Thursday, March 17, 2022

To: Durham Planning Board
From: Richard Hallett, 18 Colony Cove Road, Durham
RE: 19-21 Main Street Application, AKA Church Hill Parking Lot

It has come to my attention that my letter dated 12-9-2020 may not have been transmitted to the planning board in hard copy. In addition, it appears that because I live in Durham, NH, my letter has not been treated and posted as "expert input," despite my over two decades of experience as a research ecologist.

I am a forest ecologist and have spent my entire adult life living in, working in, and studying forests. I have a BS, MS, and PhD in Forestry and although I started my career studying rural forest ecology, during the last decade I have shifted my focus to understanding the ecology of urban forests. I have published in several scientific journals on the ecology and health of forests in Boston, New York City, Philadelphia, and Baltimore. In addition, I have served on Ph.D. committees at the University of New Hampshire, Yale University, City University of New York, Brooklyn College, Rutgers University, and the University of Maryland.

The threatened trees growing on Church Hill, some of them over 80 years old, don't occupy very much land area, only 1.3 acres. This is not about land area or numbers of trees. It's about *where* these trees are, in the center of a growing community, that makes them invaluable and irreplaceable. It's the benefits these trees provide and will continue to provide for the next 100 years or more. These benefits aren't in the form of the board feet of lumber they can provide. I have read Charles Moreno's forest assessment of the site and I agree that in comparison to a forest patch in the midst of the White Mountain National Forest, the forest on this site doesn't seem like much. However, based on my experience studying urban forests in the northeastern U.S., a patch like this in the center of an urban area is priceless, even with all the issues Mr. Moreno correctly documents.

In this particular case, it is worth elaborating on the ability of trees and greenspace to mitigate stormwater. Currently, cities across the country are spending billions of dollars to install green stormwater infrastructure. Durham has the gift of a small, forested ecosystem that is currently functioning as green stormwater infrastructure perfectly placed in its center. Its current functionality can't be replicated after the site is altered and paved. Losing this ability to mitigate and filter runoff has implications for downstream water quality including Great Bay (see AP story on EPA's effort to clean up Great Bay). Will this proposed deforestation be our town's contribution to this effort?

I am including the following relevant articles, which I urge you to review closely:

1. ***"The benefits of trees for livable and sustainable communities"*** which discusses and provides evidence for the psycho-social, ecological, and physical benefits trees provides to communities (including mitigation of the "Urban Heat Island Effect").
2. ***"Urban forest systems and green stormwater infrastructure"*** a comprehensive overview of the stormwater benefits of urban trees.

With respect to Article VII, Conditional Use Permits of the Durham Zoning Ordinance there are several points I'd like to make as they are particularly applicable with respect to the proposed parking lot being in compliance with the approval criteria of Section 175-23.

1. The ordinance specifically states that the nature and intensity of the use, shall not have an adverse effect on the surrounding environment. As per my comments above, the loss of functional vegetation and subsequent replacement by an impervious surface will have an adverse effect on the wetland and water quality of College Brook. The ordinance states that the burden is on the applicant to show that this is not so. I have not seen an analysis of what the impact of increased frequency and intensity of extreme weather events will have in the future as it relates to storwater runoff from the parking lot. Simply put, "100 year storms" are happening more frequently.
2. The ordinance specifically states that the use of the site shall not degrade identified natural resources on abutting properties. This would seem to include the identified wetlands and floodplain of College Brook.
3. The ordinance specifically states that the proposed use will not have a negative fiscal impact on the Town. Where is the cost/benefit analysis showing that the benefits outweigh the current and future environmental costs of this project (see above)?

The ordinance also states that the Planning Board may commission, at the applicant's expense, an ***independent*** analysis of the fiscal impact of the project on the town, something that must go far beyond changes in assessed values for property taxes. The independent analysis should:

- Include the cost of the loss of the ecosystem services provided by the forest that will be removed today and over the expected lifespan of the parking lot.
- Consider the increased frequency and severity of storms in the future, especially with respect to the loss of a functioning forest upslope of College Brook which subsequently drains into Great Bay.
- Consider the environmental impacts to the identified wetlands and the water quality of College Brook now and into the future.
- Consider the cost the town would need to incur to mitigate the stormwater that is currently handled by this forest patch, now and in the future.

I have deliberately confined my comments to areas which fall within my area of expertise. In addition, opinions expressed are solely my own and do not express the views or opinions of my employer.

Sincerely,

Richard Hallett, Ph.D.

USDA

U.S. Department of Agriculture

Urban Forest Systems and Green Stormwater Infrastructure

Forest Service FS 1146 FEBRUARY 2020

Summary

Trees provide considerable stormwater volume and pollution control through rainfall interception and intensity reduction, stormwater infiltration and uptake, and nutrient load reduction. This document focuses on the effects of trees on urban stormwater runoff, provides some helpful urban forest management strategies to maximize stormwater benefits, and demonstrates several examples around the United States where the stormwater benefits of urban trees are credited for reducing stormwater volume and pollutant loading. This document serves as a resource manual for natural resource professionals to help them communicate with stormwater managers and engineering professionals about the science and benefits of urban trees in stormwater management. Resources on accounting for the stormwater functions of trees are provided as a starting point for State and local governments interested in providing regulatory credit for urban forests in green stormwater infrastructure.

Introduction

Municipalities are increasingly planning for sustainability and improved quality of life for current and future residents as they work toward building healthy communities. One method of planning for sustainability involves the consideration of social, environmental, and economic impacts of proposed development, known as the triple bottom line. Trees growing in urban environments provide numerous benefits for humanity that improve quality of life and address this triple bottom line.

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Beyond the stormwater benefits covered in this document, more and more scientific evidence shows how urban trees and greenspace positively impact physical, psychological, emotional, and spiritual well-being in humans (USDA Forest Service 2018). Environmental benefits of trees such as improved ambient air quality, carbon sequestration, and reduced stormwater runoff can now be quantified using public domain software found on the internet, such as the U.S. Department of Agriculture (USDA), Forest Service, **i-Tree suite of tools**. Research has shown that trees provide economic benefits by raising property value, reducing the amount of time rental property goes unrented, and increasing the amount of time customers shop at retail establishments (Wolf 2005).

Strategically planting trees and managing the forest within a city can help to mitigate some of the negative impacts that come with urban development. A properly managed urban forest can help a municipality meet certain environmental regulations and save money through avoided costs, particularly related to stormwater runoff. To better understand how urban trees improve things like human health, economic development, water and air quality, and public safety, visit the **Vibrant Cities Lab** website.

This document provides a synthesis of the science around how urban trees help mitigate problems associated with stormwater runoff. Several tree crediting tools and case studies are provided to help State and local governments better account for the stormwater benefits of urban forests. A complementary manual for stormwater professionals that investigates incorporating forestry into stormwater management programs is available through the **Water Research Foundation**. The Urban Watershed Forestry Manual, developed by the Center for Watershed Protection, provides more detail about **methods for increasing forest cover in a watershed**, **conserving and planting trees at a development site**, and **an urban tree planting guide**.

Overview of the Stormwater Benefits of Urban Trees

Green stormwater infrastructure (GSI) is defined as stormwater mitigation practices designed to mimic natural processes that filter and retain rain where it falls. Typical GSI practices include green roofs, urban trees, bioretention, vegetated swales, permeable pavements, and water harvesting. GSI includes low impact development designs and/or engineered systems that manage stormwater runoff at its source in developed landscapes (EPA 2018). An urban forest system includes the trees within an urban area as well as the ground cover and soil. The parts of this system work together as part of a GSI “treatment train” (a series of practices designed to mitigate runoff) to provide considerable stormwater volume and pollution control through rainfall interception and intensity reduction, stormwater infiltration and uptake facilitation, and nutrient load reduction. Recent review articles have explored how the parts of the system work together to provide these benefits (Berland and others 2017, Center for Watershed Protection 2017, Kuehler and others 2017).

The canopy formed by urban trees intercepts rain as soon as it starts to fall, with part of that rainfall retained on foliage and branches, remaining in the canopy where it eventually evaporates back into the atmosphere. When the leaf and branch surface area in the upper part of the tree canopy is filled and cannot hold additional rainfall, excess water drips from these surfaces to those lower in the canopy, helping to reduce rainfall intensity and delaying runoff to storm drains or other stormwater control measures. This, in effect, allows the stormwater control system to work more efficiently and reduces the chances of it becoming overwhelmed or of water running over the top of drains and other measures.

Soils provide the bulk of stormwater volume control. Macro- and micro-pores—spaces between soil particles—allow for temporary water storage from which trees acquire water and nutrients. Tree roots condition the soil through mechanical, biological, and chemical means, increasing its ability to store greater volumes of water. Stormwater runoff not retained in the canopy drips off leaf surfaces or flows along the branches and trunk (stemflow) to the soil at the base of a tree, where it can penetrate deep into the soil profile as water moves along the root surfaces.

Once in the soil, water becomes accessible to tree roots. Through the process of transpiration, water is essentially pulled from the soil pore space and used by the tree between storms. This process allows for greater water storage capacity in the soil as water is transpired most days during the growing season.

Soils also filter nutrients and other pollutants from stormwater runoff. Trees need many of the nutrients found in runoff for growth and survival, especially nitrogen and phosphorus which can negatively impact water quality when found in excess. The uptake of these nutrients from the soil by trees reduces the amount leaching into groundwater, helping to retain and improve water quality. However, trees also store many of these nutrients in their leaves; at the end of the growing season, a large amount of these nutrients remain in senesced leaves. When the tree sheds these leaves in fall, significant amounts of nutrients can find their way to receiving waters, especially if leaves fall onto impervious surfaces such as streets.

Quantifying the stormwater benefits of trees is difficult because of many factors. These include species differences in attributes that affect rainfall storage such as crown architecture and leaf structure and surface texture. For example, needle-leafed trees generally store more rainfall than broadleaf trees, and evergreens intercept more rainfall than deciduous trees over the course of a year. Natural systems also vary in relation to regional climate differences (arid versus tropical) and microclimates, soil conditions, tree size and configuration of planting, not to mention the average frequency, intensity, and volume of local rainfall events.

In an ideal world, stormwater managers and design engineers could calculate the GSI benefits they need for planning by entering information into simple formulas for stormwater runoff mitigation by urban forest systems. Unfortunately, because of all the variables mentioned, it is difficult to calculate "the numbers" for stormwater benefits. However, good estimates can be made based on current research.

The following sections contain overviews of the various benefits that trees provide in mitigating stormwater runoff as well as urban forest management strategies that maximize stormwater runoff benefits. Basic "rules of thumb" to estimate stormwater benefits are provided where appropriate, but it is important to note that since nature is infinitely variable, these rules may be superseded by local conditions and species variability. For more information about the roles that trees play in stormwater management, visit **www.TreesAndStormwater.org**.

Rainfall Retention

Tree canopy intercepts rainfall on leaf surfaces, branches, and stems. This intercepted rainfall is either retained on canopy surfaces and evaporates over time (interception loss), flows down branches to stems and eventually to the soil (stemflow), or drips off canopy surfaces to the ground below (throughfall). Maximizing the amount of rainfall retained in the tree canopy (interception loss) is a good strategy to help reduce stormwater runoff in urban areas.

A deciduous tree typically retains approximately 20 percent of the annual rainfall that falls on its canopy, while a conifer retains close to 30 percent (Kuehler and others 2017). The amount of intercepted rainfall retained in the tree canopy depends on climatic variables such as rainfall intensity and duration, ambient air temperature, wind speed, relative humidity, and solar intensity. Tree crown structure attributes such as leaf architecture, morphology, and water repellency as well as leaf surface area and leaf area index (LAI) contribute to interception loss. Trees with rigid, rough-surfaced leaves generally retain more rainfall than those with flexible, smooth-surfaced leaves (Xiao and McPherson 2016). Trees with greater leaf area or higher LAI contribute positively to interception loss.

The amount of water remaining on canopy surfaces after a rainfall event and after excess water drips off is known as "static storage" (Keim and others 2006). This water eventually evaporates back to the atmosphere and does not contribute to stormwater runoff. The depth of static water storage has been estimated for various species using rainfall simulation techniques. **Table 1** demonstrates the high variability of static storage among species—and even among species within the same genus.

The volume of rainfall retention in tree canopy can be estimated from the leaf area of the tree. The average depth of static water storage for tree foliage is 0.2 mm/unit leaf area (Wang and others 2008). Using local growth equations to estimate the leaf area of a tree, one could multiply the leaf area by the depth of water storage to estimate the maximum volume of rainfall retention by tree for a rainfall event (**Equation 1**) (Hirabayashi 2013).

$$Vol_{max} = LA \times 0.2 \text{ mm} \times (1 \text{ m}/1{,}000 \text{ mm}) \qquad \textbf{(1)}$$

where
Vol_{max} = maximum volume of rainfall retained by tree foliage (m^3)
LA = leaf area (m^2)

For example, a tree with 250 m^2 of leaf area could be expected to retain 0.05 m^3 of rainfall per rainfall event. This is equivalent to about 13 gallons of water (1 m^3 of water = 264 gallons). This volume may not seem like much, but in a city with millions of trees, the impact is multiplied. Therefore, managing the urban forest to maximize leaf surface area can help to reduce stormwater volume (**Box 1**).

