

Research Article - urban & community forests

Assessing Urban Forest Threats across the Conterminous United States

David J. Nowak^{*✉}, Eric J. Greenfield, and Alexis Ellis

USDA Forest Service, 5 Moon Library, State University of New York, College of Environmental Science and Forestry, Syracuse, NY 13210, USA (david.nowak@usda.gov, eric.j.greenfield@usda.gov, alexis.ellis@usda.gov).

*Corresponding author email: david.nowak@usda.gov

Abstract

Numerous threats to urban forests are assessed for the conterminous United States, including projected changes in urban tree cover, air temperatures, precipitation, aridity, sea level rise, wild-fires, and flooding, as well as threats from hurricanes, tornadoes, ice storms, and insects and diseases. All potential threats were integrated into a cumulative threat index to illustrate which areas of the United States will likely face the greatest overall threat to their urban forests. Urban forests with the greatest cumulative threat per unit area are in the eastern United States, particularly in some coastal counties. Urban forests that have the greatest cumulative threat proportional to the percent of the county that is urbanized are in the highly urbanized areas along the DC–Boston corridor and in other metro areas (e.g., Atlanta, Georgia; Indianapolis, Indiana; Columbus, Ohio; Houston, Texas; Charlotte, North Carolina). By understanding local urban forest threats, management plans and policies can be enacted to help mitigate the impacts of and adapt to future threats to sustain healthy urban forests and associated benefits.

Study Implications: By understanding the magnitude and variation in potential urban forest threats, forest managers can be better prepared to potentially minimize and adapt to future urban forest damage. Threat type and intensities of threats vary by location. Understanding the distribution and intensity of urban forest threats can be used to help direct policies and forest management plans to sustain long-term urban forest health. A tool to assess urban forest threats by county is available in the supplemental materials.

Keywords: aridity, climate change, flooding, hurricanes, ice storms, insects, tornadoes, urban tree cover, wildfire

Urban forests comprise all trees within an urban area. Although most of the nation's land area (74%) is found in the western United States, most of the urban population (57%) and urban land (63%) are found within the eastern United States. This disparity illustrates the relative importance of eastern urban forests nationally. In the United States, urban forests provide billions of dollars in annual benefits and are projected to increase in extent in the coming years as urban areas increase (Nowak and Greenfield 2018b). However, percentage

of tree cover in urban areas has been on the decline recently (Nowak and Greenfield 2018a) and urban areas face forces that threaten to alter the structure and, consequently, the benefits derived from urban forests. These threats are numerous and include urban development, climate change, insects and diseases, and storms.

This study examines the current threats to urban forests across the United States related to insects and diseases, hurricanes, tornadoes, and ice storms, all of which can drastically alter urban forest health and

associated tree benefits. In addition, given climate change projections, future urban forest threats are projected related to changes in air temperature, precipitation, aridity, wildfire risk, flooding, and sea level rise. These changing environmental threats will also affect urban forest health. Finally, past patterns of urban tree cover change, often driven by development patterns and management activities, are used to project future urban tree cover changes. All of these threats can alter future urban tree cover, the health and well-being of residents, and also affect climate change impacts (e.g., tree cover versus impervious surface affecting water flow, tree cover mitigating urban heat increase). A cumulative threat index was also developed to illustrate which areas have the greatest cumulative threat among all examined threats. By understanding regional and local threats and the combination of multiple threats, urban forest managers can better prepare to sustain urban forest health and benefits in the coming years.

Urban land in the conterminous U.S. is projected to grow from 3.6% of total land area in 2010 to 8.6% in 2060 (Nowak and Greenfield 2018b). This urban expansion along with changes in tree cover within existing and new urban areas will combine to affect the amount of urban land with tree cover that municipalities can monitor and manage for their urban forest benefits, as well as affect the increasing importance of these areas in influencing regional climate change impacts. As tree cover is a dominant factor affecting urban forest benefits, loss of future tree cover in urban areas is a threat to sustaining urban forest benefits. Changes in air temperatures and precipitation will affect human and tree health with many species' ranges projected to shift in the coming decades (e.g., Iverson and McKenzie 2013). Tree responses to these changes could be either positive or negative depending upon species (Aber et al. 2001, Wang et al. 2017). In urban areas, these potential climate changes will be exacerbated by increased air temperatures due to urban heat islands and altered precipitation patterns due to urbanization (Sheppard 2005). Changes in species distribution within urban areas will be enhanced by forest management (e.g., tree selection and planting).

Changes in climate will affect aridity as well as threats associated with flooding, sea level rise, and wildfire. Changes in aridity may affect forest health (Williams et al. 2010) and the ability to supply ample water for urban trees. Increased aridity could increase the frequency of droughts due to decreased precipitation and increased evaporation (Dai et al. 2011). In urban areas, some increased aridity impacts will be

mitigated by irrigation. Changes in aridity can also affect wildfire potential (e.g., Abatzoglou and Williams 2016). Wildfires are a threat to forest health through direct tree mortality associated with fires (e.g., Hood et al. 2018). Large fires in urban areas are uncommon due to fire suppression efforts but do occur and can have devastating impacts (e.g., McBride 2018).

Changes in precipitation can also influence future flood events. Increases in the frequency and intensity of extreme precipitation events are projected for all US regions and has led to an increase in flooding events in the Midwest and Northeast (Walsh et al. 2014). Flooding and projected sea level rise will also affect forest health through excess water affecting gas exchange in the root zone and salt intrusion creating nutrient stress (e.g., Bratkovich et al. 1994, Zhai et al. 2018). Due to large amounts of impervious surfaces in urban areas and the proximity of many urban areas to rivers, lakes, and coastal areas, threats from flooding and sea level rise can be substantial.

Climate change will also likely affect future storms. Although most studies project a decrease (or little change) in the global frequency of hurricanes (Knutson et al. 2020), hurricane intensities in the United States will likely increase, leading to an increase in the destructive potential per storm for storms of a similar size. The global proportion of hurricanes that reach very intense levels will also likely increase due to anthropogenic warming over the 21st century. The Intergovernmental Panel on Climate Change (IPCC [2013]) projects a likely increase in maximum wind speed and rain rates in future hurricanes. Given this potential increase in storm intensities, the potential damage to forest and human populations will likely increase and can be substantial in the United States as nearly half of the US population lives in states along the East and Gulf coasts.

There has been an increase in the power of tornadoes over the last few decades (Elsner et al. 2019). These changes may be related to climate change, but scientific understanding is not yet detailed enough to confidently project the direction and magnitude of future change (Walsh et al. 2014). Although it is unclear how climate change will affect the frequency, intensity, and geographical distribution of ice storms, it is possible that ice storm frequency will increase west of the Appalachian Mountains as far south as Tennessee (Klima and Morgan 2015). Along with the influence of human spread of insects and diseases, climate change will also likely alter the spatiotemporal pattern of insects and diseases (Frankel et al. 2012, Pureswaran

et al. 2018). Although ice storms and tornadoes might not have major impacts in many urban areas, the threats from insects and diseases might be exacerbated in urban areas due to the relative high amount of transportation and ports that can contribute to distributing insects and diseases.

The purpose of this article is to evaluate the relative magnitude of these urban forest threats in the coming years and the geographic differences among these threats. All threats were evaluated within urban areas in each county except for storm and pest threats, which were based on the entire county area and assumed to be threats to urban forests. All urban areas were included regardless of the amount of urban tree cover. All potential threats were integrated into a cumulative threat index to illustrate which areas of the United States will likely face the greatest overall threat to their urban forests. This cumulative threat index is additive, indicating the areas that have the greatest number and/or magnitude of threats. The cumulative index does not account for potential interactions among threats. However, the cumulative index does reveal areas with the greatest overall threats. State and national policies and plans could be focused on these areas to help sustain urban forest health.

Whereas this information can be used at the local scale to aid urban forest management, it provides essential information related to the relative magnitude and distribution of threats that can aid regional, state, and national plans and policies related to protecting urban forests. By understanding how threats are likely

to change in the coming years as well as which areas in the United States face the greatest or most threats to the urban forest, local, regional, and national management plans and policies can be directed to adapt to and/or potentially lessen the damage created by these pending threats.

Methods

Several potential threats to urban forests were assessed at the county level, which was the smallest common geography among the threat databases. Some threats were assessed based on projected changes in these threats between 2010 and 2060 (e.g., urban tree cover, air temperatures, precipitation, aridity, sea level rise). Other threats that currently exist today (e.g., wildfires, flooding) were assessed by combining the existing threat level with projected changes in these threats between 2010 and 2060. The future risk from some threats could not be assessed (hurricanes, tornadoes, ice storms, insects, and diseases), so current or historical risk patterns were used to illustrate these urban forest threats (Table 1).

