RESEARCH REPORT

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Urban trees and their ecosystem services

A review of the current state of knowledge on urban trees and carbon storage, sequestration, stormwater runoff attenuation, and urban heat island mitigation

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Abstract

Urban forests and trees provide a range of benefits, called ecosystem services. A subset of these are regulating services, including carbon storage and sequestration, stormwater runoff attenuation, and urban heat island mitigation. The focus of this report was to quantify the degree to which trees contribute to these regulating services. Moreover, the factors that influence trees' contribution were explored. These aims were achieved by reviewing the scientific literature pertaining to these topics. The review methodology resulted in roughly 100 scientific articles split across the three regulating services. These articles were used to quantify and qualify the role of trees with respect to carbon storage and sequestration, stormwater runoff attenuation, and urban heat island mitigation.

The review showed that above-ground carbon storage density for trees averaged 11.5 kg of carbon per square meter of tree canopy cover (range 1.7–28.9 kg C m^{-2}), while total carbon (above and below ground) storage density for trees had an average value of 7.95 kg/m^2 (range 0.8–36.1 kg C m^{-2}). Trees also reduced stormwater runoff, primarily by intercepting between 9% and 61% of total rainfall. Finally, ground surface temperatures were 0.6–22.8°C and air temperatures were 0.8–7° cooler beneath trees than in surrounding non-treed environments.

The variation in carbon storage and sequestration, stormwater runoff attenuation, and urban heat island mitigation was shown to be related to the quantity of trees (e.g., tree density or canopy cover), their configuration (fragmentation, clustering), and their structural characteristics (e.g., height, crown volume and shape, stem diameter, leaf area or density, wood density), the latter of which is influenced by tree species and age. More trees or tree cover, in clusters, with greater total biomass and wood density, will improve the regulating services researched in this report. In contrast, development intensity and impermeable surfaces (buildings and/or pavements), which are associated with reduced tree cover, threatened the provision of carbon storage and sequestration, stormwater runoff attenuation, and urban heat island mitigation by trees.

1. Urban Forests, Trees and Their Ecosystem Services

Urban forests are broadly defined to include trees, shrubs, herbaceous vegetation, other associated plants and fungi, as well as the soil that supports them. However, for the purposes of this report, a narrow definition is used, focusing only on trees in urban areas.

Rapid urbanisation is needed to support the increasingly large proportion of people choosing to live in cities and towns. In the past decades, researchers and policy makers have begun to explore and evaluate the potential of urban trees to provide benefits to these urbanised populations (Roy, Byrne, & Pickering, 2012).

The benefits provided by urban forests are collectively referred to as ecosystem services, though more recently, the term 'nature-based solutions' has also been used in the scientific literature (Escobedo, Giannico, Jim, Sanesi, & Lafortezza, 2019). Broadly-speaking, ecosystem services can be categorised as provisioning, cultural, supporting, and regulating (Millenium Ecosystem Assessment, 2005). Regulating services are able to moderate natural phenomena and are the focus of this review. Specifically, this review will explore and quantify the effect urban trees have on carbon storage and sequestration, attenuating stormwater runoff, and mitigating the urban heat island effect.

2. Literature Review Methods

A review of the scientific literature was undertaken using the Scopus database and Google Scholar. Search strings were designed to return journal articles and reviews pertaining to urban trees or urban forests (specifically excluding articles on urban greenspaces, which include, but are not limited to trees) and the three regulating services that form the basis for this report, that is carbon storage and sequestration, stormwater mitigation, and the urban heat island effect. A scan of article titles and subsequent review of article abstracts identified a subset of articles that were included in the formal review. While the search was initially limited to the last decade of scientific literature, that was expanded through backward chaining; this is where an article from the past decade cited a previous article. Through the process of identifying an initial subset of articles, formally reviewing them for suitability, then using backwards chaining, a total of 27 articles were found related to urban trees and carbon storage and sequestration, 35 articles related to stormwater mitigation, and 37 articles related to the urban heat island effect.

