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Valuing ecosystem services of urban forests and open spaces: application of the SEEA framework in Australia*

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Around two-thirds of the global population will live in cities by 2050 requiring large urban infrastructure development. Decision-makers and planners usually rely on standard economic accounting methods for urban planning and investments on infrastructure assets. However, standard methods fail to account for the ecosystem services benefits that living infrastructure (e.g. urban forests, open spaces) provides to city dwellers. This could generate socially inefficient configurations of urban spaces and compromise the achievement of long-term urban sustainability targets. In this analysis, we applied a stochastic whole-of-life benefit–cost analysis following the System of Environmental-Economic Accounting (SEEA) framework to compare alternative long-term management strategies for living infrastructure in Canberra, Australia. Spatially explicit data, i-Tree Eco and benefit transfer methods were used to estimate the stocks and flows ecosystem services benefits of urban forests and irrigated open spaces from 2018 to 2070. Our analysis suggests that a '30 per cent canopy cover expansion' scenario has the highest benefit–cost ratio, while the business as usual scenario, where a net loss of 400 trees is expected per year, offers the lowest benefit–cost ratio. Scenarios of expanding versus not expanding irrigated open spaces in the future both result in a benefit–cost ratio of approximately two.

Key words: sustainable cities, system of environmental and economic accounting, Urban green spaces, urban planning, urban SDGs.

1. Introduction

Publicly managed natural assets in urban areas, such as parks, trees and lakes, constitute the 'living infrastructure' of a city. Such infrastructure

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provides multiple socio-economic, cultural and environmental benefits that are essential for the well-being of city dwellers and for climate change adaptation. However, since most of those benefits are not directly consumed or experienced by people, they are often taken for granted, overlooked or undervalued in city planning and infrastructure investment decisions (Villamagna *et al.* 2013). This could result in gradual deterioration of the health and extent of living assets, reductions in the provision of ecosystem services (e.g. cooling, carbon sequestration) and increasing liabilities and risks (e.g. damages due to fallen trees).

By considering living infrastructure as a key part of a city's assets portfolio, decisions around its long-term planning, design, maintenance, renewal, termination or expansion can be improved (ACT Government, 2018). However, this requires the identification, quantification and valuation of the benefits and costs of living assets to taxpayers within a framework consistent with accounting and investment principles used by governments at different levels. Such approach would allow more efficient choices and allocation of scarce resources and contribute to the development of resilient and sustainable cities.

The System of Experimental Ecosystem Accounting (SEEA) is a framework for organising biophysical data and measuring the corresponding ecosystem services (ES) in a way that is compatible with the System of National Accounts (SNA). The SNA is an internationally agreed standard for the accounting of economic activity (United Nations Statistics Division, 2009). The SEEA framework was adopted by the UN Statistical Commission in 2012 as the first international standard for environmental–economic accounting (Brouwer *et al.* 2013). The SEEA framework considers a natural asset to have two types of values: (i) the value of the stock of the asset and (ii) the value of the flow of ES the asset provides. The stock is measured by assessing an asset's extent and condition, and the flow captures the ES that the asset provides, such as pollution removal. The SEEA framework allows estimation of the economic benefits and costs from natural assets. By valuing ES in monetary terms, it is possible to better recognise their important contribution to human well-being, economic growth and sustainable development.

Urban forests and irrigated open spaces (public-access irrigated grass areas including parks, sportsgrounds and ovals) are key components of the living infrastructure of a city that are usually know as green assets. ES from those types of living assets can mitigate impacts of urbanisation and urban intensification and improve the well-being of urban residents (Xu *et al.* 2018). These assets provide key ecosystem services to cities such as: cooling and wind protection, reduced air pollution and stormwater run-off, carbon storage, habitat for native species, space for recreation and enjoyment of nature (Nowak *et al.* 2002; Nowak and Dwyer, 2000). Green infrastructure also provides direct and indirect benefits to cities in the form of increased property values generating additional tax revenue, mental and physical well-being, cultural value and amenity, which in turn reduce pressure on public health services (Pandit & Laband, 2010).

We explore how changes in management strategies for urban forests and irrigated open spaces in an urban area of Australia, impact the value of ecosystem services (ES) of living infrastructure over a 60-year time horizon. We applied the SEEA framework to organise biophysical data and measure the corresponding stock and the flow of ES services. The i-Tree eco model was utilised to assess the extent and condition of the public urban forest, including tree population, species composition, age distribution, species importance values and canopy cover. Monetary estimates of ES benefits, including carbon storage and sequestration, air pollution reduction, water run-off reduction and energy savings, were also estimated in i-Tree. Other ES benefits of urban trees that could not be estimated in i-Tree were collected via a desktop review of published peer-reviewed literature and government reports. A series of non-market valuation estimations and benefit transfer estimations were conducted to estimate the remaining ES benefits. A benefit–cost analysis was then conducted in @Risk to find a tree management regime that would maximise the net benefit of public urban forests going into the future (time horizon 2018–2070). The @Risk software allows for uncertainty to be incorporated into the benefit–cost analysis, and findings represented probabilistically, rather than deterministically. Unlike traditional ES valuations of living infrastructure, we provide a whole-of-life benefit–cost analysis of living infrastructure, capturing the ES benefits from both the stock and the flow of the asset, and controlling for uncertainty around benefits and costs estimates derived from benefit transfer of ES values. Multiple ES services were considered, including recreational, health and property price premium benefits, in addition to ES services estimated by i-Tree. The framework implemented in this analysis allows the comparison of the social benefits of investments in green infrastructure with the returns of investments in other areas. This information could help increase the overall flow of benefits, manage risks generated from asset deterioration and target the provision of sustainable levels of green infrastructure.

2. Literature review

We conducted a review of the international literature from the last decade of studies that place a value on similar green assets. The following keywords were used: public trees, irrigated open space (IOS), parks, lawn, sports oval, golf courses, public green space, parks and (ecosystem services) ES, benefits, values. Priority was given to studies in Australia, and to papers that have quantified ecosystem services benefits in monetary terms, or any other quantifiable terms, for example MWh of energy savings per year, that could be later monetised. A review of abstracts was first conducted to eliminate papers that were only marginally related to the objectives of this report. While an extensive review effort was undertaken, we acknowledge that the list of relevant research is not exhaustive.

2.1 A review of urban public tree benefits

There are two types of ES benefits derived from trees – market (or commercial) benefits and non-market benefits. Market benefits generally include food and timber that can be harvested from orchards or commercial forest. The provision of food and timber is not the role of urban forests in the context of Australian cities. Hence, we can assume that there are no market benefits from urban forests to Australia. Having said that, public trees may be planted in the future that could provide fruit to people living nearby. In any case, for this study, we focused our attention on reviewing the non-commercial benefits of trees.

Our review of the literature revealed that a comprehensive review of the ecosystem services benefits of trees in an urban context has already been conducted by Lin *et al.* (2018). From their review of the international literature (96 papers in total), Lin *et al.* (2018) provide an extensive summary of the ES benefits of trees, and the monetary benefits associated with some of the ES. A breakdown of papers in Lin *et al.*'s review by ecosystem service type are as follows: air pollution removal (1 paper); amenity value (6 papers); biodiversity benefits (4 papers); climate regulation and cooling (28 papers); cultural services (1 paper); mental health and physical health benefits (14 papers); recreational benefits (6 papers); and stormwater run-off and flood management (18 papers). Additionally, Lin *et al.* found 18 papers that assessed several ecosystem services benefits of trees. From their review of the literature, we gathered that trees provide the following ES (see Table 1). Lin and colleagues pointed out that the monetary value of some ES, such as habitat and species diversity, are difficult to quantify unlike other types of ES of trees, such as stormwater management. The correlation between tree size and stormwater run-off prevention has been quantified and therefore a monetary value for stormwater run-off prevention of trees can be estimated. The conclusion found by Lin and colleagues is also echoed by Brouwer *et al.* (2013) who stated in their review of published literature on ES valuation that 'there does not exist one single, standard "TEEB[1]" method or approach. Most efforts focus on the mapping of ES. Hardly any initiative has (yet) been able to integrate ES assessment and mapping into valuation and accounting'.

