



# Effects of Urban Heat Islands on Temperate Forest Trees and Arthropods

Steven D. Frank<sup>1</sup> · Kristi M. Backe<sup>2</sup>

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## Abstract

**Purpose of Review** Our goal is to provide an overview of how urban heat islands affect forests and synthesize recent literature on that topic. We focused on direct effects of high temperatures from urban heat islands on forest trees and indirect effects via changes in soil moisture and pest density. We also focused on the effects of urban heat islands on arthropods with particular emphasis on tree pests.

**Recent Findings** Urban heat islands can push trees and arthropods closer to their thermal limits with consequences for tree growth and arthropod fitness. Urban heat islands can alter the distribution of trees and arthropods allowing species to survive at higher altitudes or latitudes than they could otherwise. A primary risk for trees is that urban heat islands can increase pest density and damage.

**Summary** Urban heat islands can increase forest air and soil temperature and reduce soil moisture especially when combined with greater climate change. Land managers should consider the surrounding urban density and forest size when trying to determine which plants and animals can persist in urban forests. As forests are fragmented or encroached upon by urbanization, the forest environment will change and become more hospitable for some species and less hospitable for others. Overall, there is insufficient research focused on urban-forest interfaces and the consequences of urbanization for plants and animals within forests. This research is not only important for urban forest conservation. Tree and arthropod responses to urban heat islands will help scientists and land managers predict responses to climate warming in rural areas as well.

**Keywords** Urban forest · Climate change · Conservation · Tree pests

## Introduction

Urban and suburban expansion are primary threats to forest conservation and biodiversity goals [1, 2]. Forests are among the ecosystems most frequently cleared or fragmented to accommodate urban and suburban development. However, remnant and regenerated forests within urban and suburban areas (hereafter urban forests) have conservation value and

can support diverse plant and animal communities, including species of conservation concern [3, 4]. Large pristine or protected forests are a shrinking portion of the global forest area and cannot be relied upon to fulfill conservation goals. Furthermore, even protected forests are increasingly encroached upon by urbanization and influenced by the abiotic conditions, such as the urban heat island effect, that urbanization creates. Urban forests, as primary habitat and to connect rural forests, are increasingly relied upon for conservation, recreation, and ecosystem services [5]. Planning and managing urban forests will require understanding the ecological consequences of urban heat islands that can affect forest habitat quality for trees and other organisms.

Our goal is to synthesize available information on how one abiotic factor, high temperatures caused by urban heat islands, affects forest trees and arthropods. We will focus on how urban heat islands affect [1] air temperature within forests, [2] forest soil temperature and water content available for trees, [3] tree growth and survival, and [4] arthropods, particularly tree pests.

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✉ Steven D. Frank  
sdfrank@ncsu.edu

<sup>1</sup> Department of Entomology and Plant Pathology, North Carolina State University, 1575 Varsity Drive, Campus Box 7616, Raleigh, NC 27695-7616, USA

<sup>2</sup> Present Address: Division of Extension and Engagement, Oregon State University, 325 Ballard Extension Hall, Corvallis, OR 97331, USA

We will review available information on these topics, identify knowledge gaps that impede forest management, and propose future research directions to fill those gaps. We focus primarily on temperate forests of which much recent work is from North America. We include and use empirical evidence and examples from other regions when available and from street and landscape trees and other forest ecosystems as needed. Our intent is to provide a broad overview of the ecological consequences forest managers may expect from urban heat islands and provide heuristic examples rather than an exhaustive review of all relevant literature.

## The Urban Heat Island Effect

Urban areas are typically warmer than rural and natural areas, a phenomenon known as the urban heat island effect [6]. The urban heat island effect is the best studied climate modification associated with urbanization [7]. The urban heat island effect results from four factors: paved surfaces and building materials that absorb and reradiate heat, anthropogenic heat (e.g., from cars or air conditioners), three-dimensional buildings that restrict airflow, and low vegetation density to provide shade and transpirational cooling [6, 8, 9]. The urban heat island effect is measured as the difference in surface or air temperature between urban and rural areas. Daytime surface urban heat islands exceed surrounding rural temperatures by 13 °C in megacities during some times of year [10, 11]. Differences between urban and rural surface temperatures are usually greater than that of air temperatures [8].

