

The Legacy of Hurricanes, Historic Land Cover, and Municipal Ordinances on Urban Tree Canopy in Florida (United States)

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Abstract

Urban Tree Canopy (UTC) greatly enhances the livability of cities by reducing urban heat buildup, mitigating stormwater runoff, and filtering airborne particulates, among other ecological services. These benefits, combined with the relative ease of measuring tree cover from aerial imagery, have led many cities to adopt management strategies based on UTC goals. In this study, we conducted canopy analyses for the 300 largest cities in Florida to assess the impacts of development practices, urban forest ordinances, and hurricanes on tree cover. Within the cities sampled, UTC canopy ranged from 5.9% to 68.7% with a median canopy coverage of 32.3%. Our results indicate that the peak gust speeds recorded during past hurricanes events were a significant predictor of canopy coverage (P -value = <0.001) across the sampled cities. As peak gust speeds increased from 152 km/h (i.e., a lower-intensity Category 1 storm) to 225 km/h (lower-intensity Category 4 and the maximum gusts captured in our data), predicted canopy in developed urban areas decreased by 7.7%. Beyond the impacts of hurricanes and tropical storms, we found that historic landcover and two out of eight urban forest ordinances were significant predictors of existing canopy coverage (P -landcover <0.001 ; P -tree preservation ordinance = 0.02, P -heritage tree ordinance = 0.03). Results indicate that local policies and tree protections can protect or enhance urban tree canopy, even in the face of rapid development and periodic natural disturbances.

1 Introduction

Urban forests have the potential to provide nature-based solutions for cities to address environmental, health, and social issues (Escobedo et al., 2019; Turner-Skoff and Cavender, 2019). These benefits or ecosystem services include, but are by no means limited to, reducing building energy usage (Ko, 2018), improving human health (Jennings and Johnson Gaither, 2015; Kuo, 2015), providing food (Kowalski and Conway, 2019), and fostering a sense of place (Blicharska and Mikusiński, 2014). Granted, the urban forest can also be a source of disservices such as increasing airborne allergens and damaging property, in addition to being costly to maintain (Fineschi and Loreto, 2020; Roman et al., 2021b). The ability and extent to which the urban forest provides these services and disservices is a function of many interacting biophysical and human legacies and factors (Fig 1., Roman et al., 2018). Extreme weather events such as tropical hurricanes or cyclones can be a source of major disturbances in tropical and coastal cities that have dramatic impacts on the urban forest (Burley et al., 2008). Urban tropical cyclone impacts have been studied at the tree (Klein et al. 2020; Koeser et al. 2020) and plot level (Burley et al., 2008; Thompson et al., 2011; Wiersma et al., 2012; Landry et al., 2021). However, research is needed at larger, city-wide scales to understand the potential interactions between tropical storms (e.g., cyclones, hurricanes, typhoons) and social-cultural factors that have helped shape the urban forest's structure and composition. Investigating these interactions can help better predict and manage the urban forest's vulnerabilities and ensure the continuity of its services (Steenberg et al., 2017).

The extent, structure, and composition of the urban forest can be assessed through bottom-up approaches such as on-the-ground tree inventories or through top-down approaches such as evaluating canopy cover from aerial photography or LiDAR (Leff, 2016). Maps of urban tree canopy (UTC) that are hi-resolution (less than 1 m) and high accuracy ($\geq 95\%$) can provide cost-effective, valuable information about changes in UTC over time and the potential impacts of socioeconomic drivers for very large areas (Locke et al., 2017). UTC data can be used by communities to guide goal setting, planting programs, policies, and management in order to increase the benefits provided by the urban forest (Kimball et al., 2014). For example, Endreny, et al. (2017) used UTC to estimate the ecosystem services of the urban forests in ten megacities across the world. UTC is also often used by governments and other organizations to set goals that drive large scale tree planting initiatives (Young, 2011; Nguyen et al., 2017). Remote sensing data is also a valuable tool for evaluating forest damage caused by tropical cyclones over very large areas (Wang et al., 2010). Granted, aerial UTC assessment approaches are currently limited in their ability to assess age structure and species composition (Leff, 2016) and may not necessarily reflect the quality of trees (Kenney et al., 2011). Nevertheless, this approach can provide extensive spatial and temporal data about the urban forest for researchers and managers.

Biophysical factors create the bioregional context that sets the stage for the urban forest's composition, extent, and ability to regenerate. They are also a source of disturbances which have both immediate and lasting effects on the urban forest. When comparing between cities in the conterminous United States, climate factors such as mean winter minimum temperature (Jenerette et al., 2016) and potential evapotranspiration (Ossola and Hopton, 2018) can influence tree cover, composition, and structure. Patterns of pre-settlement vegetation (e.g., grasslands versus forest cover) can influence the extent of the urban forest as well as patterns of regeneration (McBride and Jacobs, 1986; Fahey et al., 2012; Fahey and Casali, 2017). Insect and disease epidemics can drastically change UTC within one to two decades, with three to four decades needed to recover from tree loss (Hauer et al., 2020a). The physical landscape of a city, its terrain and features such as proximity to waterways, can influence patterns of UTC, often in combination with other socio-economic and land

use factors (Davies et al., 2008; Lowry et al., 2012; Berland et al., 2015; Fahey and Casali, 2017). In one example of large-scale disturbance, tropical cyclones can have dramatic impacts on the urban forest, though these impacts can vary with other socio-demographic characteristics (Lewis et al., 2017; Van der Sommen et al., 2018; Landry et al., 2021). In the urban environment, biophysical factors are a key driver of UTC, though they clearly cannot be separated from anthropogenic legacies.

