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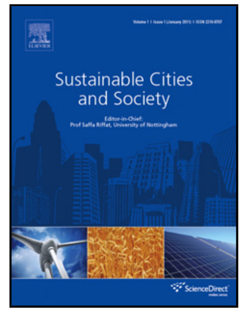

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Patterns of tree removal and canopy change on public and private land in the City of Melbourne

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Highlights

- Major developments in the City of Melbourne, Australia result in an elevated rate of loss of street trees
- Canopy loss associated with major development is significant but forms only a fraction of total losses
- Losses of young trees are high
- Canopy loss to mature tree succession and removal in parks is substantial

Abstract

Many cities face a struggle to reconcile ambitious tree canopy cover targets with urban development pressures. Canopy cover in The City of Melbourne, Australia, which has a target of 40% canopy cover on public land by 2040, was analysed together with individual tree removal data, with particular focus on how many street trees were removed near major development sites between 2008 and 2017.

We observed major gains and losses of canopy, resulting in small net changes.
Our analyses showed a net gain in tree canopy cover in public streets and a net loss of canopy cover in public parks and private properties. The most frequently removed trees in both public parks and streets were small (<15 cm stem diameter). In contrast, more large, exotic trees were removed from public parks than public streetscapes. These large park trees represented a small proportion of total tree removals, but had larger stem basal areas and therefore large canopies. From 2008 to 2017, almost 2000 street trees were removed within 10m of major development sites, equivalent to almost 20% of all street trees removed in that time period, but this constituted only 8% of streetscape tree canopy cover losses.

These findings suggest that in The City of Melbourne, mature tree succession and removal in parks has the greatest potential to hinder the achievement of canopy cover targets. Canopy cover gains could be maximised through improvements in the establishment and survival of replacement trees in both parks and streetscapes. The protection of the existing urban forest, through policy and practice, will also be critical for the retention and enhancement of tree canopy cover.

Keywords: urban development; urban forest; mortality; open data; greenspace; tree removal; UTC; canopy loss; green infrastructure; nature-based solutions

Introduction

Many cities around the world have embraced the notion of protecting and enhancing urban forests, recognising the myriad benefits of urban trees. Trees in cities can improve urban environmental conditions (Livesley et al., 2016) and help mitigate the impacts of climate change (Brink et al., 2016) by reducing ambient temperatures (Zölch et al., 2016; Kong et al., 2017), reducing air pollution (Parsa et al., 2019; Escobedo and Nowak, 2009), and helping to manage stormwater runoff (Kirnbauer et al., 2013; Grey et al. 2018). City trees are also valued greatly by city dwellers for a variety of reasons, including aesthetics (Pearce et al., 2015) and provision of habitat to wildlife (Stagoll et al., 2012; Threlfall et al., 2017). These are accompanied by a less-acknowledged suite of disservices that are perceived by urban residents, such as blocked views, allergies, fire risk, and litter (Conway & Yip, 2016).

In many cities, plans and programs to plant new trees and protect existing urban trees have been adopted (e.g., Los Angeles, see McPherson et al., 2011; Greener Spaces Australia, 2019). Tree canopy targets, being the total land area covered by tree canopy, often form the central metric for many of these strategies (Ordóñez & Duinker, 2013). Some cities also or alternatively use total number of trees planted to frame their strategies, for example a target of planting of 3,000 trees every year (City of Melbourne, 2012). Tree canopy cover datasets offer the advantage of being a closer proxy to calculate ecosystem service provision, such as shade provision and rainfall interception, as just a few large canopy trees can offer the equivalent service of hundreds of small trees (Nowak et al., 2014).

While useful as a broad strategic indicator, measures of overall percentage change in urban tree canopy within a city offer limited insight as to how much of that change is due to tree removal in response to private development as compared to tree removal as part of long-term street and park renewal and replacement programs (Kaspar et al., 2017; Hilbert et al., 2019). Total canopy change over time within a given area is the balance of canopy increase processes and canopy loss processes within that area (Nowak & Greenfield, 2012; Merry et al., 2014; Chuang et al., 2017). Canopy increase can be the result of tree planting and growth of new plantings as well as the growth of existing trees. Canopy loss can reflect loss of tree canopy due to pruning, limb drop or ill health, or the felling and removal of trees from the landscape. Tree removals themselves may be the result of many factors including failures of young trees to establish, vandalism, management of risk, impact of development, such as construction, or planned replacement of over-mature trees (Lavy & Hagelman, 2017). Better understanding the extent and drivers of change in tree canopy can assist urban tree managers to determine suitable strategic interventions (operational or policy/regulation) and progress towards stated tree canopy targets.

Each of the drivers of urban tree canopy change are significant from a management perspective, yet conventional approaches to measuring this change in urban forests rarely identify the relative importance of these different mechanisms. Applications of random point-based sampling of aerial images (Merry et al. 2014; Kaspar et al., 2017) or remotely-sensed LiDAR and multi-spectral data (Parmehr et al., 2016; Ossola & Hopton, 2018), have not been able to offer precise insights into the drivers of observed change in canopy cover. Studies of urban tree mortality rates using city-wide tree inventories have provided insights into overall rates of tree loss (e.g. Nowak et al., 2004), but these inventories have rarely been studied with additional development data (e.g., house infilling, new development constructions) to understand the drivers of this loss and gain of trees (e.g., Guo et al, 2018). Fine-scale studies based on intensive monitoring data have been able to demonstrate that tree mortality patterns are strongly associated with the characteristics of the built landscape and growing environment, such as distance to curb, home ownership, resident income level, residential density, education level, and number of years in residence (Roman & Scatena, 2011; Ko et al., 2015; Elmes et al., 2018; Hilbert et al., 2019). A handful of studies have identified residential housing development of urban areas as a major driver of tree and canopy loss, particularly in suburban residential infill contexts (Hostetler et al., 2013; Lavy and Hagelman, 2017; Morgenroth et al, 2017; Guo et al, 2018). We note that private-realm construction can also serve as a driver of public-realm street tree mortality and canopy loss through processes such as soil compaction, root severance during underground infrastructure works and removals for access both above and below-ground (Koeser et al., 2013).

To better understand different drivers of tree canopy loss, this study investigates patterns of individual tree removal and canopy change in Melbourne's central city, with a specific focus on the role of major developments on private land within the inner-city landscape. In this study we asked:

1. What are the patterns of change (gain, loss and net) in canopy in different land-use types?
2. What are the numbers and species of trees removed from different urban land-uses (e.g., streets, parks) that contribute to measured losses of canopy?
3. What is the diameter at breast height (DBH) of the individual trees being removed and which species (e.g. exotic, native or indigenous) are being removed more frequently?

4. To what extent are public street tree removals influenced by major private development in the inner city, and what proportion of canopy loss does this represent?

