# Ecosystem services of urban tree canopy for the mitigation of climate change: Measuring carbon sequestration and understory temperature reduction of Knoxville's urban forest

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**ABSTRACT:**

In the future, the city of Knoxville, Tennessee will be impacted by climate warming due to anthropogenic climate change. Yet, the ecosystem services provided by urban tree canopy in Knoxville's urban forest can help mitigate the effects of climate warming. In addition to improving air quality, regulating water flow, and reducing noise pollution, Knoxville's urban forest serves as a carbon sink and sequesters carbon dioxide on an annual basis. Utilizing methods for calculating carbon sequestration by trees in urban and suburban settings developed by the U.S. Energy Information Administration, the sequestration potential and its uncertainty is calculated until the year 2050 for each individual tree. Present sequestration offsets about 1.24% of city-wide emissions, but offset potential more than doubles by 2050 with the urban forest estimated to offset about 2.94% of city-wide emissions. In addition to sequestration benefits, urban tree canopy lowers surface and air temperatures by providing shade and evaporative cooling as two additional ecosystem services. This reduction mitigates rising ambient air temperature for species inhabiting the understory and can be compared to species' physiological sensitivities in order to estimate population responses to future climate warming. Mapping canopy cover also illustrates where wildlife corridors exist and areas where they need to be developed in order to maintain exchanges between populations fragmented by urban infrastructure. LiDAR data collected in 2016 is processed in GIS software to determine canopy density in Knoxville's urban forest and other forest land within the city. A case study highlights one application of the canopy cover layer to determine areas of thermal refuge for an understory species, *Tamias striatus* (the eastern chipmunk). For both high-emissions and low-emissions scenarios, *Tamias striatus* is not affected by climate warming through 2025, but after that year, areas of refuge beneath canopy cover become critical for maintaining biological fitness.

## 1. INTRODUCTION:

By the year 2100, Knoxville could be experiencing intense summers with up to 80 days above 35°C if we do not slow down the pace of anthropogenic climate change (Huotari, 2017). Whether temperatures this high coalesce or not, Knoxville needs to be able to adapt since the city currently averages around 5 days above 35°C every summer (Huotari, 2017). Conditions like these will only exacerbate urban heat islands and the effects felt by neighborhoods within them. The Urban Heat Island effect is a well-studied phenomena where densely populated areas observe higher temperatures than more sparsely populated areas, especially at night (Hass, 2016, p. 2). This phenomenon exists in most cities with a population of 200,000 or greater, primarily because of: 1) decreased albedo from a greater concentration of absorptive surfaces (concrete) than found in rural areas, 2) decreased evapotranspiration because of a lack of vegetation, and 3) an increase in heating from anthropogenic activities, such as using air conditioners, generators, and cars (Hass, 2016, p. 2). The year 2016 proved to be both the hottest and the driest year on record according to the National Weather Service and NOAA (2017) while 2017 proved to be the 3rd hottest year on record (NOAA, 2018). For the summer of 2018, the majority of the contiguous United States including East Tennessee experienced mean temperature departures characterized by above average temperatures (NOAA, 2018).

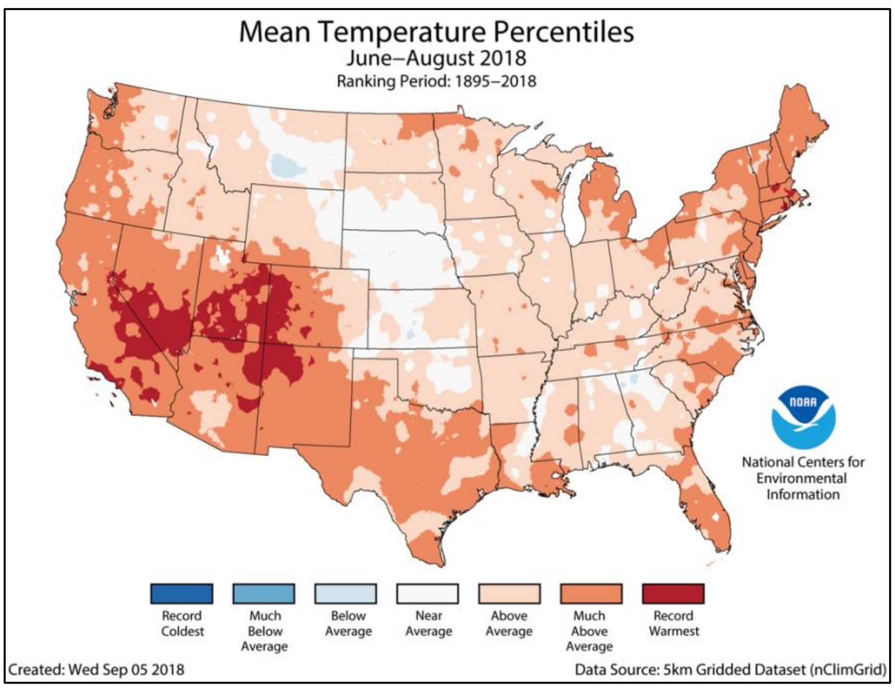


**Figure 1: Mean Temperature Percentiles, Summer 2018**
**Source:** NOAA National Centers for Environmental Information. (2018, September 12). *State of the Climate: National Climate Report for August 2018.*

## 2. REVIEW *of* RELEVANT LITERATURE:

Carbon sequestration is a process where carbon dioxide is extracted from the atmosphere and stored for a long period of time. Trees absorb $CO_2$ from the atmosphere, which is then stored in organic matter aboveground in leaves, stems, and belowground in soil within their roots. Rotting leaves, debris, and other decaying organisms make up a large percentage of soil inorganic carbon as well. All in all, forests store large amounts of carbon which in turn contribute positive benefits to the environment and human health. Since the accumulation of carbon dioxide and other greenhouse gases in Earth's atmosphere remain the primary drivers of anthropogenic climate change, trees provide a valuable ecosystem service in the form of sequestration.

In the United States, forests make up 90% of U.S. carbon sinks and offset approximately 10% of U.S. $CO_2$ emissions through sequestration (Northern Institute of Applied Carbon Science, 2017). These sinks include urban forests such as Knoxville's own which is made of about 26,000 individual trees. The City of Knoxville's Department of Urban Forestry is responsible for the upkeep for hundreds of miles of street right-of-way and street medians as well as more than 80 parks that account for more than 800 hectares on public land or about 3% of Knoxville's total area. It is noted that private land is not considered to be a part of the urban forest even though trees on private property contribute significantly to urban canopy cover (Krouse, 2017). So far, about 85% of trees in Knoxville's urban forest (21,650 trees) have been geospatially inventoried, and the carbon sequestered by these trees represents a positive externality that can be monetized (City of Knoxville - Urban Forestry Division, 2018). Kirby and Potvin have shown that carbon storage potential varies significantly among tree species and can have implications for calculating the value of small-scale carbon sinks (2007). Thus, in this project, estimates of carbon sequestration potential are calcuated at a species level of detail.

In addition to improving air quality, regulating water flow, and reducing noise pollution, trees lower surface and air temperatures by providing shade and evaporative cooling as two additional ecosystem services. Shaded surfaces, for example, may be 11–25°C cooler than the peak temperatures of unshaded materials (Akbari, Kurn, Bretz, & Hanford, 1997). Evapotranspiration, alone or in combination with shading, can help reduce peak ambient air temperatures by 1–5°C in cities during the summer (Kurn, Bretz, Huang, & Akbari, 1994). This reduction functions as an offset in ambient air temperature for species inhabiting the understory and can be compared to species' physiological sensitivities to increasing temperatures in order to estimate population responses. Moreover, the canopy cover provided by urban forest fills critical gaps as wildlife corridors–linking other forest land fragmented by the cityscape and providing temporary refugia for thermally-stressed organisms.