Table 1. Mean depth of water storage on foliage by tree species

Species Botanical name	Species Common name	Mean depth of water storage (mm)	Source
Acacia longifolia	Sydney golden wattle	0.08	Aston (1979)
Acer macrophyllum	Bigleaf maple	0.18	Keim and others (2006)
Acer saccharinum	Silver maple	0.13	Holder (2013)
Acer truncatum	Shantung maple	0.46	Li and others (2016)
Alnus rubra	Red alder	0.20	Keim and others (2006)
Catalpa speciosa	Northern catalpa	0.13	Holder (2013)
Eucalyptus cinerea	Silver dollar tree	0.11	Aston (1979)
Eucalyptus dives	Broadleaf peppermint	0.07	Aston (1979)
Eucalyptus maculata	Spotted gum	0.03	Aston (1979)
Eucalyptus mannifera	Brittle gum	0.09	Aston (1979)
Eucalyptus pauciflora	Snow gum	0.18	Aston (1979)
Eucalyptus viminalis	Manna gum	0.03	Aston (1979)
Gleditsia triacanthos	Honey locust	0.18	Holder (2013)
Pinus radiata	Monterey pine	0.08	Aston (1979)
Pinus tabulaeformis	Chinese red pine	0.43	Li and others (2016)
Platycladus orientalis	Oriental arborvitae	0.38	Li and others (2016)
Populus deltoides	Eastern cottonwood	0.19	Holder (2013)
Populus tremuloides	Quaking aspen	0.15	Holder (2013)
Pseudotsuga menziesii	Douglas fir	0.26	Keim and others (2006)
Quercus gambelii	Gambel oak	0.15	Holder (2013)
Quercus variabilis	Chinese cork oak	0.17	Li and others (2016)
Thuja plicata	Western redcedar	0.26	Keim and others (2006)
Tsuga heterophylla	Western hemlock	0.48	Keim and others (2006)
Ulmus pumila	Siberian elm	0.21	Holder (2013)

Box 1 **Urban Forest Management Strategies To Maximize Rainfall Retention**

- Where appropriate, increase leaf area by planting smaller, shade-tolerant trees under larger dominant trees.
- Use ground covers (i.e., mulch or vegetation) under tree canopy to increase surface area for interception.
- Encourage the retention and use of conifers and evergreen broadleaf trees, where appropriate and desired, to maximize interception and evapotranspiration year-round.
- Plant trees with rigid and/or rough-surfaced leaves and bark.
- Encourage the use of trees with greater leaf surface area or higher leaf area index (LAI).
- Maximize belowground soil volume to help store stormwater runoff and encourage deep root growth.
- Consider litter accumulation, root growth characteristics, and long-term maintenance in the tree selection process.
- Ensure proper tree maintenance to maximize health and LAI.

Rainfall Intensity Under Canopy and Stormwater Runoff Timing

Trees help mitigate flooding and potential soil erosion by temporarily storing rainfall in the canopy formed by branches and leaves, thereby reducing the intensity of rainfall below the canopy and delaying peak stormwater runoff rates.

Open-grown trees typically found in urban landscapes tend to have greater crown volume and thus greater leaf surface area available for water storage than forest-grown trees. As tree surfaces in the upper parts of the canopy become saturated with rain, excess water falls through the canopy. Water falling from higher surfaces fills lower surfaces in the crown until the entire canopy is saturated, a process called "dynamic storage" (Keim and others 2006).

Tree canopy essentially acts as a stormwater volume control mechanism. Although the canopy can hold no additional rainfall once saturated, the rain that continues to fall on the crown is intercepted and takes time to pass from one surface to another, slowing its eventual release as stormwater runoff. It is worth noting that the excess water drips off the tree relatively quickly after the rain has stopped, extending the rain event for a time under canopy.

Urban trees also regulate stormwater runoff by moderating rainfall intensity underneath the tree canopy. Urban trees have been shown to reduce rainfall intensity under the canopy by 25 to 70 percent (Zabret and others 2017) depending on species, rainfall characteristics, and time of year (**Figure 1**). Stormwater peak flow rate is controlled in part by rainfall intensity (Kuichling 1889, Bedient and others 2013); rainfall intensity reductions by

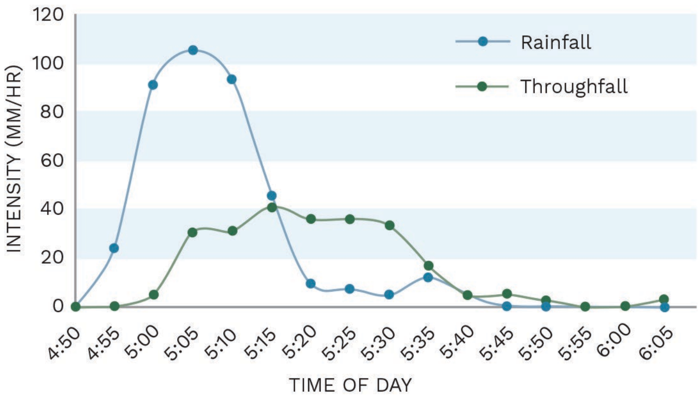


Figure 1. Growing season throughfall intensity under open-grown broadleaf deciduous trees compared to rainfall intensity above the canopy.

Source: Zabret and others 2017.

tree canopy thus reduce the peak flow of runoff leaving a site. Reducing rainfall intensity has also been shown to significantly reduce runoff by increasing soil infiltration (Nassif and Wilson 1975, Guan and others 2016). Slowing runoff flow rate and increasing stormwater storage in soils help to reduce incidences of flooding, combined sewer overflows, stormwater runoff volumes, and flows that erode stream channels and bare soil.

Tree canopy has been shown to delay stormwater runoff and increase the time it takes runoff to concentrate at the outlet of a catchment or drainage area (e.g., a storm drain or bioretention practice). Depending on rainfall volume and intensity as well as tree species, this delay can be from 10 minutes to over 3 hours (Xiao and others 2000, Asadian and Weiler 2009, Gonzalez-Sosa and others 2017). Growing trees in a catchment with significant impervious surface cover can help delay the runoff hydrograph peak (the maximum stormwater runoff volume reported during a specified time period, displayed graphically). Trees can also reduce the peak flow delivered to the storm drain or GSI practice and help prevent that practice from becoming overwhelmed, thus allowing it to function more efficiently and effectively from a water quality standpoint (**Box 2**).

Infiltration of Stormwater Into Soils

Soils generally have the capacity to store more water than tree canopies. Infiltration of stormwater into soil delays runoff flow to streams and allows for filtration and adsorption of pollutants. Unfortunately, urban soils tend to be disturbed in some way, either from compaction or loss of structure, which reduces porosity and inhibits water storage. The result is generally diminished infiltration capacity and an increase in stormwater runoff.

Box 2 **Urban Forest Management Strategies To Reduce Rainfall Intensity**

- Where appropriate, retain or plant trees with a high leaf area index (LAI).
- Encourage the use of conifers and evergreen broadleaf trees in the landscape where appropriate.
- Maximize crown volume by pruning only when necessary.
- Plant trees to encourage crown growth over impervious surfaces such as roads, sidewalks, and parking lots.
- When retrofitting a catchment with green stormwater infrastructure practices, retain as much tree canopy in the catchment as possible.

Trees help increase infiltration of water into the soil. Tree roots can condition disturbed soils and loosen compacted soils, thus increasing infiltration and percolation of stormwater runoff (Lange and others 2009, Hart 2017). In a greenhouse study, Bartens and others (2008) showed that deciduous trees increased infiltration rates of compacted clay loam subsoil by 150 percent compared to unplanted controls. In a second study under mature urban trees in Iran, Zadeh and Sepaskhah (2016) showed that significantly greater volumes of water infiltrated into soil under tree canopy compared to soils not under tree canopy cover. Depending on soil texture, the cumulative infiltration of water under canopy increased by 69 to 354 percent compared to soil not under the canopy. The rate at which water infiltrated into soil under tree canopy cover also depended on soil texture. The infiltration rate was 800 percent greater under the canopy of trees growing in clay loam soil compared to that in open clay loam soil; however, there was only a 12.5-percent increase in infiltration rates under canopy with loamy sand compared to loamy sand in open areas. In both studies tree roots were reported to cause this increase in infiltration.

Stemflow can also help with infiltration of rainfall through preferential flow along root surfaces. Unless the extent of permeable surface at the base of the tree is very limited (as can be the case with some urban street or parking lot trees), the stemflow infiltrates into the soil macropores along the root surfaces. Quantification of the influence of stemflow on infiltration rates or volumes continues to be studied (Levia and Germer 2015).

Managing urban forests to take advantage of stemflow can help mitigate stormwater runoff. Schooling and Carlyle-Moses (2015) reported that stemflow accounted for 3 percent of rainfall for events greater than 0.4 inches (10 mm). In addition to rainfall intensity and wind speed, stemflow depends on the smoothness of the bark and branch angles. Smooth-barked trees with acute branch angles have been shown to produce greater stemflow than rough-barked trees or trees with more horizontally oriented branches. Staelens and others (2008) also found that stemflow volume increased from 6.4 to 9.5 percent of total rainfall when leaves were not on the tree (i.e., during the dormant season).

Trees encourage infiltration of rainfall and stormwater runoff into the soil by directing water to a single point at the base of a tree or by slowing water dripping onto permeable surfaces under the canopy. Where appropriate, directing stormwater runoff to open green spaces such as parks, and planting trees in those green spaces can be a useful, efficient, and relatively inexpensive urban stormwater runoff mitigation strategy. Strategically planting smooth-barked trees with acute branch angles near impervious surfaces so that their canopies grow over those surfaces could help direct more rainfall to more permeable surfaces during the winter months (**Box 3**).

Transpiration and Stormwater Runoff

Trees need water to function and grow. Water stored belowground in soil is removed and used by trees and eventually returned to the atmosphere through the process of transpiration. Trees influence soil water storage through this process. As water is removed from the soil by trees, soil pore space becomes available to be filled by stormwater runoff from subsequent rainfall events.

Transpiration rates are highly variable by tree species, stem size, and leaf area. Average growing season daily water use has been reported to be as high as 47 gallons for a 23-inch diameter tulip poplar (*Liriodendron tulipifera*) while a 25-inch chestnut oak (*Quercus montana*) transpired 6 gallons (Ford and others 2011). In a California study, 15- to 22-inch diameter sycamore (*Platanus* spp.) street trees transpired between 27 and 46 gallons of water daily during the growing season, but 24-inch pines only transpired about 13 gallons (Pataki and others 2011). These differences in the amount of water transpired can be attributed, in part, to the tree's wood architecture or xylem element type. Species with deep sapwood and diffuse-porous xylem (e.g., yellow poplar, blackgum, birch, dogwood, red maple, sycamore) transpire water in greater volumes than species with shallow sapwood and ring-porous xylem (e.g., oak), species with semi-ring-porous xylem (e.g., hickory), or species with tracheid xylem (e.g., conifers).

Data collected on trees in the mountains of western North Carolina to the Gulf Coastal Plain of Georgia show that diffuse-porous species can transpire between 0.6 to 1.5 gallons of water per day per inch of stem diameter during the growing season depending on the size of the tree, while ring-porous species transpire about 0.3 gallons of water per day per inch (**Figure 2**). Because the trees studied were well watered and their roots not impeded by urban infrastructure, these rates can be considered an upper limit.

Transpiration rates also depend on many environmental factors. Foliar stomata, the pores in leaves that allow for gas exchange with the atmosphere—thus regulating water flow in the tree through the release of water vapor—open and close depending on light levels, air temperature, humidity, wind, and soil moisture. Using data from multiple urban tree transpiration studies and local meteorological data, Moore and others (2019) were able to estimate that 5,000 m^2 (53,820 ft^2) of street tree canopy area in Kansas City, KS, could transpire approximately 1,585 to 1,850 gallons of water from the soil each day during the growing season depending on xylem element type and thus allow for additional runoff storage between rainfall events. They warn, however, that this assumes the soil moisture content is not limiting and has enough water for the trees to continue transpiring at these rates.

Box 3 **Urban Forest Management Strategies To Increase Stormwater Infiltration**

- Maximize belowground soil volume and quality to enhance infiltration and storage.
- Where appropriate, use organic mulch beneath tree canopy to help improve infiltration and retain stormwater runoff.
- Plant trees in large open areas where stormwater is directed.
- Ensure adequate belowground aeration for root growth.
- Plant trees with acute branch angles near impervious surfaces to help direct rainfall to permeable surfaces.
- Ensure adequate permeable soil space directly adjacent to tree stems to allow for infiltration of stemflow.