To investigate these questions, we make use of municipal data (2008 - 2017) based on field inventories of urban trees that include information on tree removal and replacement, canopy cover maps for 2008 and 2016, and a database on the location and characteristics of major development activities in the City of Melbourne, Australia. A development qualifies as 'major' when it exceeds any of a number of set thresholds, such as 10 dwellings, or 500 m^2 of office space (City of Melbourne, 2018a).

Methods

Site Description

The City of Melbourne is an inner-city local government area of Metropolitan Melbourne. The 37.7km^2 municipality has a resident population of 160,000 people, a weekday working population of 1 million, whereas metropolitan Melbourne (9990km^2) has a population of 4.9 million (ABS, 2018). The climate of this region is temperate (i.e., oceanic climate, Köppen classification) with a mean annual temperature of 16°C, with intermittent rainfall totalling an average of 603 mm annually (BOM, 2018). The urban forest within The City of Melbourne consists of approximately 70,000 trees (CoM, 2012). Melbourne and its urban forest have experienced significant droughts and heatwaves in recent decades, which have impacted the tree population in various ways, notably in shortening the life expectancy of many mature trees (Kirkpatrick et al., 2011; May et al., 2013). The impact of drought is most notable in the dominant exotic tree species, many of which are now approaching the end of their useful life expectancy (City of Melbourne, 2012), with many programmed for removal and replacement in coming years. The City of Melbourne urban forest has the largest stand of English elms (*Ulmus procera*) in the world, as Dutch elm disease (*Ophiostoma spp*.) has not reached Australia. English elms, London planes (*Platanus × acerifolia*) and spotted gum (*Corymbia maculata*) are some of the most common trees in the city, representing 24%, 11%, and 8% of the street tree population, respectively (CoM, 2012). In response to a small number of species dominating the urban forest, there is a long-term plan for urban forest renewal which enables an opportunity for diversification of tree species, family and genera that will make up the future urban forest. This involved the development and acceptance of a well-resourced urban forestry strategy (CoM 2012; Gulsrud et al 2018) which includes a target to double tree canopy from 21% to 40% in publicly managed spaces by 2040 (CoM, 2012).

Data Sources

Two datasets form the bulk of this analysis. Firstly, point data on standing trees and tree removals on public land were collected for multiple years through field-based urban tree inventories by the City of Melbourne tree maintenance contractor. Secondly, canopy polygon layers for 2008 and 2016 were also used, covering the entire municipality including private land.

Point data for standing trees has been collected on an ongoing basis through the work of City of Melbourne arborists and contractors, with data on location and species either added to the dataset at time of planting or in the original surveys that generated the dataset. DBH data for a subset of these trees was generated in a single 2011 survey carried out by a contractor. The 2011 City of Melbourne tree inventory included stem diameter at 1.4 m (diameter at breast height, or DBH) for a significant proportion of street and park trees (55% in streetscapes and 28% in parks). Tree removals are logged by contractors as part of the removal process but the reason for removal was not recorded. Canopy polygons for 2008 are a hybrid of aerial and LiDAR data, and are rated to be accurate for that time period, though details of resolution could not be acquired for this dataset. The 2016 canopy dataset is derived from LiDAR with a 7.5cm ground sample distance. Protocols for classification of tree canopy in these datasets are unknown; the data was inspected using aerial images and misclassification of small woody vegetation (e.g. shrubs) was not observed.

To support the analysis, a layer showing major development was also used. The City of Melbourne monitors major development activities on private land by collecting data including the property parcel polygon and the completion date, known as the Development Activity Monitor (DAM) (Table 1). A total of 477 major developments were completed between 2008 and 2017 (inclusive).

The spatial layers of canopy cover, tree inventories of standing trees and removed trees, and the DAM were analysed using ArcMap v.10.4.1 and R (v. 3.4.4) software (Table 1). Other spatial layer data required for analysis were the location of streets, property boundaries and parks, sourced in July 2017.

Quantifying canopy gain and loss

The gain in tree canopy from 2008 to 2016 was measured by removing the 2008 canopy extent from the 2016 canopy. The loss of tree canopy was measured by removing the 2016 canopy extent from the 2008 canopy. These shapefiles of tree canopy gain and loss were overlain above a City of Melbourne land-use polygon shapefile to code areas of change as either ‘park’, ‘street’, and ‘property’ (i.e. land parcels, including public and private land). Estimates of overall canopy cover gain, loss, and net canopy change over this 8-year period were reported for the City of Melbourne overall and for each land-use type. Canopy loss/gain calculations focused on the land use over which the canopy fell – so in some rare cases ‘street’ canopy change is in fact a change to canopy from trees on private property where a portion of their canopy overhanging public streets.

Given the limited metadata for the LiDAR-derived canopy layers, changes in canopy cover were visually inspected using aerial imagery. Large gains and losses were detected accurately but, in some instances, smaller changes in canopy may indicate growth/losses of cover on individual trees, or may be sampling errors, as demonstrated in Figure 1. Although misclassified shrubs were not observed in our review of the data, these also would present as small canopy changes if they are present. Accordingly, we calculated that the total area of these ambiguous small canopy changes (<10sqm), and found that they formed 9% of the observed area of canopy lost, and 11% of observed gains. This suggests that estimates of canopy gain and loss have an error of up to 10% (i.e. a loss of 10ha could be as high as 11ha or as low as 9ha).

Quantifying spatial patterns of public tree removal

To classify individual tree removals according to land-use, the point shapefile of individual tree removals was intersected with a City of Melbourne land-use polygon shapefile. Approximately 93% of all tree removals from public land were from ‘park’ and ‘street’ areas, with the remaining 7% from public ‘property’ land-uses such as public plazas.

To ascertain the size and species of trees which were removed, we took a sub-sample of removals from the City of Melbourne tree removal dataset to isolate only removals made between 2011 and 2017. This was linked to the City of Melbourne tree inventory data captured in 2011. This enabled the creation of a smaller dataset of individual tree removals with known DBH (as captured in 2011). Tree species names were used to code the origin as: Native (Australian), Indigenous (local to the IBRA bioregion, see DELWP, 2018) or Exotic (not Australian). To study the size of trees being removed from different land-uses and for different tree species, trees were categorised into 5 cm stem DBH intervals, ranging from 0-5 cm to 95-100 cm and >100 cm.

For street and park trees removed between 2008 and 2010, and trees removed between 2011 and 2017 without a DBH measurement, a geometric mean stem basal area for that species was calculated. The geometric instead of the arithmetic mean was used given that the DBH data was mostly skewed towards trees with small DBH. As it is customary, the geometric mean is a way to more properly represent non-normally distributed datasets (see Hair et al., 2014). This was only calculated for those tree species with >20 instances of tree removal with a recorded DBH, from which a meaningful mean could be determined. We estimated total stem basal area of indigenous, native and exotic tree species removed from parks and streets in the City of Melbourne. Basal area was calculated from DBH using $\pi(DBH/2)^2$.

