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The Benefits and Limits of Urban Tree Planting for Environmental and Human Health

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Many of the world's major cities have implemented tree planting programs based on assumed environmental and social benefits of urban forests. Recent studies have increasingly tested these assumptions and provide empirical evidence for the contributions of tree planting programs, as well as their feasibility and limits, for solving or mitigating urban environmental and social issues. We propose that current evidence supports local cooling, stormwater absorption, and health benefits of urban trees for local residents. However, the potential for urban trees to appreciably mitigate greenhouse gas emissions and air pollution over a wide array of sites and environmental conditions is limited. Consequently, urban trees appear to be more promising for climate and pollution *adaptation* strategies than mitigation strategies. In large part, this is due to space constraints limiting the extent of urban tree canopies relative to the current magnitude of emissions. The most promising environmental and health impacts of urban trees are those that can be realized with well-stewarded tree planting and localized design interventions at site to municipal scales. Tree planting at these scales has documented benefits on local climate and health, which can be maximized through targeted site design followed by monitoring, adaptive management, and studies of long-term eco-evolutionary dynamics.

Keywords: urban ecology, forestry, sustainability, policy, climate mitigation, climate adaptation, ecosystem services, ecosystem disservices

INTRODUCTION

Urban trees in parks, yards, streets, and remnant parcels have been features of urban design and landscape architecture for centuries (Arnold, 1980), and are still integral components of civic spaces that are well-recognized for their public value. Urban trees are purported to have a number of environmental benefits, such as pollution absorption (Nowak et al., 2006, 2018), stormwater mitigation (Bartens et al., 2009), atmospheric cooling (Shashua-Bar and Hoffman, 2000), reduced energy use (Akbari et al., 1997; Akbari, 2002; Donovan and Butry, 2009; Hsieh et al., 2018), and habitat provision (Burghardt et al., 2009). In addition, studies have indicated that proximity to urban vegetation may increase property values (Sander et al., 2010; Li and Saphores, 2012; Escobedo et al., 2015), facilitate recuperation after stress and illness (Ulrich, 1983; Ulrich et al., 1991; Li and Sullivan, 2016), and reduce mental fatigue (Houlden et al., 2018). There is a substantial literature indicating that trees provide benefits for municipalities and their residents, and this perception, in part, has motivated local, regional and global initiatives that promote the planting of urban trees (McDonald et al., 2016).

However, there is also an increasing empirical understanding of the limits of tree planting as a nature-based solution to climate change and pollution. Urban forest dynamics, species composition, soil dynamics, and the costs of planting and managing designed spaces are important variables in urban forest outcomes, and must inform urban planting practices for successful planning and management (Oldfield et al., 2013). In addition, recent empirical studies highlight that spatial and temporal scales heavily influence the extent of environmental and social impacts of urban trees. Some of the purported benefits of urban forests require that trees are planted on large spatial scales beyond municipal boundaries, and maintained over the long term, to ensure effectiveness (Salmond et al., 2016). However, trees may provide other ecosystem services even when planting is constrained by the relatively limited spaces in dense cities. In this perspective, we refer to *mitigation* as strategies that aim to reduce climate change and pollution, and *adaptation* as strategies that aim to modify cities to help residents cope with climate change and pollution (Laukkonen et al., 2009). Many environmental benefits attributed to urban trees fall into one of these two categories. In addition, we discuss the evidence pertaining to both positive and negative impacts of trees on human health in the context of the extent of urban tree planting.