In addition to the review of ecosystem services benefits of trees, we also conducted a review of the literature on how trees are valued. A comprehensive review of methods is documented in Garner (1999). According to Garner (1999), during the 1970 and 1980s, several methods were introduced to place monetary values on trees. These include the 1992 Australian Draft Standard, the 1999 Australian/New Zealand Draft Standard, the 1998 Australian Burnley Method, the 1991 British Helliwell Method, the 1996 Australian Thyer Method and the USA 1991 Trunk Formula Method (Garner, 1999). What these methods have in common is that the economic value of trees is based on converting an assessment score into monetary terms. Trees are

[1] TEEB – The Economics of Ecosystem and Biodiversity.

Table 1 A summary of ecosystem services benefits of urban trees and irrigated open spaces

Services	Trees	Irrigated open spaces
Provisioning		
Food	x	
Shade	x	
Recreational value		x
Sporting value (user fee)		x
Oxygen	x	x
Supporting		
Habitat connectivity/corridors	x	x
Habitat for wildlife	x	
Species diversity/Biodiversity	x	
Regulating		
Climate regulation/amelioration (cooling)	x	x
Carbon sequestration	x	x
Air quality	x	
Noise reduction	x	
Flood control/Stormwater run-off	x	x
Water pollution reduction	x	x
Erosion control	x	x
Cultural		
Recreational value	x	x
Property price premium	x	x
Cultural heritage	x	x
Symbolic/Spiritual values	x	x
Mental/Physical health benefits	x	x
Aesthetic enjoyment	x	x
Reduce socio-economic inequalities	x	x

assessed and scored by qualified arborists. Assessment scores are commonly based on tree species, height, trunk volume, crown size, form and vigour, and life expectancy. The scores are then converted to monetary values based on an agreed monetary value per score. For example, in the case of the United Kingdom, monetary values of trees are agreed upon by the Tree Council and the Arboricultural Association (Halliwell, 2008). These values are based on nursery prices of a like-for-like replacement of the tree and the value of the land (Garner, 1999) and are updated from time to time to remain realistic with market prices (Halliwell, 2008). Figure 1 provides an example of how tree values are assessed based on the scoring method and monetary conversion following the Halliwell method.

The variation among these methods is that some also include the historical significance value, visual impact and location in the landscape of the tree, etc. Differences in assumptions across tree valuation methods can result in significant value differences for the same tree. For instance, using the Helliwell method, which incorporates a score for '*Importance*' of tree in the landscape, Garner (1999) estimated the value of one single *Eucalyptus melliodora* (Yellow Box) tree located on the Australian National University Campus to be around $407,000. However, valuing the same tree using the

Factor	Points									
	0	0.5	1	2	3	4	5	6	7	8
i. Size	$<2m^2$	$2\text{-}5m^2$	$5\text{-}10m^2$	$10\text{-}20m^2$	$20\text{-}30m^2$	$30\text{-}50m^2$	$50\text{-}100m^2$	$100\text{-}150m^2$	$150\text{-}200m^2$	$>200m^2$
ii. Duration	<2		2-5	5-40	40-100	>100				
iii. Importance	None	Very little	Little	Some	Consider-able	Great				
iv. Tree cover		>70%	>30%	>10%	none					
v. Suitability to setting	Not	Poor	Just	Very	Particularly					
vi. Form		Poor	Average	Good						

1.	Size	$40m^2$	scores 4 points
2.	Expected duration	around 30 years	scores 2 points
3.	Importance in landscape	some	scores 2 points
4.	Presence of other trees	less than 10%	scores 3 points
5.	Relation to setting	particularly suitable	scores 4 points
6.	Form	average	scores 1 point

Total score = 4 x 2 x 2 x 3 x 4 x 1 = 192, or £4,800
(1 unit = £25 for individual trees)

Figure 1 Example of tree scoring and monetary assessment based on Helliwell (2008).

Burnley method, which does not have a subjective score for '*Importance*' resulted in an estimate of around $40,700. In any case, none of these methods include the full suite of ES values from such tree.

Non-market valuation methods, such as the hedonic property price approach, willingness to pay surveys and replacement (or compensatory) value approaches have been used to estimate the value of trees and forests. For example, in Australia, Pandit *et al.* (2013) estimated the value of street trees using the hedonic property price method to be around $13,000 (or 4 per cent of averages property sales price). In Portland, Oregon, Donovan and Butry (2010) estimated the value of trees using the same method to be around US$8,870. Nowak *et al.* (2002) estimated the value of a tree using the compensatory value method to be US$394-1,187, depending on the city the tree is located. Willingness to pay surveys offers more flexibility in terms being able to value a tree, or each of the ecosystem services benefits of trees. The i-Tree tool developed by the USDA Forest Service (2018) is also able to value a tree, as well as, individual ecosystem services benefits of trees. Soares *et al.* (2011) applied the i-Tree tool to estimate the ecosystem services benefits of trees in Lisbon, Portugal. They estimated that trees provide services valued at $8.4 million annually, comprising the value of energy savings ($6.20/tree), CO2 reduction ($0.33/tree), air pollutant deposition ($5.40/tree), stormwater run-off reduction ($47.80/tree) and increased real estate value ($144.70/tree). Other studies have used i-Tree to estimate ecosystem services benefits in monetary terms from carbon storage (see, e.g., Kiss *et al.* 2015) and stormwater retention (see, e.g., Berland and Hopton, 2014). However, these studies only focused on one ecosystem service, rather than a suite of ecosystem services, unlike Soares *et al.* (2011) and this paper.

2.2 Irrigated open spaces (IOSs)

There are a handful of studies that evaluated the ES of urban IOSs that lawns or sports ground provide, particular ones that are based in Australia and have estimated the ecosystem services in monetary terms. These include tourism, recreation and cultural (see Hatton MacDonald *et al.* 2010; Hope *et al.* 2018), rainfall run-off prevention (see Zhang *et al.* 2012; The Lawn Institute, 2018), human health (see Ulrich *et al.* 1991), aesthetic (see Hatton MacDonald *et al.* 2010), biodiversity (see Mexia *et al.* 2018), climate regulation and cooling (see Yaghoobian *et al.* 2009; Wang *et al.* 2016; Meyers *et al.* 2017) and carbon sequestration (see Qian *et al.* 2010; Townsend-Small and Czimczik, 2010), to name a few. The recreational benefits of sports grounds in urban areas, as represented by government revenue generated from sports ground hire, are around $4,623/ha/year (Australian Government pers. comm.). This is the only market benefit that is accrued from IOSs. Other non-market benefits are summarised in Table 1.

3. Materials and methods

The identification and valuation of the benefits and costs of living assets is essential to facilitate a comparison of their returns to society with investment in other types of urban infrastructure.

3.1 Study area

Figure 2 presents the study site. The study site is the Australian Capital Territory (ACT), Australia. To increase the cities resiliency to climate change, the ACT has set a target of 30 per cent more canopy cover by 2045. The current extent of public trees in the ACT is as follows: the urban forest is composed of 767,636 trees (42 per cent native to Australia), covering around 21 per cent of publicly managed land (excluding nature reserves). The most common native tree species are as follows: *Eucalyptus mannifera, Casuarina cunninghamiana, and Eucalyptus polyanthemos* which account for 25 per cent, 5 per cent and 4 per cent of the tree population, respectively. *Quercus palustris, Fraxinus oxycarpa and Pinus radiat*a are the most common non-native (exotic) tree species, each accounting for around 2 per cent of the 2018 tree stock.

3.2 The SEEA framework

This research paper applied SEEA framework to measure and value the services and costs of urban forests and irrigated open spaces, and to assess the implications of alternative asset management scenarios.

