/nature-in-the-city-strategy.aspx (2017).

55. Sprei, F., Hult, Å., Hult, C. & Roth, A. Review of the effects of developments with low parking requirements. *Eceee Summer Study Proc.* **2019-June**, 1079–1086 (2019).

56. Langemeyer, J. *et al.* Creating urban green infrastructure where it is needed – A spatial ecosystem service-based decision analysis of green roofs in Barcelona. *Sci. Total Environ.* **707**, (2019).

57. Ossola, A. *et al.* Landscape and Urban Planning Small vegetated patches greatly reduce urban surface temperature during a summer heatwave in Adelaide , Australia. *Landsc. Urban Plan.* **209**, 104046 (2021).

58. Dhakal, K. P. & Chevalier, L. R. Managing urban stormwater for urban sustainability: Barriers and policy solutions for green infrastructure application. *J. Environ. Manage.* **203**, 171–181 (2017).

59. Siqueira, F. F. *et al.* Small Landscape Elements Double Connectivity in Highly Fragmented Areas of the Brazilian Atlantic Forest. *Front. Ecol. Evol.* **9**, 1–14 (2021).

60. Mimet, A., Kerbiriou, C., Simon, L., Julien, J. F. & Raymond, R. Contribution of private gardens to habitat availability, connectivity and conservation of the common pipistrelle in Paris. *Landsc. Urban Plan.* **193**, 103671 (2020).

61. Braschler, B., Dolt, C. & Baur, B. The function of a set-aside railway bridge in connecting urban habitats for animals: A case study. *Sustain.* **12**, (2020).

62. Kirk, H., Threlfall, C. G., Soanes, K. & Parris, K. *Linking Nature in the City Part Two: Applying the Connectivity Index*. https://nespurban.edu.au/wp-content/uploads/2021/02/Linking-nature-in-the-city-Part-2.pdf (2020).

63. Ossola, A., Locke, D., Lin, B. & Minor, E. Yards increase forest connectivity in urban landscapes. *Landsc. Ecol.* **34**, 2935–2948 (2019).

64. Lindenmayer, D. Small patches make critical contributions to biodiversity conservation. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 717–719 (2019).

65. Wintle, B. A. *et al.* Global synthesis of conservation studies reveals the importance of small habitat patches for biodiversity. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 909–914 (2019).

66. Rolf, W., Peters, D., Lenz, R. & Pauleit, S. Farmland – an Elephant in the Room of Urban Green Infrastructure? Lessons learned from connectivity analysis in three German cities. *Ecol. Indic.* **94**, 151–163 (2018).

67. Marissa Matsler, A. Making ‘green’ fit in a ‘grey’ accounting system: The institutional knowledge system challenges of valuing urban nature as infrastructural assets. *Environ. Sci. Policy* **99**, 160–168 (2019).

68. Meerow, S. The politics of multifunctional green infrastructure planning in New York City. *Cities* **100**, 102621 (2020).

69. Wolf, K. L. & Robbins, A. S. T. Metro nature, environmental health, and economic value. *Environ. Health Perspect.* **123**, 390–398 (2015).

70. Bell, J. F., Wilson, J. S. & Liu, G. C. Neighborhood Greenness and 2-Year Changes in Body Mass Index of Children and Youth. *Am. J. Prev. Med.* **35**, 547–553 (2008).

71. Astell Burt, T. *et al.* More green, less lonely? A longitudinal cohort study. *ISEE Conf. Abstr.* **2021**, (2021).

72. Astell-Burt, T. & Feng, X. Association of Urban Green Space with Mental Health and General Health among Adults in Australia. *JAMA Network Open* vol. 2 (2019).

73. Astell-Burt, T., Navakatikyan, M. A. & Feng, X. Urban green space, tree canopy and 11-year risk of dementia in a cohort of 109,688 Australians. *Environment International* vol. 145 (2020).

74. Miller, S. M. & Montalto, F. A. Stakeholder perceptions of the ecosystem services provided by Green Infrastructure in New York City. *Ecosyst. Serv.* **37**, 100928 (2019).

75. Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M. & Demuzere, M. Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. *Prog. Phys. Geogr.* **37**, 2–28 (2013).

76. Janhäll, S. Review on urban vegetation and particle air pollution - Deposition and dispersion. *Atmos. Environ.* **105**, 130–137 (2015).

77. Li, L., Uyttenhove, P. & Vaneetvelde, V. Planning green infrastructure to mitigate urban surface water flooding risk – A methodology to identify priority areas applied in the city of Ghent. *Landsc. Urban Plan.* **194**, 103703 (2020).

78. Haghighatafshar, S. *et al.* Efficiency of blue-green stormwater retrofits for flood mitigation – Conclusions drawn from a case study in Malmö, Sweden. *J. Environ. Manage.* **207**, 60–69 (2018).

79. Croeser, T., Garrard, G., Sharma, R., Ossola, A. & Bekessy, S. Choosing the right nature-based solutions to meet diverse urban challenges. *Urban For. Urban Green.* **65**, 127337 (2021).

80. Hansen, R., Olafsson, A. S., van der Jagt, A. P. N., Rall, E. & Pauleit, S. Planning multifunctional green infrastructure for compact cities: What is the state of practice? *Ecol. Indic.* **96**, 99–110 (2019).

81. Roy Morgan. *Return of Corporate Workforce*. https://www.melbourne.vic.gov.au/SiteCollectionDocuments/roy-morgan-report-return-to-the-workplace.pdf (2020).

82. Bloomberg CityLab. A Modest Proposal to Eliminate 11,000 Urban Parking Spots. https://www.bloomberg.com/news/articles/2019-03-29/amsterdam-s-plan-to-eliminate-11-000-parking-spots (2019).

83. World Economic Forum. Paris halves street parking and asks residents what they want to do with the space. https://www.weforum.org/agenda/2020/12/paris-parking-spaces-greenery-cities/ (2020).

84. Urry, J. The 'System' of Automobility. *Theory, Cult. Soc.* **21**, 25–39 (2004).

85. Docherty, I., Marsden, G. & Anable, J. The governance of smart mobility. *Transp. Res. Part A Policy Pract.* **115**, 114–125 (2018).

86. Taylor, E. "Fight the towers! Or kiss your car park goodbye": How often do residents assert car parking rights in Melbourne planning appeals? *Plan. Theory \& Pract.* **15**, 328–348 (2014).

87. Burdett, R. & Rode, P. *Shaping cities in an urban age*. (Phaidon Press Inc, 2018).

88. Egerer, M., Haase, D., Frantzeskaki, N. & Andersson, E. Urban change as an untapped opportunity for climate adaptation. *npj Urban Sustain.* (2021) doi:10.1038/s42949-021-00024-y.

89. New York City Department of Environmental Protection. *NYC Green Infrastructure Annual Report*. https://www1.nyc.gov/assets/dep/downloads/pdf/water/stormwater/green-infrastructure/gi-annual-report-2020.pdf (2020).

90. Eggimann, S. The potential of implementing superblocks for multifunctional street use in cities. *Nat. Sustain.* (2022) doi:10.1038/s41893-022-00855-2.

91. City of Melbourne. Open Data Platform. https://data.melbourne.vic.gov.au/ (2022).

92. City of Melbourne. Off-street car parks with capacity and type. https://data.melbourne.vic.gov.au/Transport/Off-street-car-parks-with-capacity-and-type/krh5-hhjn (2020).

93. Ding, C. & Cao, X. How does the built environment at residential and work locations a ff ect car ownership ? An application of cross-classi fi ed multilevel model. *J. Transp. Geogr.* **75**, 37–45 (2019).

94. Scheiner, J., Faust, N., Helmer, J., Straub, M. & Holz-rau, C. What ' s that garage for ? Private parking and on-street parking in a high- density urban residential neighbourhood. *J. Transp. Geogr.* **85**, 102714 (2020).

95. Arnold, J. E., Graesch, A. P., Ochs, E. & Ragazzini, E. *Life at home in the twenty-first century: 32 families open their doors*. (ISD LLC, 2012).