URBAN TREES ARE MORE EFFECTIVE FOR ADAPTATION THAN MITIGATION STRATEGIES

Early studies of urban tree ecosystem services emphasized rates of carbon (C) sequestration and air pollution reduction (Nowak and Crane, 2000; McPherson et al., 2005; Ray, 2005). Tools such as iTree[1] translated the relatively scant data on urban tree processes available at the time—primarily estimates of biomass and dry deposition rates—into easily understood, municipal-scale metrics, such as tons of pollution absorbed (Tallis et al., 2011), energy savings (McPherson, 1993), C sequestered (Nowak, 1993), and total monetary value (McPherson, 1992; Nowak et al., 2002). However, since these tools were originally developed, additional empirical studies of the influence of trees on pollution concentrations have reported negligible or inconsistent impacts (Setälä et al., 2013; Han et al., 2020), or even increases in the residence time of particulate and NO_2 concentrations in the atmosphere in the presence of tree canopies (Tong et al., 2015; Viippola et al., 2018). When atmospheric mixing is low, pollutants may be concentrated under tree canopies (Salmond et al., 2013), and when atmospheric mixing is high, studies have shown no discernable effect of the presence of trees on urban pollutant concentrations (**Figure 1**). In addition, trees may exacerbate rates of asthma due to the release of allergens and this is seldom accounted for in assessments of the impacts on trees on public health (Lovasi et al., 2013). In recent comprehensive reviews, Eisenman et al. (2019) and Xing and Brimblecombe (2020) both concluded that as a result of the many influences of trees on atmospheric composition besides dry deposition rates, current empirical evidence does not support the assumption that trees significantly and consistently reduce pollution concentrations.

Similarly, for C sequestration, tree inventories coupled with allometric equations have been commonly used to estimate CO_2 stored in urban trees in units of mass (Nowak and Crane, 2002; Nowak et al., 2013). However, to assess the potential of trees to enable climate mitigation, a systems-level approach is needed to compare C sequestration in urban forests to local fossil fuel emissions (Hutyra et al., 2014). Most studies of urban forest C sequestration attempt to estimate either tree biomass (McHale et al., 2007; Hutyra et al., 2011; Strohbach and Haase, 2012; Timilsina et al., 2014) or the rate of change in biomass over time (Net Primary Production, NPP) (Bialecki et al., 2018; Sonti et al., 2019; Trlica et al., 2020). Soil C dynamics should also be assessed as part of urban C balance, as soil C may either contribute to sequestration if organic matter is accumulating, or release C to the atmosphere if heterotrophic respiration reduces organic matter concentrations (Pouyat et al., 2002, 2006; Decina et al., 2016). But in either case, the spatial extent of urban trees and soils is quite limited relative to the magnitude of fossil fuel emissions. Cities are highly heterotrophic and expend orders of magnitude more C than they fix in photosynthesis (Collins et al., 2000). In most modern cities, fossil fuel combustion exceeds NPP per unit land area by at least an order of magnitude (Pataki et al., 2011). Hence, urban tree growth typically offsets municipal C emissions by only 0–3% annually (Pataki et al., 2009; Escobedo et al., 2010; Liu and Li, 2012; Baró et al., 2015; Velasco et al., 2016; Lindén et al., 2020), even before accounting for the energy needed to produce, transport, irrigate, prune, and fertilize urban trees (Roy et al., 2012).

This is fundamentally a problem of scale. Pollution and greenhouse gas (GHG) emissions in modern cities are disproportionately large relative to the extent of urban trees. Globally, forests are an important contributor to the C cycle because they occupy about a third of the land surface (FAO and UNEP, 2020). However, cities occupy less than 1% of the global land surface (Zhou et al., 2015; Liu et al., 2018), and within cities tree cover is highly variable but seldom equivalent to closed canopy forests (Nowak and Greenfield, 2018). Consequently, urban trees are most effective at providing ecosystem services that operate at local scales, such as parcels or urban forest/neighborhood patches.

For example, trees may improve human thermal comfort locally both through evaporatively cooling and humidifying