In North America, many different social, cultural, and economic variables have been shown to influence the extent of UTC and its changes over time. UTC can reflect population characteristics of a neighborhood, including race, income, and education (Locke et al., 2017; Pham et al., 2017; Gerrish and Watkins, 2018; Watkins and Gerrish, 2018) as well as formal and informal racial segregation (Grove et al., 2018; Locke et al., 2021). The particular effects of social characteristics can interact with other urban features such as housing density or the size of streets and sidewalks (Pham et al., 2017). As mentioned above, in some cases other features of the urban environment such as terrain may exert a stronger place-specific influence on tree cover that obscures socio-demographic patterns (Berland et al., 2015). Large scale economic changes that can lead to the depopulation of cities and the subsequent changes in patterns of vacant land also have the potential to alter vegetation and tree cover, though these plants may be perceived as more nuisance than amenity (Berland et al., 2020). Local policies such as planning and zoning regulations can also influence canopy cover, though the magnitude of these effects depends on the quality and type of regulation (Hilbert et al., 2019; Hauer et al., 2020b). While tree care professionals are recognized as important mediators between the environmental and social factors that influence UTC (Roman et al., 2018), the type of certification and education of these professionals alone may not be a useful predictor of canopy (Hilbert et al., 2019). While many UTC studies have focused on drivers of variability within cities (but see Bigsby et al., 2014; Hilbert et al., 2019; Locke et al., 2021), research is needed to evaluate both anthropogenic and biophysical legacies together in order to understand drivers of UTC across cities, particularly in regions prone to tropical cyclones.

The state of Florida, United States, provides a useful setting for studying the interacting effects of biological and socio-cultural legacies on urban tree cover in the context of extreme weather disturbances such as tropical cyclones (referred to as hurricanes in the eastern US). As of 2010, Florida had some of the largest amounts of urban land in the US and an average of 41.8% UTC (Nowak and Greenfield, 2018). Since 2010, Florida's population has increased 14% to a total of 21.5 million people in 2019 (United States Census Bureau, 2019) and its population is projected to reach approximately 33.8 million residents by 2070 (Carr and Zwick, 2016). If current development trends continue, this population growth would likely lead to increasing urban or developed land cover from 16% in 2015 to 34% of the entire state in 2070 (Carr and Zwick, 2016). Florida also periodically experiences hurricanes and tropical storms. Since 2000, the state has been impacted by 12 hurricanes (Hurricane Research Division, 2020). The state will also likely be subject to more frequent and more intense hurricanes according to high emission climate change models (Balaguru et al., 2016). Understanding large scale drivers of UTC in Florida can provide insight into managing urban forests in the face of extreme weather and continued urban expansion.

Florida is also a valuable case study because many of its municipalities have adopted various types of tree protection ordinances (e.g., Heritage Tree Ordinances, Tree Removal Permit Ordinances, etc.; Koeser et al. 2021) to preserve canopy in the face of development. Yet implementation of these ordinances is limited by a state law passed in 2019 (F.S. 163.045 Tree pruning, trimming, or removal on residential property, 2019). This statute prohibits municipalities from applying such ordinances to residential property owners who demonstrate that a tree poses a hazard to life or property based on

the assessment of a professional arborist or landscape architect. In this context, it is clearly important to understand the relationship between municipal tree protection ordinances and UTC.

The main objective of this study was to determine what biophysical and anthropogenic factors are associated with UTC in Florida municipalities. As trees are long-lived organisms, this investigation includes historical influences such as pre-settlement land cover, past hurricanes, and development history, as well as the current state of urban forest protections (through local ordinances). Our intent is to provide managers and decision makers with the data and insights needed to make informed management and policy decisions when working towards their urban forest canopy goals.

2 Methods

2.1 Study Area

This study investigated canopy coverage for the 300 largest cities (by population) in Florida (United States). Florida is a peninsular state that is surrounded by the Gulf of Mexico to the west, the Caribbean Sea to the south, and the Atlantic Ocean to the east. The state is predominantly classified as having a humid subtropical climate (Cfa), with the southernmost tip of the state and its keys (islands) being classified as being tropical monsoon, tropical rainforest, or tropical savanna (Am, Af, and Aw; respectively) climates (Beck et al., 2018). Florida has an annual hurricane season that begins June 1 and extends until November 30 (Florida Climate Center, 2021).

2.2 Urban Tree Canopy Evaluation

In conducting our canopy analysis, we used aerial imagery from the National Agricultural Imagery Program (NAIP; U.S. Department of Agriculture, 2019) - selecting leaf on imagery from 2019 to capture canopy conditions just prior to the passage of a Florida Statute which preempts local oversight of trees found on residential property (Florida Senate, 2019). The spatial resolution of the imagery was 1 m.

A random point sampling method, also known as the “dot method” (Nowak et al., 1996), was conducted to determine canopy coverage for each municipality. Boundary shapefiles for each municipality in the study were obtained from the American Community Survey (ACS; United States Census Bureau, 2015). A geographic information system (ArcGIS v. 10.2.2; ESRI, Redlands, CA, United States) was used to import NAIP aerial imagery and generate random points to evaluate UTC within each city. Each point was interpreted as “no tree,” “tree/shrub,” or “open water” by at least two interpreters per city. A minimum of 2000, non-“open water” (e.g., lakes, rivers, retention areas) sampling points were used to determine UTC for each city. To accomplish this objective, 2500 random points were placed within the city boundaries and were interpreted one by one until the total number of points labeled “no tree” and “tree/shrub” totaled 2000. Canopy percentage and agreement between interpreters were noted for each municipality.

2.3 Biophysical and Anthropogenic Factors

We derived historic land cover classifications from the natural vegetation map created by Davis (1967). Specifically, we accessed a digitized version of the map through the Florida Geographic Data Library (Table 1) and aggregated land cover types using the categories specified by Volk et al. (2017). While generally limited to description of historic vegetation cover, Davis’s map did delineate the footprint of 11 cities (i.e., Daytona Beach, Jacksonville, Lakeland, Orlando, Miami, Pensacola, St. Augustine, St. Petersburg, Tampa, Vero Beach, and West Palm Beach). For these

municipalities (categorized as “urban” in the 1967 map), we used the surrounding land cover for our model predictor.