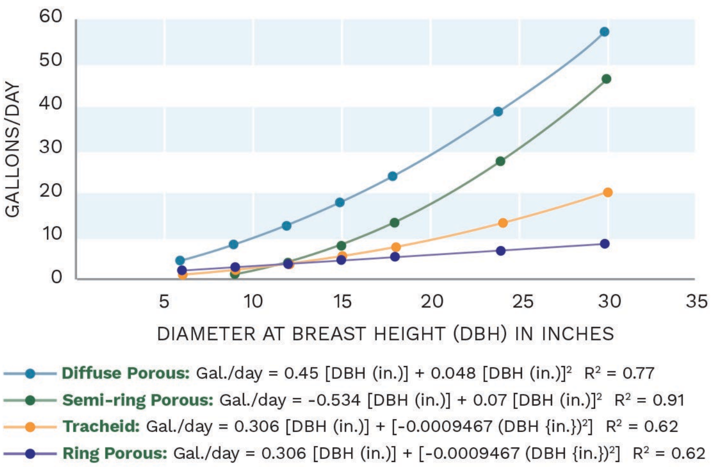


Figure 2. Average growing season daily water use for trees growing in western North Carolina and the Gulf Coastal Plain of Georgia. Coefficient of determination (R^2) was determined from the original data.[1]

Sources: Ford and others 2011; Ford and others 2008; Ford and Vose 2007; Hawthorne and Miniat, unpublished data; Oishi and Miniat, unpublished data; Vose and others 2016.

Regional weather patterns may dictate the best trees to use in urban systems. For example, in regions with a more Mediterranean climate (e.g., California) where water for irrigation may be limited, it might be best to plant tree species with ring-porous or tracheid xylem types that are able to conserve water through reduced transpiration. In a region that receives abundant rainfall (e.g., the Southeastern United States), planting diffuse-porous species could help mitigate stormwater runoff by creating increased soil storage capacity through increased transpiration.

Based on this information, it would be advantageous to plant trees with diffuse-porous xylem elements in areas used to store stormwater runoff, where soils are frequently wet, and to plant ring-porous species in drier, upland sites or in bioretention practices that use high infiltration media. To determine the xylem element type of many tree species, search the **Wood Finder** section of The Wood Database (**Box 4**).

Box 4

Urban Forest Management Strategies To Maximize Transpiration

- Ensure adequate belowground aeration for root respiration and increased water storage capacity.
- Select tree species with greater leaf surface area.
- Retain larger trees in the landscape where appropriate.
- Plant larger statured trees where appropriate.
- Plant trees having diffuse-porous xylem in large open areas where stormwater is directed.
- Plant ring-porous trees in drier, upland sites and in bioretention practices that use high infiltration media.

Stormwater Nutrient Uptake and Loading

Trees require nutrients to grow and remain healthy (Coder 2013). Urban stormwater runoff contains many of the 19 or so essential elements used by trees. As stormwater infiltrates into the soil profile, filling soil pore space, it becomes the soil solution from which tree roots absorb nutrients. Most of the chemically charged elements in stormwater adsorb to oppositely charged soil particles, holding them as exchangeable ions. When the roots absorb elements from the soil solution, these exchangeable ions are released through chemical processes into the solution, replenishing nutrient levels for plant absorption (Brady and Weil 2002). However, excessive water in the soil can also cause some of the elements in the soil solution, such as nitrate-nitrogen, to be carried or leached by gravity from the root zone to deeper ground water where they are unavailable to plants. Eventually these elements can make their way to receiving waters and can contribute to eutrophication downstream, resulting in overgrowth of plant life and the death of fish and other species from lack of oxygen.

Urban stormwater runoff is usually directed to gutters and pipes that convey the untreated water to a stream and eventually to larger bodies of water or to a treatment facility for combined sewage systems. This is done mainly to prevent flooding in our cities. However, moving large quantities of untreated urban stormwater to downstream water sources can decrease water quality, diminish recreational opportunities, negatively impact aquatic life and food sources, and increase treatment costs for human use. Green stormwater infrastructure practices are designed to mimic natural hydrological processes by directing stormwater runoff to permeable surfaces that allow soil to remove nutrients and other pollutants from runoff naturally before it reaches receiving waters.

[1] Ford-Miniat, C. 2018. Personal communication. Research ecologist, USDA Forest Service Southern Research Station, chelcy.f.minat@usda.gov.

Nitrogen (N) and phosphorus (P) are two of the most essential elements needed by trees. Urban stormwater runoff can have substantial concentrations of N and P due to natural and human causes. Controlling these elements is critical for municipalities to maintain water quality. Research studies in urban areas show how managing urban forest systems can help control N and P from stormwater runoff.

A study in Baltimore, MD, showed that intact forested areas reduced N leaching by 74 to 81 percent compared to areas of maintained, fertilized turf (**Table 2**) (Groffman and others 2009). Other studies showed that under individual deciduous trees, N leaching was 40 to 56 percent lower than under turf (Amador and others 2007, Nidzgorski and Hobbie 2016). In a study in Minnesota, Nidzgorski and Hobbie (2016) showed that leaching of phosphates was reduced by 81 percent under deciduous and 55 percent under coniferous trees in municipal parks. Extrapolating their data to an urban watershed, the authors estimated that urban trees reduce P leaching to groundwater by 1,175 to 2,648 pounds per year (18 to 39 pounds per square mile). They calculated that trees in the watershed saved $2 to $5 million per year in removal costs compared to installing engineered stormwater infrastructure.

Trees in bioretention practices have also shown to help reduce nutrient loading. Bioretention systems with trees reduced nitrates by 58 to 97 percent and phosphates by 47 to 79 percent compared to those without trees (**Table 3**) (Bratieres and others 2008, Read and others 2008, Denman and others 2016). The effects on total N and P, however, were highly variable. Compared to the amount of nutrients coming into these bioretention systems, trees were found to reduce total dissolved N by 46 to 52 percent

Table 2. Comparison of groundwater nutrient concentrations under turf, deciduous trees, and conifers from three field studies

Nutrient	Turf (mg / L)	Deciduous trees (mg / L)	Conifers (mg / L)	Source
TN	7.32 ± 1.08	3.75 ± 0.55	7.07 ± 0.95	Nidzgorski and Hobbie (2016)
NOx	3.0 3.1 – 7.3 5.63 ± 1.00	1.8 0.6 – 1.9* 2.46 ± 0.42	1.4 – 5.95 ± 0.97	Amador and others (2007) Groffman and others (2009) Nidzgorski and Hobbie (2016)
TP	0.159 ± 0.020	0.050 ± 0.004	0.085 ± 0.013	Nidzgorski and Hobbie (2016)
PO_4^{3-}	0.131 ± 0.020	0.025 ± 0.003	0.059 ± 0.011	Nidzgorski and Hobbie (2016)

TN = total nitrogen | NOx = oxidized nitrogen | TP = total phosphorus | PO_4^{3-} = orthophosphates.
*Forested area.

Table 3. Water quality data from three bioretention studies comparing effluent nutrient concentrations from systems with trees (soil + tree) and without trees (soil only)

Nutrient	Soil only ($mg\ L^{-1}$)	Soil + Tree ($mg\ L^{-1}$)	Reduced %	Source
TN	2.2 6.68	1.8 – 2.3 1.19	-5% – 18%* 82%	Read and others (2008) Bratieres and others (2008)
NOx	0.38 5.23 7.43	0.01 – 0.16 0.38 1.96	58 – 97%* 93% 74%*	Read and others (2008) Bratieres and others (2008) Denman and others (2016)
TP	0.11 0.083	0.06 – 0.10 0.07	9 – 45%* 16%	Read and others (2008) Bratieres and others (2008)
PO_4^{3-}	0.075 0.064 0.85	.020 – .025 0.034 0.18	67 – 73%* 47% 79%*	Read and others (2008) Bratieres and others (2008) Denman and others (2016)

TN = total nitrogen | NOx = oxidized nitrogen | TP = total phosphorus
PO_4^{3-} = orthophosphates. *Averaged over entire study period.

Table 4. Water quality data from two bioretention studies comparing effluent nutrient concentrations from systems with trees (soil + tree) and the dose of nutrients of the applied stormwater (dose)

Nutrient	Dose (mg/L)	Soil + Tree (mg/L)	Reduced %	Source
TN	2.21	1.19	46%	Bratieres and others (2008)
NOx	0.79 2.0	0.38 1.96	52% 2%*	Bratieres and others (2008) Denman and others (2016)
TP	0.427	0.07	84%	Bratieres and others (2008)
PO_4^{3-}	0.127 0.6	0.034 0.18	74% 70%*	Bratieres and others (2008) Denman and others (2016)

TN = total nitrogen | NOx = oxidized nitrogen | TP = total phosphorus
PO_4^{3-} = orthophosphates. *Averaged over entire study period.

(Bratieres and others 2008) and P by 70 to 84 percent (**Table 4**) (Bratieres and others 2008, Denman and others 2016). The authors explained that as trees in these systems matured and increased root mass per soil volume, their effectiveness improved. These studies suggest that bioretention practices with greater tree root biomass are better able to reduce N and P from their stormwater effluent.

Although trees have been shown to take up substantial amounts of nutrients from the soil profile, they can also contribute significantly to pollution loading in receiving waters by contributing nutrients to impervious surfaces. Airborne contaminants, including N and P, deposit on leaf surfaces and can be washed off during rainfall events. Precipitation dripping from the tree canopy over impervious surfaces has been shown to contribute to increased pollutant loading (Halverson and others 1984). Trees can move nutrients internally from foliage to other plant tissue for storage before leaves fall off during the autumn; however, about half of the N and P content remains in the leaves after they fall (Aerts 1996). Studies show that approximately 60 percent of the annual P yield in urban streams comes from autumn leaf fall onto streets (Selbig 2016). Research also shows a strong linear relationship between tree canopy cover over streets and mean gutter stormwater runoff N and P concentration in the autumn (Janke and others 2017). From this research, we can expect to see an increase in runoff concentration of approximately 0.65 mg/L in total organic N and 0.35 mg/L in soluble reactive P in autumn for every 10-percent increase in tree canopy cover over impervious surfaces (**Figure 3**).

Litter from urban trees decomposes more rapidly on impervious surfaces than in more natural settings due mainly to increased ambient temperatures and accelerated fragmentation from tires rolling over it (Hobbie and others 2013). Timely and targeted street sweeping, especially in areas with high tree canopy cover, has been shown to reduce nutrient concentrations in urban streams by over 70 percent (Selbig 2016). If tree canopy cover over impervious surfaces is desirable in municipalities to provide co-benefits and improve quality of life, a robust and targeted street sweeping operation is highly recommended to help reduce excessive nutrients in urban streams and lakes (**Box 5**).

Crediting Trees in Stormwater Programs

With the growing body of research on the stormwater benefits of urban forest systems, new approaches have been developed in recent years to provide regulatory credit for trees in stormwater management programs. Communities across the Nation are seeking cost-effective approaches to meet water quality requirements associated with Municipal Separate Storm Sewer System (MS4) permits, Combined Sewer Overflow (CSO) consent decrees, and Total Maximum Daily Load (TMDL) pollutant load reductions. Urban trees and forests play a central role in a community's green stormwater infrastructure, but they are often not accounted for as stormwater management practices, in part due to variability or uncertainty in quantifying their function relative to engineered practices.

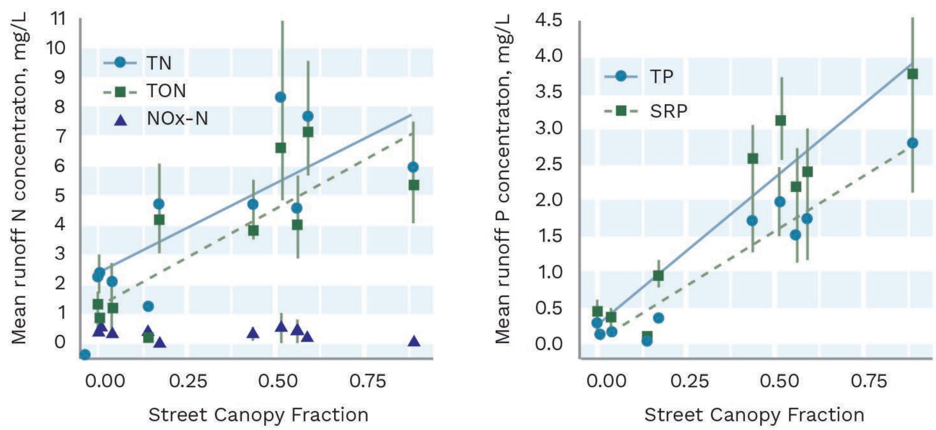


Figure 3. Mean nitrogen (N) and phosphorus (P) concentration in stormwater runoff from street gutters per street tree canopy fraction in the Minneapolis, MN, metropolitan area.

Source: Janke and others 2017.

Box 5 **Urban Forest Management Strategies To Reduce Stormwater Nutrient Loading**

- Where appropriate, direct stormwater runoff to areas where it can be infiltrated into the soil or belowground.
- Plant trees in large open areas where runoff is directed and roots can access it.
- Ensure adequate belowground aeration for root respiration.
- Identify those areas of the city where tree canopy cover overhangs impervious surfaces and ensure leaves and debris are removed frequently throughout spring and autumn.

The Center for Watershed Protection led a thorough investigation of crediting approaches for urban trees and published a number of valuable resources on the subject. Its website, **Making Urban Trees Count**, provides a comprehensive literature review and modeling documentation, national spreadsheet tools for calculating event-based volume reduction and annual pollutant load reduction credits, and sample design specifications for urban tree planting as a Best Management Practice (BMP). **Table 5** gives a summary of the two crediting tools. An additional technical guide was developed for stormwater engineers entitled "**Accounting for Trees in Stormwater Models**," which summarizes available tools and outlines an array of options for incorporating tree values into common stormwater modeling programs (Center for Watershed Protection 2018a).