[1] https://www.itreetools.org/

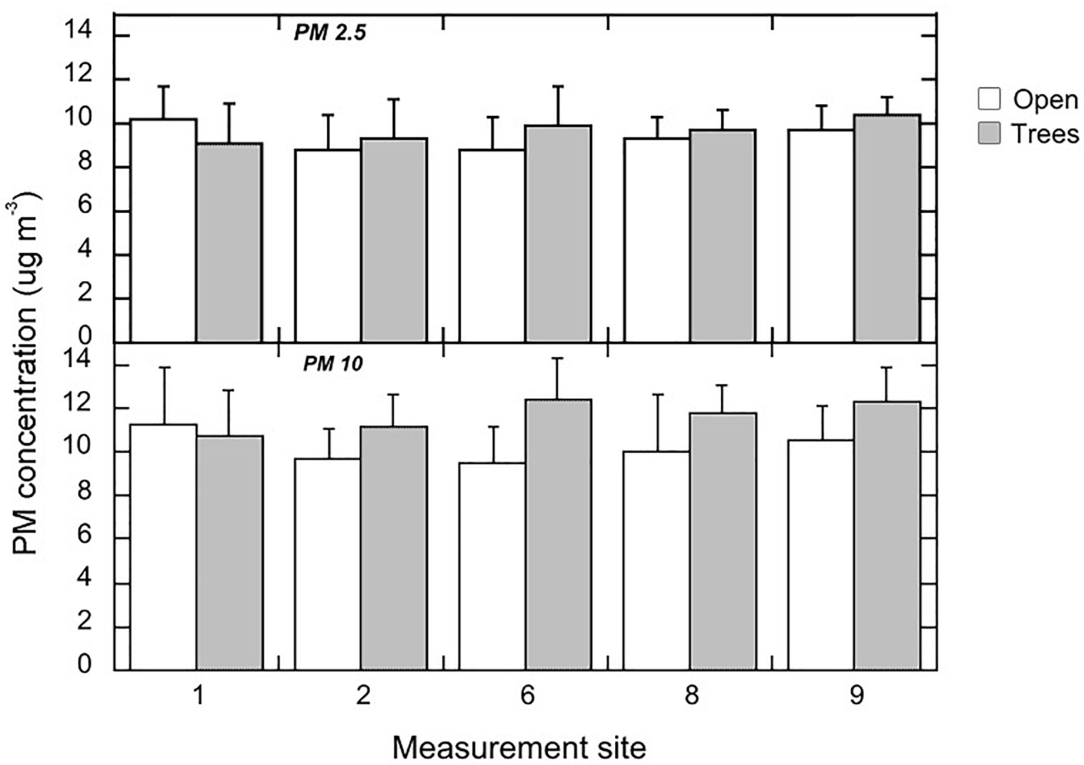

FIGURE 1 | In Lahti, Finland, researchers found that atmospheric particle deposition (the mass of particles deposited on the sampler) was significantly lower at urban sites with trees than in open areas. However, this difference did not result in significant differences in atmospheric PM 2.5 or PM 10 concentrations (particulate matter <2.5 and <10 μm in diameter) at any of their measurement sites, as shown above. This distinction is important because while many studies have inferred that trees will improve human health based on the influence of trees on particle deposition, it is atmospheric concentrations that actually impact human health directly. Error bars show SD; data from Setälä et al. (2013).

urban air, and through shading, i.e., the interception of radiation by large canopies (Shashua-Bar et al., 2011; Chen and Ng, 2012; Rupp et al., 2015; Middel et al., 2016; Wang et al., 2018; Zhao et al., 2018). Wang et al. (2018) utilized the Weather Research and Forecasting Model (WRF) and found that all urban trees in the contiguous United States lower air temperature by about 3°C across urban areas compared to scenarios in which cities contained no trees at all. This is likely an upper limit on municipal-scale cooling effects, as this study evaluated the impact of all existing urban trees. Salmond et al. (2016) pointed out that most studies of urban forest-climate interactions are regional scale modeling that use WRF or other simulation tools, and there is generally less information about cooling effects from empirical measurement at local scales. Nevertheless, cooling has been found in empirical studies as a function of canopy cover. Jung et al. (2021) showed that the capacity of urban trees to mitigate land surface temperatures is non-linear and depends on the specific land cover type and level of development. Santamouris et al. (2017) found that across a wide range of studies, the median reduction in local air temperature by cooling interventions involving urban trees was as high as 1.5°C when including modeling scenarios that largely eliminated built cover, and 0.6°C across more realistic urban conditions. By intensively sampling urban air temperature across land cover gradients, Ziter et al. (2019) estimated urban cooling of up 2°C at spatial scales of 60–90 m in radius at very high canopy cover close to 100%.