To count the incidence of repeated tree removals at single planting sites in streetscapes (because of death, vandalism or theft) a 1 m radius buffer was created around all individual tree removal points within City of Melbourne streets between 2008 and 2017.We identified any 1 m radius polygons with multiple (repeat) tree removals and the number of tree removals at these sites. From this we determined what proportion of tree loss occurs from repeated tree removal in single locations, as distinct from isolated, one-off tree removals.

Quantifying public tree removal near major private developments

We combined the 2008 to 2017 tree removal dataset with the DAM dataset for 2008 to 2017 (477 DAM projects in this time period). To explore the relationship between tree removal and distance from a development project we created buffer polygons of 10 m, 50 m and 100 m widths around each completed major development property. These values were used for the following reasons: 1) 10 m was used since most sidewalks in the City of Melbourne are between 2 and 3 m wide, so 10 m represents the approximate width of 1.5 sidewalks, which is the approximate width of a street; 2) 50 m in each direction approximately represents the length of a street in the City of Melbourne; and 3) 100 m approximately represent the size, in terms of its radius, of a city block (City of Melbourne, 2018b).

Annually there was an average of 47.7 major developments completed between 2008 and 2017, with a minimum of 31 (2008) and a maximum of 82 (2012) completed in any given year. Using the private property spatial layer, we randomly selected 230 ‘control’ properties that had not been developed, and allocated these into five groups of 46 control, or undeveloped, properties, reflecting the average count of development sites annually. Again, each property was allocated a 10 m, 50 m and 100 m wide buffer polygon. The number of trees removed from these 10 m, 50 m and 100 m buffer polygons in the year of completion and two years previous were counted by intersecting the buffer polygons with the tree removal dataset (Figure 2). Counts for two years were taken because this reflects the default requirement of completing a development within two years of commencement, under section 68 of the Victorian *Planning and Environment Act 1987* (see AustLII, 2018);

The proportion of trees removed in 10 m, 50 m, and 100 m buffers around DAM properties were compared to those removed around control (undeveloped) properties using a chi-square test (Pearson's χ^2). The rate of DAM tree removal was only significantly greater than that in the control within 10 m radius of a major development (Supplementary Figure 1), so a 10 m buffer around major developments was used in all subsequent tree removal analysis.

To measure when street trees were removed relative to the completion of major private developments (i.e., during or after construction), a 10 m wide buffer was allocated to each major development from 2008 to 2017 and the annual number of trees removed or trees living quantified and coded by the year of removal relative to the year of development completion (-6 to +6 years). For example, a tree removed in 2016 within a 10 m radius of a major development that was completed in 2013 would be coded "+3", which indicates removal three years after completion. Similarly, a tree that was removed a year before (2012) that same development would be coded "-1". Living or standing trees in that 10 m radius buffer were coded in the same way relative to the year of completion (from -6 to +6 years). The number of trees removed was quantified as a ratio or percentage relative to the standing living trees (i.e., the current tree population in that space for that year) in the 10 m wide buffer polygons each year. For the 230 control properties, we similarly coded tree removals and trees living within a 10 m buffer but only for the previous six years, in other words from 0 to -6 years relative to a theoretical completion in 2017. Thus, we could effectively compare the proportion of removals on non-development sites to the proportion of living trees, in a similar way to the approach used for major development sites.

We tested these data for statistical differences, focusing on the difference between the mean percentages of removed trees per maximum number of living trees in a 10 m radius from a development site. Multivariate regressions were used to explore relationships between tree removals (ratio of removed trees to living trees) and developed site characteristics (site area, site perimeter) using R (v. 3.4.4) software. These regression models showed no statistically significant relationships at the 95% level (all results p-value >0.05) (data not presented).

Quantifying loss of tree canopy associated with major private developments

The proportion of overall loss of canopy along streets between 2008 and 2016 that was within 10 m of a major development was estimated by intersecting the DAM spatial layer with 10 m buffers with the canopy gain and loss spatial layers. Similarly, the proportion of private tree canopy loss between 2008 and 2016 that occurred within the 477 development DAM properties themselves was estimated using the same approach.

Results

Individual tree removals

A total of 19,739 Council trees were removed from the CoM between 2008 to 2017, with 10,192 (52%) removed from streets, 8,192 (41%) from parks and the remainder (7%) from other property parcels in public ownership. In 2018 the live population of street trees was 29,197 and 40,431 in parks. 33% of all removals (n = 3342) were repeat removals, with total repeat removals from the same plot ranging from 2 to 10 (Supplementary Table 1). Young trees (0-15cm DBH) formed the majority of removals in streets, and were also removed in large numbers in parks (Figure 4). Removals of exotic trees in parks were significant from a basal area perspective, i.e. the count of removals was relatively low but these were large, old trees, likely to have significant canopy areas. Notably, just a few species formed the majority of basal area lost in both parks and streets (Table 2 and 3).

Canopy cover gain, loss and net change

In 2008, there was 181 ha of tree canopy in parks, 130 in streetscapes and 128 ha in property parcels (public and private). In parks, canopy cover was 31.1%, in streetscapes it was 15%, and within property parcels it was 5.6% (Figure 3). Between 2008 and 2016 there was an approximate net gain of 3.9 ha in public streets and an approximate net loss of 5.3 ha and 4.5 ha in public parks and private property, respectively. In all three land-use types (street, park and property) the small net change was the balance of far greater gross gains and gross losses (Figure 3).

Street tree removals near major developments

In total, 1,965 trees were removed within the 10 m buffers surrounding development sites between 2008 and 2017, equivalent to 19.2% of all street tree removals in the City of Melbourne during that period. The area covered by these 10 m wide buffers surrounding of DAM site (2008 to 2017) totals 61 ha, which is only 7.2% of the total 850 ha of streets (including footpaths) in the city. The rate of tree removal in the 10 m buffers surrounding DAM sites is nearly three-fold greater than the removal rate in overall city streetscapes and six-fold greater than the rate of removal for the City of Melbourne as a whole for the study period (i.e., 32.2 trees removed ha^{-1} vs. 5.5 trees removed ha^{-1}).

The ratio of trees removed as a proportion of living trees within a 10 m wide buffer was greater for DAM sites than for control (undeveloped) sites (Figure 5). However, these differences were only apparent at certain stages before, during and after the development activity. Four years before a development was completed, the average annual rate of tree removal within 10m of the site was between 0.2 and 0.3 trees. The equivalent of this in terms of percentage of trees removed per living trees was about 5%. The controls showed slightly lower values (Figure 5). While this may suggest a higher baseline rate of removal for development sites than for control sites, the rates between development and control sites (i.e., 0.2-0.3 average trees removed; 5% average trees removed per living trees) are essentially similar given the significant standard errors observed. In contrast to the control sites, in the three years prior to completing a major private development (-3 to 0 years) the rate of tree removal increased greatly so that between 11% and 17% of living trees were removed within a 10 m wide buffer of that development (Figure 5). In the four to five years after completing a major private development (+1 to +5 years) the number of living trees within the 10 m wide buffer increased, and the rate of tree removals in that buffer remained higher (up to 0.7 trees per year) than the long-term average removal ratio (0.2 – 0.3 trees per year) (Figure 5).