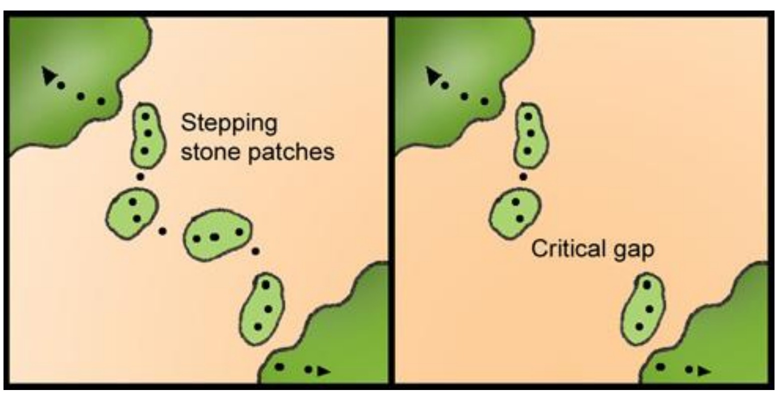


**Figure 2: Wildlife Corridors: Stepping Stones and Gaps**
**Source:** U.S. Forest Service Southern Research Station. (2008, September). *Conservation Buffers: Design Guidelines for Buffers, Corridors, and Greenways.*

Other studies have been conducted examining Knoxville's urban forest, including the Knox County Tree Survey of 2006 examining public awareness of its benefits (Jones, 2006). This resulted in a study that combined measures of attitudes, beliefs, values, and sociodemographic variables to predict homeowner support for local urban tree protection (Jones, Davis and Bradford, 2013). Knoxville residents were shown to exhibit environmental concern and valued trees for both their symbolic values and aesthetic values; however, many were shown to overlook environmental benefits (Jones, Davis and Bradford, 2013, p. 14). Additionally, the Tennessee Department of Agriculture conducted its own canopy density estimation of

Knoxville's urban forest from aerial photographs taken in 1997 and 2010 (Simpson, 2014). Knoxville's overall canopy cover averaged 40% for both years and has remained stable since (Simpson, 2014). However, no studies have estimated the urban forest's potential for carbon sequestration or examined its ability to mitigate predicted climate warming for understory species.

## 3. OBJECTIVES:

### 3.1. Quantify the sequestration benefits of Knoxville's urban forest.

Knoxville's urban forest is a carbon sink and sequesters $CO_2$ on an annual basis. It is beneficial for cities to account for carbon sequestration benefits when cities try to calculate their greenhouse gas emissions, so a net measure of emissions can be determined. Whether carbon sequestration is increasing or decreasing over time largely reflects forest health. Keeping track of these trends and the forest's monetary value are of significance to forest management and conservation programs.

### 3.2. Identify and map Knoxville's urban forest by canopy cover.

Areas with high canopy cover provide the most amount of shade and best reduce the urban heat island effect through evapotranspiration. Mapping these areas also illustrates where wildlife corridors exist and areas where they need to be developed in order to maintain exchanges between populations fragmented by human settlements and urban infrastructure. LiDAR data is available for Knoxville and is used to develop a canopy cover layer. Many applications relevant to climate change are available.

### 3.3. Determine whether the urban forest can mitigate rising temperatures for *Tamias striatus*.

A case study highlights one application of the canopy cover layer. *Tamias striatus* or the eastern chipmunk represents one example of a native understory species that is expected to be impacted by climate warming (Lawrence Chia-Huang Wang & Hudson, 1971). Typically, species threatened by rising temperatures shift their range or alter their behavior to escape areas of high heat. One way that species can alter their behavior is by moving to areas with denser canopy cover when ambient air temperatures exceed their range of thermal tolerance. Based on the thermal tolerance limits of *Tamias striatus*, areas of suitable habitat in Knoxville's urban forest are estimated for the present year and projected into the future.

## 4. METHODS:

### 4.1. Measuring carbon sequestration benefits

Utilizing methods for calculating carbon sequestration by trees in urban and suburban settings developed by the U.S. Energy Information Administration (U.S. Department of Energy, 1998), this flow and its uncertainty is calculated until the year 2050 for each tree. Data is available for around 21,650 points each representing a tree. Each point consists of latitude, longitude, species name, and general health of tree rated on a Likert scale. Knoxville's city limits were selected as the boundary because georeferenced data is recorded for each tree managed by the Department of Urban Forestry within the city limits. Variables like tree type (hardwood or conifer), growth rate (slow, moderate, or fast), and tree age are used to determine the rate at which carbon is stored for each tree. Carbon storage potential is calculated to determine the amount in metric tons of carbon sequestered per year for each species and is multiplied by 3.67 (a ratio to transform carbon values to carbon dioxide). Summing each annual sequestration rate for each tree species and multiplying that value by the proportionality constant of $\frac{100}{85}$ yields an estimation of the total amount of carbon dioxide sequestered by Knoxville's urban forest for that year. Uncertainty is determined by error propagation.

To analyze carbon sequestration dynamics in the future, tree planting and tree removals were accounted for based on trends published in the most recent *State of the Urban Forest Report* (Krouse, 2017, p. 8). Tree composition, tree age, and the photosynthetic rate were assumed to remain stable. These parameters are difficult to estimate since the urban forest is a managed landscape dependent on management decisions. However, increases in photosynthetic rate will likely be offset by decreases in tree survival due to projected climate warming and shifting precipitation patterns. In Knoxville, climate change is expected to cause decreases in number of precipitation days but increases in the amount of precipitation–resulting in more variable and more intense precipitation events (Huotari, 2017). In addition, warmer average annual temperatures will likely drive some tree species out of their current range of thermal tolerance (Prasad, Iverson, Matthews, & Peters, 2007-ongoing). These parameter ramifications are outside the scope of this analysis but should be investigated in future studies to assess sensitivities in potential carbon sequestration.

### 4.2. Identifying canopy cover

Canopy density, or canopy cover, is the ratio of vegetation to ground as seen from the air. Light Detection and Ranging (LiDAR) surveying methods can be used to determine this variable. As part of the Eastern TN LiDAR 2016 QL2 Project and the USGS 3D Elevation Program, LiDAR derived "enhanced" elevation data was collected for Knox County during February and March of 2016. Average point spacing was determined to be 0.5 meters, and a vertical accuracy of +/- 10 centimeters was achieved (STS-GIS Services). The LiDAR data for Knox County is stored in 560 .zLAS files and is used to estimate current canopy cover. Methods to estimate canopy density are generalized from Esri's "Lidar Solutions in ArcGIS" (2018). A model summarizing the steps is displayed in Figure 3 and Figure 4.