Urban heat islands can influence forest conditions at two primary spatial scales. First, forests in urban areas are subject to landscape-level changes in background temperatures that alter forest conditions. Second, forests within urban or suburban areas are subject to high local temperatures based on their proximity to impervious surfaces or other infrastructure that absorb and radiate heat. A challenge for management is that each plant and animal species may respond differently to urban heat islands and the changes they create. Urban heat islands may make forests more hospitable for certain tree or pest species but less hospitable for others. Understanding some consistent changes that occur in forest habitats could help managers predict consequences based on each species' biology.

## Landscape Effects of Urban Heat Islands on Forest Conditions

Most forest-related urban heat island studies include comparisons of rural forests and urban or suburban areas or comparisons of urban forests and these areas [11–13]. Comparisons of rural forests and urban forests, which allow for

measurement of the extent to which urban forests are subject to the urban heat island effect, are less common [14]. Sonti et al. [15] found higher maximum (up to 2.95 °C warmer) and minimum (up to 2.84 °C warmer) temperatures in urban forest fragments in New York City, Philadelphia, and Baltimore, in the USA, compared to rural forests surrounding these cities. In mixed coniferous and deciduous forests in WA, USA, O'Brien et al. [16] found that the interiors of urban forests were approximately 0.5 °C warmer than the interiors of rural forests during the day and night, indicating that even relatively large (some > 20 ha) urban forests may have elevated temperatures throughout the entire parcel. Still, parcel size affects the extent to which urban forests are subject to urban heat island effects. For example, Cao et al. [11] found that large urban parks (> 10 ha) were on average more than 4 °C cooler than surrounding urban areas, while small parks (< 0.5 ha) were less than 1 °C cooler than surrounding areas. However, the vegetation characteristics and shape were also important. Temperatures decreased as forest density, measured as tree canopy density, leaf area, basal area, and height, increased [17]. In general, forest managers should expect that forest temperatures will rise in urban areas, but this effect may be buffered by the amount of urban vegetation and forest size and shape [18–20].

The configuration of different land cover types affects the extent of urban heat islands and subsequent rise in forest temperatures. Overall, the proportion of forest cover and impervious surface cover in an urban area are the most important factors that determine urban heat island intensity. The amount of impervious surface cover in the surrounding landscape is particularly important to the magnitude and extent of urban heat island effects [21–23]. At 150 sites around Madison, WI, USA, air temperature increased linearly with the amount of impervious surface within a 500-m radius buffer, with temperatures rising by 0.04 °C per 1% increase in impervious surface during summer nights [24]. Notably, the amount of impervious surface within 500 m was a better predictor of air temperature than the amount of impervious surface within 100 m, indicating that impervious surface need not be immediately adjacent to a site to increase the temperature [24]. Trees buffer the urban heat island through transpiration and by shading impervious surfaces. Extensive tree removal following Asian long-horned beetle invasion in MA, USA, increased surface temperature by 0.7 °C following just 10% tree loss [25]. The temperature rose by 1.66 °C when tree loss resulted in a 10% increase in exposed impervious surface [25].

Forests can decrease temperatures in urban areas several kilometers away [26, 27]. Due to transpiration, forests create “cool islands” that extend beyond their boundaries, particularly on the leeward side from prevailing winds [28]. Other vegetated areas including turf and agriculture can reduce or at least not contribute to urban heat islands [29, 30]. Thus,

effects of urban heat islands on forests will become greater in landscapes as the proportion of impervious surfaces increases relative to vegetation and especially other forests. Land cover configuration (e.g., shape and connectivity of patches) can also affect urban temperatures independent of or in combination with differences caused by land cover composition [31]. The spatial arrangement, size, and shape of forests affects their interior temperatures and potential to mitigate urban heat island intensity [17, 23, 32]. Given a fixed area of forest, a patch with complex (e.g., winding) edges is cooler than a patch with simple edges [32]. At a landscape scale, surface temperatures of urban heat islands decrease as forest edge density and forest shape complexity increase, likely because of more interaction, and thus energy flow, between urban and vegetated areas [31].