The following case studies provide practical examples of how science-based tree credits have been developed and adopted in three different regulatory contexts: Minnesota, Vermont, and the Chesapeake Bay watershed. They are presented in hopes that other States and localities will learn from and/or adapt these approaches without needing to reinvent the wheel. While the tree credits are modest relative to other stormwater BMPs, they represent an important step towards better accounting for the watershed benefits of urban forests. One limitation of some of these crediting approaches is that they only provide credit for newly planted trees, not for conserving existing mature trees that generally provide far greater stormwater benefits relative to young trees. Further, the credits described below do not account for potential pollutant loading (e.g., phosphorus) associated with leaf litter falling on impervious surfaces. As the science and policy strategies around these issues continue to develop, it is anticipated that crediting approaches for trees will be strengthened accordingly.

Table 5. Summary of tree planting credits developed by the Center for Watershed Protection

Characteristic	Pollutant load reduction credit	Stormwater performance-based credit
Use of credit	» Compliance with nutrient and sediment TMDLs	» Compliance with site-based stormwater management requirements (volume-based and pollutant-based)
Required inputs	» Climate region » Number of trees planted	» Nearest city (from drop-down list) » Tree type » Surface over which the tree will be planted » Number of trees planted » A breakdown of HSG soil type/land cover combinations for the entire site » The design storm, in inches
Optional inputs (default values are provided)	» Tree type » Soil type » Surface over which the tree will be planted » TN, TP, and TSS event mean concentrations	» Tree size (DBH) » Tree canopy area » TN, TP, and TSS event mean concentrations
Outputs	» Annual reduction in TN, TP, and TSS loads (lbs/yr) for an individual tree and for a tree planting scenario	» Runoff (cubic feet), TN (lbs), TP (lbs), and TSS (lbs) reduction for user-defined tree planting scenario for a specific storm event (e.g., design storm)
Key assumptions*	» TP and TSS load reductions are directly proportional to runoff reduction » The amount of runoff reduction achieved by tree planting is not uniform across all storm events	» TN load reductions are 65 percent of runoff reduction to account for soluble forms of nitrogen reaching a stream or other waterbody through infiltration and leaching » The annual runoff reduction from the water balance model is translated to an event-based reduction using a unit runoff reduction value

TMDL = total maximum daily load | HSG = Hydrologic Soil Group | TN = total nitrogen | TP = total phosphorus | TSS = total suspended sediment | DBH = diameter at breast height. *Refer to the water balance model documentation for more detailed model assumptions.

Having supportive State policies in place, as demonstrated in these case studies, is an important condition to incentivize the conservation and planting of urban trees as a key component of the local stormwater management infrastructure. Ultimately, local governments are the drivers of community tree management and have a variety of policy options to protect and expand the many public values provided by trees, as outlined in "**Making your Community Forest-Friendly: A Worksheet for Review of Municipal Codes and Ordinances**" (Center for Watershed Protection 2018b). Incorporating tree-related targets explicitly in permits and policies related to MS4s, CSOs, and TMDLs, as has been done in the District of Columbia and other locations, can do much to bolster the role of urban forest systems in stormwater management.

Minnesota Case Study

Quick facts

Where: Minnesota Stormwater Program
When: Adopted in 2013 in the online Minnesota Stormwater Manual
What:

- Volume reduction credit for engineered Tree Trench/Box practices based on interception, evapotranspiration, and infiltration.
- Annual pollutant removal credits for total suspended solids (TSS) and total phosphorus (TP) are calculated based on volume reduction.
- Requires that users enter soil volume, treatment area, tree size, and other inputs into the Minimal Impact Design Standards Calculator.

Overview

Minnesota was the first State to develop a robust, science-based approach for crediting engineered tree BMPs within State stormwater regulations. With funding allocated in 2009 from the State legislature, the Minnesota Pollution Control Agency convened the Minimal Impact Design Standards (MIDS) Working Group to develop new standards that would ultimately be adopted into the Minnesota Stormwater Manual (Minnesota Pollution Control Agency 2013). Sub-committees were formed to develop stormwater credits and design specifications for a suite of green infrastructure BMPs, including one focused on trees. The tree BMP sub-committee was interested in credits for retaining existing trees but ultimately adopted the Tree Trench/Box credit, which was easiest to quantify and justify in stormwater standards. One valuable feature of Minnesota's crediting approach is that it encourages well-designed tree BMPs with optimal uncompacted soil volume to maximize tree growth and function in processing stormwater runoff.

Key elements of the Minimal Impact Design Standards include the following:

- Stormwater volume performance goal for new development and redevelopment projects with greater than 1 acre of new impervious surface.
- Requires post-construction runoff volume to be retained onsite for 1.1 inches of runoff from impervious surfaces.
- Standardized credit calculations and design specifications for a variety of GSI BMPs, including: green roofs, bioretention basins, infiltration basins, permeable pavement, infiltration trench/tree box, swales, filter strips, and sand filters.
- A model ordinance package that helps developers and communities implement the new standards.

The MIDS approach has received widespread national attention for its innovative and robust crediting approaches. The unique manual was designed as an online Wiki format so that it could be easily adapted over time with new science, technical, and stakeholder input. It has been revisited and updated each year.

The science behind it

The Tree Trench credit methodology was developed by Kestrel Design Group and contract team, with oversight from the tree BMP sub-committee and multiple rounds of stakeholder input (Kestrel Design Group Team 2013). It is based on an extensive literature review of tree interception, evapotranspiration, and infiltration functions. Based on mean values found in Breuer and others (2003), the interception capacity is assumed to be 0.043 inches for a deciduous tree and 0.087 for a coniferous tree, and the canopy projection area is based on the diameter of the canopy at maturity, dependent on the tree species. The MIDS calculator provides default tree size options (small/medium/large) that can be used in place of tree species.

The team's report reviews the pros and cons of a variety of methods for quantifying evapotranspiration, recommending use of the Lindsey-Bassuk (1991) single whole tree water use equation. This method relates the total water use of a tree to four measurements: (1) canopy diameter, (2) leaf area index, (3) the evaporation rate per unit time, and (4) the evaporation ratio.

Pollutant removal for infiltrated and evapotranspired water is assumed to be 100 percent and is calculated by multiplying the volume of water reduced by event mean concentrations for Total Suspended Solids (TSS) and Total Phosphorus (TP) from the International Stormwater Database, version 3.

How the credit works

Minnesota provides a total runoff volume reduction credit for Tree Trench BMPs, by adding together the reductions provided by tree canopy interception, soil storage (infiltration), and evapotranspiration. The interception credit is a function of tree type and projected leaf area at maturity. The storage credit is a direct function of soil volume. The evapotranspiration credit is a function of plant available water and is indirectly related to soil volume (e.g., available pore space). The total runoff volume achieved for a particular storm is calculated as the lower value of the total runoff volume directed to the tree trench and the total storage provided by that trench through interception, infiltration, and evapotranspiration. The total volume reduction is also translated into annual pollutant removal values for TSS and TP. A Tree Trench BMP without an underdrain is assumed to remove 100 percent of pollutants, while a Tree Trench with an underdrain provides lower volume reduction and pollutant removal credits (**Figure 4**).

To calculate the credits, users must enter into the MIDS Calculator a suite of inputs based on the design of the particular Tree Trench BMP such as:

- Site Characteristics
  - watershed area/land cover draining to the Tree Trench BMP
  - downstream/routing BMP
- Soil/Media Characteristics
  - soil volume of the tree box
  - hydrologic characteristics of the soil
- Tree Characteristics
  - number of trees
  - most common tree type (deciduous or coniferous)
  - average tree size at maturity (small/medium/large)

Figure 5 shows one of the input screens for the **MIDS calculator**, demonstrating how the volume reduction credits are calculated based on the Tree Trench BMP characteristics provided. The figure illustrates how, in this crediting approach, the volume reduction based on soil storage (1201 cubic feet) far exceeds the volume reductions for evapotranspiration (72 cubic feet) and interception (5 cubic feet). Thus, the credit incentivizes providing ample soil volume and high quality, uncompacted soil media that will promote infiltration and storage in the short term and enable trees to grow to their optimal size. A helpful summary and example of Tree Trench credits using the MIDS calculator is included in the Center for Watershed Protection's **Accounting for Trees in Stormwater Models** (Center for Watershed Protection 2018a). Detailed technical information on the credit equations, input definitions, and other guidance can be found in the online Stormwater Manual section **Calculating Credits for Tree Trenches and Tree Boxes.**

In developing the credit calculations, it is assumed the tree practice is properly designed, constructed, and maintained in accordance with guidance in the **tree section** of the Minnesota Stormwater Manual. The manual website notes that if any of these assumptions is not valid, the BMP may not qualify for full credit.

Some of the model inputs used in the MIDS calculator for Tree Trench practices are only applicable to Minnesota

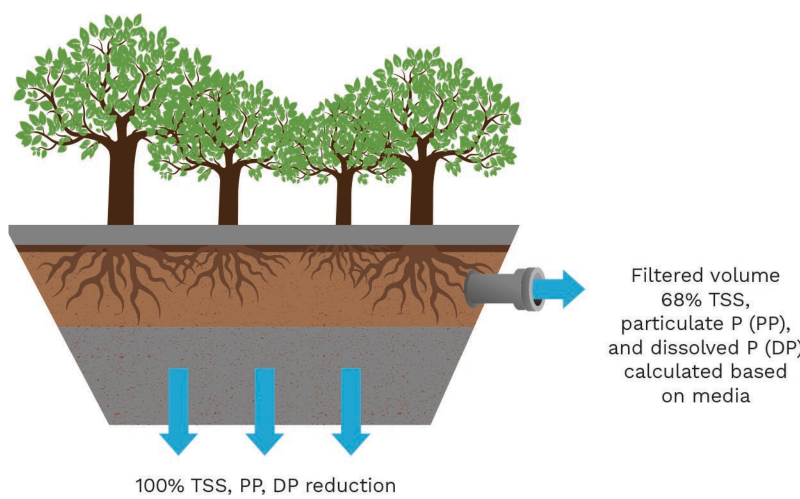
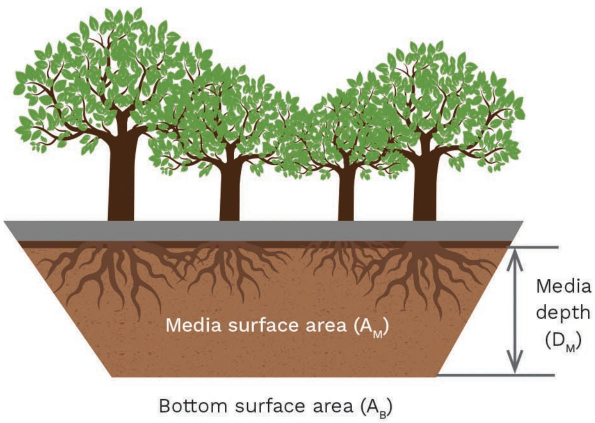


Figure 4. The Minimal Impact Design Standards (MIDS) total volume reduction is translated into annual pollutant removal values for Total Suspended Solids (TSS), particulate phosphorus (PP), and dissolved phosphorus (DP). A Tree Trench Best Management Practice (BMP) without an underdrain is assumed to remove 100 percent of pollutants, while a Tree Trench with an underdrain provides lower volume reduction and pollutant removal credits based on the type of media used.

$$V = \left(\frac{A_M + A_B}{2} \times n \times D_M \right) + V_I + V_{ET}$$



Media surface area [A_M]	2000
Bottom surface area [A_B]	2000
Media depth [D_M]	2.73
Media field capacity – wilting point [FC - WP](range 0.05-0.17)	0.12
Media porosity – field capacity [n – FC](range 0.15-0.35)	0.22
Tree type (most common)	Deciduous
Tree size (average for all trees)	Medium
Number of trees	3
Interception capacity [IC]	0.043
Canopy projection [CP]	490
Leaf area index [LAI]	4.1
Soil volume per tree [S_V]	
Underlying soil – Hydrologic Soil Group	7 MH (HSG B, 0.3 in/
Infiltration rate of underlying solids	0.3
User defined infiltration rate	
Required drawdown time	24
Volume reduction of BMP from ET [V_{ET}]	72
Volume reduction of BMP from interception [V_I]	5
Volume reduction stored in soil media	1201
Volume reduction capacity of BMP [V]	1279

Figure 5. One of the Minimal Impact Design Standards (MIDS) Calculator Tree Trench Best Management Practice (BMP) input screens showing tree and soil inputs (white boxes) and model outputs (gray).

and similar climates, so it is not recommended to use the calculator itself beyond those geographic zones. However, the equations and calculations behind the credit could readily be adapted for other climate zones.

Vermont Case Study

Quick facts

Where: State of Vermont
When: Adopted in 2017 in the Vermont Stormwater Management Manual Rule
What:

- Volume reduction credit in State stormwater permits.
- Three tree BMPs: Reforestation (active and passive), single tree planting.
- Companion local crediting framework for smaller sites not covered by State permit.

Overview

The effort to include trees and forests as key components of green stormwater infrastructure has been championed by the State forestry agency, Vermont Department of Forests, Parks and Recreation, for a number of years. Starting in 2010, the State's Agency of Natural Resources convened private and public stakeholders in a green infrastructure roundtable that resulted in strategic plans and initiatives to promote low impact development and GSI across State agencies, local governments, and professionals.