3. Urban Trees and Carbon Storage and Sequestration

3.1. Overview and Concepts

During photosynthesis, trees sequester carbon dioxide (CO_2) from the atmosphere. Energy provided by sunlight is used to combine CO_2 with water to produce oxygen and carbohydrates, the latter of which are subsequently used to support tree function and growth, i.e., increase biomass. The sequestration and storage of CO_2 from the atmosphere is one way to reduce anthropogenic climate change and urban forests can meaningfully contribute to this objective (Nowak & Crane, 2002).

3.2. Synthesis of Reviewed Literature

Studies on urban forest carbon storage and sequestration identify variability in results, but also important trends (Table 1). Some studies only measured above-ground carbon storage density, whereas most reported total (above-ground and below-ground) carbon storage density. Carbon density is a measure of how much carbon is stored (or sequestered) within the tree per square meter of canopy cover.

Above-ground carbon storage density was reported for five cities and ranged between 1.7–28.9 kg of carbon per square meter of tree canopy cover (kg C m^{-2}), with an average value of 11.5 kg C m^{-2}. Total carbon storage density was reported for 38 cities, with an average value of 7.95 kg C m^{-2} and a range of 0.8–36.1 kg C m^{-2} (Table 1). The reason that total carbon storage density is lower than above-ground carbon storage density is because below-ground carbon storage is typically much lower than above-ground carbon (Cairns, Brown, Helmer, & Baumgardner, 1997), so including it will reduce the whole tree carbon storage density.

It is important to understand that the reported carbon sequestration and storage density values are modelled, rather than measured. Things like tree height and stem diameter may be measured directly, but these are then used in mathematical formulas (called allometric formulas) to estimate above-ground or total carbon density. The allometric formulas used differ from study to study and are generally based on the best science available at the time of the study. As a consequence, we should be wary of comparing values across studies. This also helps us interpret the changes in carbon density storage that we see within individual cities. For example, many of the American cities included in the Nowak and Crane (2002) study were also included in the Nowak, Greenfield, Hoehn, and Lapoint (2013) study, a decade later. Many of those cities show reduced carbon storage density due to a combination of improvements in the allometric formulas and better estimates of tree canopy cover due to higher resolution aerial/satellite imagery.

Table 1 – Studies showing carbon sequestration and storage density.

Locality	**Sequestration density (kg C m^{-2} of canopy per year)**	**Storage density (kg C m^{-2} of canopy)**	**Above-ground or total carbon**	**Source**
Arlington, TX		6.37	Total	(Nowak et al., 2013)
Atlanta, GA		6.63	Total	(Nowak et al., 2013)
Atlanta, USA		9.7	Total	(Nowak & Crane, 2002)
Auckland, NZ	0.17		Total	(Schwendenmann & Mitchell, 2014)
Auckland, NZ		11.175	Above	(V. Wang & Gao, 2019)
Baltimore, MD		8.76	Total	(Nowak et al., 2013)
Baltimore, USA		10	Total	(Nowak & Crane, 2002)
Boston, MA	0.05		Above	(Trlica, Hutyra, Morreale, Smith, & Reinmann, 2020)
Boston, MA		7.02	Total	(Nowak et al., 2013)
Boston, MA		9.1	Total	(Nowak & Crane, 2002)
Brisbane, Australia		11.09	Above	(Mitchell et al., 2018)
Casper, WY		6.97	Total	(Nowak et al., 2013)
Charlotte, NC		5.36	Total	(Godwin, Chen, & Singh, 2015)
Chicago, IL		6.03	Total	(Nowak et al., 2013)
Chicago, IL		12.9	Total	(Nowak & Crane, 2002)
Freehold, NJ		11.5	Total	(Nowak et al., 2013)
Gainesville, FL		6.33	Total	(Nowak et al., 2013)
Golden, CO		5.88	Total	(Nowak et al., 2013)