The strength of urban heat islands depends on the season and time of day [33]. Typically, urban heat island magnitude is the strongest during summer, but in some cases, winter urban heat islands are more intense [21, 33–35]. In Madison, WI, USA, the nighttime air temperature of an urban heat island averaged 4 °C in late summer but approximately 1 °C during the rest of the year [24]. In a study of diurnal and seasonal urban heat island variation in 254 Chinese cities, summer had a higher daytime temperature than nighttime temperatures, but in winter, the urban heat island was stronger at night [35]. Rural environments cool faster after sunset than urban areas [36]. So, even when daytime temperatures are similar in urban and rural areas, elevated nighttime temperatures in urban areas reduce diurnal temperature variation, so urban temperatures are less likely to change with background temperature and weather type than rural temperatures [37, 38]. As the area around a forest is urbanized, the temperatures within the forest will be consistently higher and with less cooling at night. Sustained high temperatures can negatively affect plants and animals more than variable temperatures that provide daily opportunity for relief and recovery.

## Local Effects of Urban Heat Islands on Forest Conditions

Urbanization near a forest can have strong effects on forest temperature especially at the forest edge. Urban development near or within forests will increase the amount of forest edge exposed to the urban heat island effect. Air and soil temperatures are typically several degrees warmer at the forest edge than in the forest interior [39]. Soil temperature edge effects can be greater than air temperature edge effects. In a mixed coniferous-deciduous forest in Seoul, South Korea, air temperature was up to 2.5 °C warmer at the forest edge than in the forest interior, while soil temperature edge effects reached 6 °C [40]. Most studies of edge

effects are conducted in natural or agricultural landscapes and not in urban areas, but the available evidence suggests that temperature edge effects are at least as strong or stronger in and near cities than in similar rural forests [16]. Urbanization creates high-contrast edges (e.g., a forest adjacent to a parking lot), which generally have higher magnitude edge effects [41, 42].

The exchange of heat at forest edges often results in higher temporal variability of edge temperatures than interior temperatures [16, 40, 43]. In a mixed deciduous/coniferous forest on the edge of Seoul, South Korea, air temperature was approximately equal between the interior and edge during some parts of the night, but daytime temperatures were more than 2 °C warmer at the edge [40]. Soil temperature in the forest interior remained essentially constant throughout the day, but at the edge, soil temperatures rose during the day [40]. At an oak forest-parking lot interface in CT, USA, forest edge air temperatures were similar to parking lot temperatures during the day, while nighttime edge temperatures were more similar to the forest interior, resulting in higher diurnal air temperature variation at the edge [44]. In urban and rural forests in WA, USA, the air temperature in the coolest part of urban forests, the center, was the same as the air temperature in the warmest part, the edge, of rural forests [16].

The depth of edge influence (DEI), how far into the forest the warmer edge temperatures persist, varies and depends on the structure and composition of the forest edge, the features of the bordering matrix, and the time of day. In a summary of 40 reported air temperature DEIs in non-urban forests, Schmidt et al. [45] found that air temperature DEIs ranged from 0 to 240 m, with a median near 25 m. In Seoul, South Korea, the air temperature DEI in a mixed coniferous/deciduous forest peaked at 14.5 m at 4 p.m. and was around 10 m at other times [40]. Miller [44] detected weak air temperature effects at 40 m into the forest at an oak forest-parking lot interface. Though soil temperatures often show a higher magnitude edge effect, the DEI for soil temperatures is generally smaller than for air temperature [45]. As the area around a forest is urbanized, edge effects may become stronger and affect habitat suitability for organisms in the forest.

## Urban Heat Island Effects on Tree Growth and Functions

Temperature has direct and indirect effects on organisms' physiology, development, behavior, fitness, and distributions. Elevated temperatures due to urban heat islands or general climate warming can increase or decrease plant growth based on species specific tolerances, background climate, plant functional group, water availability, and other

factors [46, 47, 48•, 49, 50••]. Plant growth can increase in urban areas due to longer growing seasons, higher rates of photosynthesis, and less damage incurred during winter. An array of forbs in common gardens grew 115% and 60% more in urban and suburban locations, respectively, than in rural locations due to the urban heat island effect, elevated CO<sub>2</sub>, and elevated soil temperature [51]. In Ontario, Canada, cold-intolerant lianas in forest understories were more abundant in urban than in rural forests because of warmer temperatures during the winter [52]. In urban forest fragments, western red-cedar (*Thuja plicata*) basal area increased at a more rapid rate than in cooler rural forests [16]. White and red oaks in urban forest fragments in multiple cities on the east coast of the USA also grew faster than rural reference trees based on basal area measurements [15]. Tree growth can also decrease in urban heat islands. Willow oak (*Quercus phellos*) street trees grew less over an urban temperature gradient of 2.5 °C which was calculated to decrease carbon sequestration compared to unwarmed trees [53, 54•]. Growth of three temperate tree species in China also decreased as temperature increased due to surrounding impervious surface cover [55].