As a component of this effort, the State forestry agency secured a Federal grant that advanced several strategic actions, including hiring a green infrastructure coordinator within the State's stormwater agency (Department of Environmental Conservation) who helped facilitate the adoption of new policies and practices. Through the grant, a consultant was also hired to complete a comprehensive review and set of recommendations on options to credit trees within the State's stormwater management framework.

During this time, the upcoming revision of the State's stormwater management manual provided a key window of opportunity to advance the green infrastructure recommendations into policy. The initial draft version of the manual included stormwater credits for reforestation (active and passive) but no credit for single tree plantings. In subsequent stakeholder meetings and public comment, support for a single tree credit was voiced; the State worked with partners to incorporate this into the final manual that was officially adopted in 2017. A complementary GSI Toolkit was developed to aid local governments in crediting trees and other GSI practices on smaller development sites that are not covered by the State's permitting process (Vermont League of Cities and Towns 2017).

The science behind it

To establish a sound basis for establishing stormwater credits for trees, the State forestry agency contracted with Stone Environmental, Inc., to review existing research and policy examples and draft recommendations.

Stone Environmental, Inc., developed two white papers for the project. The first, describing the stormwater management benefits of trees (Moore and others 2014a) summarizes scientific knowledge about the tree processes that affect stormwater runoff (interception, transpiration, infiltration, and pollutant removal) and reviews considerations for maximizing stormwater benefits at the tree or site scale (soil restoration, engineered tree systems, tree selection, siting, and planting practices).

The second white paper (Moore and others 2014b) reviews examples from 12 States around the country that illustrate integrating tree retention or planting practices into stormwater programs. It also reviews over a dozen examples of green infrastructure crediting/incentives at the municipal scale, including examples from Seattle, WA, Washington, DC, and Nashville, TN.

The findings from these reviews helped inform the credits that were adopted in Vermont, taking into account regulatory concerns and stakeholder input.

How the credits work–State credits

The Vermont Department of Environmental Conservation Stormwater Program issues permits for post-development runoff from impervious surfaces. Permits are required for new development and redevelopment projects that will include more than 1 acre of impervious surfaces after construction. The 2017 Vermont Stormwater Management Manual Rule sets forth the treatment standards that must be met and the approved methods for calculating treatment volume (Tv) credits for the suite of structural and nonstructural stormwater treatment practices (i.e., BMPs) used onsite (Vermont Agency of Natural Resources 2017). Using the hydrologic condition method set forth in the manual, a suite of practices must be implemented to achieve the "hydrologic condition volume," which is calculated as the difference between the pre- and post-development site runoff for the 1-year, 24-hour storm.

The three types of State tree credits established under the reforestation nonstructural practice are summarized as follows:

1. **Active reforestation** involves planting a stand or block of trees, or individual trees, at a project site with the explicit goal of establishing a mature forest canopy or distributed cover that will intercept rainfall, increase evapotranspiration rates, and enhance soil infiltration rates.
   Tv credit = 0.1 inches x reforested area
   (i.e., 1 acre of reforested area = Tv credit of 363 cubic feet)

2. **Passive reforestation** consists of protecting a portion of a project site from mowing and allowing native vegetation to reestablish.
   Tv credit = 0.05 inches x practice area

3. **Single tree planting** involves planting individual trees on a project site.
   Tv credit = 5 cubic feet per tree planted (**Box 6**)

Box 6 Requirements for State Credits

Excerpts from the 2017 Vermont Stormwater Management Manual Rule:

REFORESTATION CREDITS

- The minimum contiguous area of active or passive reforestation shall be 2,500 square feet.
- The minimum width for reforested areas shall be 25 feet.
- The entire reforestation area shall be covered with an approved native seed mix covered with mulch to help retain moisture and provide a beneficial environment for the reforestation.
- Active and passive reforestation areas shall not be maintained as landscaped areas. Forest leaf litter, duff, and volunteer sapling and understory growth shall not be removed.
- The manual lists additional requirements regarding tree species selection, soil, slope limitations, planting plans, protection from development, and other design issues.

SINGLE TREE CREDIT

- Trees planted for the single tree credit shall be at least 2 inches in diameter at breast height (dbh) for deciduous trees, or at least 6 feet tall for conifers.

For full details on the State credits, see the 2017 Vermont Stormwater Management Manual, Section 4.2.1 (Vermont Agency of Natural Resources 2017).

Box 7 **Requirements for Local Credits**

The Green Infrastructure Toolkit lists a number of requirements for credit, such as:

- The tree(s) must be on the development site and within 20 feet of new and/or replaced ground-level impervious surfaces (e.g., driveway, patio, or parking lot).
- Trees must be retained, maintained, and protected on the site after construction and for the life of the development, or until any approved redevelopment occurs.
- Trees that are removed or die must be replaced with like species during the next planting season.
- See additional criteria regarding soil quality and volume and other design requirements.

RETAINED TREES

- Retained trees must be a minimum of 6 inches dbh. For trees smaller than this size that are retained, the newly planted tree credit may be applied instead.
- See additional guidelines for retained trees.

NEWLY PLANTED TREES

- New deciduous trees must be at least 1.5 inches diameter, measured 6 inches above the ground. New evergreen trees must be at least 4 feet tall.
- See additional tree selection, spacing, planting, and maintenance requirements.

For full details, see Fact Sheet #3 (**Vermont League of Cities and Towns 2015**).

How the credits work–local credits

Many smaller scale development and redevelopment projects do not meet the greater than 1-acre impervious surface threshold, and thus do not require a State permit or involve the standard treatment practice requirements and credits described above. Because these smaller projects are governed by local ordinances, the Vermont League of Cities and Towns worked with State agencies and stakeholders to develop a **Green Infrastructure Toolkit** for local use. The Toolkit features:

- **GSI Sizing Tool spreadsheet**.
- Set of **GSI fact sheets** covering credits and criteria for 10 stormwater practices, including trees.
- **Low Impact Development and Green Stormwater Infrastructure (GSI) Bylaw Template** (i.e., model ordinance) that can be used or adapted into local policy.

The crediting approach for retained and newly planted trees is based on an impervious area reduction credit, which in effect reduces the total volume of runoff that needs to be treated through other practices (**Box 7**). **Box 8** shows how the credits are calculated.

BOX 8 **Credit Calculation**

How tree credits are calculated using Vermont's Green Stormwater Infrastructure (GSI) Simplified Sizing Tool:

BMP	Tree Type	Impervious Area Reduction Credit
Retained Tree	Evergreen Deciduous	20% canopy area (min. 100 ft^2 / tree) 10% canopy area (min. 50 ft^2 / tree)
Newly Planted Tree	Evergreen Deciduous	50 ft^2 / tree 50 ft^2 / tree

TOTAL GROUND LEVEL IMPERVIOUS COVER: _______ sq. ft.

RETAINED TREES:

Total evergreen canopy area: ________ sq. ft.
Evergreen canopy area × 0.2 = ________ sq. ft. credit (min. 100)
Total deciduous canopy area: ________ sq. ft.
Deciduous canopy area × 0.1 = ________ sq. ft. credit (min. 50)

NEWLY PLANTED TREES:

Total new evergreen trees meeting requirements: ________
# of new evergreen trees × 50 = ________ sq. ft. credit (min. 50)
Total new deciduous trees meeting requirements: ________
# of new deciduous trees × 50 = ________ sq. ft. credit (min. 50)

TOTAL CREDIT: ________ sq. ft.
(Max 25% of proposed impervious cover)

Source: GSI Simplified Sizing Tool Fact Sheet #3 (Vermont League of Cities and Towns 2015)

Chesapeake Bay Case Study

Quick facts

Where: Chesapeake Bay Watershed (DC, DE, MD, NY, PA, VA, WV)
When: Adopted in 2016 as approved Total Maximum Daily Load BMP credits by Federal and State agencies
What:

- BMP credits are earned for **urban tree canopy expansion** for dispersed plantings over turf or impervious surface and **urban forest planting** for full reforestation.
- Tree canopy is mapped and credited as a land use class in the Chesapeake Bay model, with reduced pollutant loading relative to turf or impervious cover.
- States get credit for newly planted trees for 10 years, after which the tree canopy is tracked directly through high-resolution imagery.

Overview

In 2010, the U.S. Environmental Protection Agency (EPA) established the Chesapeake Bay Total Maximum Daily Load (TMDL)—or "pollution diet"—to reduce the amount of nitrogen, phosphorus, and sediment entering the Bay through the region's waterways. The TMDL covers 64,000 square miles that stretch across parts of six States and the District of Columbia. Each of these jurisdictions has committed to reaching ambitious pollutant load reductions by 2025, as documented in phased watershed implementation plans. In order to track and credit progress towards these targets, the States and the District of Columbia must provide detailed reporting of the number and type of approved BMPs implemented on all agricultural and urban lands.

While the Chesapeake Bay TMDL and modeling tools have always assigned low pollutant loading rates to forest land cover, they did not have a way to account for and credit the water quality value of urban tree canopy (individual and small patches of trees in developed areas not large enough to be classified as forest). Thanks to investments by the Chesapeake Bay Program partners in high-resolution land cover data, distinct mapping of forest, urban tree canopy over turf, and urban tree canopy over impervious cover became available in 2016.

A BMP expert panel was convened in 2015 to provide recommendations on how urban tree canopy (including urban tree planting) should be credited in the TMDL context. All documentation of the literature, modeling approaches, and crediting decisions are provided in the **report the panel developed** (Law and Hanson 2016). Following review and revision with Federal, State, and other stakeholders, a new BMP credit for urban tree canopy expansion, as well as a higher credit for urban forest planting (i.e., reforestation of developed/turf areas) were officially adopted in 2016 for use in the TMDL. Having tree BMP credits approved for use in the TMDL has helped incentivize the District of Columbia and other local jurisdictions to include tree planting targets as part of their MS4 permits.

The science behind it

The tree canopy BMP expert panel, with support from the Center for Watershed Protection, completed a thorough literature review on the water quality benefits of urban trees and existing tree crediting approaches. Hynicka and Divers (2016) constructed a water-balance modeling approach to estimate pollutant loading rates for tree canopy over turf grass, tree canopy over impervious cover relative to turf, and impervious cover without trees. To account for spatial and temporal variation in precipitation, 11 years (2005 to 2015) of daily weather data were used from each of 8 regional locations spanning the Chesapeake Bay Watershed. The relative pollutant load reductions are summarized in **Table 6**.

The expert panel used a variety of tree species, growth, and mortality scenarios in i-Tree Forecast to establish an average canopy acreage credit per tree planted (144 square feet per tree, or approximately 300 trees per acre).

Table 6. Tree canopy relative land use loading rate reductions in total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) in relation to underlying land use cover

Land use	Total nitrogen reduction (%)	Total phosphorus reduction (%)	Total suspended solids (TSS) reduction (%)
Canopy over turf	23.8	23.8	5.8
Canopy over roads	8.5	11.0	7.0
Forest	85.0	90.7	81.6*

*Percent reduction is based on an average Municipal Separate Storm Sewer System (MS4) land use loading rate for sediment. Source: Hynicka and Divers 2016.

How the credit works

Under the Chesapeake Bay modeling and TMDL framework, every acre of land in the watershed has a designated land use class and associated pollutant loading rate, based on high-resolution land cover mapping, other datasets, and best available science. Like many BMPs in the TMDL framework, the urban tree canopy BMPs are credited based on a *land use change* or the conversion of a given acreage of land from a higher loading land use (e.g., turf grass or impervious cover) to a lower loading land use (urban tree canopy or forest). For these land use change BMPs, States, and local governments track and report the total acreage of each BMP implemented on an annual basis, and the Chesapeake Bay modeling tools calculate the resulting pollutant reductions.

The **urban tree canopy expansion BMP** includes tree planting projects on developed land that increase the tree canopy overlying turf or impervious surfaces but do not create forest-like conditions. Trees do not have to be planted in a single contiguous area. Trees planted in a riparian forest buffer or as part of a structural BMP, such as bioretention practices, are not included; these are tracked under separate BMP credits. Each tree planted is given credit for creating 144 square feet of urban tree canopy (equivalent to 300 trees per acre), which reflects average growth at 10 years after planting. The credit is calculated within the Chesapeake Bay model based on the percentage reduction in nitrogen, phosphorous, and sediment pollutant loads relative to the underlying land use cover.

The **urban forest planting BMP** includes projects that create forest-like conditions. Trees must be planted in a contiguous area specified in a documented planting and maintenance plan and conform to the State's planting density and associated standards for forest conditions. Urban forest planting BMPs result in a change of land use from turf grass to forest land. The credit for this BMP is calculated based on the difference between the land use loading rate of turf grass and forest land across the acreage of the urban forest planting.

For both BMP credits, the credit expires after 10 years, at which point the canopy coverage is assumed to be tracked and directly credited as a land use through new high-resolution imagery/land use data.

Conclusion

Urban forest systems (trees, soil, and groundcover) help manage stormwater runoff by reducing stormwater volume, slowing rainfall intensity, delaying runoff, improving infiltration into soil, and increasing water storage capacity in soils. Using trees as part of a stormwater management "treatment train" can increase the efficiency of GSI practices. Larger, mature trees provide greater benefits, and healthy trees appreciate in terms of benefits over time, so managing the entire urban forest to increase leaf surface area is a good strategy to help manage stormwater runoff city-wide. Providing credits in State and local stormwater programs for retaining mature trees and strategically planting new trees is a valuable tool to encourage their use as part of a stormwater management program.