Hamburg, Germany		2.74	Total	(Dorendorf, Eschenbach, Schmidt, & Jensen, 2015)
Hartford, CT		10.89	Total	(Nowak et al., 2013)
Indiana, USA		8.8	Total	(Nowak et al., 2013)
Jersey City, NJ		4.37	Total	(Nowak et al., 2013)
Jersey City, NJ		4.4	Total	(Nowak & Crane, 2002)
Kansas, USA		7.42	Total	(Nowak et al., 2013)
Leicester, England		28.86	Above	(Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011)
Lincoln, NE		10.64	Total	(Nowak et al., 2013)
Los Angeles, CA		0.815	Total	(McPherson, Xiao, & Aguaron, 2013)
Los Angeles, CA		4.59	Total	(Nowak et al., 2013)
Melbourne, Australia	0.0218		Total	(Brack, 2002)
Midwest, USA		11.22	Total	(Schmitt-Harsh, Mincey, Patterson, Fischer, & Evans, 2013)
Milwaukee, WI		7.26	Total	(Nowak et al., 2013)
Minneapolis, MN		4.41	Total	(Nowak et al., 2013)
Moorestown, NJ		9.95	Total	(Nowak et al., 2013)
Morgantown, WV		9.52	Total	(Nowak et al., 2013)
Nebraska, USA		6.67	Total	(Nowak et al., 2013)
New York, NY		7.33	Total	(Nowak et al., 2013)
New York, NY		7.3	Total	(Nowak & Crane, 2002)
North Dakota, USA		7.78	Total	(Nowak et al., 2013)
Oakland, CA		1.1	Total	(Nowak, 1993)
Oakland, CA		5.24	Total	(Nowak et al., 2013)
Oakland, CA		5.2	Total	(Nowak & Crane, 2002)
Omaha, NE		14.14	Total	(Nowak et al., 2013)
Philadelphia, PA		6.77	Total	(Nowak et al., 2013)
Philadelphia, PA		9	Total	(Nowak & Crane, 2002)
Roanoke, VA		9.2	Total	(Nowak et al., 2013)
Sacramento, CA		1.54	Total	(McPherson et al., 2013)
Sacramento, CA		7.82	Total	(Nowak et al., 2013)
Sacramento, CA		36.1	Total	(Nowak & Crane, 2002)

San Francisco, CA	9.18	Total	(Nowak et al., 2013)
Scranton, PA	9.24	Total	(Nowak et al., 2013)
Seattle, WA	14	Above	(Hutyra, Yoon, & Alberti, 2011)
South Dakota, USA	3.14	Total	(Nowak et al., 2013)
Syracuse, NY	8.59	Total	(Nowak et al., 2013)
Syracuse, NY	9.4	Total	(Nowak & Crane, 2002)
Tennessee, USA	6.47	Total	(Nowak et al., 2013)
Washington, DC	8.52	Total	(Nowak et al., 2013)
Woodbridge, NJ	8.19	Total	(Nowak et al., 2013)
Xiamen, China - suburban	1.705	Above	(Ren et al., 2011)
Xiamen, China – urban	2.076	Above	(Ren et al., 2011)

The review identified some key factors that influence carbon sequestration and storage density. Studies identified tree characteristics that affected carbon storage or sequestration, including species (McPherson et al., 2013; Schwendenmann & Mitchell, 2014), wood density (McPherson et al., 2013), tree size (Mitchell et al., 2018; Nowak & Crane, 2002; Vincent Wang & Gao, 2020) and age (Schmitt-Harsh et al., 2013; Vaughn, Hostetler, Escobedo, & Jones, 2014), leaf area and density (Mitchell et al., 2018). Simply put, carbon storage was greatest in species with high wood densities that had large biomass (primarily wood biomass, but also leaf/needle biomass) and were able to live into maturity.

Carbon storage and sequestration were also greatest in cities or areas with more canopy cover (Ma et al., 2021), greater tree density (Nowak & Crane, 2002), and lower forest fragmentation (Godwin et al., 2015; Mitchell et al., 2018). Fragmentation refers to the relatively greater value of groups of trees, rather than isolated trees, the latter of which still provide carbon storage and sequestration, just not as effectively as groups of trees.

