A City Plagued: Leveraging Multiple Risks for Insightful Preparation and Response

September 2023

EXECUTIVE SUMMARY

Numerous cities across the United States have experienced catastrophic floods in recent years; Houston, Texas, has experienced several. The 2015 implementation of Urban Forest Inventory & Analysis (FIA) in Houston provided a unique opportunity to explore effects of flooding from Hurricane Harvey on the urban forest. Flood risk is only one of the issues facing Houston; invasive species, exotic insects and diseases, air pollution, and urban heat islands also pose risks for the city, all of which are exacerbated by tree loss or stress from storms and other disasters.

Urban FIA data collected before and after Hurricane Harvey were analyzed to determine how flooding affected Houston's trees. Special focus was on invasive plant/insect species that alter native ecosystems to identify opportunities for multiple-objective management. Impacts were investigated to determine if socioeconomic groups were affected similarly and identify efforts that can be taken to improve environmental equity. Additionally, an analysis of the intersection of tree canopy with storm data was conducted to determine what, if any, mitigating effects Houston's urban forest had on flooding.

While most species remained stable, elm (*Ulmus* spp.) and Chinese tallow (*Triadica sebifera*) increased in number post-Harvey and maple (*Acer* spp.), holly (*Ilex* spp.) and sparkleberry (*Vaccinum arboreum*) decreased. There was some indication that socioeconomic groups were disparately affected. Influence of canopy on flooding was inconclusive. Recommendations were developed for strategic urban forest management to mitigate risk of flood damage, invasive species, insects/disease, and air quality while cultivating environmental equity.

Introduction

Historic intensity hurricanes, storms, and unprecedented weather events have impacted the gulf coast and eastern seaboard of the United States in recent years, including the Texas drought (2011), Hurricane Sandy (2012), Texas Memorial Day flooding (2015), and Hurricanes Matthew (2016), Harvey (2017), and Maria (2017). These significant weather events all caused a tremendous amount of damage, including tree loss due to high winds and flooding.

Houston, Texas, has a long history of flood events, averaging a major flood every two years. Two of the most catastrophic events were Tropical Storm Allison in 2001 where rainfall exceeded 40 inches and Hurricane Harvey which inundated Houston with over 50 inches of rain that remained from several days to six weeks.

Storms that result in severe flooding can be associated with different levels of tree mortality, with some species being more susceptible than others. This can result in an increase of less desirable species if rapidly regenerating species invade areas where trees are lost. These types of storms may have a greater impact on lower socioeconomic urban areas due to the lack of intentional plantings of resilient species. Waterways and adjacent floodplains were inundated for days from rainfall associated with Harvey; it is to be expected that this flooding would likely cause some level of tree mortality.

By looking at Harvey flood extent and severity relative to inventory data the following questions may be answered:

- Did species composition affect flood level and tree mortality?
- Was there a difference in impact across socioeconomic classes?
- Have the three most prevalent and aggressively regenerating tree species in Houston's urban forest invaded the resulting areas of high tree mortality?

Identifying flood-tolerant species, particularly those that have the greatest potential to reduce stormwater runoff, and developing appropriate management recommendations can help minimize the impact of storms across all socioeconomic classes.

Urban Forest Inventory & Analysis (FIA) was implemented in Houston in 2015 with a full set of data collected in the first year and 5-year cycle remeasurement beginning in 2016, creating a unique opportunity to explore the effects of Hurricane Harvey. Plots in flooded areas that had not yet been remeasured were revisited for this study. Not many cities have comparable inventory data for one time period, much less two. And few, if any, have it before and after such a significant event.

Initially, plans were to include data from storm events in other cities across the eastern coastal states, however there were not enough inventory plots that were inundated by flood waters in any one location to draw conclusions. Knowledge learned from Harvey can be translated to these and other areas across the nation undergoing similar issues – not only coastal areas, but also inland areas dealing with flooding events.