Figure 3 presents the components of an SEEA framework, as proposed by the Commonwealth Government of Australia. The framework comprises the

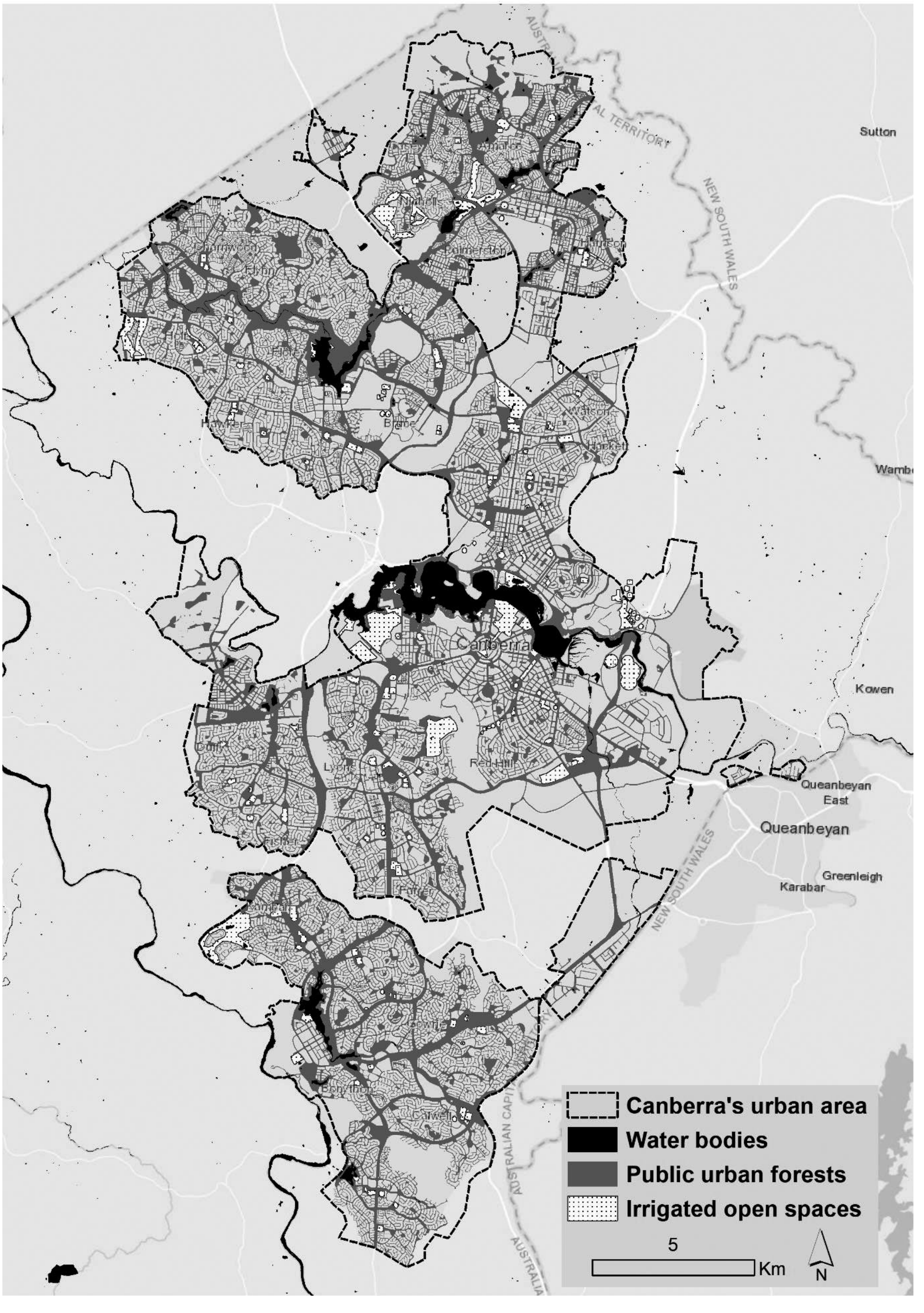

Figure 2 Distribution of urban forests and open spaces in the study area.

'measurement' and 'valuation' of natural assets. The 'measurement' component involves the classification and measurement of the extent of the natural asset, and the health condition of the natural asset. The 'valuation' component involves the measurement of the flow of ecosystem services of the natural asset to its beneficiaries, and measurement of the values (or benefits) people receive from the flow of services that the natural asset provides. Information derived from a reliable environmental–economic accounting is expected to result in more informed policy and decision making that would result in a better balance between economic, environmental and social outcomes (Australian Government, 2018).

3.3 Non-market valuation and benefit transfer methods

This analysis combines revealed preferences and benefit transfer methods to estimate the ES value of public trees and IOSs not modelled i-Tree Eco model (e.g. aesthetic values, property price impacts). The following sections describe in more detail the methods, assumptions and parameter values used.

3.3.1 Property price premium of public trees

A hedonic property price study by Pandit *et al.* (2013) in Perth, Western Australia, estimated that verge trees add around 4 per cent premium to property sales price. Using this information, we can approximate the monetary benefit of public trees that are on street verges in front of homes. We specify the property price premium of trees as:

$$\begin{aligned} Property\ price\ premium_k\ (\$/year) &= Average\ unimproved\ value_k(\$/sqm) \\ &\times Average\ land\ size_k(sqm) \times Premium\ from\ trees\ (4\%\ of\ sales\ price) \end{aligned}$$

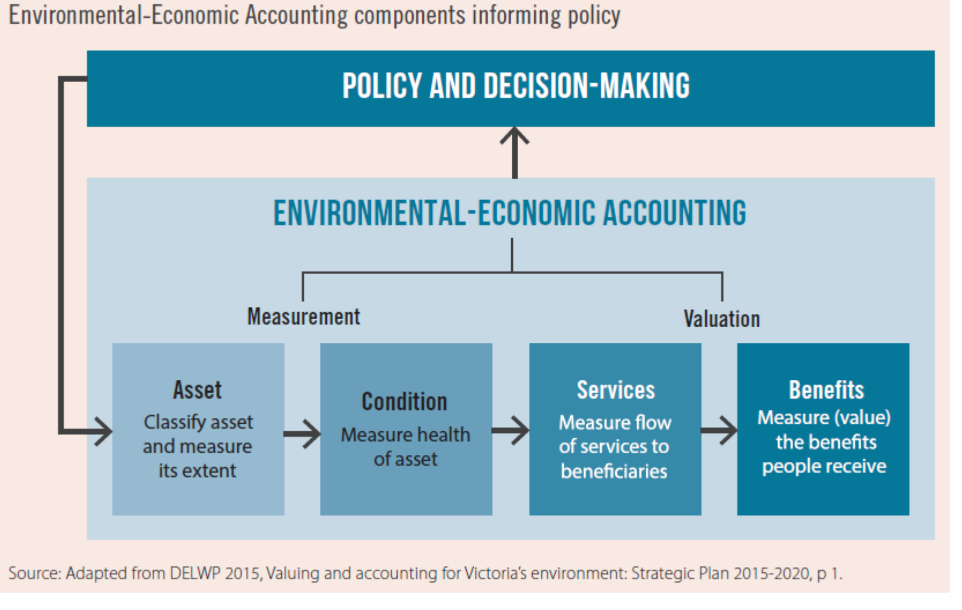

Figure 3 Components of the SEEA framework approach in Australia. [Colour figure can be viewed at wileyonlinelibrary.com]

$$\times \textit{Historical rate of increase of detached homes } (\%/\textit{year})$$
$$\times \textit{No. of detached homes}_k$$

where k is a vector of suburbs of an urban area. The total premium of trees is the property price premium sum across all k s. We assumed that the number of detached homes increases every year, at a rate that is based on the average number of approved detached homes during the period of 200–2018 (Australian Bureau of Statistics, 2018). The unimproved value (UV) of land is 'the value of a block of land before any improvements are made to it – before any buildings, fences, driveways or anything else is added to it' (Mo'r Mortgage Option, 2017). The UVs are determined by qualified, independent valuers (ACT Revenue Office, 2017). We assume that a portion of the revenue collected from rates can be attributed to a premium generated by trees, at a rate of approximately 4 per cent of property value (i.e. in this case the unimproved land value). Note that we only use the number of detached homes to estimate property price premium of trees; hence, we expect this to be a lower-bound estimation of the property price premium for all trees in Canberra. We also assumed in this calculation that there is one tree on the verge of each detached home.

