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Finding space for nature in cities: the considerable potential of redundant car parking

Thami Croeser[1,2]✉, Georgia E. Garrard[3], Casey Visintin[1], Holly Kirk[1], Alessandro Ossola[3,4,5], Casey Furlong[2], Rebecca Clements[6], Andrew Butt[2], Elizabeth Taylor[7] and Sarah A. Bekessy[1]

Nature-based solutions (NBS) are recognised as a means to address challenges such as heatwaves, flooding and biodiversity loss. Delivering these benefits at scale will require large areas of scarce urban land to be converted into green space. Here we show an approach by which cities can make substantial progress towards their sustainability targets using NBS, by converting redundant street parking into biodiverse green space. We demonstrate that up to half of street parking in our case study municipality (The City of Melbourne) could be accommodated in garages within 200 m, freeing up large areas for greening. Our modelling projects significant benefits in terms of tree canopy over, stormwater and ecological connectivity. These would represent strong progress towards 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.

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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]. Studies have highlighted the potential for well-designed NBS interventions to reduce the impact of heatwaves[3], as well as managing stormwater in flood events[5,6] and providing vital recreational space to support the mental, physical and social wellbeing of local residents[7–11]. However, as cities have densified, private green spaces such as gardens have tended to be lost, without corresponding creation of replacement green spaces in the public realm[12,13]. This has driven a loss of urban biodiversity[13,14], increases in flood risk[15], shortages of quality open space[16] (particularly in low income neighbourhoods[17]) and a vulnerability to urban heat island effects[18].

These challenges, particularly against the backdrop of increasingly severe climate change[19], have resulted in the rapid increase of municipal NBS strategies[20–22], with bold targets such as 'plant 90,000 trees' (Los Angeles)[23], 'make 50% of urban surfaces vegetated and permeable' (Paris)[24], and '50% tree canopy cover over footpaths and bikeways' (Brisbane)[25]. For many cities, the challenge is now to keep these promises. To do this, they must retrofit NBS at scale into established urban environments, where public space is often strongly contested[26,27].

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)[28,29], to reducing the impacts of more frequent and severe heatwaves and flooding as cities face climate change[30,31]. Cities also have an important role to play in conserving biodiversity[32,33] and remedying past environmental injustices that have produced inequitable access to ecosystem services[34]. 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[35] and by powerful international institutions including the OECD, EU, and UNEP[36–38].

However, while delivery of NBS at a large scale is crucial, it remains largely unrealised[39–42]; 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)[43], heavy rains can quickly exceed the capacity of the city's engineered drainage systems. The city's flood management strategy includes a target that 65 ha of public land in this small urban catchment is de-paved or made permeable by 2030[43]. This is a significant area; nearly three times the size of the largest park in the catchment (Carlton Gardens, 25 ha).

Finding 65 ha of land in a small, dense urban catchment of 308 ha is an example of the challenges associated with the scale of land use change necessary to realise NBS benefits in cities in a way that meets strategic goals. Creating this much new green space will require cities to target existing land uses that can be systematically replaced. However, urban land is expensive, and subject to numerous competing land uses, particularly in dense residential and commercial areas[27,44]. 'Trade-offs' in these contexts can be understood as changes in how land is used, selecting between multiple competing objectives, where one objective is compromised to deliver another objective, ideally to deliver a net benefit[16,45,46]. Any urban land use change requires 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 the core urban areas of many cities, particularly in more