Background temperature is critical to predicting the effects of urban heat islands on tree growth. For example, urban trees grew more, measured by 150 years of growth rings, than rural trees in boreal regions but the opposite was true in temperate regions [50••]. Forest trees at lower latitudes tend to grow less than trees at higher latitudes as temperatures increase as they exist closer to their thermal maximum. Trees at lower latitudes also do not benefit as much from the longer growing seasons and moderate winters that can benefit trees at higher latitudes. Trees at the high-latitude edge of their range tend to benefit from warming since at that point they are often cold limited. Conversely, trees at the low latitude edge of their range may already be limited by high temperatures and are subjected to even greater stress in urban heat islands.

Temperature alone is not sufficient to predict tree responses to urban heat islands since temperature is often correlated with, or interacts with, other abiotic and biotic factors. For example, red maple (*Acer rubrum* L.) street tree growth (diameter at breast height DBH) increased in Raleigh, NC, USA, across an urban heat island gradient of 2.5 °C, but the trees overall were in worse condition due to drought and pest infestations [56, 57]. The response of trees to urban heat islands, and warming generally, often depends on water availability [48•, 58, 59]. In fact, water stress can change urban heat islands from a benefit for trees—with higher growth and functioning when adequate water is available—to a detriment when insufficient water is available. Insufficient water can result in stomatal closure, less photosynthesis, and xylem embolisms that reduce tree growth. Water stress and heat reduced photosynthesis and

xylem water potential of urban red maples and red maple saplings in a common garden experiment where water stress also reduced tree growth [56, 57, 60, 61]. Laboratory experiments showed that water stress was key to reducing urban willow oak growth and physiological functioning [54•]. Willow oak saplings grown under water stress exhibited lower photosynthesis and stomatal conductance and grew less at high temperatures than unstressed trees which were not affected by temperature [53, 54•]. Evidence from street trees supports the detrimental relationships between urban heat islands, drought, and tree growth, but research on these interactive factors in urban forests is sparse. However, the combined roles of temperature and water are important to understand because forests in urban heat islands often have warmer and drier soil than rural forests due to higher evaporation and transpiration rates and urban-induced changes in rainfall. This subjects forest trees to temperature and water stress similar to that of street trees and likely has a similar array of effects. Though not the focus of this review, urban areas often have higher CO<sub>2</sub> concentrations than rural areas which can also influence plant growth [62].

## Urban Heat Island Effects on Forest Arthropods

Consequences of elevated temperature on the fitness of arthropods and other animals is often predicted by their critical thermal maximum (CT<sub>max</sub>), the temperature at which an animal dies or can no longer function [63]. Arthropods in urban heat islands are often living closer to their thermal limits and can thus be more easily pushed beyond them with consequences for fitness and species distributions [64, 65]. The costs or benefits of urban warming vary based on background temperature of a location such that urban heat islands in cold climates can increase the fitness and abundance of some species even though the same amount of warming in a warmer location could reduce the fitness and abundance of those same species [64–66].

Urban heat islands present an ecological filter for community assembly based on heat tolerances [67–69]. Ant, herbivore, spider, pollinator, and other arthropod communities are altered by urban heat islands [69–75]. Organisms that are sensitive to warming in all or some of their life stages may be extirpated from areas that develop urban heat islands [76]. Other species may remain in urban heat islands but with distributions restricted to the coolest parts, such as forest interiors or places with low impervious surface cover [68, 70]. For example, the diversity and composition of bee communities changed across an urban temperature gradient in Raleigh, NC, USA. The warmest locations in the urban heat island had lower bee diversity and abundance overall and higher representation of heat-tolerant species than cooler

locations [68, 70]. At warm urban sites, bee species with the lowest  $CT_{max}$  became less abundant, whereas species with higher  $CT_{max}$  became more abundant, changing the community composition and potentially the community's function in pollinating [68, 70]. Other arthropod communities, such as ants, also show homogenization or filtering due to urban heat islands and climate warming [71, 77]. By increasing or decreasing the survival and fitness of species, urban heat islands can lead to biotic homogenization as heat tolerant taxa become more abundant and others rare [78, 79].