Therefore, localized cooling with dense tree planting offers the potential for microclimate adaptation through highly targeted design interventions that focus on parks, bus stops, pathways, school yards, community centers and other pedestrian urban gathering spaces that significantly impact thermal comfort. In addition, the reduction of stormwater runoff from impervious surfaces may also facilitate climate change adaptation. Canopy interception, i.e., rainfall that is intercepted by the tree canopy and evaporates from the leaves, may constitute a significant fraction of water inputs from low intensity, short duration rainfall events, depending on tree species (Xiao et al., 1998; Xiao and McPherson, 2002; Asadian and Weiler, 2009; Nytch et al., 2019). Urban greenspaces typified by pervious, non-sealed soils can also absorb and store considerable amounts of rainwater in the soil. For example, urban catchments in two Finnish cities with 30–40% of permeable soils (parks and other green infrastructure) stored more than 1,000 m^3 of rain water per ha per year, measured as the difference between the amount of water entering the catchment and discharge. The result was a substantial reduction in urban runoff volume and considerable improvement of the quality of runoff water (Valtanen et al., 2014a,b). In these cities, about 70–80% of rainfall occurs in low intensity (<10 mm) events, which are the conditions under which adding pervious areas of soil to cities is impactful for stormwater mitigation. Consequently, urban forests and other greenspaces with trees and permeable soils can help ameliorate the modified urban microclimate and hydrological cycle and mitigate heat and flooding locally.

THE SPATIOTEMPORAL DYNAMICS OF URBAN FORESTS

Cities are limited in their extent globally. Space allocated to urban trees is also constrained. Urban spatial configurations that have been designed for dense human populations, movement, and social interactions leave limited options for accommodating biophysical processes like water uptake and evapotranspiration, nutrient uptake, wet and dry deposition, gas exchange, and C sequestration at the scale required to offset urban pollution. Hence cities are difficult to retrofit to accommodate greening strategies even as we discover their specific value. For example, it would be quite difficult, if not impossible, to reduce stormwater runoff by 50% using green infrastructure in a city that is 90% impervious, particularly if we can only allocate 1–2% of the land surface to greening strategies.

The spatial scale and distribution of urban greenspace reflects a range of socioeconomic dynamics and historical planning decisions made by city governments (Grove et al., 2014; Locke et al., 2020). Recent studies investigating the socioeconomic determinants of urban vegetation have predominantly shown a correlation between wealth and both vegetation cover and diversity, although this relationship is far from universal and may depend on other factors (Kendal et al., 2012; Szantoi et al., 2012; Schwarz et al., 2015; Watkins et al., 2017; Kuras et al., 2020). Trees may also present liabilities like tree falls, root damage to infrastructure, pollen allergies, and maintenance concerns. These disservices will necessarily constrain the location of trees in the built environment (Pataki, 2021). Temporal dynamics, including tree demographics, host-pathogen interactions, extinctions, and other population and evolutionary processes also influence the extent to which tree planting efforts influence urban conditions. A multitude of both anthropogenic and biophysical factors influence tree planting rates, removal, and mortality at the landscape scape, and some cities and neighborhoods are on trajectories of decreasing tree density and canopy cover (Roman et al., 2014; Ossola and Hopton, 2018; Hilbert et al., 2019). Low species diversity, poor site conditions, and planting palettes that are no longer suited to changing climatic conditions and pathogens present additional vulnerabilities for urban tree populations (Laćan and McBride, 2008; Berland and Elliott, 2014; Ordóñez and Duinker, 2014). There is increasing evidence of urban-driven evolutionary change in urban forest dynamics that interacts with ecosystem function over the long term (Johnson and Munshi-South, 2017). For example, evolutionary changes in traits that influence C cycling such as plant root traits, stomatal conductance, leaf nutrient stoichiometry, and soil microbial C cycling traits, have been shown to have significant implications for C sequestration (Monroe et al., 2018). While evolutionary processes may operate at long time scales for long-lived organisms such as trees, they have been shown to be very rapid for the microbial communities that influence plant fitness (Lau and Lennon, 2012). Both demographic and evolutionary processes are highly complex in urban forests that contain varying proportions of planted and naturally dispersed and regenerated trees (Nowak, 2012). Therefore, urban greening strategies must account for both spatial and temporal dynamics of planted urban trees and urban forest patches in defining planting strategies and management targets.