96. Beck, M. J., Hensher, D. A. & Wei, E. Slowly coming out of COVID-19 restrictions in Australia: Implications for working from home and commuting trips by car and public transport. *J. Transp. Geogr.* **88**, 102846 (2020).

97. Hensher, D. A., Ho, C. Q. & Reck, D. J. Mobility as a service and private car use: Evidence from the Sydney MaaS trial. *Transp. Res. Part A Policy Pract.* **145**, 17–33 (2021).

98. ESRI. ArcGIS Network Analyst Extension. https://www.esri.com/en-us/arcgis/products/arcgis-network-analyst/overview (2022).

99. Daniels, R. & Mulley, C. Explaining walking distance to public transport: The dominance of public transport supply. *J. Transp. Land Use* **6**, 5–20 (2013).

100. Energysafe Victoria. Managing trees near powerlines. https://esv.vic.gov.au/technical-information/electrical-installations-and-infrastructure/managing-trees-near-powerlines/#:~:text=Safety tips for managing trees near powerlines&text=Before pruning tree branches or,Avoid pruning in high winds. (2022).

101. VicRoads. *Tree Policy*. https://www.vicroads.vic.gov.au/-/media/files/documents/utilities/about-vr/acts-and-regulations/v5a_tree_policy_2016_v2.ashx?la=en&hash=1EAC34DC83A5E43B32836B72ACE845CB#:~:text=straight roads-,VicRoads supports the planting and retention of trees in line, (2016).

102. Sanders, J., Grabosky, J. & Cowie, P. Establishing maximum size expectations for urban trees with regard to designed space. *Arboric. Urban For.* **39**, 68–73 (2013).

103. Grey, V., Livesley, S. J., Fletcher, T. D. & Szota, C. Establishing street trees in stormwater

control measures can double tree growth when extended waterlogging is avoided. *Landsc. Urban Plan.* **178**, 122–129 (2018).

104. Kirk, H. *et al. Linking nature in the city: A framework for improving ecological connectivity across the City of Melbourne*. https://nespurban.edu.au/wp-content/uploads/2019/03/Kirk_Ramalho_et_al_Linking_nature_in_the_city_03Jul18_lowres.pdf (2018).

105. Jaeger, J. A. G. Landscape division, splitting index, and effective mesh size: New measures of landscape fragmentation. *Landsc. Ecol.* **15**, 115–130 (2000).

106. Spanowicz, A. G. & Jaeger, J. A. G. Measuring landscape connectivity: On the importance of within-patch connectivity. *Landsc. Ecol.* **34**, 2261–2278 (2019).

107. Casalegno, S., Anderson, K., Cox, D. T. C., Hancock, S. & Gaston, K. J. Ecological connectivity in the three-dimensional urban green volume using waveform airborne lidar. *Sci. Rep.* **7**, 1–8 (2017).

108. Garrard, G. E., McCarthy, M. A., Vesk, P. A., Radford, J. Q. & Bennett, A. F. A predictive model of avian natal dispersal distance provides prior information for investigating response to landscape change. *J. Anim. Ecol.* **81**, 14–23 (2012).

109. Duncan, D. Pollination of Black-anther flax lily (Dianella revoluta) in fragmented New South Wales Mallee: A report to the Australian Flora Foundation. 12 (2003).

110. Pebesma, E. Simple Features for R: Standardized Support for Spatial Vector Data. *R J.* **10**, 439–446 (2018).

111. Imteaz, M. A., Ahsan, A., Rahman, A. & Mekanik, F. Modelling stormwater treatment systems using MUSIC: Accuracy. *Resour. Conserv. Recycl.* **71**, 15–21 (2013).

112. Melbourne Water. Raingardens. https://www.melbournewater.com.au/building-and-works/stormwater-management/options-treating-stormwater/raingardens#:~:text=Designing a raingarden,2%25 of the catchment area. (2017).