Major developments and tree canopy cover change

Comparisons of 2008-2016 canopy gain and loss within the DAM sites to losses in all property parcels in the municipality indicated the central role these major developments make to the measured net canopy loss of the wider private realm. Of the 4.5 ha of canopy cover lost from the 128 ha of tree canopy cover in property parcels in 2008, more than two-thirds (3.1 ha) of that tree canopy loss was lost from fewer than 500 developments (Figure 6). When looking at the canopy cover change within the 10 m buffers of public streetscape around major development sites, the loss of canopy cover was balanced by canopy gains, such that the gains in canopy near these major developments served to prevent a net loss, but equally represented no progress towards the desired canopy gains (Figure 6).

Discussion

Change in canopy cover of park, street and private land-uses

There have been many studies that have quantified the patterns of change in urban tree canopy cover (e.g., Nowak & Greenfield, 2012; Merry et al., 2014; Chuang et al., 2017), but few have been able to relate this to the removal of individual trees according to land use types or private and public tenures (Kaspar et al., 2017; Ossola and Hopton 2018). Combining maps of canopy cover change with the removal of individual trees in different tenure and land-use types is challenging as it requires the availability of both: i) high-quality, remotely sensed data,; and ii) high-quality record keeping of urban tree removals and planting. Our study responds to this research gap by using publicly available data provided by the City of Melbourne to investigate the patterns of tree removal in the public realm and their relationship with tree canopy change and major developments.

In this study, it was possible to estimate a net gain in tree canopy cover in public streetscapes and a net loss in public parks and private properties over a nine-year period. The potential presence of errors in the canopy spatial layers does add some uncertainty to our findings, but the gross changes observed were substantial.

Tree canopy cover was greatest in the parks (~30%), intermediate in the streetscapes (~15%) and least in the private realm (~5%). Within the City of Melbourne, private properties are a mix of high-density office or residential land and medium-density residential. Many studies in North American cities have suggested that the greatest urban tree canopy cover can be found in private residential land (Locke et al., 2017); however, these studies are invariably undertaken at a larger spatial scale and include, or are dominated by, low- and medium-density areas of residential land. In our study, the decline in tree cover in some land-use areas and the increase in others is consistent with other similar tree canopy change studies (Hostetler et al. 2013; Chuang et al. 2017; Locke et al., 2017). In the public streets of Greater

Los Angeles, Locke et al. (2017) estimated a net loss of 2% tree canopy cover over five-years. In contrast, in our study the public street canopy cover increased slightly, confirming recent, Melbourne-wide assessments of canopy-cover change (Hurley et al., 2019)

Behind small net changes in the percentage canopy cover in public parks, streetscapes and private properties were large gross gains and gross losses in localised areas of these three land-use types. For example, tree canopy cover in the public parks decreased by <1% over nine years, but there were gross canopy losses of 6.2% being largely offset by gross canopy gains (growth) of 5.3%. So, if the percentage canopy cover of public parks was 31.1% in 2008 then more than one-third, i.e. 11.5% (6.2 + 5.3) of that canopy cover has experienced change (gain or loss) between 2008 and 2016. To understand what drives any net change in urban tree canopy cover within a given area it is helpful to quantify and consider all areas of canopy gain and canopy loss within that area (Kaspar et al., 2017). In all three land-use types, more than a third of the urban tree canopy was experiencing "churn" or "flux" (either positive or negative / gain or loss) during the nine-year period. This dynamism in urban tree canopy cover is highly localised and as such the scale at which tree canopy cover is measured or aggregated is critical to our understanding of spatial distribution, net change and the gross gains and losses in canopy cover, as well as associated ecosystem service provision (Locke et al., 2017; Kaspar et al., 2017). In six Melbourne suburbs, Kaspar et al., (2017) detected large gains and loss in tree canopy cover in different land-use types that essentially cancelled each other out and led to no net change, or only a small net change, in canopy cover at the suburb scale. Similar patterns were identified by a more recent Melbourne-wide study by Hurley et al. (2019).

Number, size and types of tree removed from public parks and public streets

The observed removals of large (>80 cm), exotic trees, especially in parks, are likely to be in response to a visible decline in tree health, and increase in public risk, after the impact of the Millennium drought (May et al., 2014). These issues reflect a legacy of species selection and management decisions made over the last 100 years or more.

The significant losses of smaller trees is more likely to be in response to tree mortality (failure), vandalism, construction disturbance or damage (Elmes et al., 2018). Tree survival, during establishment (first two years) can be greatly influenced by tree species and resilience, planting location and soil conditions, management and stewardship, vandalism, and climatic conditions/extremes (Gilner et al., 2013; Koeser et al., 2014; Roman et al., 2015; Widney et al. 2016; Layman et al., 2016; Vogt et al., 2015). Numerous repeat removals suggest that in some instances losses are aggravated by repeat vandalism (Richardson and Shackleton 2014; Koeser et al. 2014), or particularly hot, dry and/or windy planting conditions. If reasons for removal had been recorded, this could shine further light on the drivers and decisions underlying the dynamics of this public urban forest (Ordóñez et al., 2019).

Private development, tree removals and canopy cover change

Some cities have much of their tree cover on private property, yet their canopies deliver ecosystem services to both private landholders and the wider public community (Locke et al., 2017). The opposite can be true in more highly urbanised, city centre locations, such as the City of Melbourne – a central municipality that only represents a fraction (roughly 3%) of its Metropolitan area (see also Methods). Regardless, the removal of trees from private land, or the removal of public trees because of activities on private land, are of direct relevance to the local community and their environmental conditions in any urban context. However, identifying the causes of tree removal from either private or public land, let alone the decision-making process that leads to tree removal, is a complex challenge, as there is still a lack of data about reasons for tree removal and planting, and uncertainties about how such data should or could be captured (Lu et al., 2010).