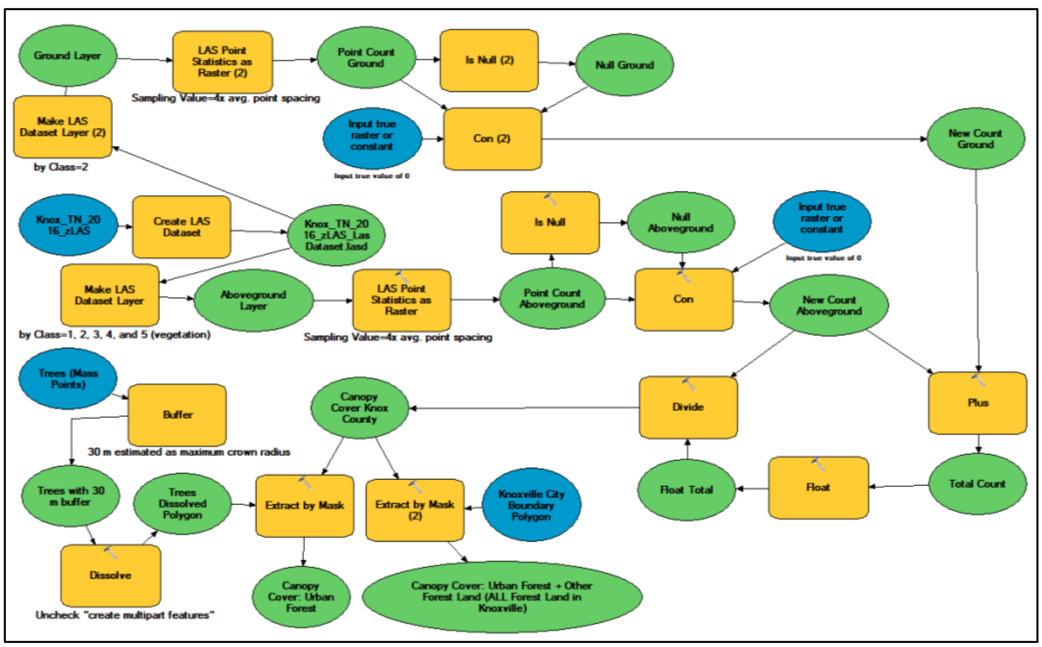


**Figure 3: Canopy Density Model, Workflow Overview in ModelBuilder**
**Source:** produced by author in ArcMap 10.6

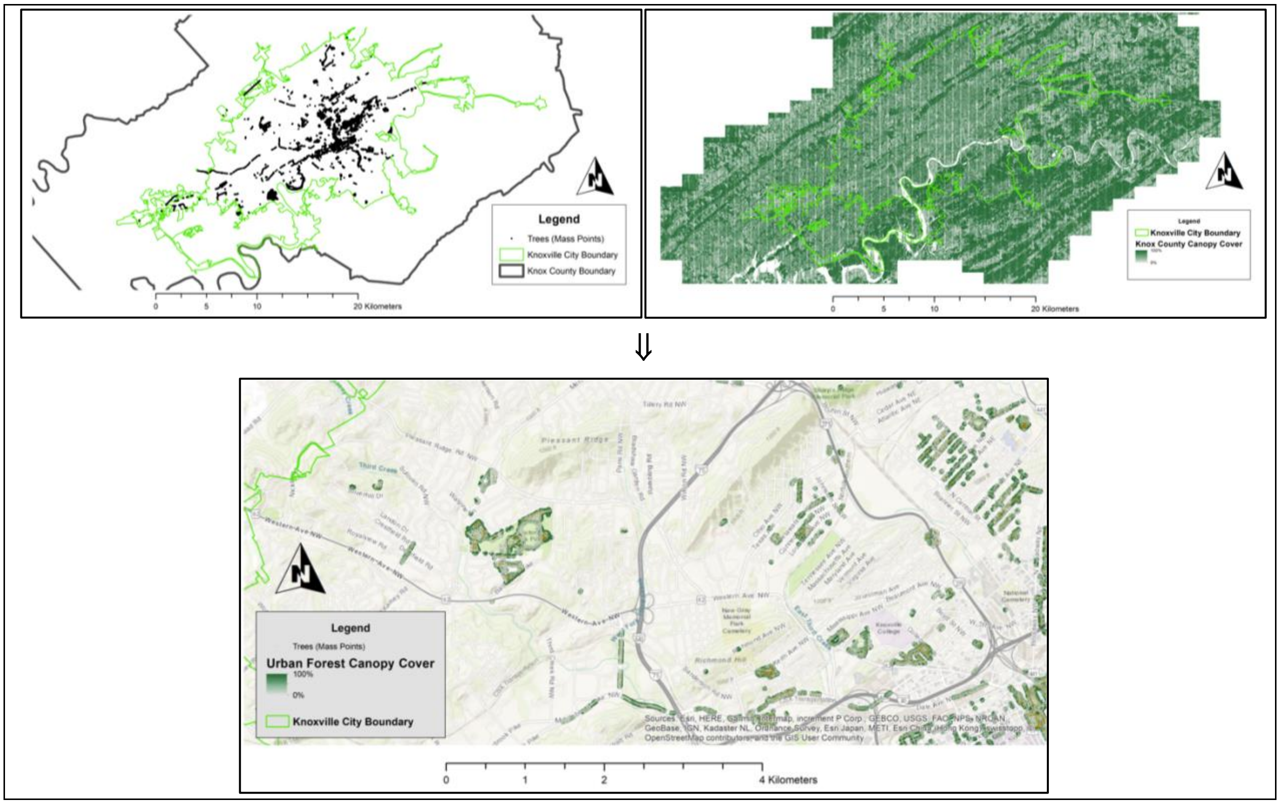


**Figure 4: Canopy Density Model, Workflow Overview Output**
Note: The bottom map represents a zoomed in view of the urban forest of Knoxville; mass points and canopy cover are visualized. Raster cell size = 4 ft. by 4 ft. (1.2192 m. by 1.2192 m.)
**Source:** produced by author in ArcMap 10.6

### 4.3 Determining patches of thermal refuge for *Tamias striatus*

*Tamias striatus* is abundant throughout its range in eastern North America, inhabiting hardwood forests of the mid-latitudes. The species is considered non-threatened, and is commonly seen throughout its range, but predicted climate warming will place the species under thermal stress according to its thermal tolerance limits (Chervenak, 2008). Thermal tolerance is a measurement of organismal fitness dependent on environmental temperature which influences metabolic processes. An endotherm's thermal tolerance limits are defined by its thermal neutral zone, the range of temperatures where an organism can maintain a steady internal body temperature with minimal metabolic regulation.

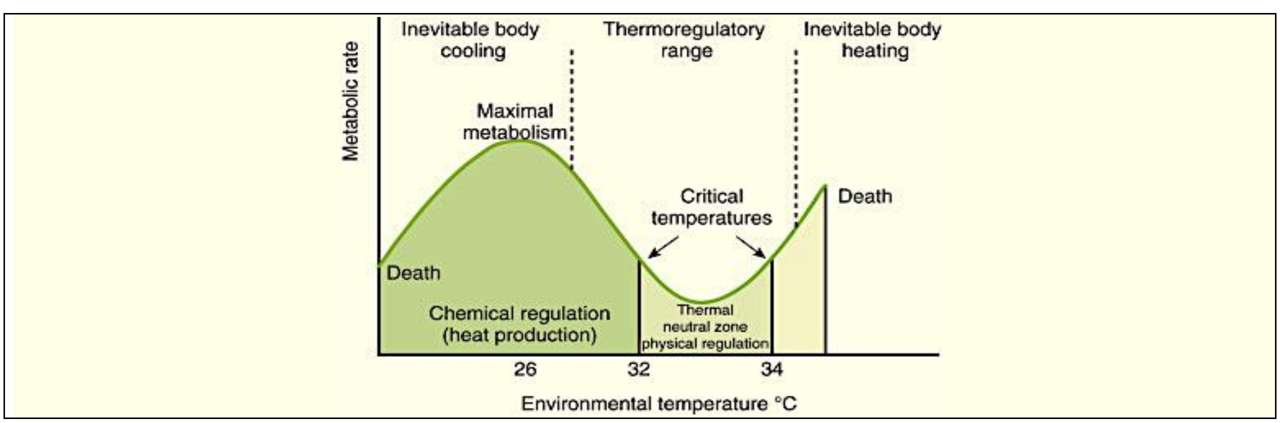


**Figure 5: Thermal Neutral Zone**
**Source:** Gleason, C. A., & Juul, S. E. (Eds.). (2018). *Avery's diseases of the newborn* (Tenth edition). Philadelphia, PA: Elsevier.

Outside of these critical temperature limits, an organism will experience thermal stress, a condition where metabolic rates will increase in order to maintain a steady body temperature. Prolonged exposure to temperatures outside of critical temperatures are correlated with decreases in fitness and even death (Deutsch et al., 2008). Thermal tolerance limits of *Tamias striatus* were first estimated by Lawrence Chia-Huang Wang and Hudson in 1971 through laboratory experiments. An upper critical temperature (UCT) of 32°C and a lower critical temperature (LCT) of 28.5°C were determined (Lawrence Chia-Huang Wang & Hudson, 1971). The UCT value of 32°C is most important for this analysis.

However, trees can help mitigate peak daily temperatures (Kurn, Bretz, Huang, & Akbari, 1994), and Hass et al. has shown that canopy cover is significant when comparing temperatures among different neighborhoods in Knoxville from May to September (2016, p. 14). The forest canopy reduces solar radiation, so the understory does not heat up or cool down as rapidly as open grassland or concrete surfaces. Consequently, areas of canopy may provide refuge for thermally-stressed organisms. According to the 1°-5°C offset derived by Kurn, Bretz, Hang, & Akbari (1994), areas of canopy cover are assigned a temperature gradient proportional to canopy density using the Reclassify tool in ArcMap 10.6. 20% minimum canopy cover is assumed to mark the beginning of the offset scale. Any cell value below 20% is likely not to provide enough shade or evapotranspiration to create a measurable temperature offset. The temperature offset is also expected to scale proportionately with percent canopy cover, but more research is needed to determine scale dynamics in the future.