Supplementary Materials

Supplementary 1: Detailed scenario results

Scenario number	1	2	3	4	5 (Lowest Impact)	6	7	8	9	10 (Policy Preferable)	11	12 (Highest)
Scenario summary	Private10%/100m	Private10%/200m	Private20%/100m	Private 20%/200m	Commercial 30%/100m	Commercial 30%/200m	Commercial 70%/100m	Commercial 70%/200m	Combo - 10P/30C/100m	Combo - 10P/30C/200m	Combo - 20P/70C/100m	Combo - 20P/70C/200m
Scenario assumption 1: which parking type was used?	Non-commercial	Non-commercial	Non-commercial	Non-commercial	Commercial	Commercial	Commercial	Commercial	All	All	All	All
Scenario assumption 2: how much max vacancy per facility?	10	10	20	20	30	30	70	70	10/30	10/30	20/70	20/70
Scenario assumption 3: maximum walking distance a space can be moved	100	200	100	200	100	200	100	200	100	200	100	200
Total parking spaces reallocated in this scenario	4284	6571	5862	9715	3151	6133	3531	7199	5964	9526	7447	11668
Median spaces	629	1053	1008	1819	721	1301	844	1573	1156	1876	1535	2373
Dining spaces	1037	1568	1303	2135	1037	2052	1131	2251	1531	2469	1774	2667
Normal kerb spaces	2617	3948	3548	5757	1388	2774	1549	3367	3268	5171	4127	6616
Tree opportunies	3127	4759	4276	6988	2373	4399	2656	5160	4351	6857	5440	8415
% of spaces where a tree could be planted	73%	72%	73%	72%	75%	72%	75%	72%	73%	72%	73%	72%
Canopy when trees are young (ha)	5.9	9.0	8.1	13.2	4.5	8.3	5.0	9.8	8.2	13.0	10.3	15.9
Canopy when trees are maturing (ha)	8.3	12.7	11.4	18.7	6.3	11.7	7.1	13.8	11.6	18.3	14.5	22.5
Canopy when trees are mature (ha)	22.3	33.9	30.5	49.8	16.9	31.3	18.9	36.7	31.0	48.8	38.7	59.9
Total area de-paved (ha)	9.0	13.8	12.3	20.4	6.6	12.9	7.4	15.1	12.5	20.0	15.6	24.5
Total number of raingardens	1577	2266	1954	3029	987	1847	1068	2103	1971	2951	2334	3486
Total stormwater (ML/yr)	41	59	51	79	26	48	28	55	51	77	61	91
Total Suspended Solids (kg/yr)	91762	131854	113699	176251	57432	107473	62145	122369	114689	171713	135811	202843
Total Phosphorus (kg/yr)	133	192	165	256	84	156	90	178	167	250	197	295
Total Nitrogen (kg/yr)	552	793	684	1060	345	646	374	736	690	1033	817	1220
Gross Pollutants (kg/yr)	12395	17811	15358	23808	7758	14517	8394	16530	15492	23195	18345	27400
Increase in Connectivity - change in effective mesh size (ha) - New Holland Honeyeater	2.5	4.3	3.9	8.3	2.2	4.3	2.5	5.2	4.2	7.1	5.7	10.3
Increase in Connectivity - change in effective mesh size (ha) - Blue-banded bee	1.4	0.9	1.6	64.3	0.0	52.9	0.0	52.9	0.6	53.7	0.8	69.2

Supplementary 2: Full Connectivity Results

Ecological Connectivity analysis results for the New Holland Honeyeater.