Urban land is delimited based on 2010 US Census Bureau definitions (US Census Bureau 2020). Urban areas represent densely developed territory and encompass residential, commercial, and other nonresidential urban land uses. Two Census Bureau urban classifications were used to delimit urban areas: urbanized areas (UAs) of 50,000 or more people and urban clusters (UCs) of at least 2,500 and fewer than 50,000 people.

Table 1. Summary of urban forest threats and method used to develop threat assessment.

Type	Threat	Threat assessment method			
		Change (2010-2060) ^a	Current + change ^b	Historical ^c	Current ^d
Development	Tree cover change	√			
Climate change	Temperature change	√			
	Precipitation change	√			
	Aridity change	√			
	Sea level rise	√			
	Flood risk		√		
	Wildfire risk		√		
Storms	Hurricanes			√	
	Tornadoes			√	
	Ice storms			√	
Pests	Insect/disease risk				√

^a based on projected change in threat between 2010 and 2060 within urban areas.

^b based on current threat level plus projected change in threat between 2010 and 2060 within urban areas.

^c based on historical pattern of threat at the county scale.

^d based on current distribution of threat at the county scale.

Eighty percent of the counties in the conterminous United States have urban land within their boundary (2,424 counties). Some counties (e.g., in Virginia) are cities and relatively small in area. Each urban forest threat was projected or assessed based on data from various sources as detailed below. For each county in the conterminous United States, a standardized threat index was calculated as *Threat index = county value/absolute value of the maximum US county value*.

This index standardizes all threats on a potential of -1 to $+1$ value with a $+1$ value indicating the county with the greatest relative threat, negative values indicating lessening threats, zero indicating no threat or change in threat value, and other values indicating the threat level relative to the maximum threat. Most threat indices were only positive throughout the United States. In these cases, the index will only vary between 0 and $+1$. A few threats had negative values due to some areas exhibiting a decrease in threats (i.e., tree cover increases, reduced flood risk). Precipitation change also had negative values, but as any change in precipitation, either positive or negative, could be a threat to forest health, the precipitation index was based on the absolute value of changes and thus any change was considered positive (higher values indicating a greater change).

Threats from hurricanes, tornadoes, ice storms, and insects and diseases are based on the entire county as these are county-based datasets. Changes in percentage of urban tree cover are based on contrasting tree cover in urban land in both 2010 and 2060. All other indices are based on changes within the urban land area that existed in 2010 because the projections of urban expansion to 2060 are at the county level with no geographical specificity as to where that expansion will occur within the county. These indices are based on national datasets that can aid in understanding both local threats and regional-to-national distribution and variation. However, these indices are simple indices that do not indicate an absolute threat; rather, they reveal the threat relative to the national maximum value.

Projected Changes in Urban Tree Cover

Urban expansion in the United States was projected for 2010–2060 based on the average growth within county urbanization classes between 1990 and 2010 (Nowak and Greenfield 2018b). For each decade, the amount of urban land at the start of the decade and new urban land added during the decade was calculated for each county. The 2010 starting percentage of urban tree cover was estimated using National Land

Cover Database (NLCD) tree cover maps (MRLC 2020) for (1) urban land (2000) remaining urban land (2010) and (2) rural land (2000) converting to urban land (2010).

As past NLCD tree cover data are known to underestimate actual tree cover (Nowak and Greenfield 2010), photo-interpretation was conducted to help determine actual tree cover values. State urban tree cover values were determined through photo-interpretation of 1,000 points per state using circa 2014 high-resolution Google Earth aerial photos (Nowak and Greenfield 2018a). Urban tree cover in each county for 2010 was adjusted based on ratio of the state average urban tree cover to the estimated urban tree cover based on photo-interpretation: *County urban tree cover = county urban tree cover (NLCD 2011) $\times$ state urban photo-interpreted tree cover c. 2014 (%) / state urban NLCD tree cover (%)*

To project urban tree cover for each subsequent decade (2020–2060), the percentage of urban tree cover at the start of the decade in each county was adjusted by the projected average annual relative percentage change in urban tree cover from the associated state average (c. 2009–2014) (Nowak and Greenfield 2018a). For example, if state urban tree cover changed from 50% to 49% between 2009 and 2014, that would equate to a 1% drop over 5 years or -0.2% per year. The -0.2% annual change was converted to a relative change based on the starting tree cover percentage (e.g., $-0.2/50 = -0.004\%$ change relative to existing tree cover). This relative change value was applied to the tree cover from the previous year to project tree cover annually (e.g., tree cover in county in 2010 = 40%; 2011 = $40\% - (40\% \times 0.004) = 39.84\%$; 2012 = $39.8\% - (39.8\% \times 0.004) = 39.68\%$, ...). The new percentage of tree cover was applied to urban land remaining urban at the end of the decade to estimate total tree cover in this area.

Total tree cover within urban expansion areas was based on the county-specific percentage of tree cover from the rural to urban land conversion (2000–2010) multiplied by the land area of urban expansion. Total decadal urban tree cover (2020–2060) was calculated by weighting the percentage of tree cover value in urban remaining urban land and rural land converting to urban land by its associated land area at the end of each decade. It is important to note that just because rural land converts to urban land, not all the land cover classes will change (e.g., to developed land cover) as natural areas (e.g., forests) can remain. Total change in percentage of urban tree cover (2010–2060)

was used to develop a tree cover change index. This tree cover change index accounts for changes within existing urban areas (gains or losses) plus the gains or losses of new tree cover as urban areas subsume the surrounding rural landscape.

Tree cover change index = $-1 \times \text{the projected change in percent tree cover in urban areas (2010–2060)} / \text{absolute value of maximum change in percent among counties (34.9\%)}$

The sign of this index was changed (multiplied by -1) so that a positive value of this index would indicate a positive threat related to a loss of tree cover.

One limitation of the tree cover estimates are that county estimates of cover and cover change are adjusted based on state average adjustment values. The state average adjustment factors for tree cover and cover change applied to county values will produce accurate estimates at the state level but can lead to erroneous estimates at the county level depending on how much county adjustment factors might vary from the state adjustment factor. More research is needed on county adjustment factors as these values are currently unknown.

Air Temperature and Precipitation Changes

Projected air temperature and precipitation data were obtained from the [National Center for Atmospheric Research \(NCAR\) Community Climate System Model \(CCSM\) \(2019\)](#). These data were obtained at a 4.5 km resolution that covered the conterminous United States but were resampled for display/analysis at 30 m resolution and projected to WGS 1984 Web Mercator Auxiliary Sphere.

Projected data represented an “ensemble average” of six model runs for representative concentration pathways (RCP) 8.5 for 2060. The RCP 8.5 scenario is characterized by increasing greenhouse gas (GHG) emissions over time, and factors in the highest GHG concentration levels of all the scenarios by 2100. These data include both the projected values and the differences between current (2010) and future (2060) modeled values for annual mean air temperature (in degrees Celsius) and annual total precipitation (in millimeters) within urban areas of each county. Although high baseline emissions are presented, illustrating a maximum effect, the index of these values among counties will illustrate the areas with the greatest relative change.

Temperature change index = $\text{projected temperature change in county (2010–2060)} / \text{maximum temperature change among counties (3.5}^{\circ}\text{C)}$

Precipitation has bidirectional changes among counties and any change can be considered a threat (e.g., both decreases and increases in precipitation can be considered an environmental threat). Thus, any change from current conditions was indexed as a positive value as

Precipitation change index = $\text{absolute value of county precipitation change} / \text{absolute value of the maximum US county value (335 mm/yr)}$

Aridity Changes

The aridity index uses precipitation and potential evapotranspiration data from the [US Environmental Protection Agency EnviroAtlas \(2019\)](#) RCP 8.5 projections. Potential evapotranspiration (PET) represents the evapotranspiration rate under ideal circumstances (i.e., a vegetated surface shading the ground and unlimited water supply) ([US EPA 2016](#)). An aridity ratio was calculated as precipitation (P) divided by PET ([Greenfield and Nowak 2013](#)). Precipitation and PET data were resampled to 30 m resolution from the original 800 m resolution.

A decrease in the aridity ratio indicates an increase in aridity. As the threat to urban forests increases with increased aridity, changes in aridity from 2010 to 2060 by county were calculated as county aridity index (P/PET) in 2010 minus aridity index in 2060, so that increasing aridity is indicated by positive values.