We accessed hurricane wind field data from the “disasters” repository housed at GeoPlatform.gov. Specifically, we looked at recent hurricanes that made landfall in Florida and were severe enough to become a Federal Emergency Management Agency declared disaster and had wind field data available. Storms included in our analysis were:

- Hurricane Dorian (Geoplatform.gov, 2019)
- Hurricane Michael (Geoplatform.gov, 2018)
- Hurricane Irma (Geoplatform.gov, 2017)

To determine the extent to which cities were impacted by past hurricanes, we overlaid our city boundary layers with the wind field layers noted above. For cities with only one weather station, the maximum recorded wind gust speed for that station was used. For larger cities with more than one station within their boundaries, the average of the recorded peak gusts was calculated prior to analysis. For smaller cities where a weather station was not present, the maximum gust values from the nearest station were used. If a city was hit by more than one hurricane event, we used the peak gust values from the more intense storm in our predictive model (Table 1).

Additionally, we sourced population, median income, population density, and percent of houses built 10, 20, and 30 years ago from the US Census Bureau (Table 1). Housing density was calculated manually based on the area of our city boundaries and the 2018 population Census projections Bureau (U.S. Census Bureau, 2018a).

Finally, as noted in detail in Koeser et al. (2021), we used a multi-mode email survey to communities and a systematic search of online resources to determine which municipal tree protection ordinances were in place within the 300 assessed communities prior to our canopy analysis. The online resources referenced included two municipal code databases (<https://www.municode.com/> and <https://www.amlegal.com/>) as well as individual municipal websites. The ordinances of interest with regard to their potential impact on canopy coverage are listed in Table 1. We coded each as being present or absent (i.e., yes or no binary) prior to our data analysis.

Data Analysis

We analyzed our data using linear regression with percent canopy coverage as the response variable (Table 1). All analyses were conducted in R (R Core team, 2020). To guide model building, we ran the `regsubsets()` function from the `leaps` package (Lumley & Miller, 2017) and plotted (by R^2 value) the 20 best subsets of our full set of predictor variables (Table 1; see Hilbert et al. 2019). We then ran a maximal model with all predictor variables using the `lm()` function (R Core Team, 2020). From this, we employed a one-at-a-time simplification strategy – removing non-significant predictors from our initial model based on p-value and the `regsubsets()` plot. With each iteration of simplification, we compared changes in overall fit between the original and simplified models using the `anova()` function in R (Crawley, 2014). Once all of the non-significant terms had been removed in this manner, we retested a few variables that had commonly been associated with high R^2 models in our subset plot, as well as potentially meaningful two-way interactions, to see if improvements to model fit could be detected.

In model building we adopted a P-value of 0.05 as our threshold for statistical significance. The underlying assumptions of our linear model were assessed visually using Q-Q plots (i.e., normality of

residuals) and residual scatter plots (i.e., homogeneity) to assure that they were not being violated. Additionally, residual plots were used to assess the presence or absence of high-leverage outliers (based on Cook's distance). Finding none, we adopted the resulting simplified model for our results and discussion.

3 Results

3.1 City Characteristics

The cities included in this study sample ranged from Florida's largest municipality, Jacksonville (population 903,889) to Sneads, a small community of 1798 (Table 2; Supplementary Data Table 1). The median population for our sampled cities was 12,678 (Table 2). The cities in our study (combined population of 10,629,924) were home to approximately 50% of the state's 2018 population. Cities ranged in area from 2,265.3 km² (Jacksonville) to 0.8 km² (Virginia Gardens).

Population densities ranged from 8 people per kilometer for Bunnell (a small community with a wildlife refuge within its boundary) to 8618 people per kilometer for North Bay Village (a chain of highly developed and largely man-made islands in the Miami-Dade metropolitan area; Table 2). The median population density for our sampled cities was 814 people per kilometer (Table 2). Median household incomes ranged from \$17,908 in the city of Opa-locka to \$154,415 for the village of Pinecrest (Table 2). Both municipalities are located in the Miami-Dade metropolitan area within 39 km of each other.

The majority (72%) of our cities were built on land that had formerly been wooded (Fig. 2). Of these cities, 31% were developed in areas of scrub and sandhill. Another 29% of communities were built in areas that had historically sustained mesic pinelands. A smaller proportion of communities were developed in former upland hardwood forests (5%) or forested wetlands (7%; Fig. 2). Of the cities established in non-forested regions, 21% were former uplands and 7% were former wetlands (Fig. 2).

Six of the eight tree ordinances evaluated as part of this study were adopted by more than half of the study cities (Table 3). The most commonly adopted tree ordinances in the surveyed cities included *Planting requirements - new development* (89.3%) and *Planting requirements - parking lots* (89.3%) followed by *Tree preservation ordinance* (86.7%) and *Ability to fine* (84.0%; Table 3). *Local licensure* was the least commonly adopted ordinance (17.7%; Table 3).

Across the 300 cities sampled in Florida, UTC ranged from 5.9% in Redington Shores to 68.7% in Sanibel, respectively. The median UTC for our sample was 32.3% (Fig. 3, Table 2). Summary statistics for developed UTC (i.e., UTC for the inhabited census blocks in a municipality), which is what we used in our modeling efforts as it excludes forest preserves and wildlife areas that might inflate city-wide canopy levels, were nearly identical to those for straight UTC (Fig. 3, Table 2).