[1]Interdisciplinary Conservation Science Research Group, RMIT, Melbourne, VIC 3000, Australia. [2]Centre for Urban Research, RMIT, Melbourne, VIC 3000, Australia. [3]School of Ecosystem and Forest Sciences, The University of Melbourne, Melbourne, VIC 3010, Australia. [4]Department of Plant Sciences, University of California, Davis, CA 95616, USA. [5]CSIRO Land and Water, Dutton Park 4102 QLD, Australia. [6]Architecture Design and Planning, The University of Sydney, Sydney, NSW 2000, Australia. [7]Faculty of Art, Design and Architecture, University of Monash, Caulfield, VIC 31445, Australia. ✉email: thami.croeser@rmit.edu.au

developed countries[27,47]. For example, streets cover 26% of all land in the city centres of Melbourne, Cape Town and Sydney, and over 30% in London, Barcelona, Hong Kong and New York[47]. A substantial portion of this land is typically allocated to on-street parking; 21% in Melbourne[48] and 28% in Vienna[27]. An abundance of off-street (i.e., garage) parking space in built-up areas means that some of this streetscape allocation may be duplicated by vacant garage parking. 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[49,50]. 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[51].

High vacancy rates in off-street parking areas are typical in many cities[52–54], with a substantial portion of street parking used by residents with access to garages[55–57]. 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%)[51]. 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[51].

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[56,58,59]. This could be achieved through existing, proven parking management mechanisms, such as the use of centralised car parking facilities (common in Germany[53] and Japan[60,61]), or peer-to-peer parking apps which operate similarly to AirBNB or Uber[62,63]. While this produces no actual loss of parking, this would represent a compromise to the familiarity of street parking[64,65], as well as the additional financial cost of facilitating garage parking (either borne by the state as a subsidy, or by drivers in a market model)[58,66,67]. Public perception is also a consideration; while not supported by evidence, there is a widely-held view that free street parking is vital for local commerce[68]. A sense of 'folk legality' to unfettered use of public space for car parking deepens sensitivities around this topic[69–71]. A loss of driver convenience may also be a concern, though a well-designed parking management system may in fact reduce the need to cruise for street spaces[72]. While some public views of the trade-off are not rational, they are politically important. Accordingly, our study seeks to minimise the real and perceived 'cost' of the parking trade-off by ensuring only street parking very close to vacant garages is identified and modelled as new green space.

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[73,74]. The city also faces heatwaves[2,75], flooding[43] and water quality problems in the adjoining bay[76]. The city has a good suite of strategies for urban forestry[77], stormwater management[43,78] and biodiversity[79], all of which will require substantial new green areas, but also has a cohort of residents that perceive on-street parking as a right[69], even in areas where garages are available[55].

These traits make central Melbourne an ideal context to explore potential trade-offs between street parking and green space to deliver NBS at scale in highly urbanised areas. A substantial (and fairly typical) proportion of Melbourne's centre is allocated to streets[47], and was originally developed following the 'conventional' parking approach, which involves generous parking provision, both mandated in buildings and provided on streets[50]. Conventional approaches have been historically common in North America[49,80] and parts of Latin America[81], Europe[53,82] and Asia[61,83]. However, Melbourne's central city has started to move away from the conventional approach, incorporating some more active 'management' approaches since the 1980s aiming to limit and price parking[84]. More recently policies have been put in place supporting both stronger parking reform[85], and the creation of new green space[77–79]. As public discourse around parking reform to date has often narrowly focused on the perceived loss of convenience of, and free access to, street parking for drivers[64,69,71], we use an interdisciplinary set of methods to explore an alternative side of the parking space trade-off, by demonstrating how multifunctional NBS could deliver a diverse set of potential ecosystem services for broader public benefit.

In the first part of this paper, 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 represent different options for how parking might be consolidated in Melbourne. These scenarios 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 (100 m and 200 m). 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. A detailed description of these scenarios is supplied in Methods and at Supplementary Fig. 1.

Next, we model a range of sustainability benefits delivered by replacing the redundant on-street parking with biodiverse green space. For each scenario, we employed a range of modelling approaches to quantify three distinct sets of ecosystem services: (1) increases in tree canopy cover, (2) interception of stormwater and (3) improvements in ecological connectivity of the landscape for local fauna. These ecosystem services were selected because they correspond to four important strategies that the City of Melbourne is working to implement. These are, respectively, the Urban Forest Strategy[77], the Total Watermark Strategy[78,86] and the Nature in the City Strategy[79]. These strategies include ambitious targets which we use to benchmark our findings.