3.3.2 Avoided cost of heat-related morbidity from planting more trees

In this analysis, we used two main factors to determine vulnerability – age and income. Age groups that are considered vulnerable are children who are younger than 5 years old, and adults who are older than 65 years of age[2]. In Australia, there is a strong correlation between income and age. As such, those who are in the older age bracket also tend to have the lowest income. Data from the ABS 2016 Census of Population and Housing reveal that around 19 per cent of the population at this time is considered vulnerable (around 79,646) and are potentially more susceptible to temperature changes. Given that we did not have the spatial distribution of vulnerable population per hectare for this analysis, we assumed an even spatial spread of vulnerable population. We approximated that there is one vulnerable person per hectare. We then assumed that out of the total vulnerable population, 7.2 per cent (based on estimates by Hondula and Barnett (2014) for the Brisbane heat-related morbidity study) will need to go to the ED due to heat-related health illness on a hot day (a day above 35°C). Given this information, and using information on the average number of ED presentations per day (Australian Institute of Health and Welfare, 2011, 2013, 2016, 2017) and the average cost per ED presentation (Independent Hospital Pricing Authority, 2018), we can estimate the avoided cost of heat-related morbidity from trees using the following specification:

[2] 'As climate change progresses heat exposure stands to cause additional heat-related illness and death, especially for the most vulnerable groups such as older people, young children, people with chronic disease and those living in built-up areas in cities.' (Loughnan et al., 2013).

$$\begin{aligned}&Avoided cost\ of\ heat\ related\ morbidity\ (\$/year)\\&\quad = Average\ no.of\ ED\ presentations\ in\ CBR(person/day)\\&\quad \times Average\ cost\ per\ ED\ presentation\ (\$/person)\\&\quad \times Expected\ number\ of\ hot\ days\ per\ year\\&\quad \times 7.2\%\ increase\ in\ ED\ presentations\ from\ heatwaves\\&\quad \times Vulnerable\ population(person/ha)\\&\quad \times change\ in\ tree\ cover(ha/year)\end{aligned}$$

where *CBR* is Canberra and *ED* is emergency department.

3.3.3 Property price premium of public irrigated open space

To estimate the property price premium of houses that are in close proximity to IOSs, we used estimates from a study by Hatton MacDonald *et al.* (2010) that was implemented in Adelaide. The reported estimates suggested that moving 1 metre closer to IOSs – IOSs in this case being sports ovals and non-sports ovals – will increase sales price, on average, by 0.11 per cent. This marginal increase is at the average distance of 0.7 km for sports ovals and 1.8 km[3] for non-sports ovals (e.g. playgrounds). The same set of assumptions used to estimate the property price premium of trees, where a portion of revenue collected from rates can be attributed to premium generated by proximity to IOSs, is used to estimate property price premium of public IOSs.

We applied a uniform property price premium method applied by Polyakov *et al.* (2017) to estimate the aggregated property price premium of being in close proximity to these three types of IOSs using the following specification:

$$\begin{aligned}&Property\ price\ premium_{ks}(\$) = Average\ unimproved\ value_k(\$/sqm)\\&\quad \times Average\ land\ size_k(sqm)P\\&\quad \times Premium\ from\ proximity\ to\ irrigated\ open\ space_s\ (\%\ of\ sales\ price)\\&\quad \times Historical\ rate\ of\ increase\ of\ detached\ homes\ for\ ACT\\&\quad \times No.of\ detached\ homes_{ds}\end{aligned}$$

where k is suburbs, s is an IOS of interest, and d is the average premium distance for each type of IOS s. The total premium of IOSs is the property price premium sum across all ks, for each type of s. In a situation where a property is in close proximity to both types of IOSs, the property price premium will be the sum of both premiums.

3.3.4 Recreation benefits of public irrigated open spaces

The economic value of a park is assumed to be based on the amount of time someone spends to travel to and stay at the park. Since most people's time

[3] 0.7 km and 1.8 km are average distances to sports and non-sports ovals, respectively, based on Hatton MacDonald *et al.* (2010)'s estimations.

has value and that value can be monetised based on their income, the value of a park could also be monetised based on how much time people spend to travel and stay there as a proxy. Given this assumption, the recreation benefits of IOSs are specified as:

$$
\begin{aligned}
Recreational\ benefits_j(\$/year) = &\ \%\ of\ CBR\ people\ who\ visit\ IOS_j \\
&\times Frequency\ of\ visit\ (visits/person/year) \\
&\times CBR\ working\ age\ population \\
&\times\ (1 - CBR\ unemployment\ rate) \\
&\times Average\ hours\ spent at\ IOS_j/person \\
&\times Cost\ of\ recreational\ time\ /hr/person
\end{aligned}
$$

where $IOS_j$is IOS type j(football/soccer and playgrounds), $1 - CBRunemploymentrate$is the proportion of employed working age people in Canberra, and the

$$
\begin{aligned}
&Cost\ of recreational\ time\ (\$/hr/per) \\
&= f\{Average\ income,\ Value\ of\ recreational\ time\ (\%\ of\ income)\}
\end{aligned}
$$

The value of recreational time is estimated to be around 30 per cent of a person's gross income (see, e.g., Englin and Shonkwiler, 1995; Lockwood and Tracy, 1995). Average income levels, along with working age population, and unemployment rate are extracted from the 2016 Census of Population and Housing (ABS, 2017).

A survey by Hope *et al.* (2018), which was commissioned by the City Renewal Authority, ACT Government, concluded that out of the 1,370 respondents surveyed, all have visited a playground at least once in the past year, but only 4 per cent said the reason for visiting the playground was for the use of open space/green space. From the same survey, it was estimated that on average residents spend 1.3 hours at playgrounds, and around 55 per cent visit playgrounds weekly. However, not all the time spent would be attributed to green space, hence we conservatively assumed that only 4 per cent of the time spent is attributed to greenspace (same percentage as a reason for visit). Given these assumptions, we estimated the value of recreational time spent on green space at playgrounds to be $38 per person per year.

With regard to football/soccer ovals, a survey conducted by AusPlay (2016) concluded that 7.4 per cent of Canberra residents play football/soccer and spend around 161 hours/person/year playing sports. This works out to be approximately 3 hours per person per week. Given these figures, we estimated the value of recreational time for football/soccer to be $7.5 per person per month.

3.4 i-Tree valuation of ecosystem services of urban forest

The monetary benefits of public urban forests were assessed through the peer-reviewed i-Tree Eco model (USDA Forest Service, 2018). The i-Tree eco model estimates the value of the 'stock' and the 'flow' of ES benefits that trees provide. The value of the 'stock' of a tree is approximately equal to the cost of replacing that tree if it were to be destroyed with a similar tree of the same age, species and condition, that is like-for-like replacement. The value of the flow of ES of a tree is derived from the benefits that trees provide from avoided stormwater run-off, carbon storage, air pollution reduction and energy consumption impact due to tree shading.

3.4.1 Replacement cost of trees

The replacement cost of a standing tree at a point in time (without considering the value of its future ES) is a function of its age, species, health condition and location. As trees grow, such cost is expected to increase up to a certain age and then decrease as trees approach the end of their useful life. Changes in the value of trees cannot be estimated in the same way as the depreciation of a built asset, such as a water treatment plant.

Tree replacement cost in this analysis is based on four tree-specific parameters: trunk area (cross-sectional area at DBH), species, condition and location (Nowak *et al*. 2008). Those parameters are used in i-Tree to estimate the replacement cost of the urban forest following the approach of the U.S. Council of Tree and Landscape Appraisers (Nowak *et al*. 2008). Trunk area and species are used to estimate an initial replacement cost estimate. Such cost is then adjusted according to the condition (per cent crown dieback) and location within urban land uses (e.g. residential, industrial, parks) of each tree to determine a final cost. Our analysis relies on Australian tree species information, but average replacement costs, transplantable size and replacement prices are the default i-Tree values collected from the International Society of Arboriculture publications (Nowak *et al*. 2002).