Aridity change index = $\text{change in aridity ratio within a county} / \text{maximum change in aridity ratios among all counties (0.405)}$

Flooding

Flood zones based on 100-year floodplain areas (2016) were obtained from the US EPA EnviroAtlas ([US EPA 2019](#)). As increases in precipitation would likely increase flooding, a combined index was created to estimate potential future flood risk. This combined index was calculated as

Flood risk index = $\text{flood area (\% of county urban area)} + \text{flood area (\% of county urban area)} \times \text{relative precipitation change in county} / \text{absolute value of maximum value in the numerator (108.8)}, \text{ where}$

Relative precipitation change = $\text{change in precipitation 2010–2060 (mm)} / \text{precipitation in 2010 (mm)}$

Sea Level Rise

To estimate how much urban area of each county could be affected by rising sea levels, projections from the National Oceanic and Atmospheric Administration ([NOAA 2017](#)) were used. Based on projections of an

“intermediate-high” scenario (Sweet et al. 2017), a projection of a 61 cm sea level rise for 2060 was used. The proportion of urban land submerged by rising sea levels was calculated and indexed for each urban county as

Sea level rise index = percent of county urban area inundated (2060)/maximum inundation among all counties (48.3%).

Wildfire Hazard Potential

Wildfire hazard potential (WHP) data were obtained from the USDA Forest Service (2018) Fire Modeling Institute and depict the relative potential for wildfire that would be difficult for suppression resources to contain. These spatial datasets of wildfire likelihood and intensity were generated for the conterminous United States in 2016 with the Large Fire Simulator (FSim), spatial fuels and vegetation data from LANDFIRE 2012, and point locations of past fire occurrence (ca. 1992–2013). Areas with higher WHP values represent fuels with a higher probability of experiencing torching, crowning, and other forms of extreme fire behavior under conducive weather conditions, based primarily on landscape conditions at the end of 2012. WHP is not an explicit map of wildfire threat but can be paired with spatial data depicting highly valued resources (e.g., communities) to approximate relative wildfire hazard potential to those resources (Dillon et al. 2015, USDA Forest Service 2018). In this report, the WHP is only analyzed within urban areas, which are areas of higher risk to humans and structures. Numerous factors will affect future fires (e.g., Martinuzzi et al. 2019), with aridity being one of these factors due to its propensity to dry fuels, which increases flammability and probability of ignition (e.g., Littell et al. 2016, Abatzoglou et al. 2018). As increases in aridity would likely increase WHP, a combined index was created to estimate potential future wildfire hazard potential. This combined index was calculated as

Wildfire change index = WHP index + WHP index × relative aridity change/absolute value of maximum value in the numerator

where WHP index = average WHP data within urban areas in county/ maximum average urban WHP among counties (3,018), and relative aridity change = change in aridity 2010–2060 (P/PET)/ aridity in 2010 (P/PET).

Hurricane Threat

To assess hurricane risk, a probabilistic risk map of potential hurricane damage based on the historical patterns of hurricane tracks and wind speeds between 1851 and 2015 was developed and combined

with topographic data to determine potential wind exposures to accumulated cyclone energy (Cole et al. 2021). Urban forest risk was based on mean cumulative accumulated cyclone energy (1851–2015) values for the county. As it is difficult to predict where future hurricanes will hit, past patterns of hurricane paths and intensity are used to help assess areas with the greatest risk for future hurricane damage. This same historical pattern analysis was used to assess potential threats from tornadoes and ice storms (see below). It is unknown how hurricane intensification may vary in coming years, so current risk is assumed to remain relatively the same, but the intensity of effects is likely to increase in the future.

Hurricane threat index = mean cumulative accumulated cyclone energy (1851–2015) in county/maximum value in mean cumulative accumulated cyclone energy among all counties (83,139).

Tornado and Ice Storm Threats

Information on tornadoes (1950–2019) and ice storm events (1996–2020) for each county was derived from NOAA’s storm events database (NOAA 2020).

Ice storm risk index = number of ice storms in county (1996–2020)/maximum number of storms among all counties (29).

Number of tornadoes times the average tornado F scale (0–5) of these tornadoes (i.e., tornado strength based on wind speed) by county were used to create the tornado index. The F scale weighting of tornadoes was conducted as the threat from tornadoes increases as wind speed increases.

Tornado risk index = number of tornados × average F scale value for all tornadoes in county (1950–2019)/ maximum value in numerator among all counties (168).

Insect and Disease Threat

Distribution data for forty-five insects and diseases (Supplemental Table 1) were obtained from the Forest Service Forest Health Technology Enterprise Team and Alien Forest Pest Explorer (USDA Forest Service 2017, 2020). Counts of total number of insects and diseases in each county were used to develop the index.

Pest index = number of insect or disease species within county/ maximum number of insects and diseases among all counties (18).

Cumulative Threat Index

A cumulative threat index (CTI) was calculated by equally combining all standardized threat indices and restandardizing the final index value as:

Cumulative threat index (0–1) = (Urban tree cover change index + Air temperature change index + Absolute precipitation change index + Aridity change index + Flood risk change index + Sea level rise index + Wildfire change index + Hurricane index + Tornado index + Ice storm index + Pest index) / maximum value in the numerator (4.994)

In theory, this index could range between –1 and +1 with negative values indicating a reduction in threats. However, all cumulative threat index values were positive in the United States. The impact of each threat is likely not equal, but an equal weighting procedure gives an indication of the counties with greatest overall relative cumulative threat from all threats. The CTI indicates which counties have the greatest overall threat per unit of ground area. Each county should be evaluated as to which threats are greatest in specific counties.

To determine which counties have the greatest overall relative threat to urban forests, the CTI was weighted by percent of county within urban areas. The percent-weighted CTI reveals the counties with the greatest overall threats and the greatest proportion of urban land (i.e., heavily urbanized counties will tend to have greater proportional threats to urban forests). High index values do not mean that a particular threat will occur in the urban area, but rather that they have characteristics that might lead to increased risk in the future.

In addition to index maps based on the county index value relative to the maximum national value, addition maps are presented in [Supplemental Figures 1–4](#) that present county index values based on the index value distribution. The supplemental figures show the rank order distribution of index values within five 20-percentile classes. In cases where zero index values comprised more than 20% of the counties (e.g., hurricane index), the distribution in classes 20.1%–40%, 40.1%–60%, 60.1%–80% and 80.1%–100% were based on distributing the positive index values among these four classes. In these cases, the 0%–20% will have more than 20% of the counties and the remaining classes will have less than 20%.

Results and Discussion

As there are numerous projected changes and threats among counties across the United States, the change in intensities and locations will vary depending on what factor is being analyzed. This information on local urban forests and potential threats could be integrated within city-scale vulnerability assessments

(e.g., [Steenberg et al. 2016](#)). The threat index results are mostly displayed on maps, but detailed results by county can be found in a supplemental tool (https://www.itreetools.org/documents/674/County_threat_projection_tool.xlsx).

Urban Tree Cover Change

Overall, 87% of counties with urban land are projected to decline in percent urban tree cover by 2060, with urban tree cover projected to drop nationally from 39.4% to 33.6%. Some counties in states with recent increases in urban tree cover (e.g., Wyoming) or where urban areas expanded into forests had projected increases in tree cover ([Figure 1](#)). Urban expansion within forests tends to lead to increased urban tree cover as about 20% of forest land subsumed by urbanization tends to remain as forest ([Nowak and Walton 2005](#)).

The greatest reduction in percentage of tree cover (2010–2060) occurred in Clayton County, Iowa (–34.9%); McCurtain County, Oklahoma (–27.9%); and Ohio County, West Virginia (–26.4%) ([Figure 1](#)). Though urban land will be increasing, current trends of mostly declining percentage of urban tree cover will affect future ecosystem services. The current trends of urban tree change (either gain or loss) have a substantial impact on future tree cover. Oklahoma has the greatest decrease in recent percentage of tree cover; thus, this recent pattern of decline leads to a relatively large decrease in percentage of tree cover in Oklahoma by 2060. The estimates of tree cover loss are probably too high in Oklahoma as it is likely that the current tree cover decline will not be sustained. Tree cover losses and gains are influenced by numerous factors through time (e.g., tree planting, natural regeneration, development, storms, insects, etc.), thus the estimated trends are likely to change based on these future factors. However, if current trends of land use and tree cover change remain true going forward, the projected changes will likely occur. Local management can change these trajectories. Also, various other threats will likely affect future tree cover. Management to sustain urban tree cover in the future given projected trends of tree cover change and varying urban forest threats are essential as numerous benefits related to human health and well-being in urban areas are derived from healthy urban tree cover.