URBAN FORESTS AND HUMAN HEALTH AT THE SCALE OF URBAN TREE PLANTING

Maintaining urban tree populations at small spatial scales appears to significantly influence human health. Recent reviews have utilized the World Health Organization's definition of health to evaluate the effects of either trees specifically, or greenspace more generally, on physical, mental, and social well-being (Nesbitt et al., 2017; van den Bosch and Ode Sang, 2017; Kondo et al., 2018; Wolf et al., 2020). Several aspects of physical health have been shown to be correlated with aspects of urban "greenery," such as mortality, longevity, and heart rates, and weight changes (Nesbitt et al., 2017; Kondo et al., 2018). There are also numerous studies relating aspects of mental health to the prevalence of vegetation (Bratman et al., 2012; Nesbitt et al., 2017; Houlden et al., 2018). Notably, some studies distinguish the effects of trees, or species of trees, from other vegetation and some do not (Nesbitt et al., 2017). As a result, the precise mechanisms linking trees, biodiversity, and the different components of health: physical, mental, and social, remain uncertain (Lee and Maheswaran, 2010; Aerts et al., 2018). However, mechanistic responses of human health to actual and perceived biodiversity have been generally categorized as those that cause or reduce harm, and restore or build capacity for physical and mental health (Marselle et al., 2021). Research has shown that the amount of greenspace, as well as the distance urban dwellers have to travel to that greenspace, can influence the benefits of trees on public health (Annerstedt van den Bosch et al., 2016), but few studies have attempted to understand the type and amount of exposure to trees that confers health benefits (Shanahan et al., 2015; Jiang et al., 2016; Zhang et al., 2017). Finally, the relationship between the prevalence and types of urban trees and social health remains largely unexplored (Dinnie et al., 2013; Nesbitt et al., 2017; Jennings and Bamkole, 2019), but may be impactful at small spatial scales and through particular configurations, such as community gardens and the associated place attachment (Petrovic et al., 2019).

The health effects of trees may be a critically important aspect of urban forest benefits, even in dense cities with relatively limited space to support urban forests. This is because it is very possible that exposure to small plantings, parks, and views of urban forests may be effective in improving human health. That is, unlike pollution mitigation, small-scale plantings may have large impacts on health. Though some urban residents avoid large wooded areas due to safety concerns (Klein and Felson, 2021), many make varied use of small greenspaces (Peschardt et al., 2012). Indeed, some urban residents are highly deprived of virtually any access to nature, such that even modest additions have been shown to have measurable positive effects (Nadkarni et al., 2017). These social and public health functions of small greenspaces have been further highlighted by the COVID-19 pandemic, which in many cities restricted recreation to small local parks (Kleinschroth and Kowarik, 2020). Similar to the call for "dose-response" relationships between exposure to nature and human health (Jiang et al., 2016), there is a great need for additional quantitative and qualitative studies of the health impacts of urban tree plantings at different spatial and temporal scales, applicable to the realistic conditions and constraints of adding and maintaining trees in dense cities.