3.4.2 Avoided stormwater run-off

In i-Tree, the annual avoided stormwater run-off attributable to trees is calculated by comparing hourly precipitation (ACT rainfall observed in 2010, the only year that also included the pollution data needed for the valuation of other ES) and total annual surface run-off volume with and without trees based on the i-Tree submodel developed by Mcpherson *et al*. (2000). For this analysis, we obtained avoided run-off costs from proposed projects to build stormwater wetlands or retention ponds in the ACT (Environment Division, Environment Planning and Sustainable Development, 2018). Hence, we can use the market value of a proposed alternative to infer the value of avoided stormwater run-off benefits of trees. The value of avoided stormwater run-off in this analysis is approximated by the average treatment cost per m^3 of stormwater. The average benefit of avoided run-off is \$1.25/m^3. As a reference, the benefit of avoided run-off in the United States is estimated to be \$2.26/m^3.

3.4.3 Carbon storage

The amount of carbon stored in above and below ground tree biomass was estimated using carbon yield formulas that account for tree health, growth conditions and species type. Based on recommendations of the ACT's Climate Change Council the value of the carbon stored in standing urban forests is approximated by the social cost of carbon ($SCCO_2$) emissions. The $SCCO_2$ is a monetary estimate of the climate change impact to multiple economic sectors (e.g. agriculture, real estate, energy consumption) due to additional carbon emissions (Interagency Working Group, 2016). The $SCCO_2$ used in this analysis is $65 per tonne of CO_2 (Revesz *et al.* 2017).

3.4.4 Pollution removal

Pollution and weather data for the year 2010 (the most recent data set available in the i-Tree database) were used to estimate the removal of ozone, nitrogen dioxide, particulate matter less than 2.5 microns (PM2.5), sulphur dioxide and carbon monoxide (USDA Forest Service, 2018). i-Tree relies on leaf area index and multi-layer canopy deposition models to estimate the flow of this service. The value of pollution removal is $22 per metric tonne for carbon monoxide, $4,300 per metric tonne of ozone, $641 per metric tonne of nitrogen dioxide, $234 per metric tonne of sulphur dioxide and $149,365 per metric tonne of (PM2.5) (USDA Forest Service, 2018). These values are based on international estimates of the health impacts of urban pollution (Nowak, Crane, and Stevens, 2006) adjusted by the 2018 urban population in Canberra estimated at 419,192 people (ABS, 2017).

3.4.5 Building energy savings and avoided energy emissions

Estimates of the seasonal effect of trees on building energy use in i-Tree are based on the distance and direction from each tree to the nearest building within a 20 m radius (USDA Forest Service, 2018). Energy effects are estimated using United States estimates (Nowak *et al.* 2017) for a region with similar climate, building types and landscape geography as Canberra, Australia. The net value of energy savings is based on a price of $2.98 per therm for heating, 2.831 cents per MJ cost of the second tier of residential gas use from ActewAGL for the period 2017–2018 (ActewAGL, 2017), and $0.25 per kWh of average residential electricity use (ICRC, 2018).

By reducing energy consumption, trees contribute to emission reductions from the energy sector. The emissions generated by fossil-fuel based power plants for the estimated energy savings are multiplied by the $SCCO_2$ to estimate the value of this service. For the scenario assessment, the value of avoided emissions gradually moves towards zero to approximate the impact of carbon-neutral electricity policy in Canberra, Australia (Environment Division, Environment Planning and Sustainable Development, 2019).

3.5 Data collection

Data for this research were obtained from multiple government agencies, CSIRO's databases, reports and peer-reviewed articles. Estimates of the current urban forest services are based on spatially explicit tree condition information collected between 2010 and 2012. Such data were updated to represent the characteristics of the urban forest in 2018 using tree cohort changes and 2012–2018 plantings and removals information. Tree data coupled with local socio-economic, pollution and climate information were used in the i-Tree Eco software (USDA Forest Service, 2018) to value key services provided by the urban forest. The i-Tree results were complemented with estimates of the health and property impacts of urban forests based on studies implemented in other Australian regions.

The extent, location and characteristics of irrigated open spaces were identified through spatially explicit data sets provided by the Australian Government. Current and projected management costs and benefits were estimated using local usage data and indirect benefits (e.g. higher property prices) based on research from other Australian cities. The scenario analysis of alternative management strategies relies on Benefit–cost Analyses to identify the net return of investments into urban forests and irrigated open spaces.

3.6 Scenario analysis

The objective of scenario analysis is to examine how the whole-of-life costs and benefits change from 2018 to 2125 for urban forests, and from 2018 to 2070 for IOSs, given different management decisions affecting those assets under projected socio-economic and climate change trend trajectories.

3.6.1 Public urban forests

Three scenarios of different removal and replanting strategies were assessed under projected climate change. These scenarios include (i) continuation of existing trend of tree loss (business as usual), (ii) maintaining current tree numbers and (iii) increasing tree canopy cover. We expect that under all the modelled scenarios tree plantings will aim at increasing the flow of ES, reducing management costs and externalities, and increasing tree canopy in socio-economically vulnerable areas. However, due to uncertainties associated with technological development, climate change impacts on urban vegetation and spatially explicit data on available space for new plantings, we use historical data and tree growth models to estimate future costs and benefits of the reconfigured urban forest.

Scenario 1. Business as usual (BAU). The proportion of trees at the end of their useful life expectancy (ULE) is gradually reaching critical levels (Brack, 2015). Consequently, the extent and flow of services from public forests is expected to decrease. In addition, a large number of dead trees could require increasingly frequent and expensive management. From 2013 to 2017, around 1700 trees were removed and 1300 trees were planted annually (pers. comm. TCCS, 2018). The removal of dead trees is based on reducing risks to people and people's assets, and replanting does not necessarily occur when and where trees are removed. Such net loss of 400 trees per year is modelled from 2018 to 2045 with tree removals continuing at 1700 per year from 2045 to 2125. Under these assumptions, the proportion of standing trees that have reached the end of the ULE is gradually increasing.

Scenario 2. Maintaining the current extent of the urban forests (Current extent). The health of public urban forests is declining and significant levels of tree removal and replanting are required to maintain their flow of ES (Brack, 2015). The distribution and composition of the urban forest are proactively managed to improve its resilience to climate pressures and to enhance their flow of ES. To maintain the overall condition and flow of services observed in 2018, trees at the end of their useful life are removed and similar numbers of trees are planted; that is, the objective is to maintain the tree stock observed in 2018. An underlying (non-modelled) assumption is that tree species selection under this scenario aims at achieving a more efficient configuration of the urban forest and that replanting prioritises a spatially balanced distribution of the urban forest.

Scenario 3. Expanding canopy cover to 30 per cent (TCC30 per cent). The distribution and composition of the urban forest are proactively managed to gradually increase tree canopy cover from 21 per cent to 30 per cent of publicly managed land (excluding nature reserves). Improvements in the extent and health of the asset increase its resilience to climate change impacts and enhance the provision of ecosystem services. Replanting and removals (based on useful life expectancy) target the development of a balanced distribution of trees age, size and species composition. Table 2 contains the parameterisation of the modelled public urban forest scenarios. For scenario analysis, we assume that all standing trees provide some ES. This assumption is not expected to have a significant impact in the analysis unless the proportion of death trees that have not been removed is larger than 3 per cent of the urban forest.

3.6.2 Irrigated open space

Similarly, we evaluate the implications of two alternative management strategies for irrigated open spaces assuming current trends in socio-economic, population and climate change projections.

Scenario 1. Business as usual (BAU). This scenario assumes that the current distribution and extent of irrigated open spaces does not change. Benefits are modelled based on property price increases, sports ground hires and recreational use.

Table 2 Summary of key parameters for the modelled public urban forests scenarios

Scenario specific (trees)	BAU	Maintaining the current extent	30% canopy cover by 2045
Interest rate	3%, 7% and 10%		
Climate change	Local warming of 2 °C by 2070		
Time horizon	2018-2125 (tree plantings only from 2018 to 2045)		
Tree replacement p.a.	1700 trees removed 1300 trees planted	Based on useful life expectancy (ULE) of trees	Based on ULE
Balanced tree distribution across suburbs	No	Yes	Yes
Scenario specific (irrigated open space):	**BAU**	**50% more**	
Expansion of IOSs cover within the study area	No	50% more	
Water availability	Not constrained	Not constrained	

Scenario 2. 50 per cent increase in the area of irrigated open spaces (50 per cent more IOS). In response to projected population growth, increasing average temperatures and increasing bushfire risks, the total area of irrigated open spaces increases 50 per cent by 2045 (around 240 additional hectares). The area and location of new irrigated open spaces target the mitigation of heat island effects, the reduction of bushfire spread risks, enhancement of amenity values and the promotion of active recreation in socio-economically vulnerable regions.