Climate Change and Associated Impacts

Average annual air temperatures in urban areas are projected to increase across the conterminous United States, with increases ranging from 1.2°C to 3.5°C by

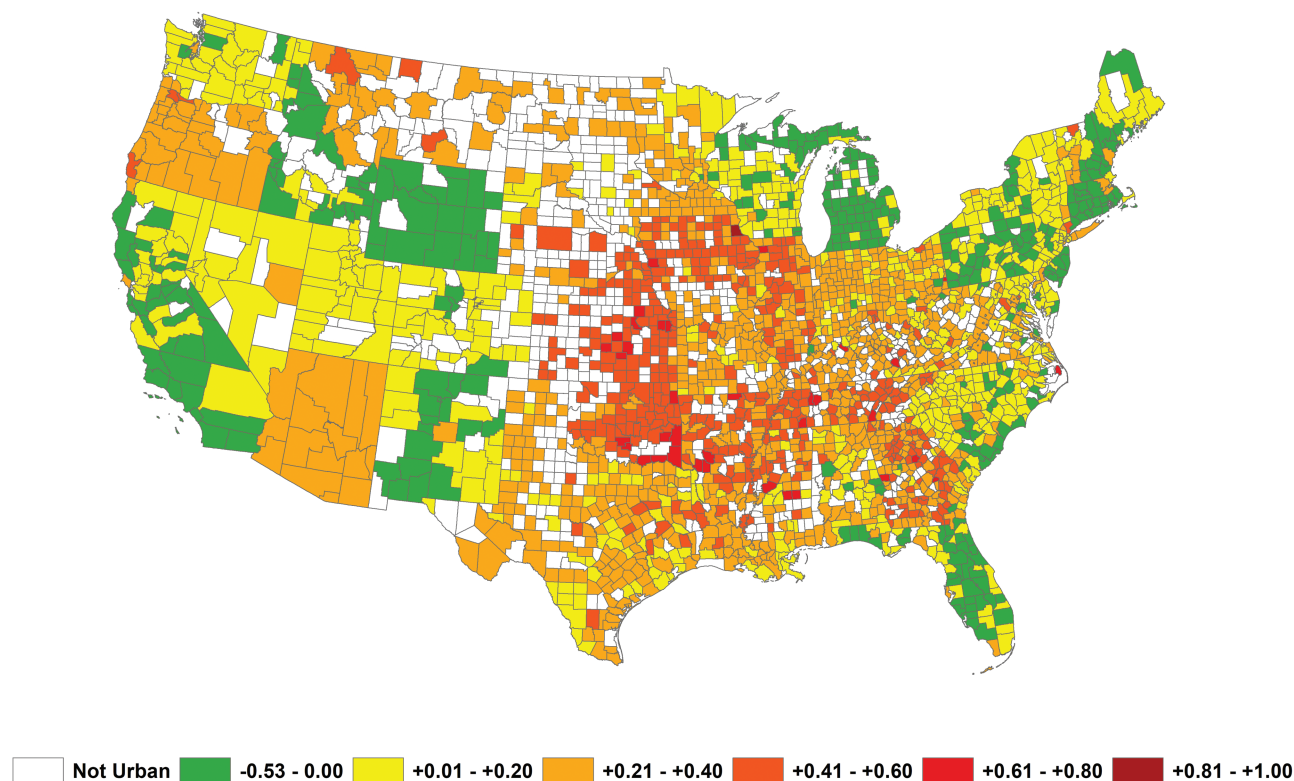


Figure 1 Urban tree cover change index, 2010–2060. Positive values indicate projected reductions in percent urban tree cover. Counties with no urban land in 2010 are excluded.

2060 among counties. Counties with the greatest projected increase in air temperatures in urban areas are Bonneville (+3.5° C), Madison (+3.5° C), and Jefferson (+3.4° C) Counties in Idaho, with highest temperature increases occurring in the Rocky Mountains and various areas of the Midwest (Figure 2A).

Annual precipitation in urban areas is projected to change between −111 mm/yr to +335 mm/yr by 2060 with average change of +10.5% (range: −13.9% to +40.0%). Counties with the greatest projected changes in precipitation in urban areas are Putnam (+335 mm/yr), DeKalb (+329 mm/yr), and Smith (+326 mm/yr) Counties in Tennessee, with the greatest changes (increases) in precipitation occurring in the eastern United States (Figure 2B, Supplemental Figure 5).

Aridity (P/PET) in urban areas is projected to increase across the conterminous United States, with increases ranging from 0.009 to 0.405 by 2060 among counties. Counties with the greatest projected increase in aridity in urban areas are Tillamook (+0.405), Lincoln (+0.379), and Curry (+0.370) Counties in Oregon, with greatest increases in aridity occurring along the northern Pacific coast and the northeastern United States (Figure 2C).

Projected sea level rise will affect coastal areas with urban areas in Camden County, North Carolina (48.3%); Monroe County, Florida (+44.0%); and New York County, New York (+32.4%) experiencing the greatest proportion of their urban areas inundated by sea level rise by 2060 (61 cm rise) (Figure 2D). Estimates of inundation are based on urban area elevation near coastal areas. Management actions (e.g., sea walls) can limit the proportion of urban areas inundated.

Counties with the greatest projected wildfire hazard potential in urban areas in 2060 are in the western United States, with the counties with highest urban wildfire hazard potential index being Elko, Nevada (+1.000); Calaveras, California (+0.849); and Amador, California (+0.822) (Figure 2E). Areas with higher index values indicate areas with greater wildfire hazard potential due current wildfire conditions in combination with increasing aridity (Figure 2C).

The wildfire index is relatively simple as it assumes static WHP conditions and only changes in aridity through time. Numerous other factors will affect future wildfires (e.g., fuel loads, drought, tree mortality, fires). In addition, wildfire conditions surrounding urban areas may substantially influence wildfire risk in urban areas and these external risks are not considered

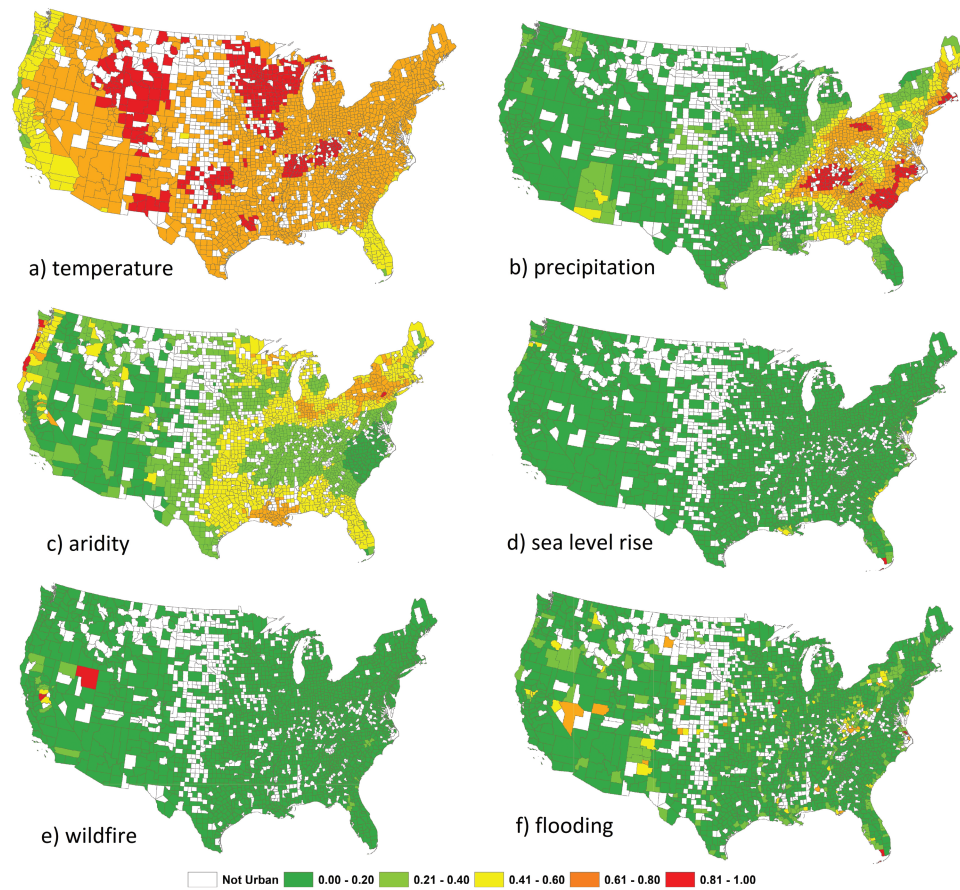


Figure 2 Climate change related indices: a) temperature, b) precipitation, c) aridity, d) sea level rise, e) wildfire, and f) flooding, 2010–2060. Counties with no urban land in 2010 are excluded.

(e.g., a city may have a low risk, but the risk might be substantial in adjacent rural areas and therefore increase the risk to the city). WHP data do not provide an explicit map of wildfire threat or risk. Rather, it highlights places where vegetation treatments may be needed to reduce the intensity of future wildfires. Its application to urban areas is likely limited, but it does provide information on relative risk and wildfire hazard potentials. More detailed wildfire analyses are needed to determine wildfire risk and potential changes in wildfire risk, particularly in urban areas.

Counties with the greatest potential urban flood risk index values in 2060 are Camden, North Carolina (+1.000); Henderson, Illinois (+0.841); and Currituck, North Carolina (+0.831), with areas with highest flood risk (2060) occurring in various counties throughout the United States (Figure 2F). Flood risk was based on the proportion of urban areas within 100-year flood zones and projected change in annual precipitation within urban areas. Areas with higher index values indicate areas with greater potential risk to flooding due to a relatively high proportion of potential flood zones

and/or a relatively high increase in precipitation. Most counties (98%) have flood plains in urban areas and 87% of these counties have projected increases precipitation in urban areas.