3.2 Predictors of Urban Tree Canopy

Of the 16 variables initially modeled, we retained five for our final, simplified model (adjusted R²=0.230). They included historic land cover (aggregated more simply as forested versus non-forested after initial exploratory modelling showed this was the main delineation), maximum hurricane gust speed, population density, the presence of a tree preservation ordinance, and the presence of a heritage tree ordinance (Table 4). Of these, increases in population density and increases in hurricane gust wind speeds were associated with decreases in developed UTC (Fig. 4, Table 4). Similarly, non-forested historic land cover and the presence of a tree preservation ordinance

were negatively associated with developed UTC (Table 4). Only the presence of a heritage tree ordinance (70% of cities) was positively associated with developed UTC. Median income, housing age, home ownership, and the other six ordinances were not included in the final model.

4 Discussion

4.1 Legacy Effects of Environment and Anthropogenic Factors on Urban Tree Canopy

Our analysis of 300 cities in Florida demonstrated that both natural and anthropogenic legacies can influence UTC at the city scale. Overall, this finding is in line with observations within other U.S. cities such as Toledo, OH (Berland et al., 2015), Philadelphia, PA (Roman et al., 2021a), Chicago, IL (Fahey et al., 2012), and Baltimore, MD (Grove et al., 2018), among others (Roman et al., 2018). This analysis of Florida's largest cities is an important addition to this body of research because our study included an examination of hurricanes. Considering that climate change is predicted to increase the intensity and intensification of hurricanes and other tropical cyclones (Bhatia et al., 2018), it is imperative to understand how these extreme weather events can influence UTC in regions vulnerable to this type of extreme weather.

Our analysis demonstrated the impact of hurricanes across Florida on the urban forest, though hurricane impacts can be lessened or exacerbated by other factors. Other research in Florida has observed that wind resistance varies among tree species and is also affected by pruning practices (Duryea et al., 2007a, 2007b). Additionally, in Florida larger trees were more likely to fail during a hurricane while neighbouring trees and structures appear to offer little protection from high winds (Landry et al., 2021). Escobedo et al (2009) observed interacting effects between wind speed, tree cover, and urban land cover on debris generation in Florida following the 2004 and 2005 hurricane seasons. Hurricane related tree losses also varied by land use type following Hurricane Ike in Texas, US (Staudhammer et al., 2011). However, Thompson et al. (2011) found that urban forest structure was a better predictor of hurricane woody debris generation rather than hurricane related variables such as wind speed. Further research is needed to understand the extent to which hurricane associated tree loss is a direct result of hurricane damage versus tree removals driven by property owner responses to extreme weather. Clearly, hurricane severity can have a significant impact on the urban forest, though understanding the influence of other factors such as pruning and species selection can help to moderate these impacts.

The influence of historic vegetation cover on current UTC reflects both the influence of biogeographical constraints on tree growth and the contributions of remnant forest patches. Florida has fairly high average rainfall across the state ranging from 102 to 178 cm annually (Florida Climate Center, 2021) and a distinct dry season (Misra and Mishra, 2016). This dry season and abundant sandy soils with low water holding capacity (Kern, 1995) may constrain tree establishment. Indeed, irrigation can improve tree establishment and condition for tree plantings in the state (Koeser et al., 2014; Blair et al., 2019). In environments with low average annual rainfall, UTC can increase in historical non-forest habitats during urbanization as management activities overcome water limitations (McBride and Jacobs, 1986; Nowak, 2012). Though considering the negative association between non-forest historical cover and current UTC, this effect observed in drier environments does not occur in Florida. The positive association between historical forest habitats and higher UTC suggests remnant forest habitats likely play a key role in contributing to cover as observed in Chicago, Illinois, United States (Fahey et al., 2012). This finding suggests that protecting remnant forests from encroaching development or densification would be an important strategy for maintaining urban tree cover.

The negative relationship between population density and UTC (Fig. 4) in Florida at the coarse spatial resolution used in this study was fairly unsurprising and consistent with other research (Bigsby et al., 2014; Locke et al., 2016; Fahey and Casali, 2017). Presumably as a city's human population grows the extent of infrastructure such as buildings and roads increase, consequently reducing tree canopy. Similarly, increases in impervious cover (Davies et al., 2008) and housing density (Iverson and Cook, 2000; Hilbert et al., 2019) are also associated with decreased urban tree cover. When examining anthropogenic drivers of urban tree cover within cities, socio-demographic factors such as race, income, public policies, and local history may be more useful predictors at finer resolutions (Gerrish and Watkins, 2018; Roman et al., 2018; Watkins and Gerrish, 2018; Locke et al., 2021). Though, Nesbitt et al. (2019) observed education level and income were important predictors of tree cover across cities. For regions with expected population increases such as Florida (Carr and Zwick, 2016), special attention should be paid to protecting tree cover as urban populations and development increase.

While municipal ordinances are one method for protecting the urban tree canopy, the contrasting relationships between different types of ordinances and UTC in this study likely suggests that simply having an ordinance is not sufficient for maintaining or increasing canopy cover. Hilbert et al. (2019) observed that across 43 Florida cities, heritage tree ordinances were also associated with greater urban tree cover. This type of ordinance may be particularly effective because they are designed to protect larger trees which contribute to more cover. Or alternatively, communities which already have substantial urban tree cover may adopt such an ordinance to protect what they already have. Landry and Pu (2010) observed properties in Tampa, FL built after the adoption of a tree protection ordinance had higher UTC compared to properties in nearby communities without such an ordinance. By contrast, our analysis of 300 cities in Florida observed a negative association between the adoption of a tree protection ordinance and urban tree cover. It is unclear the amount of time needed to elapse between the adoption of any tree related ordinance and the observation of meaningful improvements in UTC. If a community already has a comparatively lower amount of tree cover to begin with, a tree protection ordinance at best would maintain that level of cover rather than producing dramatic increases. And importantly, an ordinance can only be effective if it is enforced.