Our models were based on a modular green space design we prepared for this study (Fig. 1), which was informed by the principles of both Water and Biodiversity Sensitive Urban Design (WSUD & BSUD)[14,87].

We find that the modelled benefits of converting redundant parking into biodiverse green space would result in substantial progress towards a number of the strategic targets, and could meet these 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

Redundant parking

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 Fig. 1.

There is substantial opportunity to convert parking into biodiverse green space in every scenario modelled (Fig. 2A; Supplementary Fig. 1). We identified between 3146 and 11,668 redundant on-street spaces, depending on input assumptions.

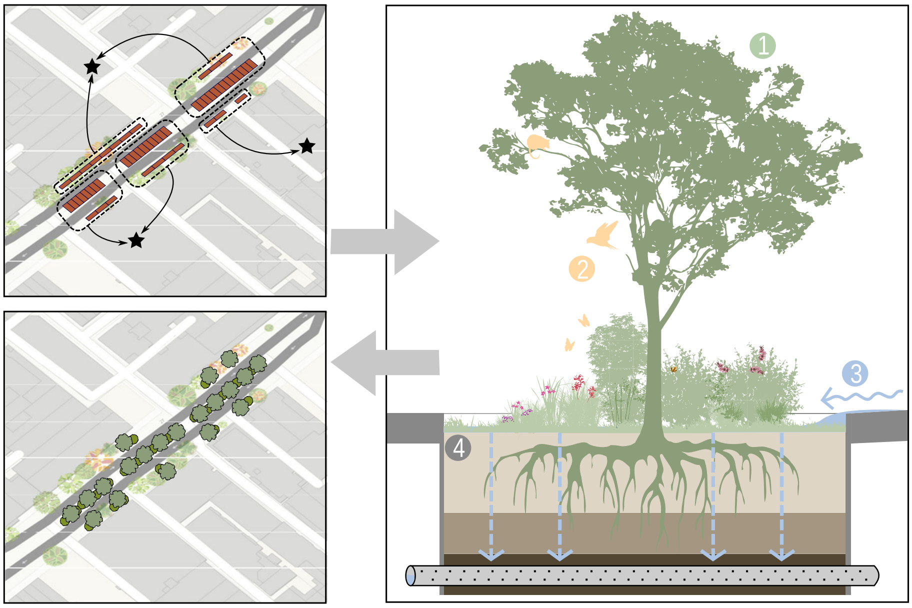

Fig. 1 Summary of the process used to estimate the benefits of replacing redundant on-street carparking with biodiverse green space. On-street car parks close to parking garages with vacancy are identified and reallocated. Then, redundant street parking is replaced by biodiverse green space, as per the 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). Lastly, the 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).

11,668 spaces represent 47% of the 24,745 total on-street spaces in the city, which cover approximately 50 ha.

Tree canopy cover

We estimated an increase of between 31 and 59 ha of tree canopy cover expansion generated by trees at maturity, with 11 to 22 ha provided in intermediate years as trees mature (Fig. 2B). This is a considerable contribution to the city's 254 ha of existing public-realm tree canopy[88], 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 (Fig. 2C).

De-paving

The large amounts of redundant parking identified in the spatial scenarios represent an opportunity to remove a substantial area of asphalt (Fig. 2D). In total, 6.6–24.5 ha 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 7.7 ha 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 (Fig. 2E), as well as hundreds of kilograms of nutrient pollutants phosphorus and nitrogen (Fig. 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 (Fig. 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 7.7 ha of de-paving delivered in the flood-prone Elizabeth Street Catchment at the heart of the municipality represents between 4% and 12% of the 65 ha target for de-paving in this area, highlighting the need for complementary measures such as rooftop greening, permeable sidewalks and other de-paving solutions.

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 ecosystem service improvements in highly urbanised areas with historic use of minimum parking requirements.