In our study in the City of Melbourne, the removal of 2000 public street trees near major development sites suggests the important role of private land activities and decision-making related to development processes in the context of a public urban forest in a city centre. This loss of 2000 public street trees accounted for almost 20% all street tree removals in the City of Melbourne in our study period, but only 8% (-2.5 ha) of the gross street canopy cover loss (-30.4 ha) in the City of Melbourne (see Figure 6). This suggests that many of the public street trees removed because of major development activities were smaller in size and canopy extent. The loss of public street trees near major private developments has served to slow (but not negate) the net growth in streetscape canopy from existing trees and new tree planting near the same developments. In contrast, the impact of major private development on canopy cover change above private land was far greater, as the canopy cover loss within the 477 DAM developments was 3.1 ha, which represents two-thirds of the net 4.5 ha of canopy loss from private land areas (Figure 6) in the City of Melbourne. Clearly, major private developments were the key driver of tree canopy cover loss in private lands during these nine years. This private tree canopy is that fraction of urban forest that the City of Melbourne does not manage directly, but does influence indirectly through oversight of the planning application process, planning overlays, tree-removal permissions, and significant tree registry and management. These findings build upon some of the recent findings in the literature, such as Steenberg et al. (2018a; 2018b), who investigated the impact of private house renovation or redevelopment on the urban forest of Toronto, Canada between 2003 and 2014. This study was not able to identify a clear relationship between renovation and canopy change because of variations in tree re-planting rates, land use mixtures and trajectories of development, as well as the legacy of past urban forest management decision, such as approval of tree removal permits (Steenberg et al., 2018a; 2018b). In addition, other studies of North American cities have identified that private development can lead to an annual 1% decrease urban tree canopy cover area above private land (Hostetler et al., 2013; Lee et al., 2017). This represents a serious concern in cities that are predicting and planning for considerable population increase and urban densification in coming decades, including Greater Melbourne (VPA, 2018).

In the studies focused on tree loss and canopy change in private lands, a key concern has been the increasing size (footprint) of residential homes after redevelopment (Hostetler et al., 2013; Lee et al., 2017; Morgenroth et al, 2017; Guo et al, 2018). However, in our study, the size of residential dwellings will not explain the increased loss of public street trees near major city centre developments in the City of Melbourne, as this is likely to be more to do with large vehicle access or below-ground infrastructure works in and around construction sites. This issue has been previously identified as a cause for the removal of large heritage trees in Hong Kong (Jim, 2005). In Hong Kong, construction activities were identified as the indirect cause of heritage tree removal, as soil and root disturbance and damage during the construction process led to the subsequent removal of these heritage trees as their health declined (Jim, 2005). Our study builds upon this understanding by investigating another aspect of how major construction developments can lead to increased removal of public street trees and reduced canopy cover beyond the obvious loss of trees on the developed private property itself.

An interesting finding of this study was the peak in tree removals two to three years before completion of a private development; a peak that was up to three-fold greater than tree removal rates near undeveloped control properties. This again may suggest that large vehicle access during demolition or early groundworks for foundations and construction are a major driver of tree removal from the surrounding public streetscape. Yet, any removals of recently planted trees at or after completion of the development appear to be offset by an increase in annual tree planting near the development, either by the developer or the City of Melbourne in an attempt to restore the urban forest as soon as possible.

Conclusion

This study offers insights into patterns of individual tree removal and tree canopy cover losses/gains from public land in an inner-city landscape, and the impact of major private developments on these removal rates. This study made use of detailed tree inventory, tree removal and canopy cover change data from the City of Melbourne, Australia, but the findings have relevance to many inner-city landscapes of major global cities experiencing urban densification and renewal.

This study's focus on the role of major developments on tree-removal patterns indicates that the role of development in canopy cover loss is small but significant. The total loss of streetscape canopy to major development is a small proportion of total loss, but this study identified much higher rates of canopy loss near major development sites than in other streets. Our focus on major properties limited the analysis to only a few hundred developments. Future research can help clarify the role of smaller infill development in the significant total amount of observed streetscape canopy losses.

This paper's use of tree removal analysis offered further insight into likely drivers of canopy loss. It is apparent that the majority of removals of individual trees from public parks and streetscape involve the loss or replacement of small, young trees. While the drivers of these losses of small trees are not fully characterised, it is clear that management focus on retention and successful establishment of young trees is warranted, especially in streetscapes.

The net loss of park and property parcel canopy underlines the rising importance of street trees and the canopy they provide as a source of ecosystem services, human nature connectedness and biodiversity habitat. It also suggests that the City of Melbourne's program of street tree planting and tree protection policies has been effective in preventing major net losses of canopy, though the large observed gross losses may undermine the achievement of the Urban Forest Strategy's canopy target of 40% by 2040 at current rates of canopy loss and planting. These findings should serve as a basis for enhanced investment in urban tree planting, at the same time as strengthening and enforcement of planning policies relating to tree valuation, retention and protection in both public and private land areas.

Declaration of interest:

This paper is about tree removal in the City of Melbourne.

This research was funded through a grant in which the City of Melbourne is a financial partner.

David Callow is an employee of the City of Melbourne.

As the objective of this research is to improve tree management in the City of Melbourne, these relationships have not compromised the integrity of the work.

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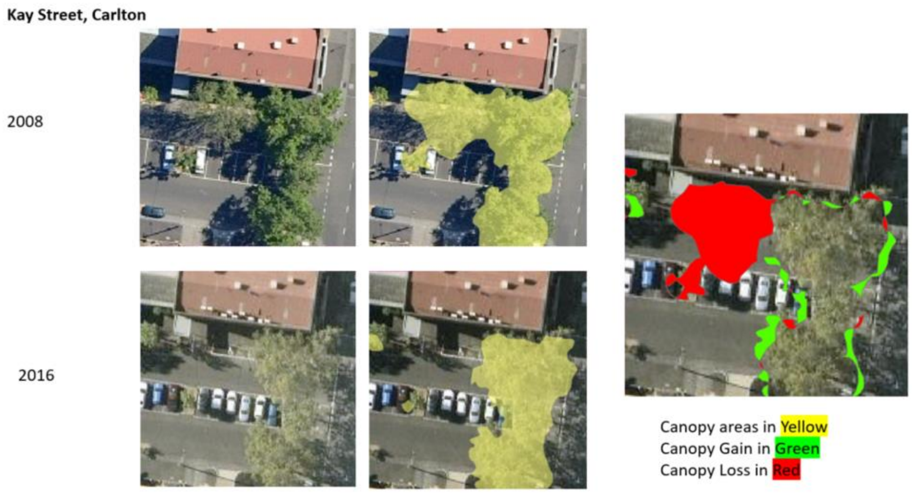

Figure 1. Example of canopy change analysis. Note how the large losses due to tree removal are captured, but smaller 'slivers' of loss and gain on trees to the right are more ambiguous. It is these small changes that form 9% and 11% of the loss and gain datasets respectively.