In addition to tree-related characteristics, the studies clearly showed that carbon storage density was affected by development intensity, whereby greater development intensity was associated with lower carbon storage and sequestration densities (Dorendorf et al., 2015; Godwin et al., 2015; Hutyra et al., 2011; Ma et al., 2021; Mitchell et al., 2018; Sun, Xie, & Zhao, 2019).

4. Urban Trees and Stormwater Runoff Attenuation

4.1. Overview and Concepts

Impervious surfaces reduce the ability of rainfall to infiltrate into the soil and increase the speed at which it runs off the surface. This has impacts on local hydrological cycles, including increasing peak discharges, the incidence and duration of flooding, and water quality (Jacobson, 2011; Tsihrintzis & Hamid, 1997).

Urban trees and forests attenuate stormwater runoff by intercepting and storing rainfall in their canopies. This intercepted rainfall either returns to the atmosphere through evaporation, or reaches the ground more slowly as a result of stemflow or throughfall (Kuehler, Hathaway, & Tirpak, 2017). Trees also limit runoff by promoting infiltration into the soil via root channels (Johnson & Lehmann, 2006). Once rainfall has infiltrated into the soil, tree roots absorb it and that water is used to support growth and function, eventually being returned to the atmosphere via transpiration (loss of water vapour from the tree back into the atmosphere via open stomata during photosynthesis). Thom, Szota, Coutts, Fletcher, and Livesley (2020) showed that street trees in Melbourne, Australia transpired the equivalent of 3.4 mm of rainfall per m^2 of tree canopy per day.

4.2. Synthesis of Reviewed Literature

Studies on the effect of urban forests on stormwater runoff attenuation were rare, perhaps because of the complexity of directly measuring urban runoff in-situ. One study was able to undertake a direct measurement at the scale of a city street (Selbig et al., 2022). In that study, all street trees were removed due to an infestation from the invasive emerald ash borer (*Agrilus planipennis*), providing the opportunity to measure runoff before and after tree removal. After tree removal, runoff increased, on average, by approximately 4%, but no changes to peak discharge were detected. It was estimated that trees resulted in 66 fewer litres of runoff per m^2 of canopy during the 5 months of measurement (Selbig et al., 2022). The previous result is consistent with another study that explored the impact of trees on stormwater runoff. In that study, researchers used statistical modelling to estimate that trees caused a 2.4% reduction in stormwater runoff (Zölch, Henze, Keilholz, & Pauleit, 2017). One other study also modelled how stormwater runoff from extreme rainfall events and peak discharge rates decreased with increasing tree canopy cover at catchment scales (Loperfido, Noe, Jarnagin, & Hogan, 2014).

Other studies that quantified the effect of tree canopy on stormwater did so by measuring rainfall interception. Rainfall interception was measured in all reviewed studies, clearly identifying the important role played by urban trees in mitigating stormwater runoff. While interception was consistently identified, the scale of the effect was highly variable, ranging between 9% and 61% of total rainfall (Table 2).

Table 2 – Studies showing rainfall interception by tree canopy

Locality	**Interception (% of rainfall)**	**Interception (mm of rainfall)**	**Source**
Vancouver, Canada	49.1–60.9	20.4–32.3 mm	(Asadian & Weiler, 2009)
Raleigh, USA	9.1–21.4		(Inkiläinen, McHale, Blank, James, & Nikinmaa, 2013)
Lab experiment		0.36–0.63 mm	(Li et al., 2017)
Melbourne, Australia	29–44		(Livesley, Baudinette, & Glover, 2014)
San Juan, Puerto Rico	16.7–22.7		(Nytch, Meléndez-Ackerman, Pérez, & Ortiz-Zayas, 2019)
Oakland, USA	14.3–27		(Xiao & McPherson, 2011)
Sacramento, USA	11.1		(Xiao, McPherson, Simpson, & Ustin, 1998)
Davis, USA	15–27		(Xiao, McPherson, Ustin, Grismer, & Simpson, 2000)