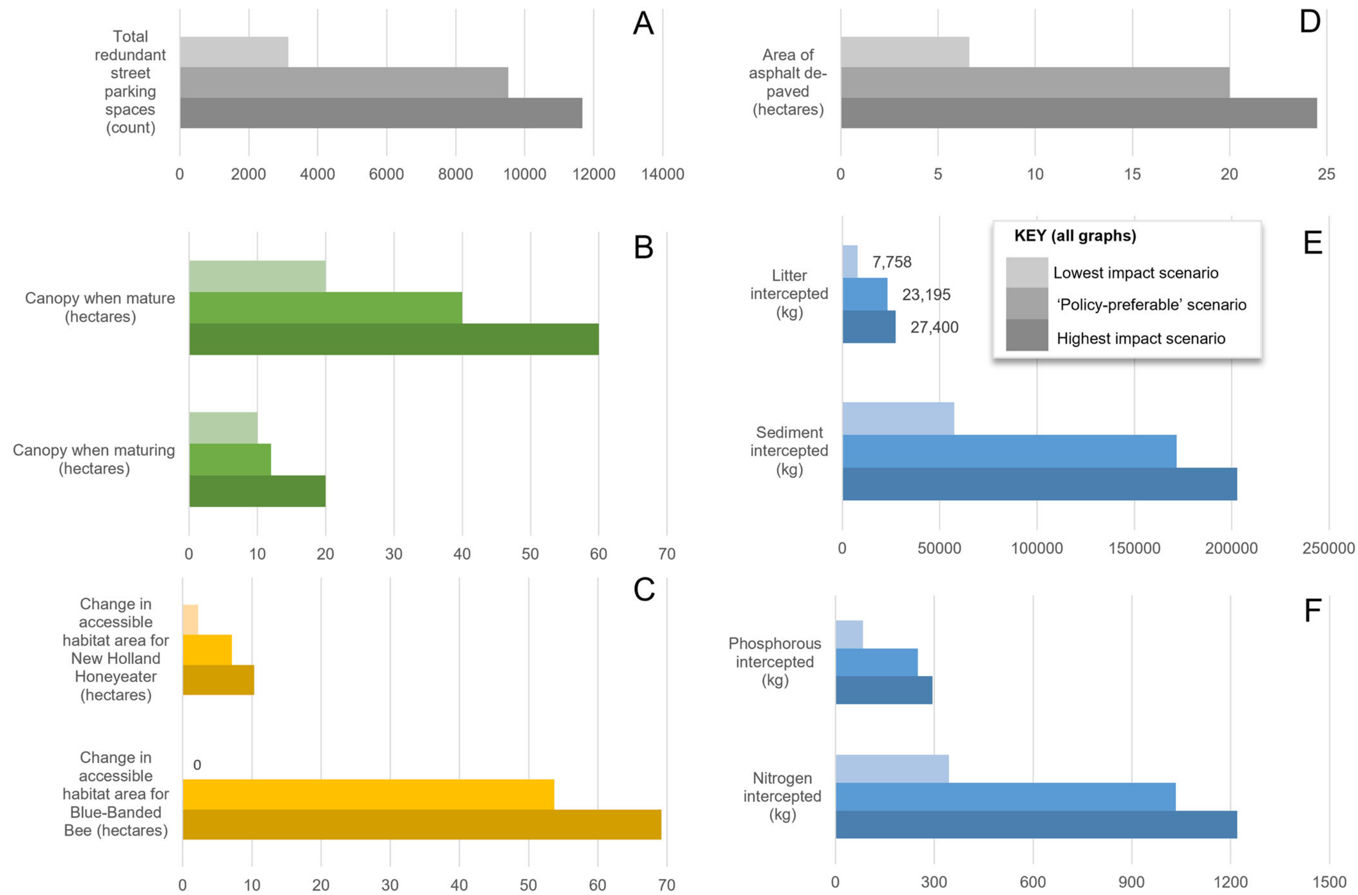

Fig. 2 Summary of results. Highest and lowest results are included in Fig. 2A–F to show the range identified in our twelve scenarios. We include a full table of results at Supplementary Fig. 1. The lowest impact scenario used commercial parking only, assumed low vacancy (up to 30%), and a 100 m maximum 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 200 m 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 200 m maximum distance; this is included to represent a beneficial and attainable result.