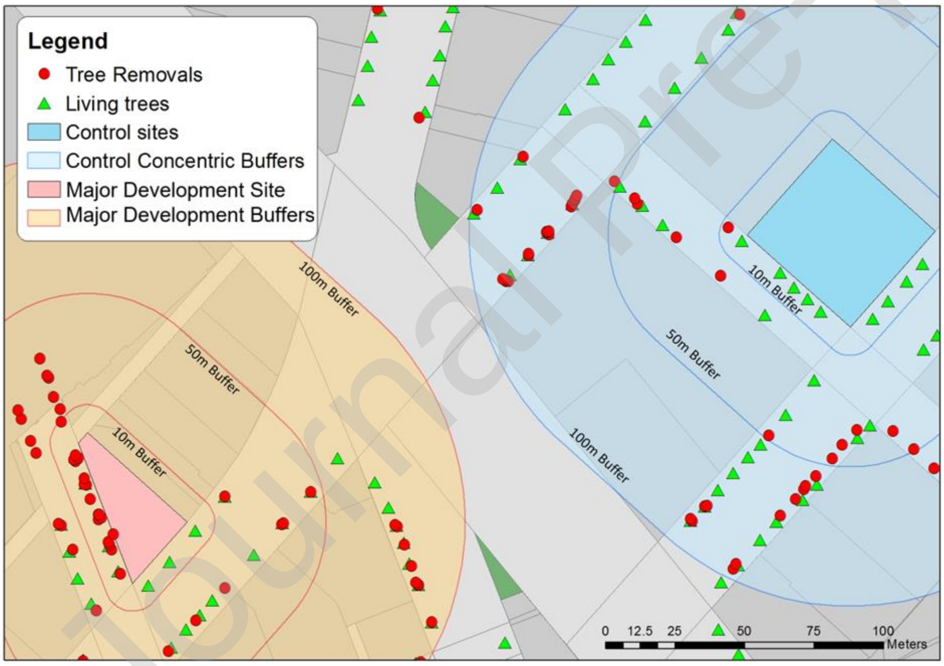

Figure 2. Example of major development sites and control sites with 10m, 50 m and 100 m buffers. The number of trees removed or retained within each concentric buffer was counted.

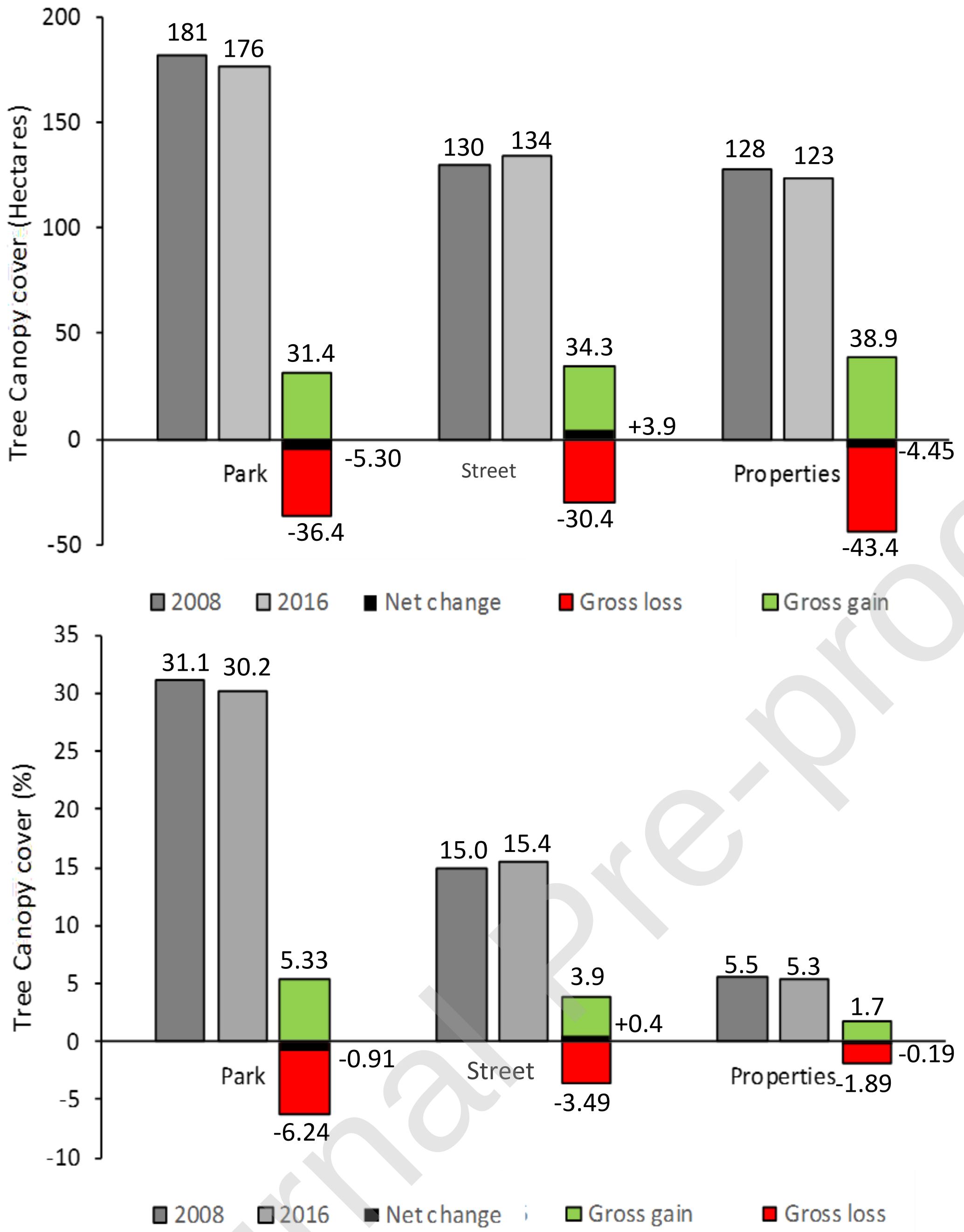

Figure 3. Changes in canopy cover (2008-16) by area (A) and percent (B) for three land-use types (park, street, and property), indicating total change, gross gain, gross loss and net change.