DISCUSSION

Going forward, a central question across many disciplines and stakeholders is: "What types of urban spaces promote social, economic, and environmental sustainability and prosperity?" As cities struggle to address myriad social, economic, and environmental problems, it is important to identify the specific social and environmental goals that can be achieved by the location, density, and extent of tree planting. Hence, the spatiotemporal dimensions of urban forest dynamics are a critical research uncertainty. For some ecosystem services, such as C sequestration, the ecological dynamics of C uptake by trees are well understood, but the direct impacts on atmospheric CO_2 concentrations and climate depend on the spatial extent of urban trees, their demographic and population dynamics, and the interactions between productivity, heterotrophic respiration, and soil C dynamics at large spatial and temporal scales. Conversely, the reciprocal impacts of the atmosphere, including urban pollution and heat, on urban forest ecological processes are also in need of additional empirical measurements (Meineke et al., 2016). For other ecosystems services, the interactions between tree and soil processes and the built environment will determine the net influence of urban forests. For example, the effects of buildings, street design, and urban morphology on atmospheric dispersion, and their interactions with tree canopies, play a significant role in atmospheric pollutant concentrations (Han et al., 2020). Integrating trees into the built environment

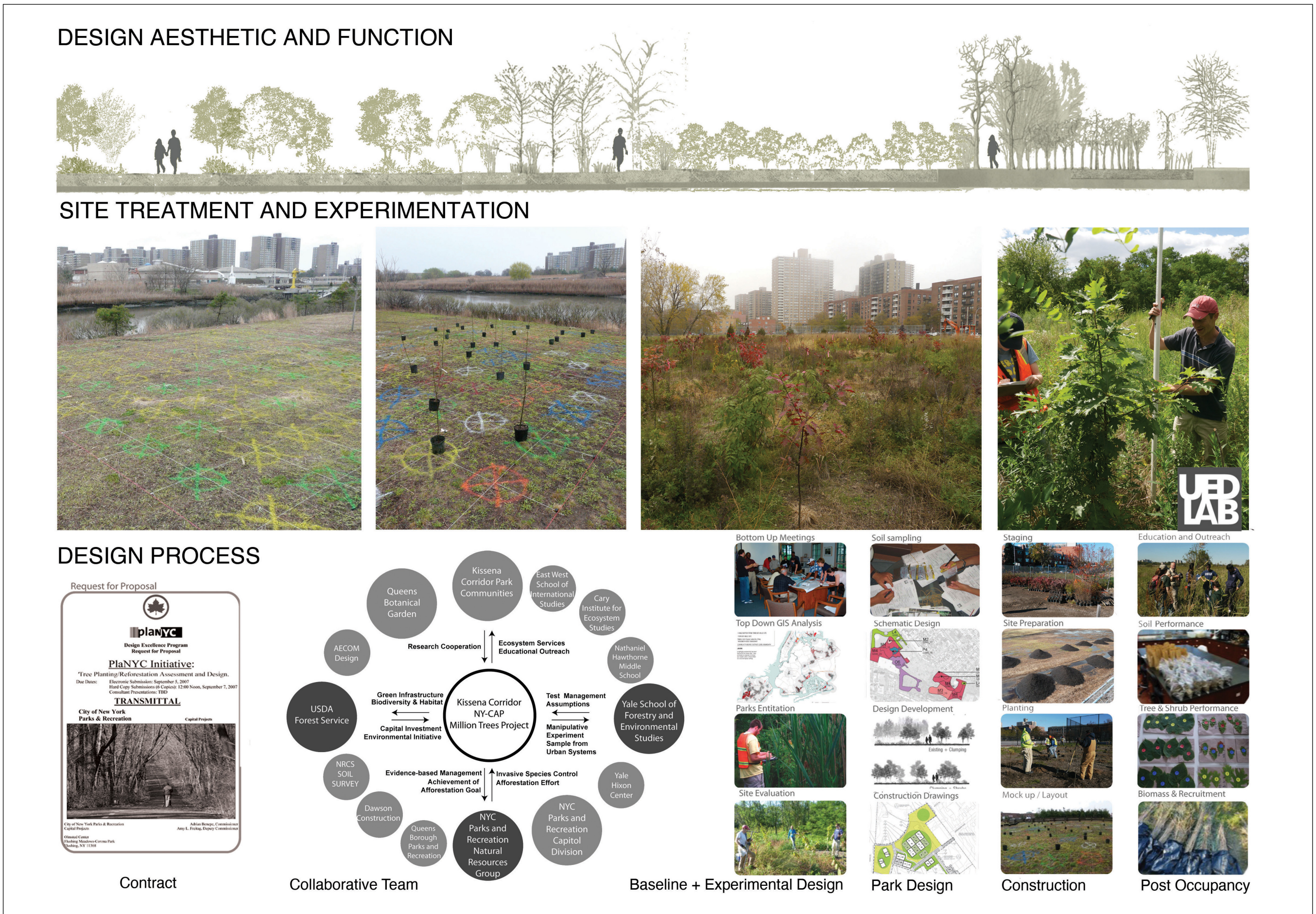

FIGURE 2 | The MillionTrees NYC Initiative uses the model of designed experiments to engage ecologists and designers in the creation of a long term and large-scale urban green infrastructure research program. Adapted from Felson et al. (2013a,b).

may also facilitate interventions to increase active transportation (Tsai et al., 2019; Young et al., 2020). Overall, we conclude that is difficult to significantly offset urban GHG and atmospheric pollution with localized tree planting, given the magnitude of emissions in modern cities. However, trees have localized effects on climate, thermal comfort, human health, and habitat for other species that may be impactful at the site scale.

The public health impacts of urban trees have been particularly difficult to characterize because collaborative, interdisciplinary approaches are needed to ascertain the nature of these impacts. Assessing the effects of planting interventions may require techniques such as virtual and/or real life walks or progressions through different types and scales of landscape designs (Berman et al., 2008). Browning et al. (2020) suggested that a lack of randomized treatments and experimental controls has hampered our understanding of the influence of natural landscapes on cognitive and mental health. There have also been disciplinary gaps and barriers between urban ecological and forestry