Rainfall interception was influenced by leaf and plant surface area (Baptista, Livesley, Parmehr, Neave, & Amati, 2018; Livesley et al., 2014), canopy structure (Asadian & Weiler, 2009; Xiao & McPherson, 2011), and tree species (Nytch et al., 2019; Xiao & McPherson, 2011; Xiao et al., 2000). In general, species traits and canopy structure resulting in greater leaf or needle density and surface area resulted in greater rainfall interception. In addition to these tree characteristics, interception was also influenced by rainfall intensity and duration (Asadian & Weiler, 2009), as well as wind speed (Nytch et al., 2019). The effectiveness of rainfall interception by tree canopy was greatest during short, low-intensity storms and lowest as rainfall volume and intensity increased (Kuehler et al., 2017; Qin, 2020; Xiao et al., 1998). The preceding studies are indirectly related to stormwater runoff attenuation as intercepted rainfall is less likely to contribute to runoff since it either evaporates into the atmosphere or reaches the soil slowly via stemflow/throughfall, where infiltration is likely if the surface is permeable.

5. Urban Trees and Urban Heat Island Mitigation

5.1. Overview and Concepts

Temperatures in cities are often higher than in surrounded rural areas (Bowler, Buyung-Ali, Knight, & Pullin, 2010). This so-called 'urban heat island effect' is due to the differing properties of vegetated and built environments. Materials in built environments (e.g. bricks, asphalt pavements, dark roofing tiles or corrugated iron) often have low albedo, meaning they absorb sunlight and store heat. In contrast, trees generally have high albedo, meaning they reflect more radiation and do not store heat. Moreover, their canopies provide shade and their leaves or needles transpire, thereby cooling the surrounding air and improving human thermal comfort (Meili et al., 2021). Interestingly, due to transpirational cooling, trees provide greater thermal comfort than artificial sources of shade (Shashua-Bar, Pearlmutter, & Erell, 2011).

Because of these vegetation characteristics, trees can alleviate people's discomfort during periods of heat stress (Lafortezza, Carrus, Sanesi, & Davies, 2009) and their mitigation effects are greatest in close proximity to tree canopy (Hwang, Wiseman, & Thomas, 2015; Misni, Baird, & Allan, 2013).

5.2. Synthesis of Reviewed Literature

The review identified two types of study that related tree canopy and temperatures in urban areas. The first type employed direct measurement of temperature beneath, adjacent to, or away from tree canopy to explain changes in air or surface temperature at small scales. The second type used remote sensing estimates of tree cover to explain changes in air or surface temperature at larger scales.

Urban surface and air temperatures were affected by the presence of trees and also by impervious surfaces. While impervious surfaces had a heating effect, particularly at night (Buyantuyev & Wu, 2010), trees cooled their environs. This effect was greatest in summer months (Hamada & Ohta, 2010). The reviewed studies were unanimous in showing reduced temperatures beneath trees, or associated with, tree canopy cover (Table 3). In studies that measured both ground surface temperature and air temperature (air temperature typically taken 1–3 m above ground surface), ground surface temperature decreased comparably more than air temperature. Ground surface temperatures beneath trees were 0.6–22.8°C cooler and air temperatures were 0.8–7°C cooler than surrounding control temperatures. Control temperatures were typically measured away from trees above paved or grassy surfaces.

Table 3 – Studies showing air and surface temperature reduction by trees. Changes in temperatures (Δ) are relative to experimental controls, typically a measurement away from trees above paved or grassy surfaces. All values are negative, meaning that temperatures beneath trees were lower than control temperatures.