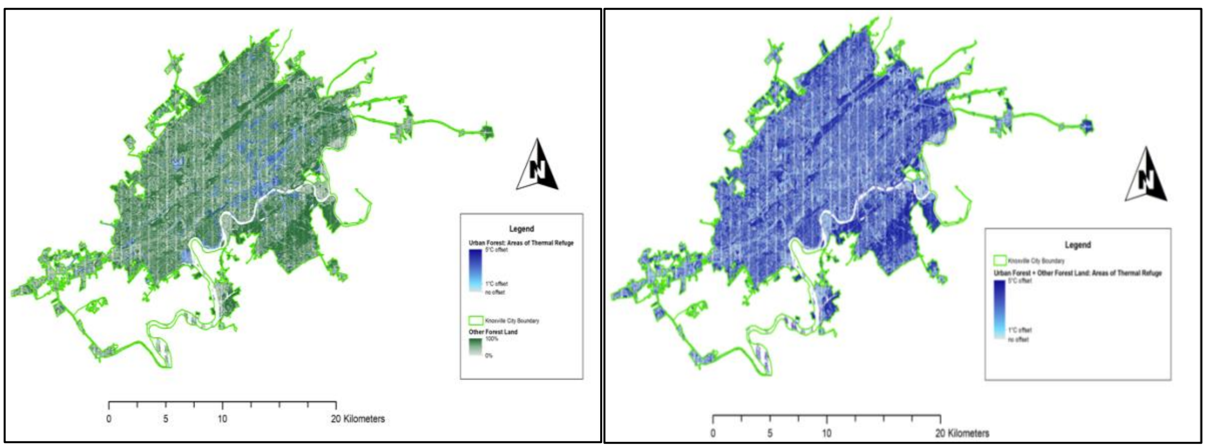


**Figure 6: Comparing Areas of Thermal Refuge: Knoxville's urban forest (on left) vs. Knoxville's total forest area (on right)**
Raster cell size = 4 ft. by 4 ft. (1.2192 m. by 1.2192 m.)
**Source:** produced by author in ArcMap 10.6

The temperature offset for each raster cell is subtracted from the average summertime (June, July, and August) maximum temperature projected for Knox County by the NOAA (NOAA Climate Explorer Toolkit). If the cell value is higher than 32°C, then the cell does not represent an area of suitable habitat for thermal refuge. Cell values lower than 32°C represent areas of suitable thermal refuge. Percent suitable habitat $_{\text{Knoxville}}$ and percent suitable habitat $_{\text{Urban Forest}}$ are calculated for 2018 and projected into the future for years 2025, 2050, and 2075. Low emissions and high emissions scenarios based on Representative Concentration Pathways (RCPs) are used to determine a range of estimates as seen in Figure 7. RCP 4.5 is the low emissions scenario used in this analysis and projects radiative forcing to stabilize at 4.5 Watts per meter squared by the year 2100 (IPCC, 2018). RCP 8.5 is the high emissions scenario used in this analysis and projects radiative forcing to rise to 8.5 Watts per meter squared by the year 2100 without any sign of stabilization (IPCC, 2018).

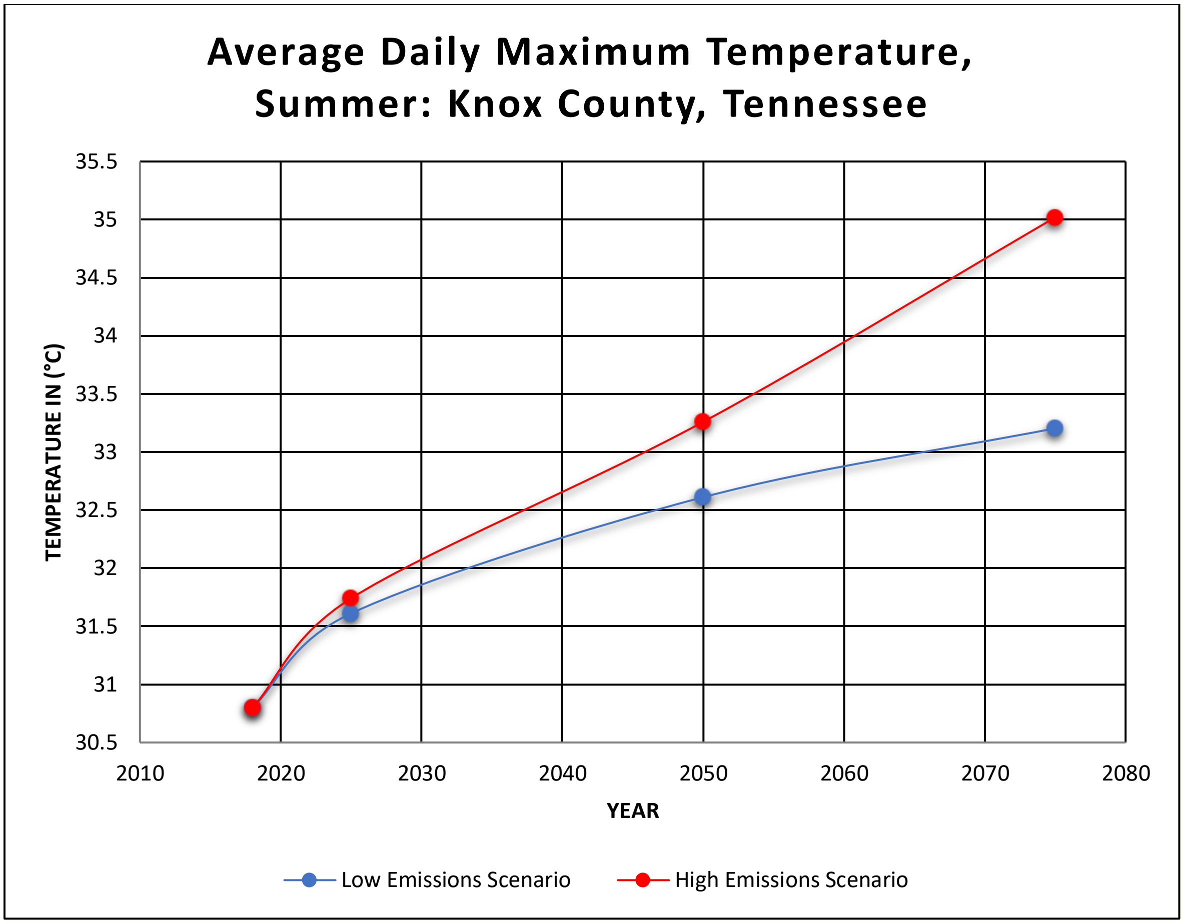


**Figure 7: Average Daily Maximum Temperature (°C), Summer: Knox County, Tennessee**
Note: In 2018, the average summertime daily maximum temperature was 30.8°C. Low emissions (RCP 4.5) and high emissions (RCP 8.5) scenarios are forecasted.
**Source:** Adapted from U.S. Federal Government. (2018). *U.S. Climate Resilience Toolkit Climate Explorer*.

## 5. RESULTS:

### 5.1. Measuring carbon sequestration benefits

In 2018, the annual sequestration rate is estimated to be 717.8272 $\pm$ 2.1181 metric tons of $CO_2$. In 2050, the annual sequestration rate is estimated to increase to 1,053.0874 $\pm$ 3.1074 metric tons of $CO_2$. This increase accounts the planting of 550 trees per year (on average) by Knoxville's Department of Urban Forestry. No spatial relationships between sequestration rate and tree location were observed. In 2017, Knoxville's Office of Sustainability updated its greenhouse gas emissions inventory and projected city-wide emissions at 57,867 metric tons of $CO_2e$ for 2018 (p. 10). If Knoxville remains on track to reach its goal of 20% reduction in emissions every 15 years, city-wide emissions in 2050 are estimated to drop to 35,840 metric tons of $CO_2e$. Even though present sequestration only offsets about 1.24% of city-wide emissions, offset potential more than doubles by 2050 with the urban forest estimated to offset about 2.94% of city-wide emissions. And this offset only represents the urban forest which does not account for the sequestration benefits from trees on private land within the city boundary. In order to conduct a sensitivity analysis on the results, error in calculating the rates of carbon sequestration was considered and is displayed in Figure 8.