This set of findings is of international relevance. In the core areas of many cities, streetscapes form between a quarter and a third of all land cover[47], and street parking in turn constitutes around a quarter of that space[27]. 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 (both in developing and developed nations[53,81–83]) have created extensive areas of garage space as they developed[49,55,89]. This effectively duplicates street parking. While the extent of the spatial opportunity we observed in Melbourne cannot be assumed to be the same for every city, our findings highlight a valuable avenue of enquiry. 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 for planners seeking to retrofit dense urban areas. This is significant both because space for NBS is especially difficult to find in these areas[27], and because the inner city tends to be particularly susceptible to heat island effects[2] and flooding[90] 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[77]. This is valuable from a heat mitigation perspective, as even small tree canopy patches have been demonstrated to significantly decrease extreme heat[91]. 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[92]. 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[93–100].

Our integrated, interdisciplinary 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[101,102]. 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[103] and is associated with lower rates of obesity[104]. Access to green space can reduce loneliness[8], and tree canopy is associated with a range of mental health benefits[7] and may reduce dementia risk[9]. Intangible NBS benefits like aesthetic appeal and socio-cultural values have also been quantified and found important for residents[105]. We also do not directly quantify cooling[3,18], air quality improvements[106] or reductions in localised flooding[107,108], nor is job creation through construction and maintenance estimated. The value of urban renewal and local

Fig. 3 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 200 m instead of 100 m. Supplementary Tables 1, 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.

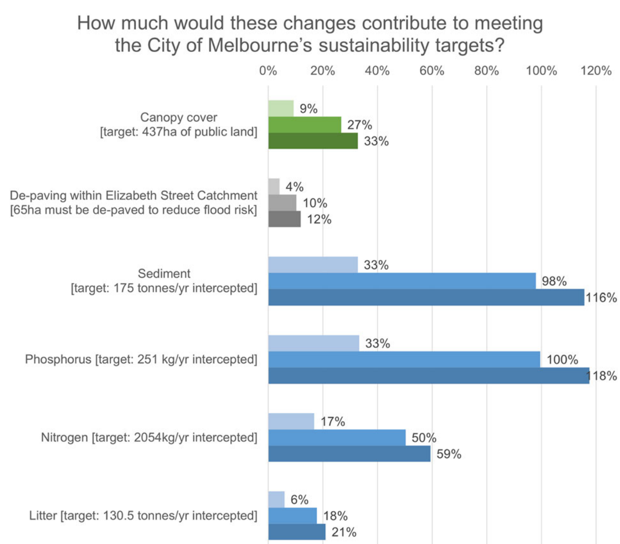

Fig. 4 Summary of policy impacts of parking replacement, showing the impact of each scenario as a proportion of the total change required to deliver the relevant sustainability target. The canopy target is from the City of Melbourne Urban Forest Strategy[77]. The de-paving target is from the Elizabeth Street Catchment Strategy, which covers a highly urbanised, flood-prone watershed within the central city[43]. Sediment, Litter and Phosphorus targets are articulated in the city's 2009 Total Watermark strategy[86]. The Nitrogen target is from a 2014 iteration of the same strategy[78]. 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[79]. Our modelling indicates that this is possible under most scenarios (Fig. 2).

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[102,109,110].

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[27], and in response to changing working patterns resulting from pandemic management[111]. For example, Amsterdam is removing 1500 spaces annually[112], and Paris has pledged to remove half of its 140,000 street spaces[113]. 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 200 m 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[114,115]. 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[53,55,69]. 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[116]. 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. Moving street parking into large private office and residential garages will require retrofits to enable safe public access to support a range of users from casual to long-term. This may either require public subsidy to keep prices low or be a transparent move to a more costly for-profit model of parking allocation, much like commercial carparks[58,66,67]. 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[117], 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 600 ha between 2010 and 2020, at a cost of USD$1bn[118]. 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[119]. 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.