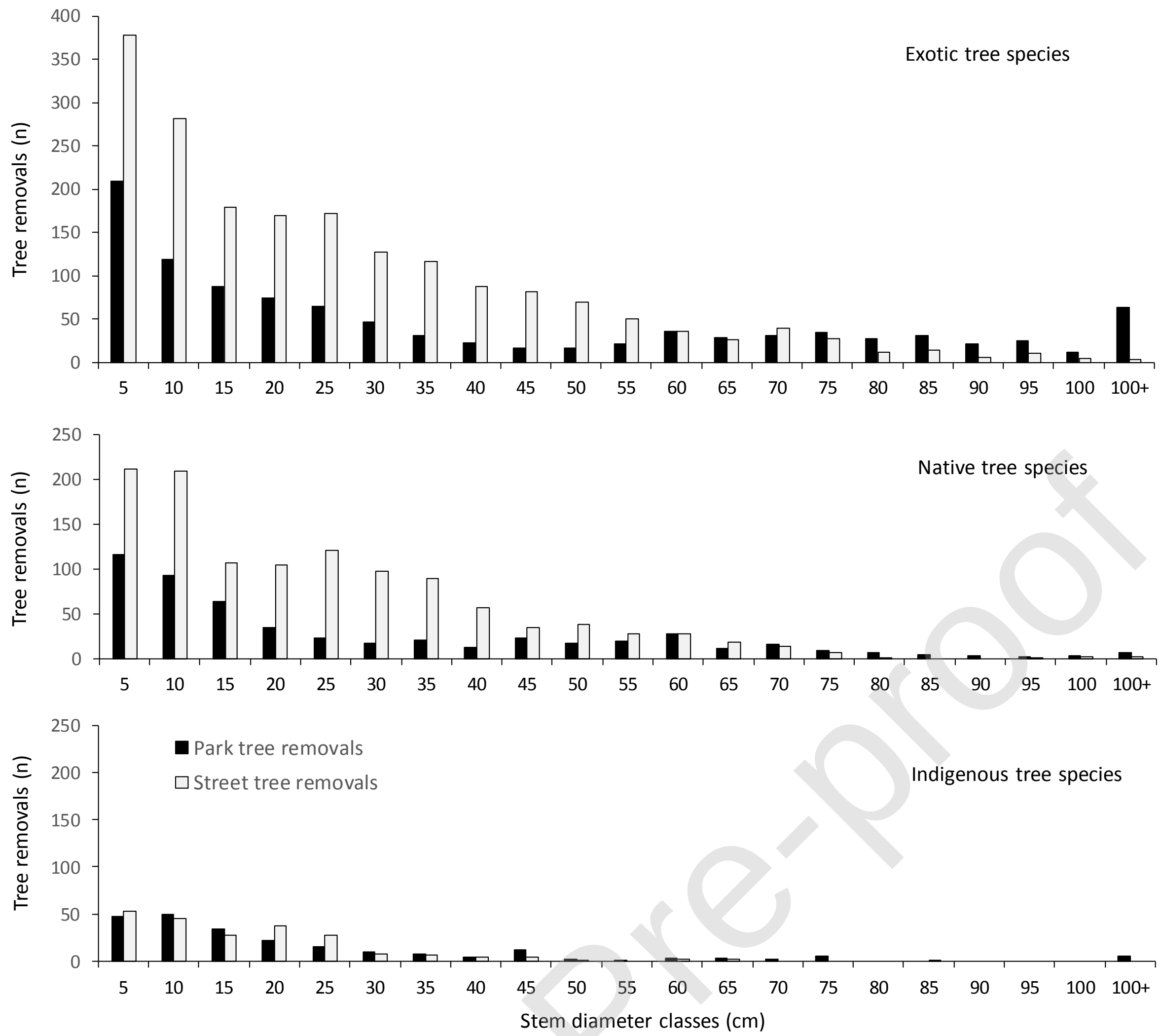

Figure 4. Total number of tree removals by stem diameter classes (in cm), separating land type (parks, streets) and tree species types (exotic, native, and indigenous)

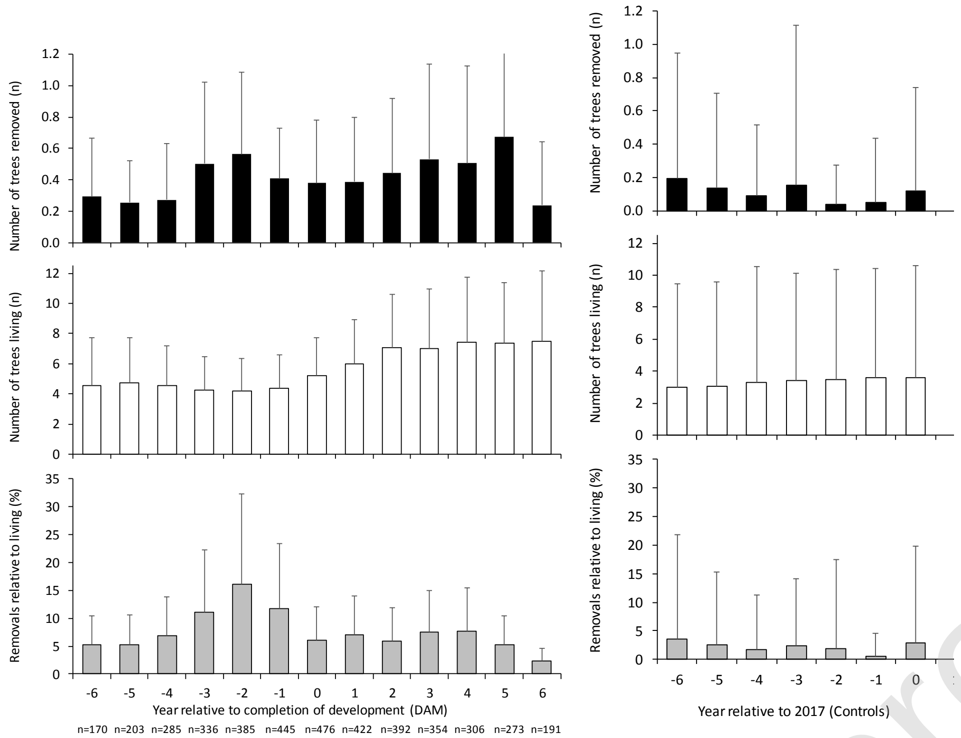

Figure 5. Number of living trees and trees removed and removed as a proportion of those living (%) within a 10 m buffer around DAM properties (2008-2017) according to year relative to completion, denoted as ‘0’ on x-axis (note that the number N of development projects changes by year of completion).