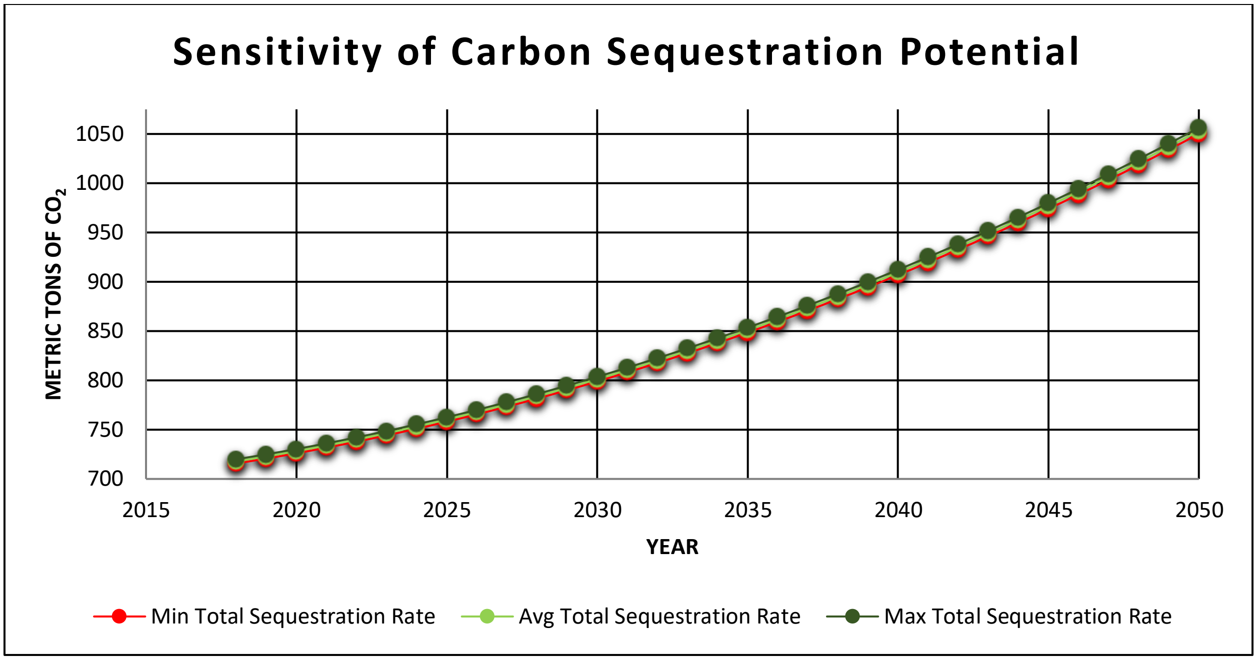


**Figure 8: Sensitivity of Carbon Sequestration Potential: Knoxville's Urban Forest**
**Source:** produced by author

One explanation for low sensitivity across carbon sequestration potential is that future projections did not simulate potential changes in tree composition, tree age, or photosynthetic rate. Another reason is that this valuation is conducted at the tree level which is difficult for many cities due to the lack inventoried tree data; Knoxville is one of the few cities with such highly detailed data and a representative sample size. Rather than estimating the sequestration rate of a patch of forestland from a satellite image, initial estimates of carbon sequestration are accurate at the kilogram level since individual trees are the unit of analysis. As a result of this method, there is a less error in estimating the total sequestration rate of the urban forest.

### 5.2 Determining patches of thermal refuge for *Tamias striatus*

| **Low Emissions Scenario, RCP 4.5** | | | | | | |
|---|---|---|---|---|---|---|
| Year | | Percent Area of Suitable Habitat, Urban Forest | Percent Decrease from 2018 | | Percent Area of Suitable Habitat, Knoxville | Percent Decrease from 2018 |
| 2018 | | 100.00% | N/A | | 100.00% | N/A |
| 2025 | | 100.00% | 0.00% | | 100.00% | 0.00% |
| 2050 | | 65.65% | 34.35% | | 73.65% | 26.35% |
| 2075 | | 63.43% | 36.57% | | 71.88% | 28.12% |
| **High Emissions Scenario, RCP 8.5** | | | | | | |
| Year | | Percent Area of Suitable Habitat, Urban Forest | Percent Decrease from 2018 | | Percent Area of Suitable Habitat, Knoxville | Percent Decrease from 2018 |
| 2018 | | 100.00% | N/A | | 100.00% | N/A |
| 2025 | | 100.00% | 0.00% | | 100.00% | 0.00% |
| 2050 | | 56.17% | 43.83% | | 66.14% | 33.86% |
| 2075 | | 32.85% | 67.15% | | 46.11% | 53.89% |

**Figure 9: Canopy Cover Application: Predicting Future Areas of Thermal Refuge for *Tamias striatus***
**Source:** produced by author

For both scenarios, *Tamias striatus* is not affected by climate warming through 2025, but after that year, areas of refuge beneath canopy cover become critical for its survival. Based on RCP 4.5, about 30% of Knoxville's land area will experience peak temperatures above the species' UCT (32°C) by 2075. The urban forest is even more severely impacted with only 63% of its canopy able to offset peak summer temperatures by 2075. Even in current fossil fuel use were to drastically decrease, eastern chipmunk populations are still projected to be negatively impacted by climate warming.

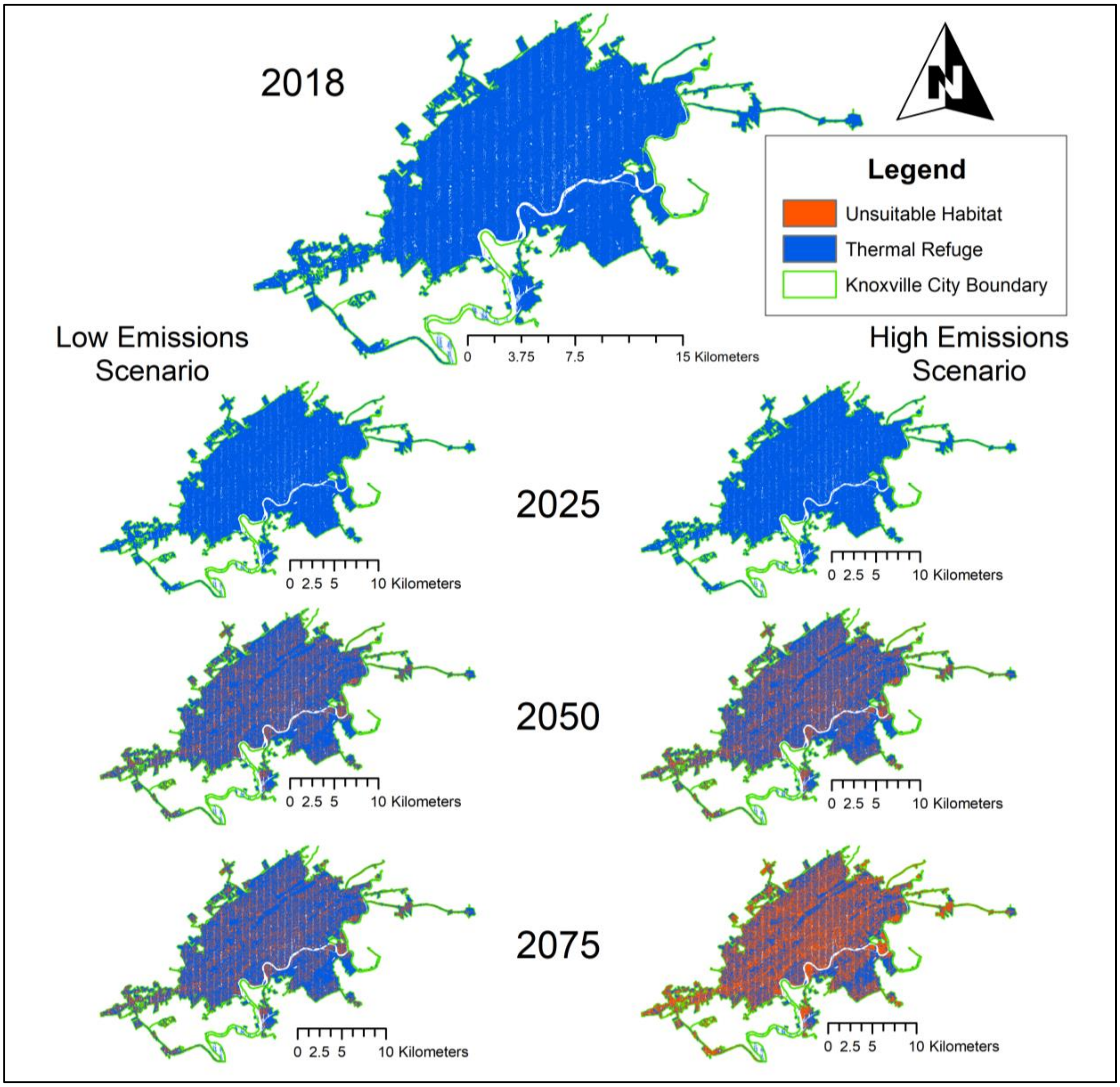


**Figure 10: Areas of Thermal Refuge for *Tamias striatus* Decline by 2075**
Raster cell size = 4 ft. by 4 ft. (1.2192 m. by 1.2192 m.)
**Source:** produced by author in ArcMap 10.6