Support for and knowledge of municipal tree ordinances can be highly variable. In a survey of Canadian communities, Conway and Bang (2014) observed that while residents had generally neutral to favourable attitudes about the urban forest, they expressed less support for particular policies. Knowledge of and support for municipal tree bylaws in the Greater Toronto Area tended to be higher among residents with higher levels of formal education and residents who were born in Canada (Conway and Lue, 2018). Zhang et al. (2007) also observed differences in attitudes towards financing urban tree programs along socio-demographic lines, where individuals with young families and individuals younger than 56 were more likely to feel that financing urban forestry initiatives is the government's responsibility. In their survey of Florida municipalities after the passage of a bill that limits municipal implementation of tree protection ordinances, Koeser et al (2021) observed that some municipalities have positive relationships with the public and tree care companies and enjoy support for their programs while other municipalities have more counter-productive relationships with the local tree care industry. The adoption and enforcement of municipal tree ordinances not only directly impacts urban tree cover, but they can also be another mechanism by which a city's socio-demographic characteristics and culture can influence the urban forest.

4.2 Study Limitations

Photointerpretation as a method to evaluate urban tree canopy has its limitations (O'Neil-Dunne et al., 2014; Locke et al., 2017), though it is a proven and affordable approach to land classification

used in the urban forestry field (Nowak et al., 1996; Walton et al., 2008; Morgan et al., 2010). To improve accuracy, each city was assessed by two photo interpreters. Of the 300 cities in the study, 82% had interpreter agreement greater than 90% with agreement for the remaining cities ranging between 80 and 90% (Supplementary/Appendix Table). UTC is only one metric of the condition of the urban forest, consequently this study's findings cannot offer insight into drivers of other characteristics such as diversity and age structure (Leff, 2016). Though our findings offer interesting avenues to investigate drivers which may affect these other characteristics of the urban forest that are more time and labour intensive to measure.

4.3 Conclusion

We tested the effects of 16 biophysical and anthropogenic factors on UTC across 300 cities in Florida, US. Florida provided a valuable test case for this study because it has been affected by many tropical cyclones which can be an important cause of disturbance in coastal urban forests (Burley et al., 2008). Our analysis found both biophysical (historic land cover and hurricane maximum wind gust) and anthropogenic (population density, heritage tree ordinances, and tree protection ordinances) factors explained the most variation in UTC across cities in Florida. Interestingly, while heritage tree ordinances were associated with greater canopy cover, tree protection ordinances were associated with lower canopy cover. The negative correlation between hurricane maximum gust and canopy demonstrates how tropical cyclones can have lasting impacts on the urban forest. This finding has important implications in the context of climate change and potentially increasing tropical cyclone intensity (Balaguru et al., 2016) and emphasizes the importance of considering tropical cyclone impacts in urban forestry planning and management in coastal regions.

5 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6 Author Contributions

AK, RH, DH, AA, MA, KB, SL, ML, and LR – Conceptualization. AK, RH, DH, AA, SL, and LR – Methodology. AK, DH, and HT – Validation. AK – Formal analysis. AK, DH, and HT – Data Curation. AS, AK – Writing - Original Draft. AK, RH, DH, AA, MA, KB, SL, ML, LR, and HT – Writing - Review & Editing. AK – Visualization. AK and DH – Supervision. AK – Project administration. AK, AA, MA, KB, SL, and ML – Funding.

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10 Data Availability Statement

The dataset generated for this study is available upon request (to the corresponding author).

Figure 1. Biophysical and anthropogenic factors that influence urban tree canopy (UTC).