Arthropod metabolism increases with temperature, so some arthropods benefit from faster development, more generations per year, higher reproductive rates, longer warm seasons, and greater winter survival in urban heat islands [80–82]. Some species benefit from lower winter mortality, but urban heat islands can harm some overwintering species by increasing metabolic processes during diapause leading to lower adult weight, fecundity, or survival [83, 84]. Mimosa webworm (*Homadaula anisocentra* Meyrick) winter survival and spring defoliation increase in warm urban locations [85, 86]. Pine processionary moth caterpillars (*Thaumetopoea pityocampa* Denis & Schiffermüller) develop faster in urban heat islands than in rural forests [87]. Therefore, whereas rural populations enter winter primarily in the smaller fourth instar, urban populations have already reached the larger fifth instar, which has higher survival in cold temperatures. Also, nests in urban heat islands are larger and have more caterpillars [87]. This well-studied insect provides a robust example of the interactive effects that can increase survival and population sizes in cities.

The benefits of warming can be conferred upon damaging forest pests or invasive species including scale insects, caterpillars, bark beetles, and others [88–91]. Climate warming and urbanization facilitate the spread of exotic invasive arthropods and native invasive species often called sleeper species [82, 90, 92, 93]. Some arthropod species, including pests and invasive species, can survive in cities at higher latitudes or elevations than they could survive in rural areas due to the thermal protection of urban heat islands [71, 94–97]. Geographically native herbivores can become forest pests due to urban heat islands or general climate warming. Distributions of mountain pine beetles and southern pine beetles in the USA have expanded to higher latitudes and elevations in response to climate warming. Higher forest temperatures, which could be conferred by urban heat islands, increase winter survival, generations per year, and reproductive success [98, 99]. Urban heat islands increase densities of oak lecanium scale (*Parthenolecanium quercifex* Fitch), which is native to the USA, and its exotic congener, European fruit lecanium (*Parthenolecanium corni* Bouché), due to greater survival and higher reproduction due to advanced oviposition phenology and delayed parasitism [54•, 100, 101]. In addition, water stress on trees, caused by urban warming

and drought, exacerbates the negative effects of these scale insects on tree growth [53, 54•, 100]. Gloomy scale (*Melanaspis tenebricosa* Comstock) is an herbivore of red maples in the southeastern USA where it is native [102]. Its geographic distribution is limited by cold temperatures [103]. Although not yet a pest of rural forests, gloomy scale densities increase exponentially on urban street trees since warming and drought increase its fecundity [104, 105]. Importantly, gloomy scale also becomes more abundant on trees in rural forests due to higher temperatures associated with climate change [20, 106••]. Winter survival also increases in urban heat islands which allows gloomy scale to persist in cities north of where it can survive in rural forests [90, 103, 105, 106••]. Taken together the evidence suggests a gloomy scale, and species that respond similarly to the urban heat island effect, could be sleeper species that become important pests of urban forests and rural forests due to climate warming [90, 91].

Many other herbivorous arthropods become more abundant and damaging on urban trees than rural trees [107, 108]. More research is needed to understand which of these are responding to urban heat islands and thus could become forest pests and which are responding to other features of urbanization [73, 109]. For example, fall cankerworms (*Alsophila pomataria* Harris) and spring cankerworms (*Paleacrita vernata* Peck), native to the USA, frequently have sustained multiyear outbreaks in and around urban areas, but the contribution of temperature, versus other urban features, is unknown [110–112]. Forest tent caterpillar (*Malacosoma disstria* Hübner) survival, geographic range, and outbreaks are also increased by warm temperatures, suggesting it could become more pestiferous in urban heat islands, but urbanization specifically has not been studied [89, 113, 114]. Oystershell scale (*Lepidosaphes ulmi* L.) has been a pest of urban trees for at least a century but has recently become an invasive pest of aspen forests as well [115–117]. Hemlock woolly adelgid (*Adelges tsugae* Annand) is an exotic invasive pest that has infested and killed millions of eastern hemlocks and Carolina hemlocks throughout the eastern USA. Minimum winter temperature is the primary factor limiting the range of this invasive pest so it too can likely gain purchase in urban landscapes and forests at higher latitudes than in rural forests [118–120]. Other tree pests that respond similarly to urban and overall climate warming may also eventually become problematic in urban forests [91, 100, 121].