The result is amplified based on a higher emissions scenario, RCP 8.5. Suitable habitat in Knoxville's urban forest decreases drastically to 56% by 2050 and drops to about 33% by 2075. Considering Knoxville as a whole, the result is more optimistic albeit marginally. Still, less than half of all land area is projected to be suitable for the eastern chipmunk by 2075. These areas are determined to lie outside its range of thermal tolerance.

**6. DISCUSSION:**

**6.1. Measuring carbon sequestration benefits**

Other findings suggest that the city of Knoxville will face potential tradeoffs in the future concerning urban forest management. *Cornus florida* or the flowering dogwood is currently the most common tree in the urban forest comprising about 7.83%. The dogwood remains a cultural symbol for Knoxville, but as a slow-growing hardwood, the species is relatively poor at sequestering carbon–ranked 156$^{th}$ out of the 167 tree species by carbon sequestration potential. Although native, *Cornus florida* is also predicted to prefer a cooler climate than Knoxville by the year 2100 with an associated range shift of 2° north in latitude (Prasad, Iverson, Matthews, & Peters, 2007-ongoing). Overall slow-growing hardwoods were shown to sequester carbon dioxide about 10x less than fast-growing hardwoods suggesting that slow-growing hardwoods should be planted sparingly if carbon sequestration is a forest management priority. *Quercus pagoda* and *Quercus coccinea* are 2 examples of preferred hardwood species.

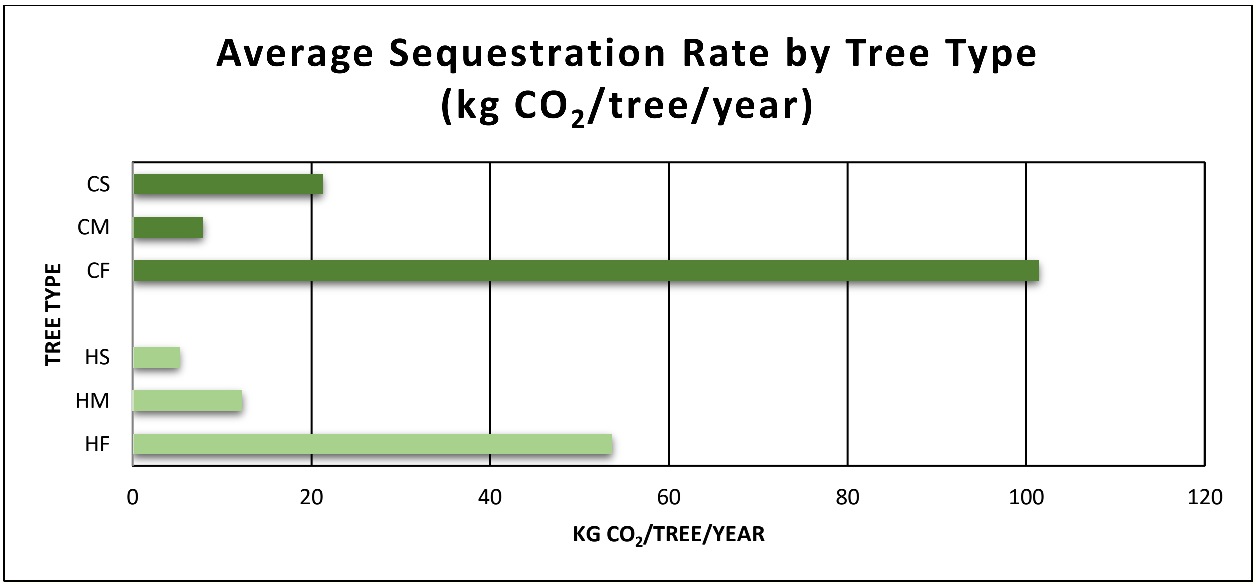


**Figure 11: Average Sequestration Rate by Tree Type**.
Key: CS– slow-growing conifers
CM – moderate-growing conifers
CF – fast-growing conifers
HS – slow-growing hardwoods
HM – moderate-growing hardwoods
HF – fast-growing hardwoods
**Source:** produced by author

Fast-growing conifers were shown to be the best tree type for carbon sequestration with an average annual sequestration rate of 101.5 kg/$CO_2$ per tree. This rate is roughly double that of fast-growing hardwoods which sequester about 53.7 kg/$CO_2$ per tree on average. One of the main reasons for this is that conifers were found to live about twice as long as hardwoods according to the inventory (City of Knoxville - Urban Forestry Division, 2018). Still, fast-growing conifers only comprise about 5.53% of the tree population. Native, fast-growing pines like *Pinus echinata*, *Pinus taeda, Pinus palustris,* and the eastern redcedar, *Juniperus virginiana*, are recommended for their carbon sequestration potential and longevity.

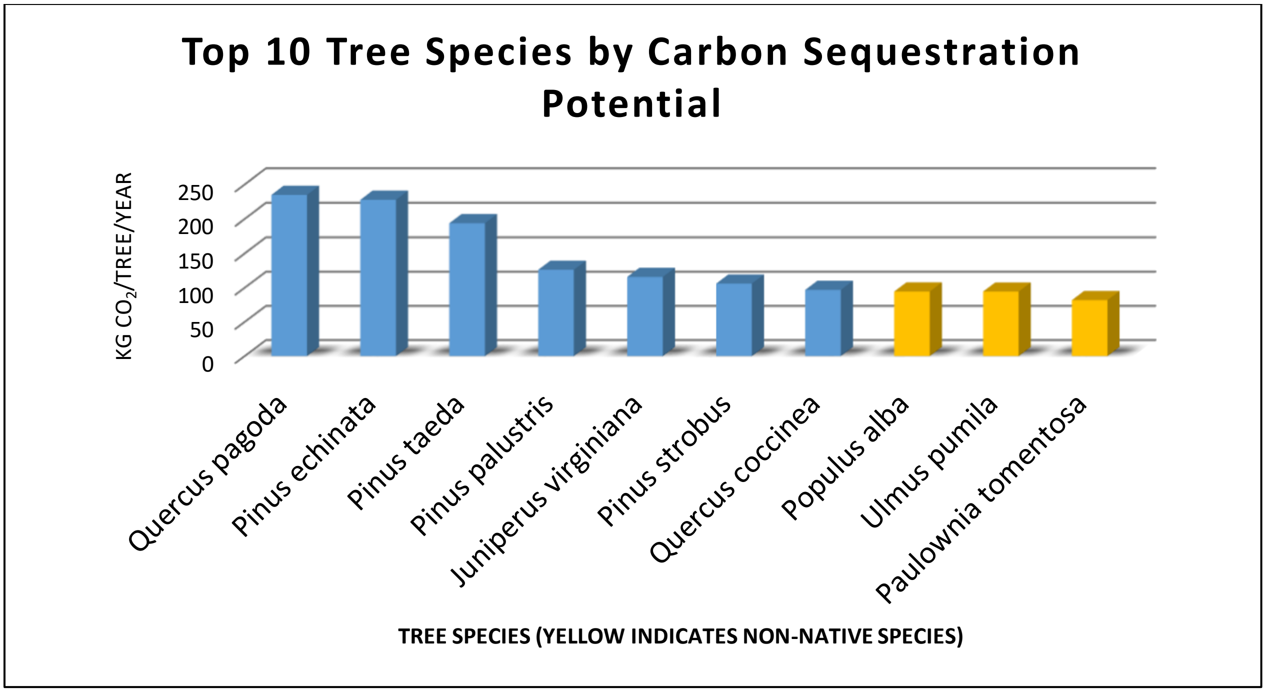


**Figure 12: Top 10 Tree Species by Carbon Sequestration Potential**
Note: The last 3 of the top 10 species are non-native species which could potentially become invasive species. Vulnerability assessments should be considered when choosing to plant non-native species.
**Source:** produced by author