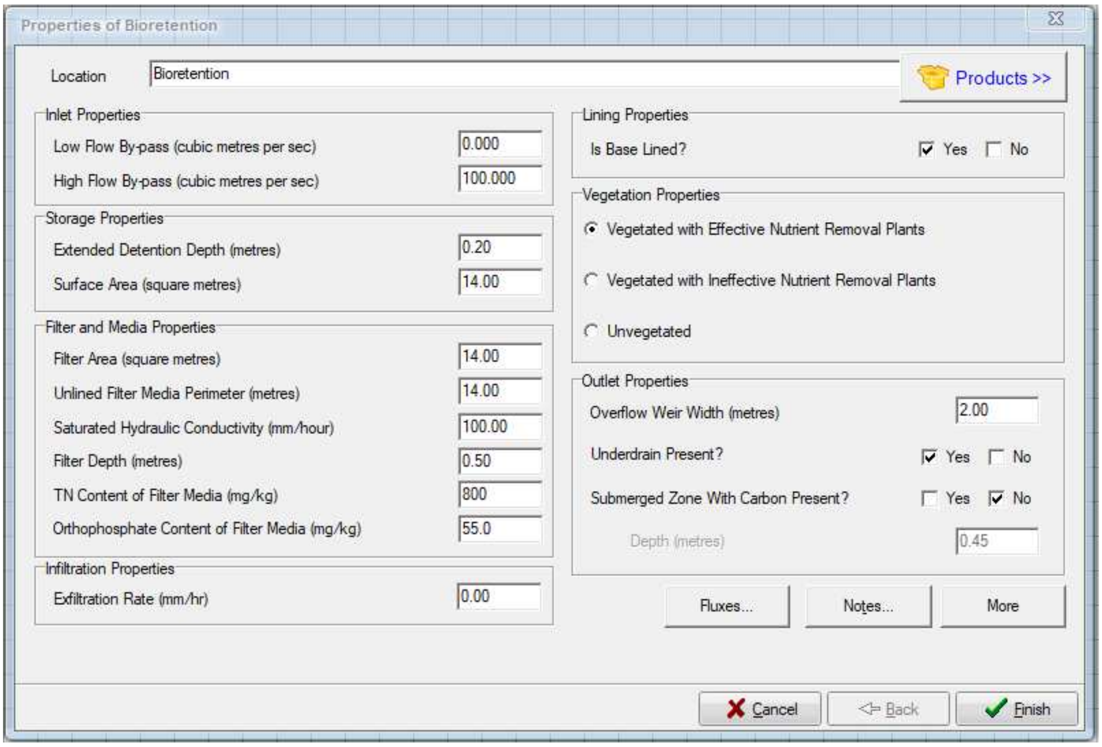
New Holland Honeyeater

Scenario	Number of spaces	Effective mesh size (Ha)	Mean connected area size (Ha)	Number of connected areas	Total habitat area (Ha)	Increase in Connectivity
One	4284	233.62	29727	90	2675415	2.46
Two	6571	235.47	24606	110	2706705	4.31
Three	5862	235.05	28104	96	2697977	3.89
Four	9715	239.49	22731	121	2750451	8.33
Five	3151	233.32	44281	60	2656883	2.16
Six	6133	235.42	33698	80	2695869	4.27
Seven	3531	233.62	41590	64	2661728	2.46
Eight	7199	236.38	31521	86	2710844	5.22
Nine	5964	235.35	28382	95	2696245	4.20
Ten	9526	238.26	24295	113	2745370	7.10
Eleven	7447	236.82	27177	100	2717690	5.66
Twelve	11668	241.45	22579	123	2777239	10.29
Existing		231.16	52434	50	2621723	

Ecological Connectivity analysis results for the Blue-banded bee.

Blue-banded bee						
Scenario	**Number of spaces**	**Effective mesh size (Ha)**	**Mean connected area size (Ha)**	**Number of connected areas**	**Total habitat area (Ha)**	**Increase in Connectivity**
One	4284	265.76	16053	256	4109506	1.42
Two	6571	265.20	17167	242	4154507	0.86
Three	5862	265.91	17324	239	4140386	1.57
Four	9715	328.66	20286	208	4219446	64.32
Five	3151	263.72	16090	254	4086867	0.00
Six	6133	317.25	19581	212	4151163	52.90
Seven	3531	263.34	16506	248	4093501	0.00
Eight	7199	317.28	19771	211	4171778	52.94
Nine	5964	264.96	17040	243	4140643	0.62
Ten	9526	318.08	19427	217	4215712	53.74
Eleven	7447	265.10	18534	225	4170222	0.76
Twelve	11668	333.53	21513	198	4259547	69.19
Existing		264.34	13157	308	4052443	

Supplementary 3 – inputs to MUSIC Stormwater modelling software



Inputs to the MUSIC stormwater modelling tool (all default other than dimensions and the base being lined which is typical of all dense urban areas of inner Melbourne).