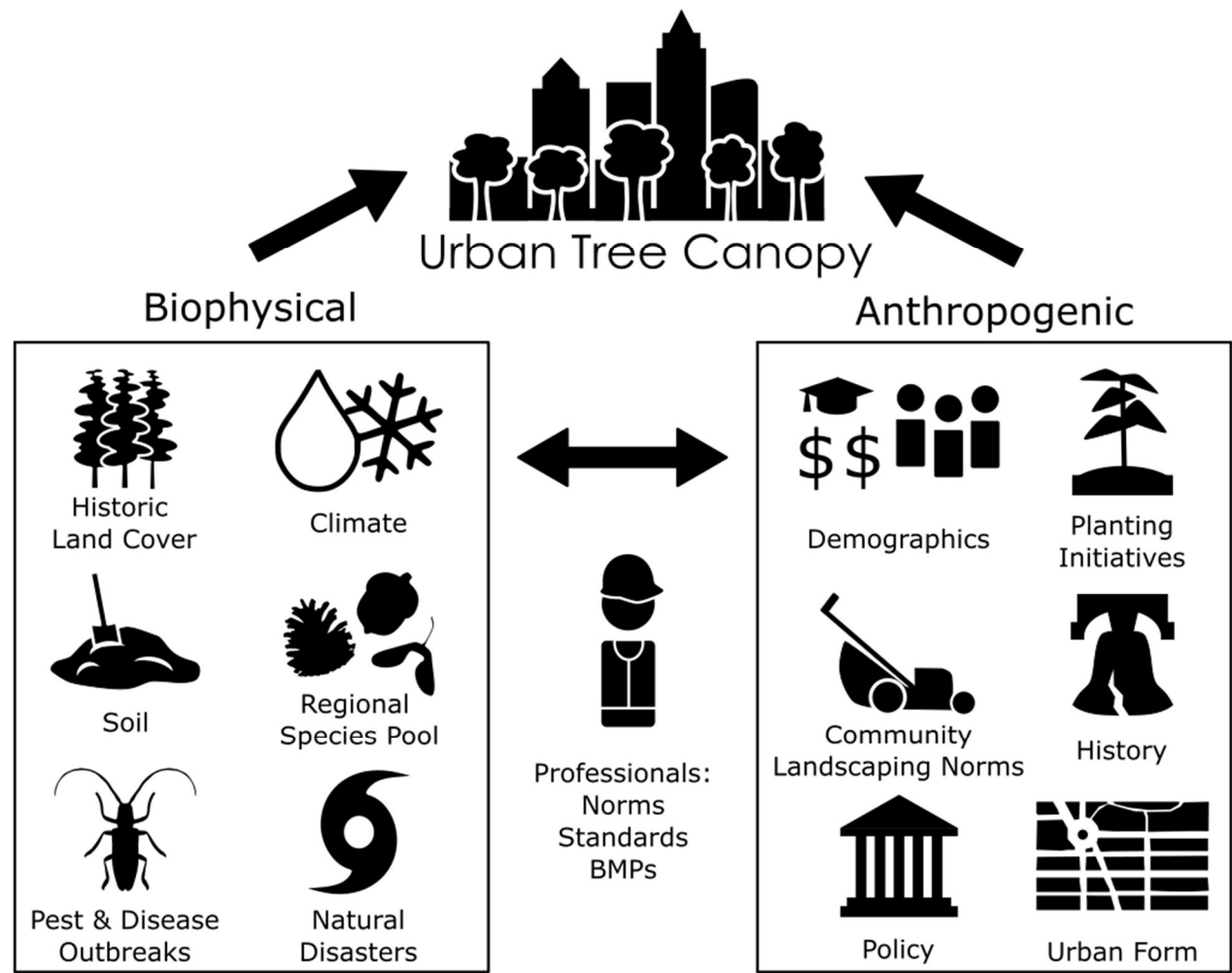


Figure 2. Historic land cover for the municipalities investigated in this study. Historic land cover was used to model percent urban tree canopy for Florida’s 300 largest municipalities.

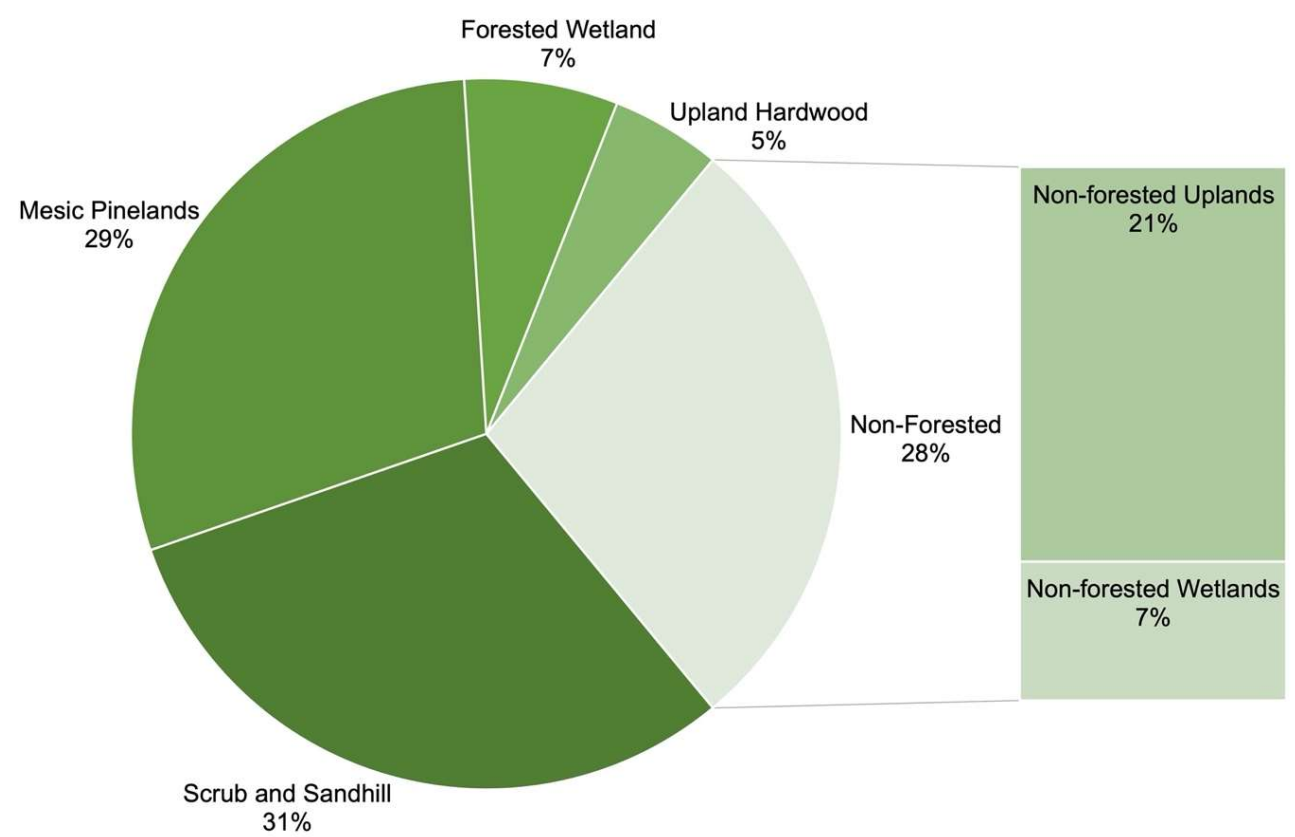


Figure 3. Distribution of municipal percent urban tree canopy (UTC). The vertical solid black line represents the median UTC value. The two dashed lines represent the 25th percentile (left) and 75th percentile (right).