However, individual tree species do matter as to: 1) how much carbon dioxide they are able to sequester annually, and 2) whether those species are native or non-native. In general, trees that are "fast-growing, native, and drought resistant" are best for the Knoxville's future climate according to an interview with Dr. Gary Crites, a paleoethnobotanist employed by the McClung Museum (2017). Cities are having to uproot and replant often since 3-5% of urban street trees die every year according to research ecologist, Lara Roman (2014). Moreover, the average life expectancy of an urban street tree is between 18 and 29 years (Roman, 2014). As such, the literature suggests low-maintenance and long-living trees are best for cities trying to maximize goals of carbon sequestration and cost reduction (U.S. Department of Energy, 1998). These goals have co-benefits as well since low-maintenance trees would require less fossil fuel use from transport and power tools. Another co-benefit is that the top 7 trees by sequestration rate are also native to Knoxville. Native trees make up about 74% of the urban forest and provide habitat as well as many other provisioning services for local biodiversity. Non-native trees have the potential to become invasive, a risk that will only become more uncertain due to species' heterogeneous responses to climate change. In short, urban forests provide many ecosystem services that help maintain the biological infrastructure of cities and their inhabitants; the total quantity of services provided by Knoxville's urban forest is by no means estimated by this analysis.

### 6.2 Determining patches of thermal refuge for *Tamias striatus*

Identifying areas of thermal refuge is important for two reasons. First, climate warming is occurring at such an unprecedented rate that many species are predicted to experience thermal stress resulting in reduced biological fitness (Kingsolver, Diamond, & Buckley, 2013, p. 1416). Further, thermal stress is predicted to occur most frequently at mid-latitude sites (Kingsolver, Diamond, & Buckley, 2013, p. 1422). Acclimation, adaptation, range shifts, and behavioral plasticity will all help mitigate the adverse impacts of climate change; still, these responses are unlikely to completely offset the decreased fitness predicted for many organisms (Deutsch et al., 2008). Moreover, adaptive evolutionary responses like expanding one's thermal neutral zone are unlikely for slow-reproducing species like most endotherms. Although canopy cover will help mitigate thermal stress by providing temporary areas of relative cooling during peak summer temperatures, by 2075, gaps in canopy density become more influential (see Figure 13). Canopy cover will not be able to offset inevitable body heating for some native species unless canopy density is augmented.

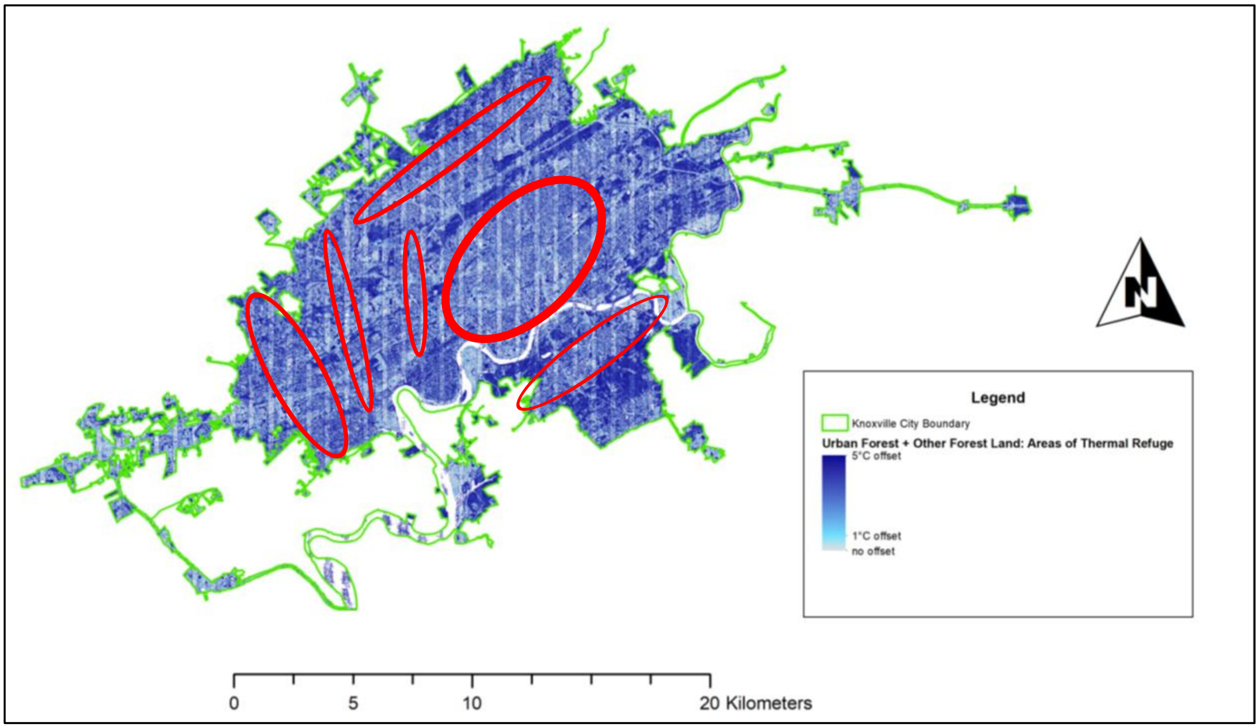


**Figure 13: Critical Gaps in the Urban Mosaic of Knoxville Become More Influential by 2075**
Raster cell size = 4 ft. by 4 ft. (1.2192 m. by 1.2192 m.)
**Source:** produced by author in ArcMap 10.6

Second, for populations opting to shift their range, areas of thermal refuge function as stopovers in the often-disjointed urban mosaic. Rapid range shifts have already been observed. Chen et al. estimates that the distributions of species have shifted to higher latitudes at a median rate of 16.9 kilometers per decade (2011, p. 1024). A higher percentage of suitable areas will help populations complete their journey more successfully and result in a greater conservation of biodiversity. Trees in the urban forest are expected to shift their range as well–by about 1.2° north in latitude on average by 2100 (Prasad, Iverson, Matthews, & Peters, 2007-ongoing). But unlike other ecosystems, the urban forest is an actively managed area, so canopy cover should remain relatively stable due to planting efforts by management, even if the abundance of certain tree species will likely decrease by 2100.

**7. FUTURE RESEARCH:**

In coming decades, future studies forecasting sequestration benefits of urban forests will face uncertainty in determining carbon sequestration rates since the rate is dependent on the number of trees in the urban forest, age of trees, photosynthetic rate, and the rate of tree plant and removal. Forecasts in this analysis only accounted for the latter, but future research should be funneled into estimating the impact of the other variables. Other studies should also examine whether patches of urban forest contribute co-benefits to sequestration. One co-benefit that needs to be examined is whether patches of urban forest contribute significantly as wildlife corridors. Are there significant differences in patches of urban forest compared to rural forest or publicly protected forest concerning wildlife preference? If so, measures need to be taken to ensure patches of urban forest remain intact especially if these patches border other types of forest land. 3-dimensional simulations in ArcScene may provide helpful information in this regard from a literal “bird’s-eye view” (or “chipmunk’s” or “beetle’s”, etc.) that is of critical importance to the field of urban ecology.

Regarding understory temperature reduction, only one understory species was examined, but this analysis can be extended to many more species. Other understory species of interest and their critical temperature limits can easily be retrieved from GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. The database contains experimentally derived species’ thermal tolerance data currently comprising over 2,000 species and is updated regularly (Bennet et al., 2018). In addition, sites with canopy cover have been shown to provide an insulating effect during the winter (Osman, 2013, p. 28), and differences between forest and grassland sites can be as great as 4°C (Mueller, 2004). Because of this effect, areas of suitable habitat can also be mapped for species threatened by ambient air temperatures approaching their LCT. In short, only one application of the canopy cover layer has been shown; equally, canopy cover is vital to achieving accurate biomass estimates, simulating forest management options, and estimating the energy savings for homeowners and municipalities. The possibilities abound.