METHODS

Case study

The City of Melbourne municipal area (37.7 km^2) is an inner-city municipality within a larger metropolitan area (9992 km^2) 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[77–79], as well as having appropriate open data[120] 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[69].

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 (100–200 m) of these vacant parking spaces, and flag them as potentially redundant parking spaces (i.e., candidates for replacement with biodiverse green space).

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[120]. 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'[121].

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[51]. This partly reflects the lower need for car ownership in dense areas with good access to jobs, public transport and services[122]. 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[55]; in Dortmund, Germany, that rate was 12–22%[123]. Studies in Los Angeles and Sacramento, USA, measured 75% and 76% of residential garages were used as storage respectively[57,124].

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[111]. This evidence is consistent with the finding that many workers found working from home positive[125] and that billions of dollars of lost time was saved by avoided commutes[126]; 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[51], but is more difficult to offer to other users). A figure of only 10–20% was adopted despite the known 26–41% vacancy rate, to account for likely difficulties in retrofitting private parking garages; not every office or apartment block will necessarily want to absorb street parking, even with appropriate compensation or incentives. 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

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%

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.

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.

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[127]. 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 parking space would be considered a candidate to be allocated into an off-street carpark. To be conservative, we ran the analysis for distances of 100 m and 200 m, 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 (400 m)[128]. 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 200 m of home[65]. 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 100 m and 200 m.

This analysis assumed that every on-street parking space must be replaced. This is a conservative assumption; for the city's 4414 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%[51]. 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

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).

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).

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 (Fig. 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 (Fig. 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 (Fig. 5).

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.
Stormwater interception	Where possible, the design includes a raingarden, sunken slightly below street level to facilitate flow. Raingardens are specialised garden beds designed to intercept and filter stormwater[129]. Substrates are tailored to this function, as are inlets, drainage and overflows. Raingardens were assumed to be lined, as is currently the standard for implantation of Water Sensitive Urban Design (WSUD) features in streetscape substrates otherwise not designed for stormwater infiltration.
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[14].

Table 3. Constraints guiding the design.

Constraint identified	Response
Overhead cables	As per EnergySafe Victoria advice[130]: - 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[131]: - Include subsurface reinforced sleeves for crash barriers (noted as a remedy on roads above 60 km/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.

A number of these are broad remedies that would require site-by-site problem-solving by an appropriately skilled team to deliver.