The flood index is relatively simple as it only considers precipitation and flood area within urban areas in the county and does not consider intercounty transfers of flood waters. Numerous downstream areas could flood due to changes in upstream precipitation outside of a county. This index only targets local changes in precipitation. Also, the index only considers average projected changes in precipitation, not the intensity distribution of the precipitation, which can substantially affect flooding. More detailed hydrologic analyses are needed to determine potential changes in local flooding, but this index provides a simple means to illustrate local areas of concern due to local flood areas and changes in annual precipitation.

Storms and Pests

Storm and pest threats were evaluated based on the average threat within a county, not specifically urban

land within a county, due to limitations of the storm and pest data. Hurricane threat increases with proximity to the southeast United States coastline. The counties with the greatest hurricane threat index are Terrebonne Parish, Louisiana (+1.000); New Hanover, North Carolina (+0.975); and Carteret, North Carolina (+0.966) (Figure 3A). Areas with higher hurricane index values indicate areas with greater potential risk to hurricane damage due to the historical number and strength of hurricanes and exposure to winds.

Areas with greatest number and strength of tornadoes tend to be in the central and southern United States, with counties with the greatest tornado threat index being Harris, Texas (+1.000); Oklahoma, Oklahoma (+0.935); and Jefferson, Alabama (+0.756) (Figure 3B). Ice storms tend to occur most in the Appalachian region and central United States. Counties with the greatest number of ice storms are Garrett, Maryland (twenty-nine storms); Centre, Pennsylvania (twenty-one storms); and Clinton, Pennsylvania (twenty-one storms) (Figure 3C). As tornado and ice storm risks are based on past storms, the distribution and amount of these events may change due to projected changes in air temperature and precipitation.

The greatest number of insects and diseases tend to occur in various counties in the Northeast, North Central, Northwest, and Southwest United States (Figure 3D). The maximum number of insects and diseases found in a county (out of the forty-five pests

analyzed) was eighteen. Having a large number of pests increases the potential for pest-related damage but does not necessarily mean greater pest damage. Local forest composition relative to pest distribution is critical for assessing potential pest impacts.

Cumulative Threat Index

The CTI was calculated by equally weighting all threat indices (urban tree cover, air temperature, precipitation, aridity, flooding, wildfire, sea level rise, hurricanes, tornadoes, ice storms, and pests). This index reveals the greatest cumulative threat per unit area of urban land. Different weightings would produce different CTI values. Different weighting effects can be visualized using maps in Figures 1–3 and could be calculated using data in the supplemental tool. There are multiple possible outcomes that could occur based on various weightings that could be selected among the eleven analyzed threats. At the local scale, the most significant threats could be addressed as the highest priority to sustain local urban forest health.

CTI values were greatest in the eastern United States (Figure 4A). The counties with the greatest CTI values are Camden, North Carolina; Dare, North Carolina; and Garrett, Maryland (Table 2, Figure 4A). Camden County has high risk to sea level rise, flooding, precipitation change, hurricanes, and temperature change; Dare County has high risk to hurricane, precipitation

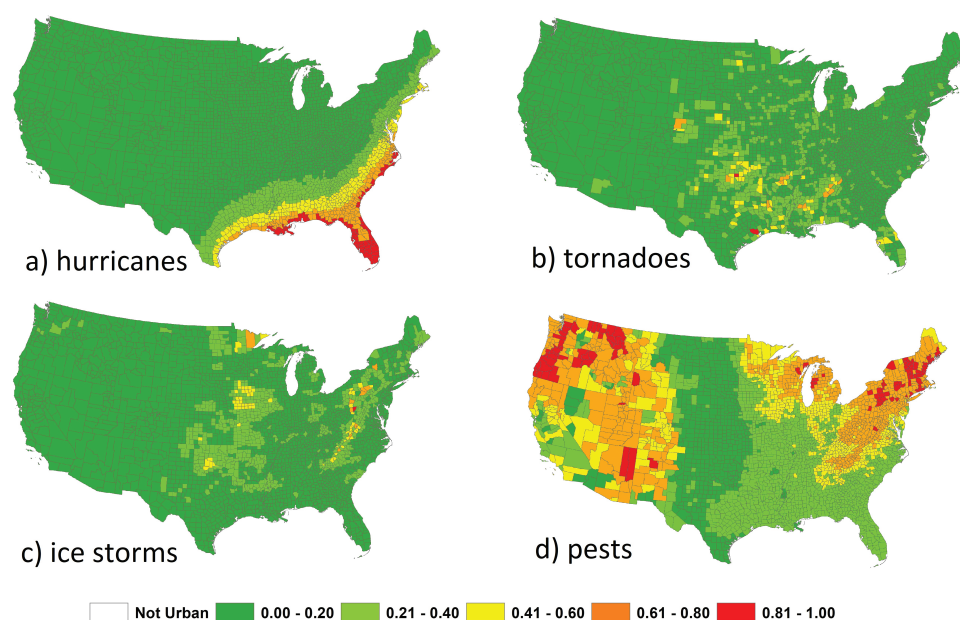


Figure 3 Storm and pest related indices: a) hurricanes, b) tornadoes, c) ice storms, d) insects and diseases. Indices are based on entire county, not just data within urban areas.

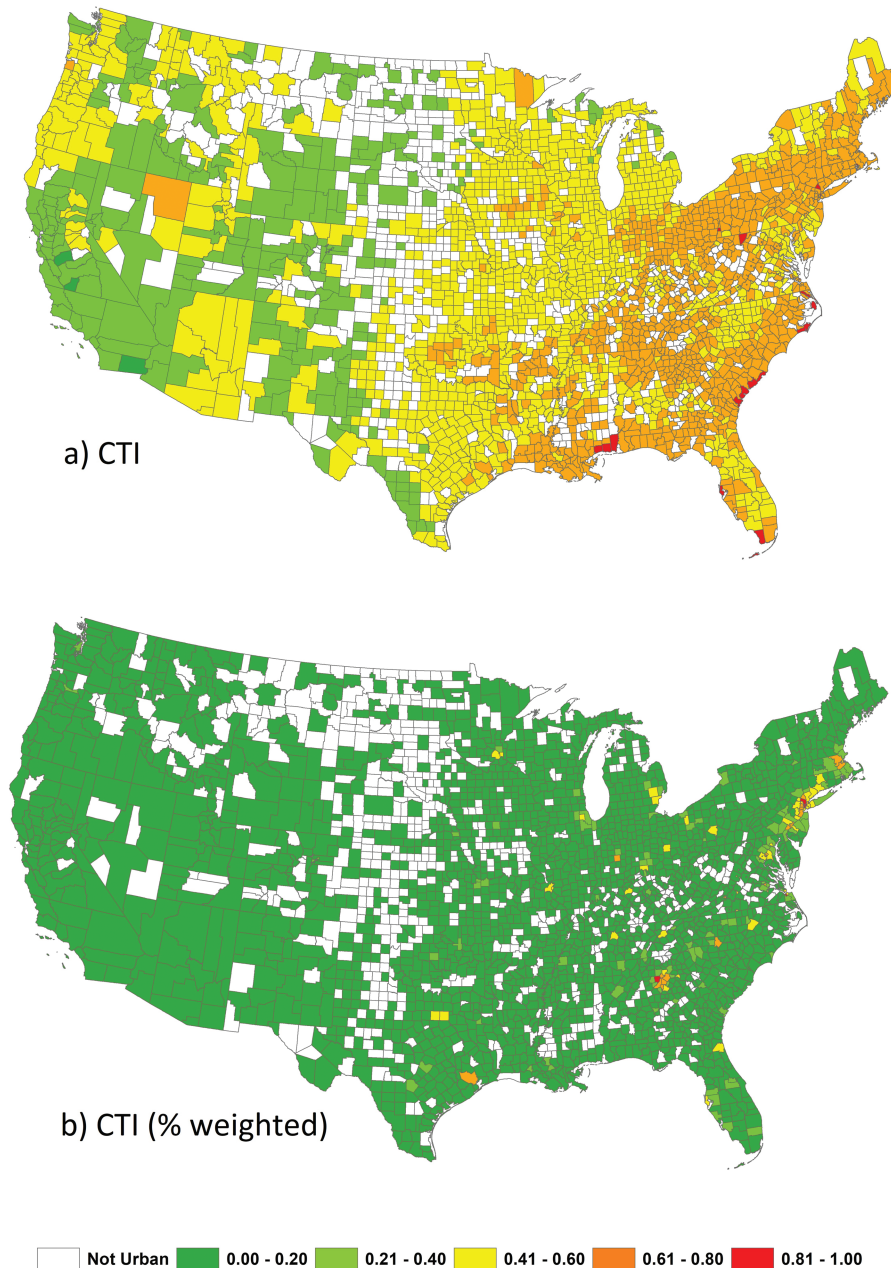


Figure 4 Cumulative threat indices: a) unweighted and b) weighted by percent of county in urban land. Counties with no urban land in 2010 are excluded.

change, flooding, and loss in percentage of urban tree cover; Garrett County has high risk to ice storms, temperature and precipitation changes, aridity, and pests (Table 2).