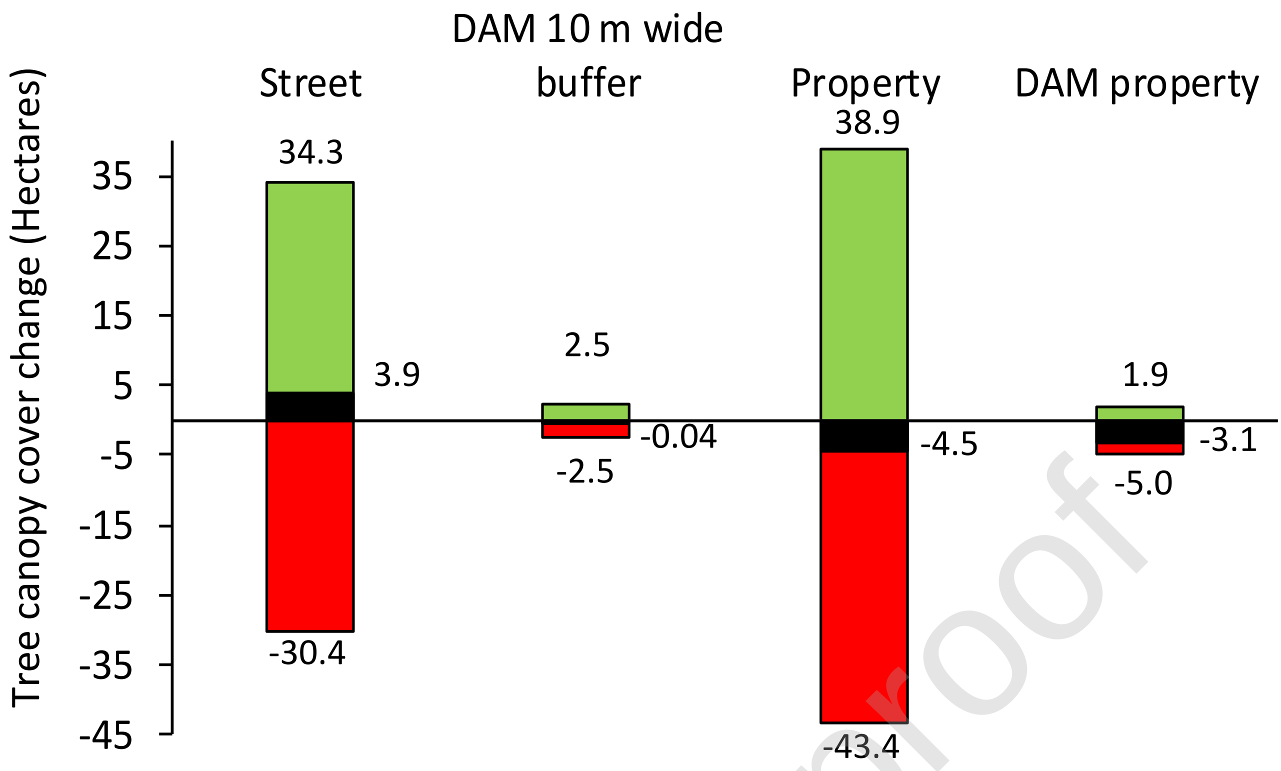

Figure 6. Gross gain, loss and net change in tree canopy cover (2008-16) in City of Melbourne streets and properties overall, as compared to a 10 m street buffer next to major developments and within the development site itself.

Table 1. Datasets (ArcMap v.10.4.1 shapefiles) from the City of Melbourne, Victoria, Australia used in this study.

Dataset	**Measures**	**Reference**	**Date Accessed**
Tree removals from 2008 to 2017	• Unique identifier • Year Planted • Date removed • Scientific Name, Genus, Family • Age • Location	City of Melbourne unpublished	2018
Tree inventory 2011	• Unique identifier • Year Planted • Scientific Name, Genus, Family • DBH • Age • Useful Life Expectancy • Location	City of Melbourne unpublished	2017
Tree inventories 2008 to 2017	• Unique identifier • Year Planted • Scientific Name, Genus, Family • DBH • Age • Useful Life Expectancy • Location	*https:// data.melbourne.vic.gov.au/ Environment/ Trees-with-species-and-dimensions-Urban-Forest-/ fp38-wiyy*	2018
Tree canopies 2008	• Tree canopy extent (ha)	*https:// data.melbourne.vic.gov.au/ Environment/ Tree-canopies-2008-Urban-Forest-/ xmnz-a7qy*	2017
Tree canopies 2016	• Tree canopy extent (ha)	*https:// data.melbourne.vic.gov.au/ Environment/ Tree-Canopies-2016-Urban-Forest-/ pih2-628i*	2017
Development Activity Monitor from 2008 to 2017	• ID • Property Name • Polygon area • Year completion • Street Address • Location (other data not included)	*https:// data.melbourne.vic.gov.au/ Property-Planning/ Major-development-projects-Development-Activity-Mo/ gh7s-qda8*	2018

Table 2. Total trees removed, basal area, and cumulative basal area of trees removed in streetscapes from the City of Melbourne between 2008 and 2017.

Status	**Species**	**Number removed**	**Geometric mean basal area (cm^2)**	**Total basal area based on extrapolation**
Exotic	*Platanus acerifolia*	1899	229.9	72.7
	Ulmus spp.	624	957.5	82.8
	Platanus orientalis Digitata	368	222.1	11.6
	Ulmus procera	335	25.5	1.8
	Quercus palustris	147	34.4	0.8
	Ulmus parvifolia	140	122.6	2.1
	Prunus cerasifera Nigra	76	194.4	1.6
	Robinia pseudoacacia	58	511.0	3.3
	Ulmus minor	38	393.1	1.6
Native	*Corymbia maculata*	609	141.3	11.8
	Melaleuca linariifolia	332	1801.6	62.5
	Lophostemon confertus	320	333.1	12.8
	Lagunaria patersonia	213	719.2	16.1
	Corymbia ficifolia	183	179.1	4.7
	Callistemon salignus	145	517.2	8.8
	Eucalyptus scoparia	140	104.8	2.3
	Eucalyptus unknown	129	217.7	3.3
	Eucalyptus nicholii	49	1580.4	8.1
	Ficus macrophylla	43	173.8	2.2
Indigenous	*Eucalyptus leucoxylon*	274	61.4	2.2
	Allocasuarina verticillata	146	72.1	1.2
	Eucalyptus camaldulensis	137	53.5	1.3
	Eucalyptus melliodora	97	191.8	2.1
	Banksia integrifolia	92	39.0	0.4
TOTAL		6594	N/A	318

Table 3. Total trees removed, basal area, and cumulative basal area of trees removed in parks from the City of Melbourne between 2008 and 2017

Status	**Species**	**Number removed**	**Geometric mean (cm2)**	**Species basal area based on extrapolation**
Exotic	*Ulmus procera*	679	124.0	17.0
	Ulmus unknown	279	1651.3	69.5
	Platanus acerifolia	242	494.6	6.1
	Populus x canadensis Aurea	190	5021.8	31.4
	Quercus robur	168	160.3	5.7
	Photinia robusta	132	295.8	3.4
	Populus alba	89	1262.7	24.8
	Ulmus parvifolia	45	99.5	1.2
	Ulmus x hollandica Vegeta	44	3045.9	17.2
	Pittosporum crassifolium	37	137.5	1.3
Native	*Corymbia citriodora*	431	21.1	0.6
	Corymbia maculata	234	564.8	3.6
	Casuarina cunninghamiana	203	38.4	0.8
	Corymbia ficifolia	111	411.3	4.8
	Pittosporum undulatum	108	1574.1	8.8
	Eucalyptus mannifera	84	51.7	0.9
	Agathis robusta	80	23.6	0.1
	Grevillea robusta	58	2190.4	11.8
	Syzygium smithii	52	118.8	0.8
Indigenous	*Eucalyptus camaldulensis*	1077	110.7	3.3
	Eucalyptus leucoxylon	271	29.1	0.4
TOTAL		4614	N/A	213.3