The cost of establishing and maintaining the new spaces is compared with potential recreational use benefits and increases in property value for residential properties located in the vicinity of the new assets. Table 2 contains a summary of scenario assumptions for the analysis of irrigated open spaces.

4. Results and discussion

The following sections present a summary of the findings from the ecosystem services valuation and scenario analysis for trees and irrigated open spaces.

4.1 Current flow and value of benefits

Around 236,355 m^3 of stormwater run-off was intercepted by urban forests in 2018 at a value of $295,402. The benefits of removing around 154 tonnes of pollutants per year (ozone, carbon monoxide, nitrogen dioxide, particulate matter less than 2.5 microns) in that year represented savings on health expenditures in the order of $863,382. Tree shade helps reduce ambient temperature and provide wind protection for buildings. The combined effect of those services was estimated to reduce energy consumption around 120,369

MWh in 2018, which represented savings in energy bills of around \$9.1 million. The avoided energy emissions (33,319 tonnes of CO_2) had a social benefit of \$514,392. This value could decrease given the transition to carbon-neutral electricity and gas in the ACT. Carbon sequestration in tree biomass (around 39,068 tonnes of CO_2) during 2018 provided a benefit of \$2.15 million. Average tree benefits are provided in Table 3. The value of the carbon accumulated during the lifespan of trees standing in 2018 was estimated at \$56.55 million (around 1.03 million tonnes of CO_2). This represents an average of 29 kg of CO_2 per m^2 of tree cover, which is consistent with studies from 28 U.S. cities that report an average of 21 kg of CO_2 (Nowak *et al.* 2013).

In comparison with findings from Soares *et al.* (2011), their i-Tree estimates of ecosystem services benefits from energy savings (\$6.20/tree), CO2 reduction (\$0.33/tree), air pollutant deposition (\$5.40/tree) stormwater run-off reduction (\$47.80/tree) and increased real estate value (\$144.70/tree) are quite different from our findings. This is expected given the contextual differences, for example climate, tree species planted, household energy costs and land values, between Lisbon, Portugal and Canberra, Australia. Even within Australia, contextual differences between Canberra and other cities render it difficult to make comparisons.

As for IOSs, these types of spaces provide a flow of benefits to the city via higher land rates of properties that are in close proximity to sports ovals and IOSs. We estimated that around 97,000 homes are within the premium distance (740 metres) to a sports ground, and around 62,500 homes are within the premium distance (1.8 kilometre) to an IOS. There are also high recreational benefits derived from using sports ground and other IOSs.

4.2 Scenario analysis of flows and values of the urban forest

Planting and removal decisions under the BAU scenario are unrelated to the ULE of the trees in the urban forest. From 2018 to 2045, a net loss of 400 trees is assumed (Figure 4a) with annual removal of 1,700 trees continuing from 2046 to 2125. The net change in tree numbers of both the current extent and increasing tree canopy cover to 30 per cent scenarios is driven by the number of trees reaching the end of their ULE. From 2018 and 2071, tree removals are the same for both scenarios. Afterwards, tree removal is larger for the former scenario due to replanted trees from 2018 to 2045 gradually reaching the end of their ULE.

Planting of around 246,000 new trees would be needed to reach the target 30 per cent canopy cover by 2045 (Figure 4b). This represents an increase of around one-third of the number of standing trees in 2018. Under the Maintaining the current extent of the urban forest scenario the removal of dead trees and new plantings could result in a gradual increase in tree canopy cover of around half the change in the Increasing tree canopy cover scenario (Figure 4c). The BAU scenario indicates increasing tree canopy cover until around 2025, while leaf biomass increases until around 2040 (Figure 4d).

Table 3 Estimated ecosystem services of public forests in 2018

Benefits	Biophysical flows	Total value (2018 $)	Per tree basis (2018 $)
Carbon sequestration[1]	39,068 tonnes of CO_2	2,145,011	2.79
Avoided stormwater run-off[2]	236,355 m^3	295,402	0.38
Pollution removal[3]	154 tonnes	863,382	1.12
Building energy savings[4]	120,369 MWh	9,096,938	11.85
Avoided energy emissions[5]	33,319 tonnes of CO_2	514,392	0.67
Land rate premium[6]	105,518 houses	14,191,296	18.98
Cooling effect (avoided heat-related morbidity) [7]	Assumed 3 hot days	12,644	0.01

[1]The annual CO2 sequestered in tree biomass was valued using the social cost of carbon estimate recommended by the ACT's Climate Change Council.
[2]Stormwater intercepted in tree biomass valued using the average cost per m3 of water treatment in the ACT (pers.comm. ACT Environment, Planning and Sustainable Development Directorate, 2018).
[3]Ozone, carbon monoxide, nitrogen dioxide, particulate matter less than 2.5 microns removed by trees estimated using ACT pollution and climate data for 2010 (latest data set available in i-Tree). These values are based on international estimates of the health impacts of urban pollution adjusted by the 2018 urban population in the ACT (ABS, 2017).
[4]Building energy savings from micro-climate effects generated by trees within a 20 m radius of buildings. Energy savings were valued using average residential prices of gas and electricity.
[5]CO2 emissions avoided in the energy sector due to energy savings valued using the social cost of carbon.
[6]Land rate premium on detached homes with verge trees estimates is based on tree premium estimates in Perth, and land value data in the ACT
[7]Health benefits (from avoided hospital visits due to heat-related morbidity) from increase canopy cover to create cooling effects are based on hospital admission data from Brisbane, and hospital costs in the ACT.

Such increases are due to the growth of trees that have not reached the end of their ULE.

A significant difference across the modelled scenarios is that all standing trees in the Maintaining the current extent and Increasing canopy cover scenarios have positive ULE. However, under the BAU scenario not all dead trees are replaced. This generates a reduction in the number of trees able to provide ES of around one-half of the 2018 tree stock. In addition, the growing number of dead trees increases risks to people and property, and gradually increases the investment needed for them to be replaced.

The forecasting component of i-Tree Eco provides estimates of changes in tree stock, canopy cover, biomass, leaf area and other indicators of urban forest vegetation. Such software directly estimates changes in the value of pollution removal (Figure 5a) and carbon sequestration (Figure 5c). Annual changes in leaf area from 2018 to 2125 were used to estimate annual changes in the baseline 2018 value of avoided stormwater run-off and energy savings (Figure 5b,e), since those services are mostly influenced by non-woody tree biomass. A similar approach was applied to model changes in the value of avoided energy emissions but considering a gradual transition towards energy neutrality from 2018 to 2045 (Figure 5d). Changes in the capital value of the urban forest from 2018 to 2125 were approximated using estimates of change in tree biomass (Figure 5f).

From 2018 to 2045, under BAU the value of pollution removal decreases around 5 per cent, and 26 per cent for avoided stormwater run-off and energy savings. The value of carbon sequestration increases around 65 per cent, despite a reduction in tree biomass growth, due to the increasing social cost of additional carbon emissions under global warming. The value estimates of the Maintaining the current forest extent scenario indicate a 21 per cent increase for pollution removal services, 76 per cent for energy savings and stormwater reduction and 82 per cent for carbon sequestration. The increasing tree canopy scenario generates the largest value gains with a 40 per cent increase for pollution removal, 142 per cent for energy savings and avoided stormwater run-off and 102 per cent for carbon sequestration. Under all scenarios, the value of avoided energy emissions is zero after 2045.

Due to the growth of young trees, the capital value of urban forests increases around 9 per cent for the BAU scenario. For the maintaining the current extent and increasing tree canopy cover scenarios, the increase is around 16 per cent and 32 per cent, respectively. Long-term tree growth dynamics generate increases in ES provision and capital asset value even under the assumption of no replanting after 2045 for the two scenarios that gradually replace or increase tree stocks.