The CTI weighted by percentage of urban area reveals counties with the greatest relative urban forest threats overall. Highly urbanized areas along the DC–Boston corridor and in other metro areas (e.g., Atlanta, Georgia; Indianapolis, Indiana; Columbus, Ohio; Houston, Texas; Charlotte, North Carolina) have relatively high urban forest risk and/or a high proportion

of the county in urban land (Figure 4B). Counties with the highest percent-weighted risk are New York, New York; Hudson, New Jersey; and Portsmouth City, Virginia (Table 3). These counties may be small in area but have higher relative urban forest risks as urban forest loss in these areas would affect a higher proportion of the county area. New York and Hudson Counties have high risks to temperature and precipitation changes, sea level rise and pests; Portsmouth City County has high risk to precipitation and temperature changes and hurricanes.

Table 2. Counties with the highest cumulative threat index (CTI) values and their individual threat indices.

County	CTI	Hurr	Torn	Ice	Pest	UTC	T°	Prec	Arid	Fld	SLR	Fire
Camden, NC	1.00	0.72	0.01	0.00	0.33	0.19	0.68	0.80	0.21	1.00	1.00	0.00
Dare, NC	0.92	0.93	0.13	0.00	0.28	0.62	0.59	0.74	0.28	0.65	0.29	0.01
Garrett, MD	0.92	0.14	0.09	1.00	0.72	0.12	0.76	0.75	0.75	0.19	0.00	0.00
Jackson, MS	0.91	0.89	0.27	0.00	0.33	0.32	0.62	0.39	0.63	0.50	0.40	0.16
Poquoson city, VA	0.88	0.74	0.00	0.00	0.28	0.58	0.63	0.72	0.14	0.63	0.62	0.00
Rockland, NY	0.85	0.26	0.01	0.10	0.83	0.34	0.73	0.70	0.63	0.20	0.27	0.12
Chatham, GA	0.84	0.84	0.16	0.07	0.33	0.20	0.60	0.64	0.29	0.47	0.38	0.18
Bristol, RI	0.84	0.44	0.01	0.00	0.67	0.40	0.66	0.81	0.53	0.24	0.37	0.00
Charleston, SC	0.84	0.89	0.16	0.24	0.33	-0.02	0.58	0.85	0.16	0.39	0.48	0.08
Harrison, MS	0.83	0.94	0.37	0.00	0.33	0.21	0.62	0.31	0.65	0.37	0.20	0.10

Detailed results for all counties can be found in a supplemental tool (https://www.itreetools.org/documents/674/County_threat_projection_tool.xlsx).

CTI, cumulative threat index; Hurr, hurricane index; Torn, tornado index; Ice, ice storm index; Pest, insect/ disease index; UTC, urban tree cover change index; T°, temperature index; Prec, precipitation index; Arid, aridity index; Fld, flood index; SLR, sea level rise index; Fire, wildfire potential index

Table 3. Counties with the highest cumulative threat index weighted by percent of county occupied by urban land (CTI %) and their individual threat indices.

County	CTI%	Hurr	Torn	Ice	Pest	UTC	T°	Prec	Arid	Fld	SLR	Fire
New York, NY	1.00	0.34	0.00	0.03	0.67	0.14	0.70	0.69	0.39	0.41	0.67	0.03
Hudson, NJ	0.95	0.34	0.01	0.00	0.61	0.06	0.70	0.66	0.39	0.46	0.63	0.03
Portsmouth city, VA	0.86	0.60	0.02	0.00	0.44	0.19	0.61	0.71	0.16	0.44	0.32	0.00
Cobb, GA	0.85	0.29	0.23	0.17	0.44	0.51	0.76	0.62	0.40	0.06	0.00	0.03
Bergen, NJ	0.82	0.31	0.06	0.07	0.61	0.14	0.73	0.70	0.53	0.14	0.16	0.12
Bronx, NY	0.79	0.35	0.01	0.03	0.61	0.17	0.70	0.69	0.40	0.30	0.30	0.05
DeKalb, GA	0.79	0.31	0.08	0.17	0.44	0.52	0.75	0.66	0.37	0.05	0.00	0.02
Gwinnett, GA	0.78	0.30	0.10	0.21	0.44	0.47	0.75	0.65	0.35	0.05	0.00	0.02
Colonial Hgts, VA ^a	0.77	0.44	0.01	0.00	0.44	0.33	0.73	0.77	0.12	0.21	0.17	0.01
District of Columbia	0.76	0.32	0.00	0.07	0.44	0.42	0.70	0.50	0.24	0.20	0.22	0.00

Detailed results for all counties can be found in a supplemental tool (https://www.itreetools.org/documents/674/County_threat_projection_tool.xlsx).

Hurr, hurricane index; Torn, tornado index; Ice, ice storm index; Pest, insect/ disease index; UTC, urban tree cover change index; T°, temperature index; Prec, precipitation index; Arid, aridity index; Fld, flood index; SLR, sea level rise index; Fire, wildfire potential index

^a Colonial Heights city, VA.

These cumulative indices illustrate which counties have the greatest overall threat with each threat weighted with equal importance. However, not all threats are equal and threat magnitude will vary based on amount of urban cover, potential damage to the forest, and probability of occurrence. As each individual threat index will vary across the United States, it is important to locally assess which threats are most likely to affect urban forest health in the future. By understanding local urban forest threats, management plans and policies can be enacted to help adapt to and mitigate future threats to sustain healthy urban forests and associated benefits.

Limitations

The results are based on the assumptions detailed in the methods and are not projections of what will happen, but rather indices of various threats relative to the highest national values. Some indices are based on projections to 2060; others are based on current or historical patterns with the assumption that those patterns will hold in the future. The farther one projects into the future, the more likely these patterns may change. These projections and trends may change in the future if various policies or other factors change that would alter future conditions. Although these limitations associated with future projections exist, the maps

reveal variations in the distribution and intensities of potential threats. This information can aid urban forest managers and policy makers as they prepare for current and future issues that may alter urban forest health and sustainability. Limitations also exist based on the assumptions used for calculating individual indices, and the threat indices do not consider interactions among counties (e.g., precipitation in upstream counties may affect flooding in downstream counties). Various limitations of individual threats are discussed above. Although most threats were assessed within urban areas only, these threats will also affect rural forests. Due to high concentrations of people in urban areas, the threats within urban areas can have substantial impacts on human health and well-being. Although the actual threat to numbers of trees will be relatively low in urban areas nationally compared to rural forests, the impact of loss per tree will be relatively high.

Threats to urban forests vary across the United States depending upon geographic location and will vary through time due to differences in urban growth, geography, and climate. Some of these threats will interact, creating enhanced or lessened potential threats. For example, climate change will affect insect abundance and distribution (Stange and Ayers 2010) as well storm strength and distribution (Michener et al. 1997). These changes will affect tree mortality related to insects and storm damage; changes in tree mortality will consequently affect wildfire distribution and intensity. Also, as changes in air temperature and precipitation affect pest, storm, and wildfire intensity and distribution, and changes in tree cover will affect local air temperatures (Sinha et al. 2021), precipitation (Sheppard 2005), and create feedbacks that affect the pests, storm, and wildfire effects. Many of these interactions are not accounted for in this assessment due to limited information on these potential interactions.

Management Implications

Nationally, counties averaged 1.7 threats with an index value greater than 0.5. However, an average 3.2 threats with an index value greater than 0.5 were found in the eastern United States. Seven states, all in the East, averaged more than three threats with values greater than 0.5: Rhode Island (4.2 threats), Connecticut (4.0), Massachusetts (3.7), Ohio (3.3), New Jersey (3.2), Pennsylvania (3.2), and New York (3.0). The maximum number of threats with an index greater than 0.5 was six in Poquoson city, Virginia. Ten states, also all in the East, had an average CTI greater than 0.6: Connecticut (0.69), Rhode Island (0.69),

Massachusetts (0.66), Pennsylvania (0.63), New York (0.63), Ohio (0.63), New Jersey (0.62), South Carolina (0.62), New Hampshire (0.61), and Delaware (0.60) (Supplemental Figure 4). These findings are not surprising as many threats are found in the East. Some threats are limited to forested regions (e.g., insects and diseases) which are common in the East and West, hurricane threats are an eastern phenomenon, sea level rise threats are an East and West Coast risk, and projected precipitation changes are greatest in the East (Supplemental Figures 2 and 3). The convergence of a greater urban population and urban land base in the eastern United States with more prevalent urban forest threats in the East creates a need for heightened vigilance and action by eastern urban foresters to help sustain urban forest health in the coming years. However, vigilance and actions by all urban foresters nationally could help sustain urban forest health given the changing environment and diversity of threats across the nation.