Trees increase the quality of life in our cities for residents, visitors, and business owners. Using them purposefully can help to reduce some of the disservices that come with development and improve the long-term sustainability of urban ecosystems.

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Glossary of Terms

Bioretention—a green stormwater infrastructure practice that uses soil or engineered planting media and plants to retain/detain water and filter pollutants from stormwater runoff. Raingardens are a subset of bioretention practices.

Diffuse-porous xylem—water-conducting vessel elements in hardwood tree stems having no clear earlywood or latewood arrangement and no discernable difference in pore diameter size.

Dynamic storage—the temporary storage of rainfall on tree canopy surfaces eventually released as throughfall or stemflow to become stormwater runoff.

Green stormwater infrastructure (GSI)—stormwater mitigation practices designed to mimic natural processes that filter and retain rain where it falls. Typical GSI practices include green roofs, urban trees, bioretention, vegetated swales, permeable pavements, and water harvesting.

Interception loss—the amount of rainfall that is intercepted on aboveground surfaces and evaporates back to the atmosphere—does not contribute to stormwater runoff.

Leaf area index (LAI)—the total single-side leaf surface area per unit of ground surface area. An LAI of 3 indicates that a plant has three times as much leaf surface area as the ground area under that plant.

Leaf surface area—the areal sum total of all single sides of leaves in a tree.

Macropores—small holes or pores in the soil greater than 75 µm from which water drains relatively quickly by gravity, thus providing adequate oxygen for root growth and playing a role in stormwater infiltration.

Micropores—smaller pores in soil (generally 5 to 30 µm) that tend to hold water in the soil profile where it is available for plant uptake.

Preferential flow—the uneven and rapid movement of water through soil due to cracks or channels in the soil profile caused by the root/soil interface, decayed roots, or other biotic and abiotic activities such as geologic processes.

Ring-porous xylem—water-conducting tissue in hardwood tree stems that features earlywood pores that clearly form concentric rings.

Runoff hydrograph peak—the maximum stormwater runoff discharge volume reported during a specified time period as related in graphical form (hydrograph). The runoff hydrograph depicts flow (discharge) versus time.

Semi-ring-porous xylem—water-conducting tissue in hardwood tree stems where pores do not form discernable rows and sizes of pores gradually decrease from earlywood to latewood. Static storage—rainfall intercepted by tree canopy tissue after a rainfall event that eventually evaporates into the atmosphere and does not reach the ground surface or become stormwater runoff.

Stemflow—the movement of water intercepted by tree canopy down the stem to the ground.

Throughfall—rain that passes through the tree canopy and drips onto the ground below.

Tracheid xylem—water-conducting pores in soft-wooded trees (i.e., pine).

Transpiration—the process where plants take in water from the soil through their roots, passing it to leaves, where it is released as water vapor through pores (stomata) to the atmosphere through evaporation.

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REVIEW

Plants People Planet PPP Open Access

The benefits of trees for livable and sustainable communities

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Societal Impact Statement

Trees play a critical role for people and the planet. Numerous studies have demonstrated that the presence of trees and urban nature can improve people's mental and physical health, children's attention and test scores, the property values in a neighborhood, and beyond. Trees cool our urban centers. Trees are essential for healthy communities and people. The benefits that trees provide can help cities and countries meet 15 of the 17 internationally supported United Nations Sustainable Development Goals. This critical review provides a comprehensive argument that trees should be considered an important part of the equation by project managers and civic leaders as we collectively work toward reaching these sustainability goals.

Summary

We live in an era influenced by humans to the point that the Earth's systems are now altered. In addition, a majority of the world's population live in cities. To meet the needs of people in a changing world, The United Nations General Assembly created the United Nations Sustainable Development Goals (UN SDG) to improve the quality of life for people. These broad goals outline the greatest challenges of our time. An effective strategy to assist in meeting these goals is to plant and protect trees, especially in cities where the majority of people live. This paper serves as a critical review of the benefits of trees. Trees promote health and social well-being by removing air pollution, reducing stress, encouraging physical activity, and promoting social ties and community. Children with views of trees are more likely to succeed in school. Trees promote a strong economy and can provide numerous resources to the people that need them. While cities are getting hotter, trees can reduce urban temperatures. They provide habitat and food for animals. Finally, trees are valuable green infrastructure to manage stormwater. Money spent on urban forestry has a high return on investment. As we navigate this human-dominated era, we need skilled people who understand the nuances of the built environment and trees as we strategically plan the cities of the future. The overwhelming evidence from the scientific literature suggests that investing in trees is an investment in meeting the UN SDG, and ultimately an investment for a better world.

KEYWORDS

benefits of trees, cities, climate change, ecosystem services, human health, sustainability, United Nations Sustainable Development Goals, urban forest

1 | INTRODUCTION

This current era, the Anthropocene, is driven by human influence and it has ushered in a growing number of direct and indirect challenges that can greatly impact the health and prosperity of people and the planet (Ellis, 2015). Climate change is driving an unprecedented number of extreme climatic events and causing ocean levels to rise (Goudie, 2019). The human population continues to increase (UN, 2015a) and metropolitan regions are growing and expanding. By 2050, most of the world's population (70%) will live in cities (FAO, 2016). These concentrated populations have a wide variety of challenges, ranging from people not having access to clean water to pollution-related health issues (UN, 2015b).

People and cities need efficient and effective solutions to address the challenges of this current era. In 2015, the United Nations (UN) outlined 17 goals for sustainable development. The UN Sustainable Development Goals (UN SDG), while ambitious, have the promise to improve the quality of life for the billions of people on this planet and serve as a strong example of what the global society prioritizes (UN, 2015b).

Environmental and nature-based solutions can help address a majority of these outlined goals. Previous work has aligned environmental topics, such as plant conservation (Sharrock & Jackson, 2017), soil and soil science (Keesstra et al., 2016), and the prevention of land degradation (Vlek, Khamzina, & Lulseged, 2017) as solutions to meet the UN SDG. One additional way to address the challenges that the urban population faces is to provide people with green spaces and to plant, maintain, and protect trees (FAO, 2016; Endreny et al., 2017; Endreny, 2018; World Resources Institute, 2018). The direct and indirect benefits of trees and nature are vast (Blackmore, 2009; Brack, 2002; Hirons & Thomas, 2018; Kuo, 2015; Tyrväinen, Pauleit, Seeland, & De Vries, 2005), and much research has focused on the benefits of trees to urban residents (Jennings & Johnson Gaither, 2015).

This paper provides a critical and succinct review on how the benefits of trees can increase the well-being of a majority of the world's population. The authors classify the benefits of trees into five categories: (a) health and social well-being; (b) cognitive development and education; (c) economy and resources; (d) climate change mitigation and habitat; and (e) green infrastructure (Table 1). In addition to the benefits in these categories, the presence of trees and green space can help a city to meet Goal 11, sustainable cities and communities, of the UN SDG through providing universal access to green and public spaces. This paper expands on the work of the FAO (2016) and highlights additional goals of the UN SDG that can be met through a healthy urban forest.

2 | THE SCIENTIFIC BENEFIT OF TREES

2.1 | Health and social well-being

One of the most important benefits for human health that urban forests can provide is the interception and reduction of air pollution (McDonald et al., 2007, 2016; Nowak, Crane, & Stevens, 2006; Nowak, Hirabayashi, Bodine, & Greenfield, 2014; Nowak, Hirabayashi, Doyle, McGovern, & Pasher, 2018). Air pollution (e.g. particulate matter (PM), ozone, carbon monoxide, polycyclic aromatic hydrocarbons, nitrogen dioxide, sulfur dioxide, etc.) is linked to bronchitic symptoms, intraocular pressure (leads to glaucoma), myocardial infarction (i.e. heart attacks), changes in autonomic and micro-vascular function, autism, blood pressure, cognitive development problems in children (slower processing speeds, behavioral problems, attention deficit/hyperactivity disorder symptoms), blood mitochondrial abundance, heart failure, and mortality in humans (Berhane et al., 2016; Di et al., 2017; Hoek et al., 2013; Mustafić et al., 2012; Nwanaji-Enwerem et al., 2019; Peterson et al., 2015; Shah et al., 2013; Volk, Lurmann, Penfold, Hertz-Picciotto, & McConnell, 2013; Weichenthal, Hatzopoulou, & Goldberg, 2014; Zhong et al., 2016). Trees remove a tremendous amount of air pollution. It is estimated that from the contiguous United States, urban trees remove 711,000 metric tons of air pollution each year (Nowak et al., 2006). Previous research demonstrated that out of 35 woody species studied, all accumulated PM (Mo et al., 2015). Further, Chen, Liu, Zhang, Zou, and Zhang (2017) suggested that $PM_{2.5}$ accumulation capacity increases as a tree matures, and a diverse planting of species augments the trapping of $PM_{2.5}$.

There is a link between trees, green spaces and mortality, and it is documented in the literature (James, Hart, Banay, & Laden, 2016; Nowak et al., 2018; Villeneuve et al., 2012). In one particular study, the authors associated the increase in cardiovascular and respiratory deaths with the infestation and death of ash trees (genus *Fraxinus*) in counties within the United States (Donovan et al., 2013). Having more trees, especially the right mature species planted in the right locations, can reduce particulate matter and other forms of air pollution, which could reduce mortality and morbidity in our urban centers.

Beyond pollution removal, the presence of trees provides additional direct and indirect benefits to human health and wellness (Donovan, 2017). Regardless of why trees provide so many benefits (see *Biophilia hypothesis* [Wilson, 1984; Kellert & Wilson, 1995] and *Attention Restoration Theory* [(Kaplan & Kaplan, 1989; Kaplan, 1995]), the presence of trees and green space promotes well-being. Trees and greener environments are strongly linked to reduced negative thoughts, reduced symptoms of depression, better reported moods, and increased life satisfaction (Berman et al., 2012; Bratman, Hamilton, Hahn, Daily, & Gross, 2015; Li, Deal, Zhou, Slavenas, & Sullivan, 2018; Lohr & Pearson-Mims, 2006; Mayer, Frantz, Bruehlman-Senecal, & Dolliver, 2009; Taylor, Wheeler, White, Economou, & Osborne, 2015; White, Alcock, Wheeler, & Depledge, 2013). A view of trees can help patients recover in a hospital (Ulrich, 1984) and reduce diastolic blood pressure and stress in research participants (Hartig, Evans, Jamner, Davis, & Gärling, 2003; Jiang, Larsen, Deal, & Sullivan, 2015). Residents of tree-lined communities feel healthier and have fewer cardio-metabolic conditions than their counterparts (Kardan et al., 2015). The presence of trees can even improve the condition of people with a neurodegenerative disease (Mooney & Nicell, 1992).

TABLE 1 A high-level overview of the benefits that urban trees provide, and how the direct and indirect benefits relate to the corresponding United Nations Sustainable Development Goals. Further, the presence of trees and green space can help a city meet Goal 11, or sustainable cities and communities, through providing universal access to green and public spaces

Benefit of urban trees category	Corresponding United Nations Sustainable Development Goals	Scientific benefits of trees highlights
Health and social well-being		
Trees promote physical and mental health for urban residents. They support community ties and reduced crime rates.	Goal 3: Good health and well-being	Reduce pollution
	Goal 11: Sustainable cities and communities	Improve physical and mental health
	Goal 16: Peace, justice, and strong institutions	Strengthen community ties
		Increase physical activity
		Decrease aggression and violence
		Reduce crime
Cognitive development and education		
Trees increase a student's ability to succeed in school.	Goal 4: Quality education	Improve student performance
		Reduce stress
		Increase in concentration
		Reduce symptoms of ADD/ADHD
		Increase in attention
		Increase in self-discipline
Economy and resources		
Trees are good for the economy and they reduce energy bills. They provide many resources, such as food, to a community.	Goal 1: No poverty	High return-on-investment
	Goal 2: Zero hunger	Support tourism
	Goal 7: Affordable and clean energy	Increase home prices and rental rates
	Goal 8: Decent work and economic growth	Reduce energy use and bills
	Goal 10: Reduced inequalities	Promote food sustainability
	Goal 12: Responsible consumption and production	Provide resources and firewood
Climate change mitigation and habitat		
Trees mitigate the Urban Heat Island Effect and store and sequester carbon. They are important for habitat.	Goal 3: Good health and well-being	Reduce Urban Heat Island Effect
	Goal 13: Climate action	Store and sequester carbon
	Goal 15: Life on land	Provide critical habitat
Green infrastructure		
Trees are important forms of infrastructure, especially for storm water management	Goal 3: Good health and well-being	Manage storm water
	Goal 6: Clean water and sanitation	Reduce pollution
	Goal 9: Industry, innovation and infrastructure	Protect life below water and on land
	Goal 11: Sustainable cities and communities	
	Goal 12: Responsible consumption and production	
	Goal 14: Life below water	
	Goal 15: Life on land	

In addition, as people value trees and natural environments, they like being around them and viewing them (Dwyer, Schroeder, & Gobster, 1991; Kaplan, Kaplan, & Wendt, 1972; Lohr, Pearson-Mims, Tarnai, & Dillman, 2004). The presence of trees and green spaces may encourage physical activity (Bell, Wilson, & Liu, 2008; Ellaway, MacIntyre, & Bonnefoy, 2005), which is related to physical and mental health. Given the multi-faceted health benefits of the ecosystem service ecotherapy (Summers & Vivian, 2018), the very act of planting and caring for trees may promote mental and physical health. Trees not only make people happier and healthier, but they make communities more livable.