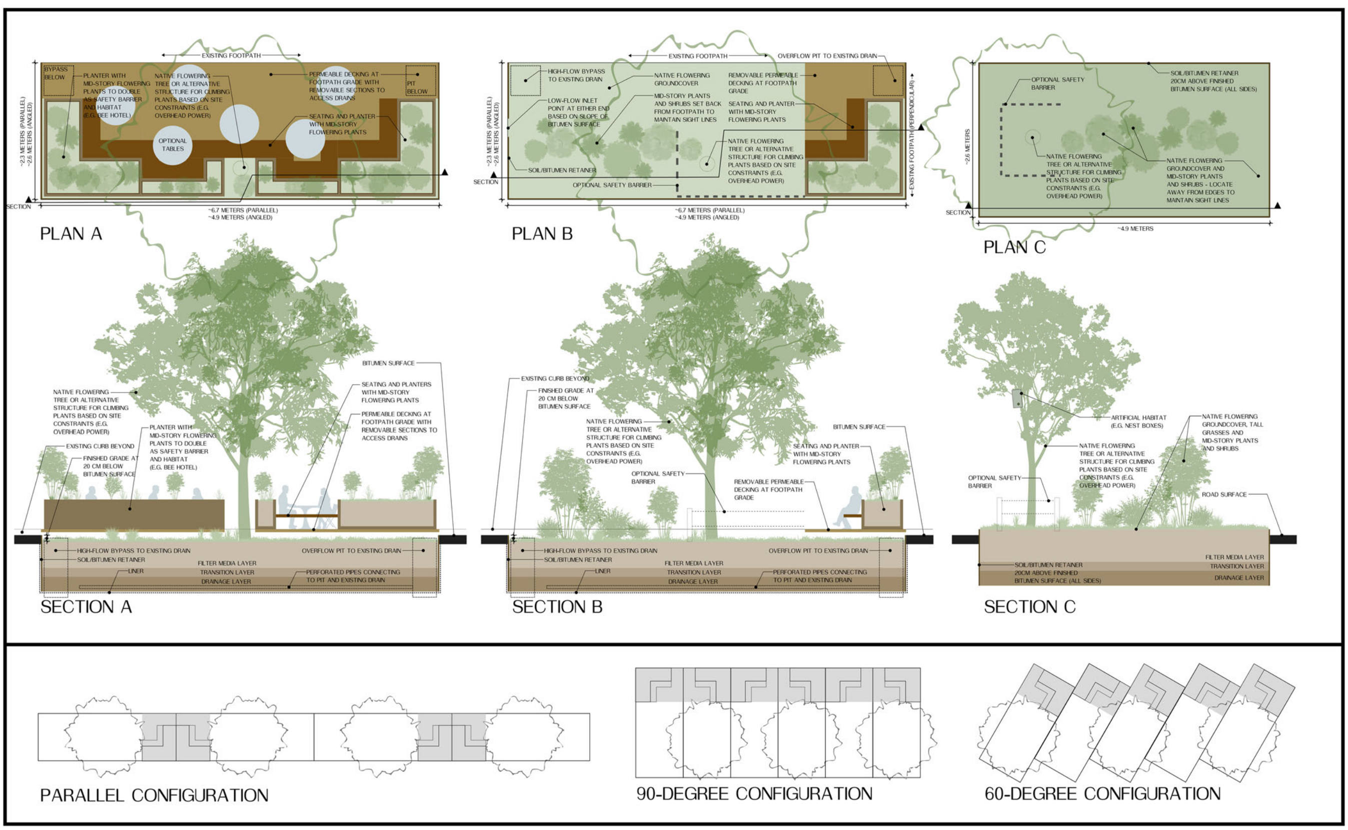

Fig. 5 Schematic designs modelled in this study. These are tailored to replace different kinds of redundant parking. The design on the left replaces kerbside parking in commercial areas, the centre design replaces kerbside parking in all other locations, and the design on the right applies to median 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.