**8. CONCLUSION:**

In the future, Knoxville will be impacted by climate warming due to anthropogenic climate change. Direct consequences of climate change can be observed by examining the impact of increasing temperatures on the thermal tolerance of species like the eastern chipmunk. Whether eastern chipmunk populations opt to shift their range by 2075 may depend on fossil fuel emissions as roughly twice as many hectares of suitable habitat are predicted under a low emissions scenario. In addition to understory temperature reduction, cities need to recognize the positive externality provided by urban forests through the removal of carbon dioxide from the atmosphere. Because of these benefits and many more aforementioned, cities should not only seek to protect urban forests, but also strategize best management practices to maximize co-benefits of their ecosystem services. Knoxville can expand its canopy density and reduce net greenhouse gas emissions through the planting of native, fast-growing and thermally-tolerant trees in the most vulnerable parts of the urban mosaic, critical gaps. The resilience of the city, its biodiversity, and future generations depend on these efforts.

## REFERENCES


Akbari, H., Kurn, D. M., Bretz, S. E., & Hanford, J. W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings*, 25(2), 139–148. https://doi.org/10.1016/S0378-7788(96)01003-1

Bennett, J. M., Calosi, P., Clusella-Trullas, S., Martínez, B., Sunday, J., Algar, A. C., … Morales-Castilla, I. (2018). GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. *Scientific Data*, *5*, 180022. Retrieved from http://dx.doi.org/10.1038/sdata.2018.22

Chen, I.-C., Hill, J. K., Ohlemuller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science*, *333*(6045), 1024–1026. https://doi.org/10.1126/science.1206432

Chervenak, J. E. (2008, December 5). Eastern chipmunk (*Tamias striatus*) *Mammals of Mississippi*. Mississippi State: College of Forest Resources, Division of Agriculture, Forestry, and Veterinary Medicine, Mississippi State University. Retrieved from http://www.cfr.msstate.edu/wildlife/mammals/?a=detail&id=16

City of Knoxville - Office of Sustainability. (2017). *City of Knoxville Energy & Sustainability Initiative: 2017 Work Plan and Energy & Emissions Inventory Update*. Retrieved from http://www.knoxvilletn.gov/government/city_departments_offices/sustainability

City of Knoxville - Urban Forestry Division. (2018). *Knoxville Trees, May 17, 2018.* Dataset. Distributed by the City of Knoxville.

Crites, G. (2017, April 18). Personal Interview.

Esri. (2018). Estimating forest canopy density and height: ArcMap 10.6. Retrieved from http://desktop.arcgis.com/en/arcmap/latest/manage-data/las-dataset/lidar-solutions-estimating-forest-density-and-height.htm

Gleason, C. A., & Juul, S. E. (Eds.). (2018). *Avery's diseases of the newborn* (Tenth edition). Philadelphia, PA: Elsevier.

Hass, A., Ellis, K., Reyes Mason, L., Hathaway, J., & Howe, D. (2016). Heat and Humidity in the City: Neighborhood Heat Index Variability in a Mid-Sized City in the Southeastern United States. *International Journal of Environmental Research and Public Health* 13(1), 117. Retrieved from https://doi.org/10.3390/ijerph13010117

Huotari, J. (2017, June 8). Climate data: Knox County could have 20-80 more days above 95 by 2100. *Oak Ridge Today*. Retrieved from https://oakridgetoday.com/2017/06/08/climate-data-knox-county-could-have-20-80-more-days-above-95-by-2100

IPCC. (2018, May 14). SCENARIO PROCESS FOR AR5: REPRESENTATIVE CONCENTRATION PATHWAYS (RCPs). Retrieved from http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html

Jones, R. E. (2006). *Understanding Public Opinion and Support for the Maintenance and Protection of Trees in Knox County, Tennessee: A Mail Survey of Area Homeowners. University of Tennessee*. Retrieved from https://pdfs.semanticscholar.org/f940/f9ed2056b-90190d1ae4512796ecd27cb0508.pdf

Jones, R. E., Davis, K. L., & Bradford, J. (2013). The Value of Trees: Factors Influencing Homeowner Support for Protecting Local Urban Trees. *Environment and Behavior* 45(5), 650–676. Retrieved from https://doi.org/10.1177/0013916512439409

Kingsolver, J. G., Diamond, S. E., & Buckley, L. B. (2013). Heat stress and the fitness consequences of climate change for terrestrial ectotherms. *Functional Ecology*, *27*(6), 1415–1423. https://doi.org/10.1111/1365-2435.12145

Kirby, K. R., & Potvin, C. (2007). Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. *Forest Ecology and Management*, *246*(2), 208–221. https://doi.org/10.1016/j.foreco.2007.03.072

Krouse, K. (2017). *2016 City of Knoxville Urban Forestry Program Progress Report*. Retrieved from http://knoxvilletn.gov/UserFiles/Servers/Server_109478/File/PublicService/Trees/state_of_urban_forest2016.pdf

Kurn, D. M., Bretz, S. E., Huang, B., & Akbari, H. (1994). *The potential for reducing urban air temperatures and energy consumption through vegetative cooling* (No. LBL--35320, 10180633). https://doi.org/10.2172/10180633

Lawrence Chia-Huang Wang, & Hudson, J. W. (1971). Temperature regulation in normothermic and hibernating eastern chipmunk, Tamias striatus. *Comparative Biochemistry and Physiology Part A: Physiology, 38(1),* 59–90. https://doi.org/10.1016/0300-9629(71)90098-3

Mueller, R.F. (2004, March). Soil Temperature and Forest Type, III. *Forests of the Central Appalachians Project*. Online. Accessed December 11, 2018. Retrieved from http://www.asecular.com/forests/soiltemperatures/

NOAA National Centers for Environmental Information. (2017). *State of the Climate: National Climate Report for Annual 2016*. Retrieved from https://www.ncdc.noaa.gov/sotc/national/201613

NOAA National Centers for Environmental Information. (2018, September 12). *State of the Climate: National Climate Report for August 2018*. Retrieved from https://www.ncdc.noaa.gov/sotc/national/201808.

NOAA National Centers for Environmental Information. (2018). *State of the Climate: National Climate Report for Annual 2017*. Retrieved from https://www.ncdc.noaa.gov/sotc/national/201713

Northern Institute of Applied Carbon Science. (2007). Carbon sequestration. Retrieved from https://www.nrs.fs.fed.us/niacs/local-resources/docs/CarbonSequestration.pdf

Osman, K. T. (2013). *Forest Soils*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-02541-4

Prasad, A. M., Iverson, L. R., Matthews, S., & Peters, M. (2007-ongoing). *A Climate Change Atlas for 134 Forest Tree Species of the Eastern United States*. Database. Distributed by Northern Research Station, USDA Forest Service, Delaware, Ohio. Retrieved from https://www.nrs.fs.fed.us/atlas/tree

Roman, L. A. (2014, Spring). How Many Trees Are Enough? Tree Death and the Urban Canopy. *Scenario Journal, 4*(1). Retrieved from https://scenariojournal.com/article/how-many-trees-are-enough/

Simpson, T. (2014). City of Knoxville, *TN Tree Canopy Report*. Nashville: Tennessee Department of Agriculture-Forestry Division.

STS-GIS Services, Tennessee Department of Finance & Administration. (2016). Elevation | LiDAR. Retrieved from https://www.tn.gov/content/tn/finance/sts-gis/gis/gis-projects/gis-projects-elevation.html

U.S. Department of Energy, Energy Information Administration. (1998, April). *Method for Calculating Carbon Sequestration by Trees in Urban and Suburban Settings*.

U.S. Federal Government. (2018). *U.S. Climate Resilience Toolkit Climate Explorer*. Online. Accessed December 10, 2018. Retrieved from https://climate-explorer2.nemac.org

U.S. Forest Service Southern Research Station. (2008, September). *Conservation Buffers: Design Guidelines for Buffers, Corridors, and Greenways.* Retrieved from https://www.fs.usda.gov/nac/buffers/guidelines/2_biodiversity/7.html