Well-maintained trees are associated with improving the social capital and ecology of a community (Coley, Sullivan, & Kuo, 1997; Elmendorf, 2008; Holtan, Dieterlen, & Sullivan, 2015; Kuo, 2003;

Kuo, Sullivan, Coley, & Brunson, 1998), reducing violence and aggression in households (Kuo & Sullivan, 2001a), and limiting criminal activity in neighborhoods (Donovan & Prestemon, 2012; Kuo & Sullivan, 2001b; Troy, Morgan Grove, & O'Neil-Dunne, 2012; Troy, Nunery, & Grove, 2016). In one study, Kondo, Han, Donovan, and MacDonald (2017) demonstrated that the loss of ash trees due to the emerald ash borer in Cincinnati, Ohio, USA, was positively associated with increases in crime. This could be an example of "cues to care," which is the idea that a well-tended landscape is valued and viewed (Troy et al., 2016). While there is a perception that the presence of trees can increase crime, it is likely related to unmanaged and smaller trees that provide greater protection to a criminal (Donovan & Prestemon, 2012). Regardless of this perception, evidence indicates that trees make residents feel safer (Kuo, Bacaicoa, & Sullivan, 1998).

Based on literature cited, trees can help meet our societal goals as outlined in the UN SDG, especially Goal 3: Ensure healthy lives and promote well-being for all at all ages; Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable; and Goal 16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels. These benefits from trees, if distributed throughout communities, can help make cities more sustainable and livable (Table 1).

2.2 | Cognitive development and education

To increase literacy and numeracy, children need to have access to nature, and at the very least, green and natural views of trees (Berman, Jonides, & Kaplan, 2008; Faber Taylor, Kuo, & Sullivan, 2002; Lin, Tsai, Sullivan, Chang, & Chang, 2014; Tennessen & Cimprich, 1995). As reviewed in Kuo, Browning, Sachdeva, Lee, and Westphal (2018), stress levels, concentration, and intrinsic motivation are likely strong factors in a child's success as a student. Students who are focused, attentive, and engaged are more likely to succeed in school and receive a quality education. Attention Deficit Disorder (ADD) and Attention Deficit Hyperactivity Disorder (ADHD) can impact a student's success in school (Rief, 2012). Green environments, such as open spaces with big trees, are related to reduced symptoms of ADD and ADHD (Faber Taylor & Kuo, 2009; Faber Taylor, Kuo, & Sullivan, 2001).

Tree cover is strongly linked to student academic performance (Kuo, Browning, Sachdeva, et al., 2018; Kweon, Ellis, Lee, & Jacobs, 2017; Matsuoka, 2010). In one study, views of trees and shrubs at schools, as opposed to grass, were strongly related to future education plans and graduation rates (Matsuoka, 2010). Li and Sullivan (2016) found that students who had views of trees and green environment from their classrooms, as compared to being in a room without windows or a room with a view of a brick wall, scored substantially higher on tests measuring attention, and they had a faster recovery from a stressful event. Students who learn in the presence of trees and nature have improved classroom engagement (Kuo, Browning, & Penner, 2018). Trees can promote a quality education, which has innumerable advantages for society. Access to trees supports a quality education and can help countries meet the UN SDG, especially Goal 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all (Table 1).

2.3 | Economy and resources

Trees provide many ecosystem services that can benefit a city environment, ranging from reducing energy use and removing pollution (Nowak & Greenfield, 2018) to increasing property values, developing the local economy, and supporting tourism (Nesbitt, Hotte, Barron, Cowan, & Sheppard, 2017). In the United States alone, it is estimated that trees provide $18.3 billion in annual value due to air pollution removal, reduced building energy use, carbon sequestration, and avoided pollutant emissions (Nowak & Greenfield, 2018). Allocating resources in tree planting and maintenance can be a fiscally sound decision based on the benefits and ecosystem services that trees provide (McPherson, Simpson, Peper, Maco, & Xiao, 2005). This high return on investment can be multiples of invested capital over time (McPherson, van Doorn, & de Goede, 2016). Many benefits are not fully captured in this return on investment. In addition, the presence of shade trees can reduce the rate of ageing of road and pavement surfaces (McPherson & Muchnick, 2005), influence shoppers to visit a shopping area (Wolf, 2005), and increase the selling price of a home (Anderson & Cordell, 1988; Donovan & Butry, 2010; Sander, Polasky, & Haight, 2010). As long as trees do not block the view of an office building, quality landscaping with properly maintained trees can increase rental rates (Laverne & Winson-Geideman, 2003). A properly planted tree can also reduce energy use (Akbari, 2002; Donovan & Butry, 2009; Pandit & Laband, 2010; Simpson, 1998), which can reduce the cost of energy bills.

While urban trees can provide economic benefits, they can also provide resources, such as food, to a community. The idea that trees can provide food security and promote well-being is not new. In fact, agroforestry was previously recognized as a way to meet the United Nations Millennium Development Goals (Garrity, 2004). Hundreds of tree species are used for agroforestry to promote food sustainability and nutritional security (Dawson et al., 2013; Orwa, Mutua, Kindt, Jamnadass, & Simons, 2009). Urban orchards, or urban food forestry, can be an efficient way to consistently provide free or low-cost nutrient-dense food to the people that need it (Clark & Nicholas, 2013). Urban street trees can provide many resources to the inhabitants of cities. In New York City, 88% of tree species present are forgeable for medicine, food, etc., including nine out of ten of the most common tree species (Hurley & Emery, 2018). The "Incredible Edible" movement is an example of how underutilized plots in urban environments can be used to grow food, as a means to reduce food deserts and build community (Morley, Farrier, & Dooris, 2017). Planting urban orchards in available spaces could prove an important tool to reduce hunger and increase social ties. Urban foraging may not be practiced in areas of higher opportunity (Larondelle & Strohbach, 2016), and so it may not receive the attention it deserves as a solution for food security.

Forests also provide the habitat for non-timber forest products (NTFP) that can provide valuable resources to a local community (Turner, 2015). Some examples of NTFP include American ginseng (*Panax quinquefolius* L.), maple syrup (derived from *Acer* spp.) and nuts (from trees like the European Chestnut, *Castanea sativa* Mill.; Poe, McLain, Emery, & Hurley, 2013; Turner, 2015). Traditionally NTFP are associated with a rural environment, yet urban NTFP can provide additional financial, food, and medicinal security to people living in cities (Kaoma & Shackleton, 2015; McLain, Hurley, Emery, & Poe, 2013; McLain, Poe, Hurley, Lecompte-Mastenbrook, & Emery, 2012; Poe et al., 2013).

Finally, wood is an important source of material and energy for much of the world. Trees that are cut down in cities or communities can be used for timber (Sherrill, 2003). This could be used for fuel or for producing goods. Innovative programs can promote sustainability and creative usage of urban wood. An example of this is the "Working for Water" program which trains people in South Africa to remove woody invasive species, and then the cleared wood can be used for a variety of secondary industries (Binns, Illgner, & Nel, 2001). While this program works with invasive species, it serves as an example of creative solutions involving the community with urban issues involving trees. Urban forests can also help supply affordable energy to people that need it (FAO, 2016). It is important to note, however, that burning wood is a large contributor to air pollution in urban environments (Favez, Cachier, Sciare, Sarda-Estève, & Martinon, 2009). Therefore, if wood is used for fuel, it should be burned in such a way that the benefits outweigh the harm to human health. Trees are a valuable resource, even after they are cut down.

Trees can help countries meet the UN SDG by providing food, resources and economic advantages to countries. These goals include: Goal 1: End poverty in all its forms everywhere; Goal 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture; Goal 7: Ensure access to affordable, reliable, sustainable, and modern energy for all; Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all; Goal 10: Reduce inequality within and among countries; and Goal 12: Ensure sustainable consumption and production patterns.

2.4 | Climate change mitigation and habitat

Climate change directly impacts where people live. One of the most pressing risks for human health associated with a changing climate are the increases in heat-related deaths, diseases, and infectious diseases (Patz, Campbell-Lendrum, Holloway, & Foley, 2005). The increase in heat and heat-related health problems is especially prevalent in cities, where the Urban Heat Island Effect increases the impact of heat waves (Ward, Lauf, Kleinschmit, & Endlicher, 2016). Properly placed trees can mitigate temperatures in built environments. Not only do trees provide shade through intercepting and absorbing light, but through evapotranspiration trees actively cool the air of cities (EPA, 2008; Hirons & Thomas, 2018; Schwab, 2009). An analysis of 94 urban areas around the world indicates that trees have a significant impact on the temperature, and are responsible for, on average, 1.9°C (*SD* 2.3) of cooling in a city (Figure 1a). Trees incorporated into the built environment can reduce a city's temperature by 9°C (Figure 1b). This reduction of temperature in major cities (Akbari, Pomerantz, & Taha, 2001; Loughner et al., 2012; McDonald et al., 2016) can ultimately help ameliorate the impact of climate change on human health.

One of the key ways to limit the impacts of climate change is to reduce the amount of carbon released into the atmosphere. Trees are beneficial to storing carbon, which is a major contributor to climate change (Nowak, 1993). Nowak and Crane (2002) determined that not only do urban trees in the coterminous United States sequester 22.8 million tons of carbon each year, but the urban forest in this area stores 700 million tons of carbon. The more mature a tree is, the more carbon it stores in its woody biomass (Schwab, 2009). Although trees are not the single answer, healthy and mature trees have the potential to make significant carbon mitigation returns.

Finally, trees, specifically mature ones, perform a keystone role in terrestrial ecosystems (Manning, Fischer, & Lindenmayer, 2006). Trees are critically important, especially in urban areas, as they provide food and habitat for birds, invertebrates, mammals, and plants (Fahey, Darling, & Anderson, 2015; Schwab, 2009; Tyrväinen et al., 2005). Improving and maintaining biodiversity is necessary for a sustainable city.

Therefore, planting and protecting trees can help a country meet the following UN SDG: Goal 3: Ensure healthy lives and promote well-being for all at all ages; Goal 13: Take urgent action to combat climate change and its impacts; and Goal 15: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

2.5 | Green infrastructure

Trees are considered "decentralized green infrastructure" and can be important tools for managing water, especially in an urban ecosystem (Berland et al., 2017). Water runoff is a serious issue in the city environment, as runoff can increase the exposure to pollution and cause property damage (Braden & Johnston, 2004). Trees can help reduce and intercept stormwater and improve the quality of runoff water (Berland et al., 2017; Bolund & Hunhammar, 1999; Brack, 2002; Livesley, McPherson, & Calfapietra, 2016; Scharenbroch, Morgenroth, & Maule, 2016). With less contact on impervious surfaces, stormwater is cooler and has fewer pollutants when it enters local waterways and water-related ecosystems (Schwab, 2009). Trees can also be valuable in phytoremediation, where they can remove heavy metals and other contaminants from the environment (French, Dickinson, & Putwain, 2006). While gray infrastructure depreciates over time, trees appreciate in value as they mature (Hauer & Johnson, 2003). Therefore, an investment in trees can make economic sense and align with the UN SDG.