4.3 Benefits and costs of management scenarios

We conducted a series of BCAs to assess how the outcomes of each scenario compare. The main output of interest is the BCR. Table 4 presents the BCR

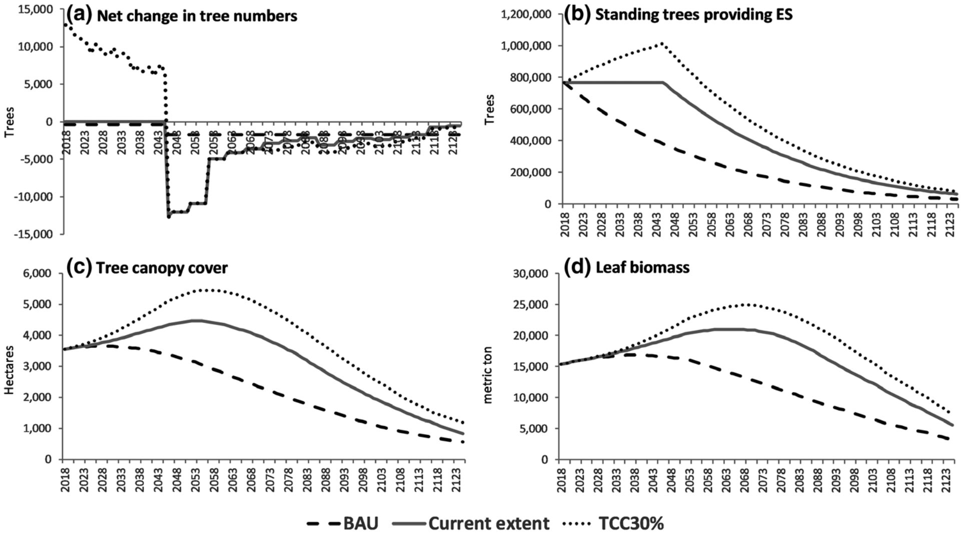

Figure 4 Annual net change in tree stock, standing forests, tree canopy and leaf biomass. *Notes*: The scenarios represent tree planting strategies from 2018 to 2045. In 2045, Figure 3a shows a significant decrease in tree numbers for the Current extent and TCC30% scenarios due to old trees reaching the end of their useful life and assuming zero replanting. The BAU scenario does not assume the removal of all trees at the end of their useful life. Therefore, the net tree loss post-2045 is smaller in this scenario. The number of trees that need to be removed is around 10,000 between 2045 and 2055, and around 2,500 from 2055 to 2080. The impact of assuming zero tree planting after 2045 is also reflected in the trends observed in Figure 3b.

for the three urban forest management scenarios at different discount rates. Note for example that the BCR for BAU scenario, assuming 3 per cent discount rate, is on average 0.65, while the BCR for a 10 per cent discount rate is on average 1.13. The BCR at 3 per cent discount rate is worse than at 10 per cent because the upfront costs of tree planting is high, while the ecosystem services benefits are realised in later years. In any case, depending on the discount rate chosen, the average BCR for the BAU scenario is between 0.65 and 1.13.

To examine how much the costs and benefits translate to cost per person, we examined the net cost per person per week for each of the three tree management scenarios during the 2018–2045 time horizon. The net cost is the total cost minus the total ecosystem services benefits. The current population in the ACT is 420,321 and is estimated to reach 614,633 by 2045 (Chief Minister, Treasury and Economic Development Directorate, 2019). Table 5 presents the number of trees in 2018 and 2045 for the three tree management scenarios. Trees per person decline under all scenarios during 2018–2045, as does cost per person per week (in 2018 $). Under the Business as usual scenario, the net cost to taxpayers is negligible (effectively $0), as the cost under the Business as usual scenario is low. However, the decline in the number of trees is substantial. A net loss of 387,946 trees is expected by 2045

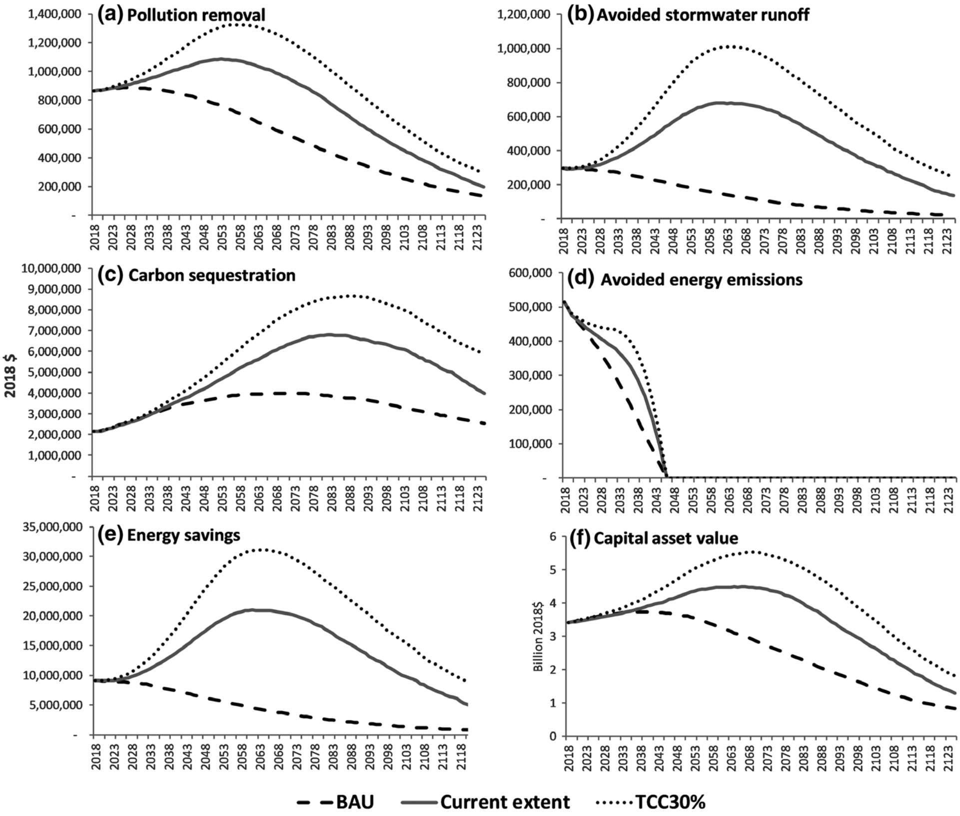

Figure 5 Ecosystem services and capital asset value under modelled urban forest management scenarios (2018–2125). Plantings are assumed to stop under all management scenarios by 2045.

under the Business as usual scenario, resulting in an average number of trees per person of 0.62 by 2045 (a drop from 1.83 trees per person in 2018). This situation can be avoided at an additional cost of $0.71 per person per week in 2018 (declining to $0.51 by 2045) under the Maintaining the current extent of the forest scenario. For an extra $1.05 per person per week in 2018 (declining to $0.70 by 2045) the tax payer funds a net increase of 245,984 trees under the Increasing tree canopy cover to 30 per cent scenario, which is 633,930 trees more than BAU in 2045.

Table 6 presents the NPV of the benefits and costs of the two irrigated open space management scenarios. The benefit–cost ratio for both cases is greater than one, indicating a situation where benefits outweigh costs. The scenario where 50 per cent more irrigated open spaces is planned for in 2045 shows a slightly lower benefit–cost ratio than the business as usual case. Regardless of which discount rate is used, the BCR of the two management scenarios both show a ratio of greater than 2. Hence, the findings are very robust to any discount rate assumption proposed in this analysis.