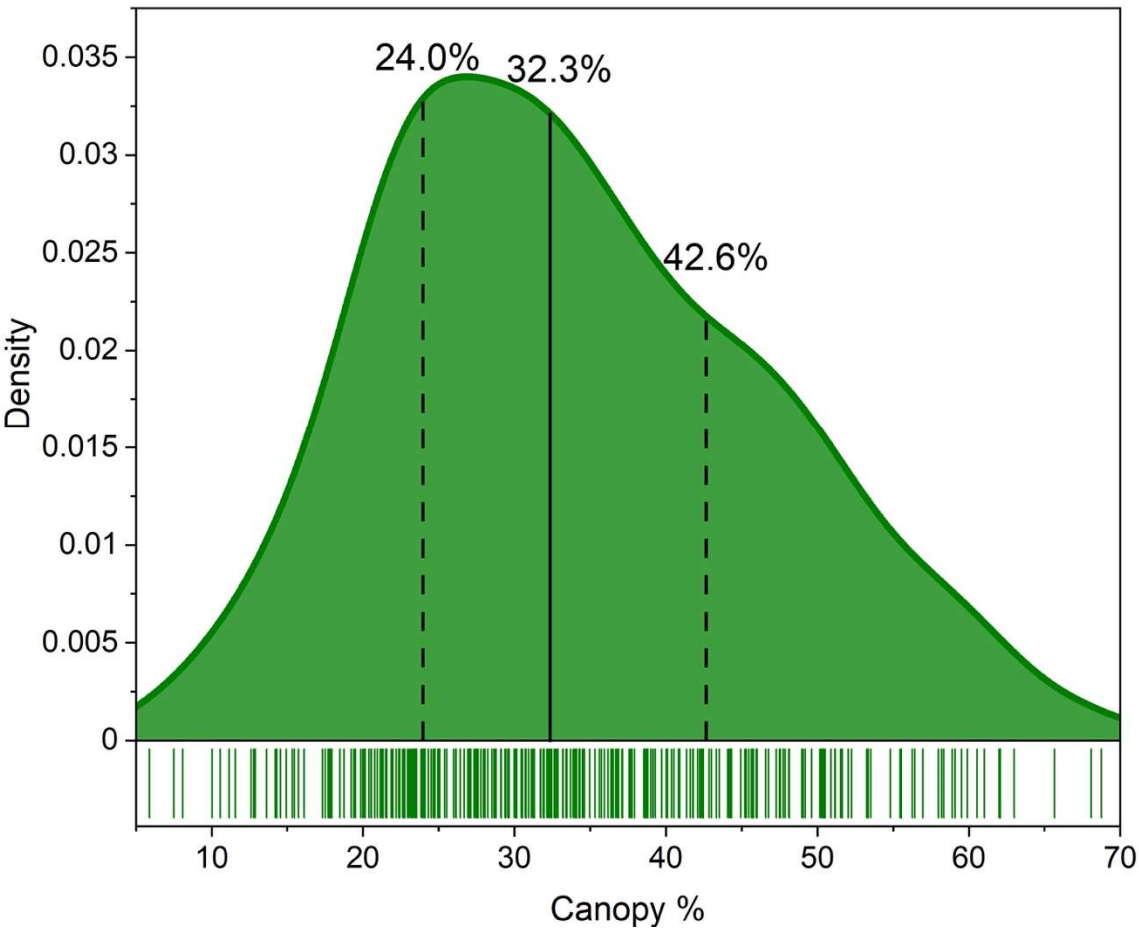


Figure 4. Comparison of urban tree cover and population density among the 300 Florida, United States, municipalities included in this study.

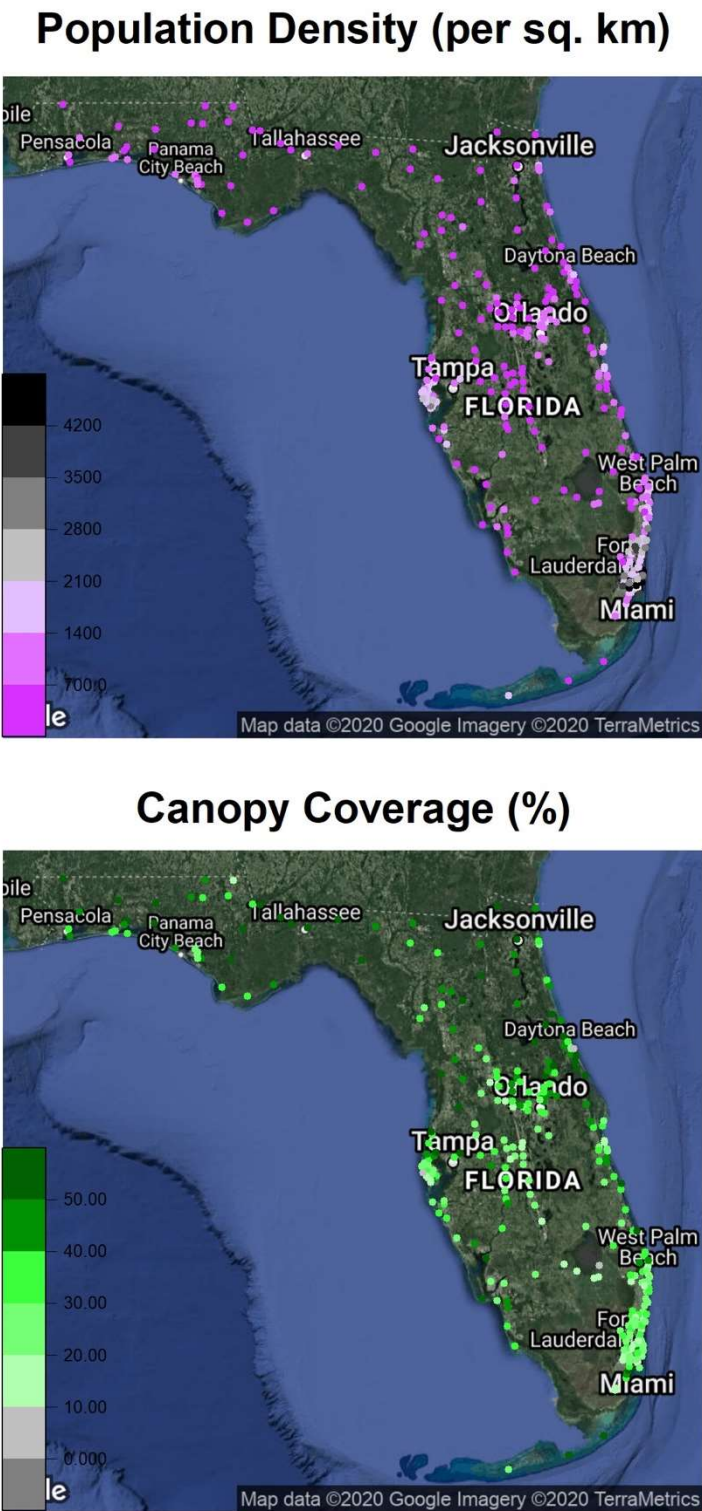


Table 1. Initial model variables tested in predicting urban tree canopy coverage. For this model predictions were limited to inhabited Census blocks within a city boundary (omitting nature preserves and other large uninhabited tracts of land that might be found within the limits of a given city).