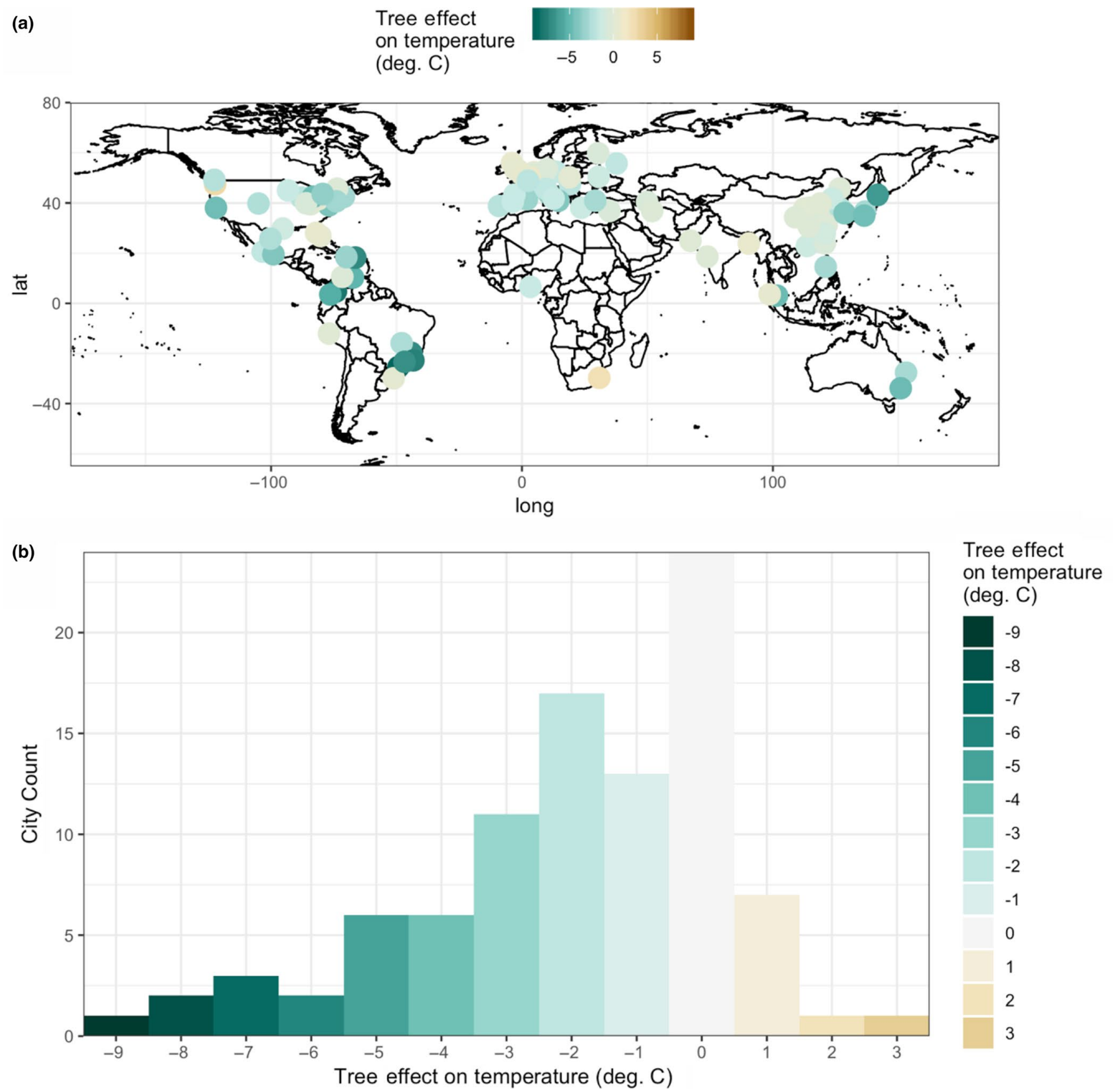

FIGURE 1 (a) Trees greatly contribute to urban cooling. Cities included in this evaluation have an estimated population in the metropolitan area greater than 2 million in the year 2000, a metropolitan area greater than 1,000 km^2, and an urban heat island effect greater than 1°C (Center for International Earth Science Information Network - CIESIN - Columbia University, 2016). The effect of trees on urban cooling was calculated by subtracting the temperature in areas without trees from the observed temperatures; (b) while the standard deviation is large, it is not normally distributed. The impact of trees on cooling the urban environment is ecologically and statistically significant. Figures are created by Dr Christy Rollinson, Forest Ecologist at The Morton Arboretum

Green infrastructure protects life below water and life on land, while promoting sustainability. The ability of trees to reduce the pollution in the waterways is beneficial to human health and well-being. Therefore, by promoting trees as green infrastructure, the following UN SDG can be met Goal 3: Ensure healthy lives and promote well-being for all at all ages; Goal 6: Ensure availability and sustainable management of water and sanitation for all; Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable; Goal 12: Ensure sustainable consumption and production patterns; Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development; and Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation and halt biodiversity loss (Table 1).

3 | IMPORTANT CONSIDERATIONS

While the above outlines how the benefits of trees can help build sustainable cities in the future and reach the collective agenda of the UN SDG, there are important considerations associated with this review. First, while there is strong evidence that nature benefits humans, much of the research conducted has been correlative. Future studies should address methodological limitations and minimize potential errors or bias in research (such as self-reporting moods, sampling bias, lack of control group, and short-time frames of research; Keniger, Gaston, Irvine, & Fuller, 2013). Despite these concerns, the vast number of studies illustrating the breadth of benefits related to trees is compelling.

Many of these papers describe the importance of urban green space. Green space can be defined as herbaceous or woody vegetated areas such as parks, forests, or gardens (Jennings & Johnson Gaither, 2015). It is unlikely that the papers that asked questions about green space focused on grassy fields that lacked trees. In addition, research shows that green spaces without trees or dense vegetation can have negligible or negative impacts on people (Kuo, Browning, Sachdeva, et al., 2018; Kweon et al., 2017; Matsuoka, 2010; Reid, Clougherty, Shmool, & Kubzansky, 2017).

While this review stresses the importance of trees, this is not to say that other forms of nature will not provide similar benefits. However, in the space-limited city, trees are practical. They provide a strong return on investment given their vertical orientation and size.

Trees do not only provide positive benefits, however, as there can be negative associations surrounding trees. These disservices to people can range from financial strains associated with tree maintenance and care, to property damage, to safety issues associated with limited visibility and security, and the inconvenience of messiness (Escobedo, Kroeger, & Wagner, 2011; Lohr et al., 2004; Lyytimäki & Sipilä, 2009; Roy, Byrne, & Pickering, 2012; Staudhammer, Escobedo, Luley, & Bond, 2009; Wyman, Escobedo, Stein, Orfanedes, & Northrop, 2012).

One of the most commonly cited disservices associated with trees is the production of biogenic Volatile Organic Compounds (bVOCs) which react with nitrogen oxides, to increase air pollution in the form of ozone (Hirons & Thomas, 2018; Salmond et al., 2016). This negative impact on air quality can be exasperated during heat waves (Churkina et al., 2017) or in street canyons (Salmond et al., 2016). As it is situational, measuring the impact of bVOCs is complicated. Species, number of trees, and location planted makes a difference in the type and amount of air pollution produced or accumulated by trees (Calfapietra et al., 2013; Donovan, Stewart, Owen, MacKenzie, & Hewitt, 2005; Janhäll, 2015). Complicating the issue of disservices/benefits, the amount of ozone that a tree intercepts and uptakes may be greater than any ozone produced through bVOCs (Calfapietra et al., 2013; Salmond et al., 2016). Further, trees are more effective at absorbing and accumulating gas and particulate pollutants than other city surfaces (as reviewed in Salmond et al., 2016).

Since trees can produce disservices, trees should be valued for what they holistically contribute to a community, rather than being valued for singular benefits. For example, while trees in a street canyon may result in more localized pollution, they may provide secondary benefits such as reducing the movement of pollutants to other locations or masking noise pollution (Salmond et al., 2016). In fact, the benefits of trees are often so valued that any disservices that can be associated with them are outweighed (Lohr et al., 2004; Wyman et al., 2012). When planting trees, people can reduce possible disservices through careful species selection, and selecting species with low potential for invasion. Resources exist, like the Northern Illinois Tree Selector (2019), which can help people select the appropriate tree for the appropriate site, all the while considering disservices, services, and if a tree species has invasive traits.

The benefits of trees are relative to seasonal and temperate zone differences. Another important consideration is that not all trees are equal. Some benefits may be more pronounced in specific species (Chen et al., 2017; Grote et al., 2016; Xiao & McPherson, 2016). Benefits differ within a species as well. A small street tree does not provide the same benefits as a large, 100-year-old tree. Mature and old trees are increasingly rare, and yet they can provide the greatest benefits (Lindenmayer, 2017; Lindenmayer & Laurance, 2017; Lindenmayer, Laurance, & Franklin, 2012). Given that they are single organisms, large old trees provide a disproportionate impact on biodiversity and ecological processes, from providing habitat for other animals and plants to facilitating important ecological cycles (Le Roux, Ikin, Lindenmayer, Manning, & Gibbons, 2015; Lindenmayer, 2017; Lutz et al., 2018; Stagoll, Lindenmayer, Knight, Fischer, & Manning, 2012). A larger tree can provide substantially greater benefits than a smaller tree can (Stephenson et al., 2014). There is also cultural value associated with large and mature trees (Blicharska & Mikusiński, 2014). Cities and urban centers should manage their forests to conserve large-diameter trees to maximize the ecosystem services the trees can provide (see Cavender & Donnelly, 2019).

Few trees reach maturity in an urban environment (Watson & Himelick, 2013). While many cities participate in tree plantings, the lack of follow-up care can impact survival rates, thus result in a waste of resources (Widney, Fischer, & Vogt, 2016). However great the number of benefits a mature tree can provide, it takes time for the benefits of trees to exceed the costs associated with the planting and maintenance (Vogt, Hauer, & Fischer, 2015). One way to increase survival rates of planted trees—and thus, ensure a wise investment—is to garner community support with tree plantings. This can reduce vandalism and create a sense of ownership (Black, 1978). For example, Sklar and Ames (1985) found that trees planted with community participation had significantly higher survival rates (~60%–70%) as compared to trees that were planted without community participation (<1%). Involving the local community in tree planting may also increase neighborhood ties (Watkins et al., 2018). This may lead to a positive social effect.

A major issue that extends beyond the scope of this paper is that often low-income countries have the greatest need for improved urban conditions, and therefore, they may have the greatest need for trees. However, many of these countries may not have the climate to support trees; they may be xeric or in areas that are susceptible to droughts (McDonald et al., 2016). The variance in climates emphasizes the importance of proper selection of trees, identifying trees that are adapted to local climates or have high plasticity and can survive in unfavorable conditions. Green infrastructure that collects and integrates stormwater drainage where trees are planted may offer a solution to tree survival in xeric environments. Regardless, water availability must be considered before planting (McDonald et al., 2016).

Moving forward, emphasis should be placed on reducing the inequality of tree distribution in the urban forest within and among cities. Trees and green spaces are often unequally distributed among communities with varying demographics such as income and race (Jennings, Johnson Gaither, & Gragg, 2012; Landry & Chakraborty, 2009; Pincetl, 2010). Schwarz et al. (2015) found that when analyzing seven major cities, the authors found a strong relationship between urban tree cover and income: the lower the income, the fewer the trees. Decision-makers may underestimate the importance of trees and plants in humanitarian work due to bias of plant blindness (Balding & Williams, 2016), but this paper illustrates the benefits.

Future research is needed to understand all of the benefits and disservices that trees provide to people. First, moving beyond correlation, more experimental studies should be conducted that evaluate the benefit of trees to people. Jennings and Johnson Gaither (2015) outlined how future research should focus efforts on understanding how health and green space are related in low-income populations and rural minorities. Historically, research has been geographically biased with many of the studies occurring in North America and Europe (Keniger et al., 2013). There are many opportunities to expand this research to the southern hemisphere. Given the short-time frame of most social and psychological studies (Keniger et al., 2013), longitudinal studies will help determine longer-term impacts of trees and nature on people. As discussed in Salmond et al. (2016), researchers should work to understand the scale of benefits or disservices. This includes a more localized approach to research, such as understanding the local impacts of street trees in regulating air quality, rather than at regional scale. In addition, rather than focusing on individual pollutants, research is needed that investigates the interaction of air pollution, pollen, and temperature at a local scale (Salmond et al., 2016). Understanding the benefits of nature, beyond trees, is important for strategic urban planning in xeric environments. Finally, while there are trade-offs between disservices and services, future-focused urban planning and research is needed so the right species are planted in the right environment to minimize the negative impacts of any disservices and maximize the benefits.

4 | CONCLUSION

Investing in trees will result in sustainable cities with happier and healthier people. We reviewed the substantial evidence to better understand the tangible and real benefits that trees provide. While there are considerations, planting and protecting trees is a real solution to many of society's challenges, offering high potential with relatively small input and energy. The results can be profound in the long term. In particular, the five categories of benefits outlined in this article (health and social well-being, cognitive development and education, economy and resources, climate change mitigation and habitat, and green infrastructure) are of particular importance, especially as there is a great global migration into cities. While previous work illustrated that trees can help meet several of the UNSDG, this review demonstrates that planting and protecting of trees can directly and indirectly contribute to 15 of the 17 goals. This is more than previously described. Beyond the UN SDG, the planting and protecting of trees supports the United Nation's New Urban Agenda (NUA). The NUA, which was created to promote the development of sustainable cities, stresses the importance of green and quality public spaces, as well as green infrastructure (United Nations, 2017). For people to receive their benefits, the urban forest needs to be healthy and diverse to create the most sustainable and livable communities possible.

We have entered a new era in which humans are the dominant species and the main influencer of the planet. The built environment as it currently exists is not conducive to most trees (Watson & Himelick, 2013). In order to receive the benefits that trees provide, we need people who have the skills required to care for trees. Horticulture experts and plant scientists are of vital importance to the world, and they need to be future-focused in their work, actively seeking positive outcomes for society's challenges (Blackmore & Paterson, 2006; Raven, 2019; Smith, 2019). This new era of the Anthropocene requires a new era of horticulture. Experts need to understand how to address society's needs and the realities of the urban environment, while taking trees and adapting them to where people live. This requires skills in arboriculture, sourcing, cultivation, production, and care in a way that is calculated and encompasses urban planning. We also need broad engagement across all sectors (Cavender & Donnelly, 2019) to strategically plan and manage the urban forest to gain the most benefits (Miller, Hauer, & Werner, 2015).

If we want to have the benefits of urban trees in the future, we must think of our urban forests as an investment. Like any investment, if trees are not cared for, they depreciate in value and can become a liability. Through planting and care, however, urban forests can have compounding benefits, trickling through every layer of society, leading to a better world. As the proverb says, “The best time to plant a tree is twenty years ago, the second best time is now.” We must act now for a better world.

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