studies and health scientists that continue to limit progress in linking trees and health (Eisenman et al., 2019). The next phase of planning and managing tree planting programs will require collaborative teams of natural scientists, social scientists, and practitioners from the health sciences including epidemiologists, ecopsychologists, and clinicians to evaluate the specific dimensions—including forest composition, biodiversity, soil health, and spatiotemporal dynamics—that interact with human health.

The study of socioecological interactions in cities provides a framework for generating and organizing place- and site-specific data across the many disciplines involved in planning and designing urban spaces. Furthermore, the growing field of ecological design and urban-focused landscape ecology provides hands-on approaches to planning and managing urban flora and fauna (Beck, 2013; Felson et al., 2013a, **Figure 2**). The COVID-19 pandemic has provided an unparalleled opportunity to re-configure urban landscapes in ways that integrate trees, forest patches, and green corridors into the built environment with evidence-based ecological designs. There may be unique opportunities to expand tree canopies in abandoned or re-zoned urban lands if remote work becomes commonplace on a permanent basis, causing redistributions of commercial and/or residential land uses (Boyd, 2020; Eltarabily and Elghezanwy, 2020; Ferrini and Gori, 2021). There are previous examples of "urban shrinkage" that resulted in reconceptualized urban greenspaces, open space networks, or forest regrowth (Kowarik and Körner, 2005; Nassauer and Raskin, 2014; Frazier and Bagchi-Sen, 2015; Haase et al., 2018). Where this is feasible, cost effective relative to other land use priorities, and implemented with resources to maintain tree planting over decadal timescales, extensive urban forests have observable environmental and social benefits. However, cities have competing demands for space that include pressing human needs for affordable housing, renewable energy generation, and food production, among other uses. Nevertheless, we suggest that even small-scale and temporary tree planting may have specific benefits. To maximize these benefits, it is essential to establish collaborative teams working through the design process to influence the direction of the built environment (Felson et al., 2013b). Focusing on comprehensive and phased planning alongside targeted site design and monitoring for the specific attributes of trees that contribute to climate adaptation and human health may be most effective for integrating urban forests into sustainability strategies.

AUTHOR CONTRIBUTIONS

DP conceived of the manuscript and organized the text and manuscript. AF, MM, HS, and TW contributed images and figures. All authors contributed equally to writing the text. All authors contributed to the article and approved the submitted version.

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