The effects of urban heat islands on natural enemies in forests has not been well studied but the effects of climate change have been studied and reviewed [91, 122–124]. However, herbivores may benefit from high temperatures due to negative effects on their predators and parasitoids. Warming has direct effects on natural enemies by altering life table parameters, such as reproduction, development



time, and longevity [125]. High temperatures also alter natural enemy physiology, abundance, behavior, or phenology [91, 122, 124]. Generally the consequences of warming for natural enemies are more severe or occur at lower temperatures than that of their prey and hosts [126, 127]. Predator and parasitoid communities can also change with warming as heat-intolerant species become less abundant or are replaced with more tolerant species [73]. Often these changes allow herbivores to persist with less risk of predation or parasitism. The effects of urban warming on natural enemies overall, and in forests specifically, require more research to help predict indirect effects on herbivores and their damage.

Urban warming affects the phenology of plants and animals which can affect essential ecological interactions such as pollination and herbivory [126, 128]. Plants in temperate regions often have advanced spring phenology (e.g., earlier budburst) in urban areas [129, 130]. In Wisconsin, the growing season was 5 days longer in the city than in rural areas because of an earlier start and later end to the season in urban areas [131]. In eastern North America, the growing season was 15 days longer in urban areas because of warmer temperatures [128]. Notably, the effects of urban areas on vegetation phenology extended up to 10 km from the edge of urban land cover, indicating that forests in urbanizing regions experience significant changes even when urban land cover does not reach the forest border [128].

Phenological changes among plant and animal species are often incongruent. Plants may be unsynchronized with their herbivores or pollinators, and herbivores may become unsynchronized from their predators or parasitoids [126, 132]. For example, oak lecanium scales develop earlier in warm urban areas than in cool areas, but the phenology of parasitoids that help control scale populations does not change [101]. This phenological mismatch contributes to scale insect infestations in urban areas [100, 101]. Tree phenology affects survival and feeding by caterpillars and other herbivores with consequences for trees and organisms at higher trophic levels like birds [133–136]. Forest caterpillars including winter moth (*Operophtera brumata* L.), eastern tent caterpillar (*Malacosoma americanum* F.), and forest tent caterpillar (*Malacosoma disstria* Hübner) develop phenological asynchrony with trees due to warming [133, 136–138]. Butterflies, bees, ants, and other arthropods show a range of responses to urban warming, greater climate warming, and their interaction such that the phenology of some species advances and others are delayed [139–142]. Altering the strength of ecological interactions due to community or phenological changes is among the most important yet least understood effects of urban heat islands on forest ecosystems and species of conservation concern.

## Conclusions

Ideally, tree and arthropod responses to urban heat islands will help scientists and land managers predict responses to climate warming in urban and in rural areas. Cities can be valuable proxies to study effects of climate change on plants and animals [106••, 121]. More research is needed to determine the shared and unique responses of organisms to warming in urban and rural ecosystems. In addition to the challenges posed by predicting and managing the effects of urban warming, the urban heat island effect will be exacerbated by overall climate warming. Thus, temperatures in and around cities will become greater than what would be predicted by city size and density alone. This will increase consequences for urban forests and the organisms living within them. The interaction of urban heat islands and climate warming will cause trees and arthropods to reach the limits of their thermal tolerance faster and at lower latitudes and elevations than under either urban or climate warming alone. Phenological advancements and asynchronies may become more severe, with greater disruption to ecological interactions. These and other consequences of warming will cause more rapid and severe changes in plant and animal community composition. Ecosystem functions, such as energy capture by plants and energy transfer to higher trophic levels, and ecosystem services, such as pollination, decomposition, and carbon sequestration, will be disrupted. Forests are increasingly encroached upon by urban and suburban development. Research is needed to predict and manage these increasingly valuable yet imperiled ecosystems. Knowledge of these dynamic ecosystems is essential to achieving conservation goals and preserving the services and recreational opportunities provided by urban forests.

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## Compliance with Ethical Standards

**Conflict of Interest** Steven Frank and Kristi Backe declare that they have no conflicts of interest.

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- Of major importance

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