The Northeast tends to have a greater threat from pests and aridity than the Southeast, whereas the Southeast tends to have a greater threat from hurricanes, tornadoes, sea level rise, and fire than the Northeast (Supplemental Figures 2 and 3). Both regions have a relative high risk of ice storms and changes in precipitation. Given the relatively large amount of urban land and population in the eastern United States, these eastern threats pose potential changes to urban forests that will affect many people. Western US threats tends to be greatest related to wildfire, temperature changes, and pests, but generally has lower overall threats than the eastern United States. Threat distribution patterns make sense based on meteorologic patterns, forest distribution, and coastal influences, but the integration of the multiple threats within forest planning can better prepare areas for future urban forest threats.

Some threats are more sudden and devastating to urban forests (e.g., hurricanes, tornadoes, wildfire) whereas other can create changes over longer periods (e.g., temperature, sea level rise). Some threats can affect large areas (e.g., climate change, hurricanes), and other threats are quite local (e.g., tornadoes) or species-specific (e.g., pests) in terms of damage. Management activities to minimize threats can vary based on the specific threat, but all involve altering forest structure (e.g., changing species and maintenance practices that affect forest structure). Understanding specific local threats is critical to determining appropriate management activities to minimize threats. Also, understanding regional threats can aid regional, state, and national plans and

policies in facilitating proper management and funding to minimize these threats. Regional plans could support each other to reduce forest threats. Understanding cumulative and multiple threats can help focus management activities (e.g., maintenance, species selections) that can address multiple threats at the same time. Efficiencies can be gained by understanding and acting on multiple threats versus addressing each threat individually or addressing a threat after the threat has already occurred.

As not all threats are equal in terms of their potential effect on urban forests, urban forest managers should evaluate which risks are most prevalent in their area and which could likely cause the greatest impacts on forest health and sustainability. Various management actions and policies could then be prescribed to help adapt to and/or mitigate the most potentially damaging threats. In exploring the local threat indices, potential interactions need to be considered as well as which threats are most likely to alter urban forest structure. Enhancing urban tree cover can help mitigate some threats. Reductions in local air temperatures from urban trees will have some of the greatest impacts, as not only is increased air temperature a direct threat but it can also affect other threats (e.g., pests, wildfire, aridity). Enhanced tree cover can also reduce the impacts of other threats such as increased precipitation (through interception and reduced runoff) and storm damage (through reduced wind speeds). In some cases, increased tree cover can increase potential damage (e.g., from ice storms), but proper tree management and care could help reduce these risks. A goal of local management could be to sustain healthy tree cover to provide benefits to society with consideration of species selection, location, and tree health to minimize potential damages and loss from local threats. Management actions would likely vary depending on the greatest local threats.

One of the dominant factors affecting tree cover loss is urban development. Urban tree cover in the United States and globally has been on the decline while impervious cover has increased (Nowak and Greenfield 2018a, 2020). In areas with high projected tree cover losses, management could focus on understanding the causes of loss and mitigating those causes. Efforts could focus on tree preservation, ensuring adequate space for trees, tree planting, facilitating natural regeneration, and the maintenance of trees in developing areas.

Climate changes (temperature, precipitation, and aridity changes) will affect species health and mortality in the coming years. Management efforts could

focus on ensuring future species selections are adapted to these changing environmental conditions. As urban heat islands already create warmer conditions, studying trees in urban areas may give an indication of which tree species will perform well under future warmer conditions (e.g., Carreiro and Tripler 2015). Although some climate changes will be gradual, there will also be more intense shorter-term events that trees must endure (e.g., droughts, floods, heat waves, storms, etc.). Managers could adapt site conditions and maintenance to help mitigate some of these effects (e.g., enhance water drainage from sites, watering trees). Also, trees could be used to help mitigate some of the future climate changes (e.g., reducing air temperatures through shading and transpiration, reducing runoff through rainfall interception, and increasing stormwater infiltration into soils) which affect both human and forest health and well-being. Sea level rise is another outcome of climate change. Although urban forests can do little to lessen rising sea levels, urban forest species selections could be shifted toward more salt-tolerant species and forest designs (e.g., mangrove forests) could be implemented to mitigate damage from storm winds, storm surge, and wave action (Spalding et al. 2014).

In areas of high wildfire risks, urban forests could be managed to reduce risk by ensuring adequate watering to minimize drought effects, maintenance to sustain tree health, removal of dead trees and fuel loads, and forest designs to minimize fire spread to structures.

Regarding areas with high risk of flooding, species in flood plains could be selected to be tolerant to waterlogged conditions, sites could be designed to reduce stormwater runoff and minimize flooding potential, and tree debris could be cleared from sites to prevent clogging of drains or potential damming of streams.

Urban forests can also be managed to reduce storm damage. By maintaining healthy and strong trees that can withstand strong winds or ice accumulation, storm damage can be reduced. In addition, it is important to consider that trees in urban areas reduce wind speeds (e.g., Giometto et al. 2017) and thus could potentially protect people and property from high winds in urban areas. However, for some storm intensities (e.g., Category 5 hurricanes, tornadoes), wind speeds are so intense that forest management activities can do little to limit storm damage.

Numerous insects and diseases continue to threaten urban forest health. By understanding local forest composition in relation to local insect and disease populations, pest threats can be better evaluated and addressed. Matching local forest composition and

local pest risks can be assessed using i-Tree Eco (www.itreetools.org) in the United States (e.g., Nowak et al. 2018) and is being assessed within the Forest Service's Urban Forest Inventory and Analysis program (Edgar et al. 2021). Management to reduce pest populations can reduce risk but sustaining forest health and shifting species composition away from susceptible species can also reduce the potential impact of many pests.

Changes in urban forests are based on a continuous input of human and natural processes. Many natural processes (e.g., storms, pests, climate, fire) are changing due human actions that affect climate and movement of pests. Given changing natural processes, human actions (i.e., management, planting) could adapt to help sustain forest health and benefits, as well as help mitigate the impacts of and enhance adaptation to changing future threats. These human actions include species selection, tree locations, and management actions (e.g., pruning) to enhance tree health and mitigate potential damage to trees and the surrounding urban landscape.

Conclusion

Urban forests will face numerous threats that can alter forest health and diminish the forest capacity to produce benefits to society. These threats vary depending on location, but cumulative threats tend to be more prevalent in the eastern United States, where the most US urban land is and most of the population resides. As the urban forest composition, conditions, and threats vary locally, the forest vulnerability to threats will vary, as will cities' abilities to adapt to these threats. As any one individual threat can cause potential damage to forest health, local threats need to be evaluated. Various limitations exist due to the assumptions used in creating the individual and cumulative threat indices, but these indices can be used to better understand the numerous threats to urban forests. By understanding the potential local threats, forest management plans and policies can be devised to help adapt to and/or mitigate these threats and sustain healthy and functional urban forests for current and future generations.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