Locality	**Δ surface temperature (°C)**	**Δ air temperature (°C)**	**Source**
Manchester, England	-19	-5 – -7	(Armson, Stringer, & Ennos, 2012)
Lisbon, Portugal		-1 – -3	(Grilo et al., 2020)
Nagoya, Japan		-1.9	(Hamada & Ohta, 2010)
Dresden, Salzburg, Szeged, and Vienna	-13.58 – -22.69	-2.7 – -5.07	(Helletsgruber et al., 2020)
Various		-0.8	(Knight et al., 2021)
Phoenix, Singapore, Melbourne, Zurich		-3.1 – -5.8	(Meili et al., 2021)
Shah Alam, Malaysia		-3	(Misni et al., 2013)
Florence, Italy	-13.8 – -22.8		(Napoli, Massetti, Brandani, Petralli, & Orlandini, 2016)
Worcester, USA	-0.6 – -4.1		(Rogan et al., 2013)
Oslo, Norway	-7 – -10		(Venter, Krog, & Barton, 2020)
Madison, USA		-1.1 – -5.7	(Ziter, Pedersen, Kucharik, & Turner, 2019)

The factors influencing the magnitude of temperature reduction include the characteristics of individual trees, such as crown density (Rahman et al., 2020), leaf area (Napoli et al., 2016; Rahman, Moser, Rötzer, & Pauleit, 2019), and tree size (Hartigan, Fitzsimons, Grenfell, & Kent, 2021; Helletsgruber et al., 2020). These characteristics are related to species (Ballinas & Barradas, 2016; Helletsgruber et al., 2020), but also age since older trees (within a species) typically have larger crowns with more leaves, thus influencing the shade cast by trees and their transpiration. Together with albedo, these factors mitigate the urban heat island effect.

Other factors are related to the amount and configuration of canopy, including tree density (Grilo et al., 2020), canopy cover (Hart & Sailor, 2009; Kong, Yin, James, Hutyra, & He, 2014; Venter et al., 2020; Ziter et al., 2019) and fragmentation (Greene & Kedron, 2018). For example, Ballinas and Barradas (2016) showed that reducing air temperature by 1°C in Mexico City would require planting 63 large *Eucalyptus camaldulensis* or 12 large *Liquidambar styraciflua* trees per hectare. Meanwhile, a 10% increase in canopy cover in Nanjing, China would see a reduction in air temperature of 0.83°C (Kong et al., 2014). Likewise, to lower air temperatures by 1 °C in Hong Kong would require increasing canopy cover to 33% (Ng, Chen, Wang, & Yuan, 2012). In Worcester, Massachusetts, removal of tree canopy cover resulted in increased ground surface temperatures, thereby extending the duration of the summer warm period by up to 15 days (Elmes et al., 2017).

In addition to the amount of canopy cover, the configuration of canopy cover was also shown to have an effect, whereby contiguous tree canopy cover decreased temperatures more than the same amount of fragmented canopy cover (Greene & Kedron, 2018). As with individual tree characteristics, tree density, canopy cover and fragmentation all have an effect on shading and transpiration, so they too affect urban temperatures.

6. Summary

The reviewed literature identified large variability in carbon storage/sequestration, stormwater attenuation, and urban heat island mitigation by urban trees. The review showed that above-ground carbon storage density for trees ranged between 1.7–28.9 kg of carbon per square meter of tree canopy cover, while total carbon (above and below ground) storage density for trees ranged between 0.8–36.1 kg C m^{-2}. Trees reduced stormwater runoff by intercepting between 9% and 61% of total rainfall, and reduced ground surface temperatures by 0.6–22.8°C and air temperatures by 0.8–7°C.

While there was considerable variability in the reported results, it is clear that trees achieve all these regulating services to a certain degree. The scale and effectiveness of these regulating services are primarily affected by the quantity of trees (measured as either tree density or canopy cover), their configuration (fragmentation, clustering), and their structural characteristics (e.g., height, crown volume and shape, stem diameter, leaf area or density, wood density), the latter of which is influenced by tree species and age. More trees or tree cover, with greater total biomass and wood density, configured in clusters, rather than fragmented will lead to increased carbon storage/sequestration, greater stormwater runoff attenuation, and improved urban heat island mitigation. Threats to these regulating services included development intensity and impermeable surfaces (buildings and/or pavements), both of which have been shown to be associated with lower tree cover.

7. References

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