Variable	Definition	Source
Developed UTC	Response variable. Urban tree canopy for all inhabited census blocks within a city boundary	Calculated using point-based photo interpretation
Historic Land Cover	Categorical. Pre-development natural land cover	Davis (1967); Florida Geographic Data Library (1999); Volk et al. (2017)
Maximum Gust Speed	Continuous. Maximum recorded wind speeds	Federal Geographic Data Committee (undated)
Population Density	Continuous. The number of inhabitants per square kilometer.	Computed from U.S. Census Bureau (2018a) based on GIS-derived area of clipped city boundaries.
Median Income	Continuous. Median household income	U.S. Census Bureau (2018b).
House percent since 2010	Continuous. Percent (%) of total housing units constructed after 2010	U.S. Census Bureau (2018b).
Home percent 2000 to 2009	Continuous. Percent (%) of total housing units constructed between 2000 and 2009	U.S. Census Bureau (2018b).
Home percent 1990 to 1999	Continuous. Percent (%) of total housing units constructed between 1990 and 1999	U.S. Census Bureau (2018b).
Owner-occupied Percent	Continuous. Percent (%) of total housing occupied by homeowners	U.S. Census Bureau (2018b).
Hazardous tree ordinance	Binary (yes/no). Cities regulate the removal of dead, diseased, or dangerous trees	Survey results; City Websites; American Legal Publishing Corporation (2018), Municode (2018).
Tree preservation ordinance	Binary (yes/no). Community has an ordinance requiring the preservation of trees during development	Survey results; City Websites; American Legal Publishing Corporation (2018), Municode (2018).

Planting requirements - new developments	Binary (yes/no). Community has an ordinance requiring tree planting/coverage in new developments	Survey results; City Websites; American Legal Publishing Corporation (2018),Municode (2018).
Planting requirements - new parking lots	Binary (yes/no). Community has an ordinance requiring tree planting/coverage in parking lots	Survey results; City Websites; American Legal Publishing Corporation (2018),Municode (2018).
Removal permit ordinance	Binary (yes/no). Community has an ordinance restricting tree cutting on private property	Survey results; City Websites; American Legal Publishing Corporation (2018),Municode (2018).
Heritage tree ordinance	Binary (yes/no). Community identifies and protects heritage/significant trees	Survey results; City Websites; American Legal Publishing Corporation (2018),Municode (2018).
Ability to fine	Binary (yes/no). Community has an ordinance that allows regulators to fine parties for non-compliance with tree ordinances	Survey results; City Websites; American Legal Publishing Corporation (2018),Municode (2018).
Local licensure	Binary (yes/no). Community has an ordinance requiring tree care companies to be licensed locally	Survey results; City Websites; American Legal Publishing Corporation (2018),Municode (2018).

Table 2. Descriptive statistics (i.e., minimum, median, maximum, mean, and standard deviation) for the continuous variables used to model canopy coverage in the 300 largest municipalities in Florida, United States. Includes the response variable, developed urban tree canopy (Developed UTC).

Variable	Min	Median	Max	Mean	Std. Dev.
Developed UTC (%)	5.9	32.3	68.7	33.9	12.7
Maximum Gust Speed (kmph)	37.2	124.4	225.8	130.6	26.5
Population Density (per km ²)	7.9	813.9	8617.7	1175.9	1171.3
Median Income (\$USD)	17,908	50,788	153,417	56,022	22,431
House percent since 2010 (%)	0.0	2.6	39.8	3.6	4.6
Home percent 2000 to 2009 (%)	0.0	12.8	60.4	16.0	11.7
Home percent 1990 to 1999 (%)	0.4	12.9	52.0	14.1	8.1
Owner-occupied Percent (%)	26.2	64.2	95.7	64.2	13.9

Table 3. Proportion of municipalities in our study with the following tree-related ordinances. These ordinances were included in our efforts to model percent urban tree canopy in Florida’s 300 largest municipalities.

Ordinance	Yes (%)	No (%)	Unknown (%)
Hazardous tree ordinance	81.3	16.7	2.0
Tree preservation ordinance	86.7	11.3	2.0
Planting requirements - new developments	89.3	8.7	2.0
Planting requirements - new parking lots	89.3	8.7	2.0
Removal permit ordinance	46.0	51.7	2.3
Heritage tree ordinance	70.3	27.7	2.0
Ability to fine	84.0	14.0	2.0
Local licensure	17.7	80.3	2.0

Table 4. Final model and regression results in predicting Developed Urban Tree Canopy (UTC) for the 300 most populous municipalities in Florida, United States (adjusted $R^2=0.230$).

Variable	Coefficient	SEM	P-value	95% CI Lower	95% CI Upper
Intercept	56.401	4.346	<0.001	47.849	64.954
Historic Land Cover – Non-Forested	-5.934	1.546	<0.001	-8.977	-2.891
Max Gust (kmph)	-0.287	0.068	<0.001	-0.421	-0.153
Population Density	-0.003	0.001	<0.001	-0.004	-0.002
Tree preservation ordinance	-5.635	2.339	0.016	-10.237	-1.033
Heritage tree ordinance	3.548	1.641	0.031	0.318	6.777