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Literature Cited

- Abatzoglou, J.T., and A.P. Williams. 2016. Climate change has added to western US forest fire. *Proc. Natl. Acad. Sci. U.S.A.* 113(42):11770–11775.
- Abatzoglou, J.T., A.P. Williams, L. Boschetti, M. Zubkova, and C.A. Kolden. 2018. Global patterns of interannual climate-fire relationships. *Glob Chang Biol.* 24(11):5164–5175.
- Aber, J., R.P. Neilson, S. McNulty, J.M. Lenihan, D. Bachelet, and R.J. Drapek. 2001. Forest processes and global environmental change: predicting the effects of individual and multiple stressors. *BioScience.* 51(9):735–751.
- Bratkovich, S., L. Burban, S. Katovich, C. Locey, J. Pokorny and R. Wiest. 1994. *Flooding and Its Effect on Trees*. USDA Forest Service, State & Private Forestry, Northeastern Area, St. Paul, MN. 77 p.
- Carreiro, M.M., and C.E. Tripler. 2015. Forest remnants along urban-rural gradients: Examining their potential for global change research. *Ecosystems.* 8(5):568–582.
- Cole, J., D.J. Nowak, and E.J. Greenfield. 2021. Potential hurricane wind risk to U.S. rural and urban forests. *J. For.* 119(4):1–14.
- Dai, A. 2011. Drought under global warming: a review. *Wiley Interdiscip. Rev. Clim. Change.* 2(1):45–65.
- Dillon, G.K., J. Menakis and F. Fay. 2015. Wildland Fire Potential: A Tool for Assessing Wildfire Risk and Fuels Management Needs. P. 60–76 in Keane, R.E.; Jolly, M.; Parsons, R.; and Riley, K., eds. *Proceedings of the Large Wildland Fires Conference*; May 19–23, 2014; Missoula, MT. Proc. RMRS-P-73. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 345 p.
- Edgar, C.B., D.J. Nowak, M.A. Majewsky, T.W. Lister, J.A. Westfall, and N.F. Sonti. 2021. Strategic National Urban Forest Inventory for the United States. *J. For.* 119(1):86–95.
- Elsner, J.B., T. Fricker, and Z. Schroder. 2019. Increasingly powerful tornadoes in the United States. *Geophys. Res. Lett.* 46(1):392–398.
- Frankel, S., J. Juzwik and F. Koch. 2012. *Forest Tree Diseases and Climate Change*. USDA Forest Service, Climate Change Resource Center. Accessed January 2021. www.fs.usda.gov/ccrc/topics/forest-disease.
- Giometto, M.G., A. Christen, P.E. Egli, M.F. Schmid, R.T. Tooke, N.C. Coops, and M.B. Parlange. 2017. Effects of trees on mean wind, turbulence and momentum exchange within and above a real urban environment. *Adv. Water Resour.* 106(2017):154–168.
- Greenfield, E.J. and D.J. Nowak. 2013. *Tree cover and aridity projections to 2060: a technical document supporting the Forest Service 2010 RPA assessment*. USDA Forest Service Northern Research Station General Technical Report NRS-125, Newtown Square, PA. 35 p.
- Hood, S.M., J.M. Varner, P. van Mantgem, and C.A. Cansler. 2018. Fire and tree death: Understanding and improving

- modeling of fire-induced tree mortality *Environ. Res. Lett.* 13(11):113004.
- IPCC, 2013: Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge University Press, Cambridge, UK, 1535 pp.
- Iverson, L., and D. McKenzie. 2013. Tree-species range shifts in a changing climate: detecting, modeling, assisting. *Landscape Ecol.* 28:879–889.
- Klima, K., and M.G. Morgan. 2015. Ice storm frequencies in a warmer climate. *Clim. Change.* 133(2):209–222.
- Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.H. Ho, J. Kossin, M. Mohapatra, et al. 2020. Tropical cyclones and climate change assessment. Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society.* 101(3): 303–322.
- Littell, J.S., D.L. Peterson, K.L. Riley, Y. Liu, and C.H. Luce. 2016. A review of the relationships between drought and forest fire in the United States *Global Change Biol.* 22:2353–2369.
- Martinuzzi, S., A.J. Allstadt, A.M. Pidgeon, C.H. Flather, W.M. Jolly, and V.C. Radeloff. 2019. Future changes in fire weather, spring droughts, and false springs across U.S. national forests and grasslands. *Ecol. Appl.* 29(5):e01904.
- McBride, A. 2018. “Camp Fire: Death toll rises to 86 after hospitalized man dies from burn injuries” *San Francisco Chronicle*, December 11. <https://www.sfchronicle.com/california-wildfires/article/Camp-Fire-Death-toll-rises-to-86-after-13458956.php>.
- Michener, W.K., E.R. Blood, K.L. Bildstein, M.M. Brinson, and L.R. Gardner. 1997. Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. *Ecol. Appl.* 7(3):770–801.
- Multi-Resolution Land Characteristics Consortium. 2020. Accessed March 2020. [Data. https://www.mrlc.gov/data?f%5B0%5D=category%3Atree%20canopy](https://www.mrlc.gov/data?f%5B0%5D=category%3Atree%20canopy).
- National Center for Atmospheric Research. 2019. NCAR Community Climate System Model (CCSM) projections in GIS formats. Accessed January 2021. <https://gisclimatechange.ucar.edu/gis-climatedata>.
- National Oceanic and Atmospheric Administration (NOAA). 2017. Sea Level Rise Data Download. US Department of Commerce. Accessed June 2017. <https://coast.noaa.gov/slrdata/>.
- National Oceanic and Atmospheric Administration (NOAA). 2020. Storm events database. Accessed June 2020. <https://www.ncdc.noaa.gov/stormevents/>.
- Nowak, D.J., A.R. Bodine, R.E. Hoehn, A. Ellis, S. Hirabayashi, R. Coville, D.S.N. Auyeung, et al. 2018. *The Urban Forest of New York City. Resource Bulletin NRS-RB-117.* USDA Forest Service Northern Research Station, Newtown Square, PA. 82 p.
- Nowak, D.J., and E.J. Greenfield. 2010. Evaluating the National Land Cover Database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates. *Environ. Manage.* 46:378–390.
- Nowak, D.J., and E.J. Greenfield. 2018a. Declining urban and community tree cover in the United States. *Urb. For. Urb. Greening.* 32(2018):32–55.
- Nowak, D.J., and E.J. Greenfield. 2018b. U.S. urban forest statistics, values and projections. *J. For.* 116(2):164–177.
- Nowak, D.J., and E.J. Greenfield. 2020. Recent changes in global urban tree and impervious cover. *Urb. For. Urb. Greening.* 49(2020):126638.
- Nowak, D.J., and J.T. Walton. 2005. Projected urban growth and its estimated impact on the U.S. Forest Resource (2000–2050). *J. For.* 103(8):383–389.
- Pureswaran, D.S., A. Roques, and A. Battisti. 2018. Forest insects and climate change. *Curr. Forestry Rep.* 4:35–50.
- Shepherd, J.M. 2005. A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interact.* 9: Paper No. 12 1 27.
- Sinha, P., R.C. Coville, S. Hirabayashi, B. Lim, T.A. Endreny, and D.J. Nowak. 2021. Urban tree cover saves lives from extreme heat. *Ecol. Model.* 449(2021):109553.
- Spalding, M., A. McIvor, F.H. Tonneijck, S. Tol and P. van Eijk. 2014. Mangroves for coastal defence. Guidelines for coastal managers & policy makers. Wetlands International and The Nature Conservancy. 42 p. Accessed November 2014. <https://www.nature.org/media/oceansandcoasts/mangroves-for-coastal-defence.pdf>.
- Stange, E.E. and M.P. Ayres. 2010. Climate Change Impacts: Insects. In *Encyclopedia of Life Sciences (ELS)*. John Wiley & Sons, Ltd, Chichester, UK.
- Steenberg, J.W.N., A.A. Millward, D.J. Nowak, and P.J. Robinson. 2016. A conceptual framework of urban forest ecosystem vulnerability. *Environ. Rev.* 25:115–126.
- Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler and C. Zervas. 2017. *Global and Regional Sea Level Rise Scenarios for the United States.* NOAA Technical Report NOS CO-OPS 083, Silver Spring, MD. 56 p.
- US Census Bureau. 2020. 2010 Census Urban and Rural Classification and Urban Area Criteria. <https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/2010-urban-rural.html>. last accessed May 2020.
- US Environmental Protection Agency. 2016. Climate Scenarios (1950–2099): Potential Evapotranspiration. EnviroAtlas Fact Sheet. 2 p. Accessed December 2019. www.usepa.gov/enviroatlas.
- US Environmental Protection Agency (US EPA). 2019. EnviroAtlas. www.usepa.gov/enviroatlas. Last accessed December 2019.
- USDA Forest Service. 2017. *Mapping and reporting.* Washington, DC: USDA Forest Service Forest Health

- Protection. Accessed March 2017. <https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/damage-agent-range-maps.shtml>.
- USDA Forest Service. 2018. Wildfire Hazard Potential. Accessed May 2016. https://www.firelab.org/sites/default/files/images/downloads/whp2014_cls_fa_q_metadata.pdf.
- USDA Forest Service. 2020. *Alien Forest Pest Explorer*. USDA Forest Service Northern Research Station, Madison, WI. Accessed January 2021. <https://www.nrs.fs.fed.us/tools/afpe/maps/>.
- Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, et al. 2014. Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 19–67. Washington, DC: U.S. Government Printing Office.
- Wang, W.J., H.S. He, F.R. Thompson, J.S. Fraser, and W.D. Dijak. 2017. Changes in forest biomass and tree species distribution under climate change in the northeastern United States. *Landscape Ecol.* 32(7):1399–1413.
- Williams, A.P., C.D. Allen, C.I. Millar, T.W. Swetnam, J. Michaelsen, C.J. Still, and S.W. Leavitt. 2010. Forest responses to increasing aridity and warmth in the southwestern United States. *Proc. Natl. Acad. Sci. USA*. 107(50):21289–21294.
- Zhai, L., K.W. Krauss, X. Liu, J.A. Duberstein, W.H. Conner, D.L. DeAngelis, and L.S.L. Sternberg. 2018. Growth stress response to sea level rise in species with contrasting functional traits: A case study in tidal freshwater forested wetlands *Environ. Exp. Bot.* 155(2018):378–386.