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

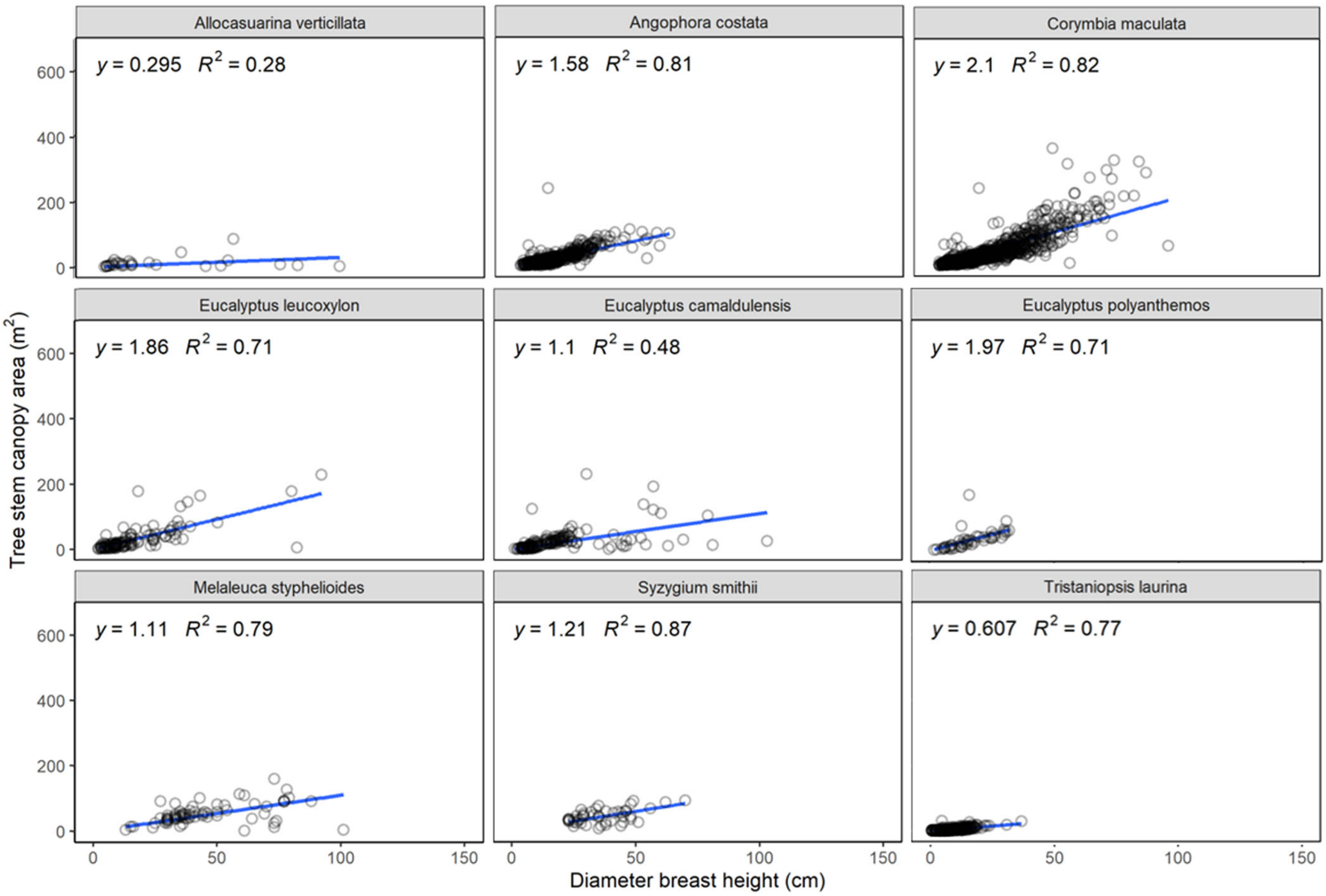

Fig. 6 Tree canopy growth projection using linear regression. Relationships between tree DBH and canopy of mature trees in the City of Melbourne, plotted for each of the nine species used in this study.

raingardens; only rain that falls directly on greened median sites infiltrates. Trees and understorey vegetation are retained.

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 Fig. 5. Our modelling considers stormwater interception, canopy cover and habitat connectivity.

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)[120]. 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 (9065 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 (Fig. 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[129]. 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.

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 (Fig. 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[130], which is an important element of our design.

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.[96,131]. 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[132,133]. We used a functional connectivity approach[134] 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[120]. 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[135]. 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[136]. The movement ability estimates for both target species are conservative as the connectivity model is sensitive to changes in the distance threshold used[96].

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[132,133] 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 Tables 1, 2).

All spatial layers were cleaned, combined and analysed in R 4.0.3 (R Core Team, 2020) using the `sf` spatial analysis package[137].

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[138]. 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 Fig. 2.

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)[139]. As our area is generally 100% impervious asphalt, we have opted for 3.5% of the catchment area (14 m^2/395 m^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).

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

DATA AVAILABILITY

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

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AUTHOR CONTRIBUTIONS

T.C.—Writing, Conception of the study, Figures, Location-allocation analysis S.B., G.G., R.C., A.B., L.T.—Review, Conceptual development C.F.—Stormwater analysis H.K.—Ecological connectivity analysis, Review, Figures A.O.—Canopy analysis, Review, Figures C.V.—Design, Review, Figures.

COMPETING INTERESTS

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Thami Croeser.

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