Table 4 Results from the sensitivity analysis on the discount rate for the BAU and alternative scenarios for public trees (NPV $ 2018–2125)

	Discount rate	Total cost ($M)	Total benefit ($M)	BCR		
				Min	Mean	Max
BAU	3%	$774.56	$502.64	0.56	0.65	0.74
	7%	$464.12	$490.22	0.96	1.05	1.13
	10%	$361.69	$414.84	1.06	1.13	1.26
Maintain	3%	$1,342.33	$1,375.75	0.98	1.02	1.07
	7%	$707.39	$720.84	1.00	1.02	1.11
	10%	$511.37	$515.73	0.99	1.01	1.09
30% Canopy cover	3%	$1,659.47	$1,977.11	1.15	1.19	1.25
	7%	$867.46	$1,000.19	1.11	1.15	1.19
	10%	$624.50	$669.63	1.05	1.07	1.14

Table 5 Net cost per person for each tree management scenario (2018 $)

	No. of trees providing ecosystem services		Net cost/person/YEAR		Net cost/person/WEEK	
	2018	2045	2018	2045	2018	2045
BAU	767,636	379,690	$37.33	$0.85	$0.72	$0.02
Maintain	767,636	767,636	$36.75	$26.40	$0.71	$0.51
30% Canopy cover	767,636	1,013,620	$54.79	$36.22	$1.05	$0.70

Currently, the average area of IOS per person is around 11.52 m^2 per person (see Table 7). With the urban population expected to reach over 614,633 by 2045 (Chief Minister, Treasury and Economic Development Directorate, 2019), the average area per person will drop to 7.87 m^2. However, at an additional cost of $0.13 per week ($1.29–$1.16) in 2018, dropping down to $0.09 ($0.88–$0.79) per person per week in 2045, the area of IOSs could be increased by 50 per cent. This could increase the average area of IOS per person to 11.81 square metres in 2045.

4.4 Policy implications

The ACT Government's '*Canberra's Living Infrastructure Plan: Cooling the City*' has set a tree canopy target of 30 per cent by 2045 (ACT Government, 2019). Our analysis suggests that the ACT needs to plant over 450,000 trees over the next 25 years to reach this target. At this point, the ACT has announced funding for 25,000 trees to be planted in the first stage of this aspiration (ACT Government, 2020) with more tree planting expected to be funded in the future. In any case, there are two main challenges to tree planting, which are space (i.e. limitations of planting trees around existing built infrastructure including buildings, road networks and easements) and funding (i.e. to support the planting, establishment, maintenance and

Table 6 Results from the sensitivity analysis on the discount rate for the BAU and alternative scenarios for IOSs

	Discount rate	Total cost ($M)	Total benefit ($M)	BCR		
				Min	Mean	Max
BAU	3%	$432.16	$1,142.72	2.51	2.64	2.77
	7%	$236.43	$579.81	2.32	2.45	2.58
	10%	$173.87	$411.07	2.25	2.36	2.48
50% more IOS	3%	$547.53	$1,339.26	2.32	2.44	2.56
	7%	$270.40	$625.91	2.19	2.31	2.44
	10%	$188.43	$427.87	2.14	2.27	2.38

Table 7 Cost per person for each of the two IOSs management scenarios

	m^2 per person		Cost per person		Cost/person/ week	
	2018	2045	2018	2045	2018	2045
BAU	11.52	7.87	60.38	41.29	1.16	0.79
50% more IOS	11.52	11.81	67.27	46.00	1.29	0.88

removal of trees). Although irrigated open spaces provide high BCR, space availability within the city may be a limitation also. One of the ACT's strategy to deal with limitations of space is to consider other forms of living infrastructure that may work well within the constraints of existing infrastructure. These alternative forms of living infrastructure include green roofs and green walls (ACT Government, 2019).

In terms of funding, our analysis has shown that green infrastructure has a significant capital asset value and provides important direct and indirect benefits to the city. These results can guide gradual investments to avoid asset deterioration and the challenges of replacing large proportions of the living infrastructure that have reached or exceeded the end of their useful life. The scope of this study was limited to whole-of-life costs being borne by the Government and does not include consideration of innovative financing models whereby costs are shared by private organisations and households. For example, Friends of the Urban Forest, a not-for-profit organisation work with the City and Country of San Francisco and the community to plant trees and vegetation on public nature strips (www.fuf.net). There appear to be a number of other examples already in the ACT including: ACT businesses investing in accredited carbon offset schemes which funds reputable tree planting projects as part of their corporate social responsibility goals to reduce their carbon footprint. Universities in the ACT, such as the Australian National University (ANU) is investing and maintaining 12,000 trees on its campus. A number of ACT public and private schools have invested in large scale on campus living infrastructure projects entirely funded by the school community. Additionally, the ACT Government is partnering with ACT Greening Australia, the community and citizen scientists to plant and maintain 300,000 tree seedlings with help of 15,000 volunteers. Approximately 35 ACT urban 'Parkcare' volunteer groups that help to plant and maintain trees and expand and maintain ACT living infrastructure assets via the 'Adopt a Park' programme.

4.5 Contributions and caveats

Our analysis integrates highly detailed cost information and comprehensive valuation of ecosystem services from green assets using the SEEA framework and accounting for input data uncertainty through stochastic cost-benefit analysis. This approach could inform more efficient allocation of resources towards the configuration of more resilient and liveable urban spaces. In any case, we acknowledge certain limitations to the generalisability of these research findings because our ES benefits estimations are based on Canberra's weather and climate patterns (Köppen-Geiger climate zone Cfb) and tree species that are mostly native to Australia. We also acknowledge that several ES benefits of public trees and IOSs were difficult to value due to insufficient data or lack of accepted methodologies. Omitted benefits include the following: species diversity, habitat and habitat corridors; avoided stormwater run-off (for IOSs); building energy savings (for IOSs); mental health and well-being benefits; tourism, cultural and symbolic values; and noise reduction. Inclusion of the value of such services will increase the benefit–cost ratio of the assessed green assets, which will further enhance the case for investing on those types of urban infrastructure.

Non-market valuation methods could be applied to reduce some of the knowledge gaps limiting a more comprehensive valuation of ES benefits of public trees and IOSs. Additionally, mapping the distribution of stocks and flows of ES could help identify regions where new green assets could provide large benefits to urban dwellers (Serna-Chavez, *et al.* 2014). Modelling spatiotemporal changes in urban built and green infrastructure could also contribute to more robust assessments of the potential of green infrastructure to influence urban microclimates, energy demand, carbon sequestration and other ecosystem services (Schandl, *et al.* 2020).

5. Conclusion and recommendations

Our analysis suggests that out of the set of assessed tree management scenarios, the tree management scenario that aims to expand tree canopy cover has the highest benefit–cost ratio. Sensitivity analyses suggest that this benefit–cost ratio is robust to uncertainty in the magnitude of the cost and benefit estimates used in the analysis. The two modelled scenarios for irrigated open spaces provide evidence of the net social benefits of this type of asset.

A number of lessons were learned from this analysis of the whole-of-life benefits and costs of urban forests and irrigated open spaces. Firstly, there is a lack of appropriate biophysical, socio-economic and health data to accurately model the costs and benefits of both public urban trees and irrigated open spaces. Updated spatially explicit information on the number, location and condition of publicly managed trees is urgently needed to improve the estimation of costs and benefits and facilitate the long-term management of the urban forest. Secondly, research is needed to estimate the value to urban residents and visitors of non-modelled ecosystem services (including mental health and well-being, tourism and cultural values, species diversity, habitat and habitat corridors, and noise reduction). Empirical analysis of the benefits of urban living infrastructure by ecosystem service type (i.e. provisioning, regulating, cultural and supporting) or by type of green infrastructure (e.g. urban forests, irrigated open spaces) is required to support long-term city planning and investments. Since covering the identified data and research deficiencies would be resource intensive, an assessment of the trade-offs and benefits of data acquisition and valuation studies should be made to prioritise the generation of information that supports improved city asset management, liveability and adaptation to climate, demographic and economic pressures.

From this research, we recommend accounting for stochasticities in the valuation of ecosystem services benefits and costs of urban green infrastructure. Such an approach could reduce the impact of uncertainty in input data and control for people's heterogeneous perception and valuation of the services provided by urban green infrastructure. Urban intensification trends under changing climatic conditions highlight the relevance of long-term assessments of urban policies to ensure timely investments and planning decisions towards sustainable and resilient cities.

Data availability statement

Data available on request due to privacy/ethical restrictions. The data that support the findings of this study are available from [third party – the ACT Government]. Restrictions apply to the availability of these data, which were used under licence for this study. Data available on request from the authors.

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