Trees and stormwater

Trees impact stormwater runoff in three general ways: rainfall interception, increased soil infiltration and reduced runoff velocity. Twenty tree species were researched by Xiao and McPherson (2016) to evaluate their effects on rainfall interception. They found that interception (also referred to as surface water storage capacity) is affected by tree species and rainfall intensity, with conifers having greater overall storage capacity than broadleaf species. Trees are sometimes used in stormwater bioretention areas because they store water and return it to the atmosphere through transpiration. While trees are critical for reducing runoff, not all tree species are equally suited for a functional role in bioswales (Scharenbroch, Morgenroth and Maule, 2016). Not surprisingly, tree species that are larger at maturity reduce more runoff. Ring-porous species, those that have larger pores in xylem vessels such as oak, ash and elm, are considered more efficient water users than diffuse-porous species (e.g., birch, maple, willow). Known to be advantageous in times of drought, this efficiency could potentially translate to greater tolerance of inundation by flood waters (Copini et al., 2016). However, most referenced studies of stormwater interaction and flood tolerance across species simulate flooding instead of reporting on actual events. As Berland et al. (2017) noted, additional data across different landscape settings and time periods are needed to more fully understand how trees interact with stormwater. Houston and Hurricane Harvey provided the opportunity to do just that.

Houston's urban forest

Houston's urban forest comprises over 33 million trees across 401,663 acres, with a canopy that covers an estimated 18.4 percent of the city. The species make-up reflects the two major ecoregions of the area, the Gulf Coastal Plain and the East Texas Pineywoods. Houston's urban forest is diverse, with seventy different species present within the city. Dominant native upland species include yaupon (*Ilex vomitoria*), loblolly pine (*Pinus taeda*), American elm (*Ulmus americana*), and sweetgum (*Liquidambar styraciflua*). Native tree species found along the numerous bayous in the area include green ash, water oak, and boxelder. Non-native and invasive species are common as well.

In fact, the three most prevalent tree species in Houston are considered problematic (Nowak et al., 2017). Introduced into the Houston area sometime around 1910, the invasive Chinese tallow (*Triadica sebifera*) has rapidly colonized the area and is now, at seventeen percent of all trees, the second most common in the city. While tallow appears to be distributed throughout the city, a greater percentage of the trees are found on public property (81%) relative to private property (19%). Additionally, the majority of this species (over 95%) is found in non-maintained areas such as along stream banks. Chinese privet (*Ligustrum sinense*), another non-native invasive tree species, is the third most common tree species in the City of Houston, making up seven percent of the tree population. The most prevalent tree species in Houston (22%) is the native yaupon; a shrub-like tree that readily regenerates in non-maintained areas. Storm impacts could be expected to result in an increase in the number of less desirable trees, because these species rapidly colonize disturbed areas.

More than three percent (greater than one million) of trees in Houston are ash species (*Fraxinus spp.*). All species of ash are susceptible to the emerald ash borer (EAB; *Agrilus planipennis*), an exotic beetle that has killed millions of ash trees since its initial detection in 2002 in Detroit, Michigan (emeraldashborer.info, 2018). Not yet known to be in Houston, EAB was detected in northeast Texas in 2016. A number of conditions affect the time between initial establishment of EAB and subsequent ash mortality (Mercader et al., 2011). While excessive environmental stress such as flooding is not specifically identified as an affecting condition, it is known that the beetle is attracted to stressed trees (McCullogh, Poland and Cappaert, 2009; Mercader et al., 2011). Frequently found in moist woods, Houston's ash and implicit vulnerability to EAB may be impacted by Harvey floodwaters.

When identifying community forest attributes today, the concept of environmental equity or justice must also be considered. The U.S. Environmental Protection Agency (2012) defines environmental justice as, "The fair treatment and meaningful involvement of all people regardless of race, color, sex, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies." Several studies over the last two decades have shown that lower-income neighborhoods are less likely to have street trees and public open space, compared to affluent neighborhoods (Donovan and Mills, 2016; Frey, 2016; Landry and Chakraborty, 2009).

What isn't well-known nationally is how species composition compares across sociodemographic classes. In Houston, only two of the top ten species present in census block groups representing the two lowest income classes are considered shade trees, compared to seven in the two highest income classes (www.mycitystrees.com, 2020). While public investment in disadvantaged areas across the country has historically lagged behind that of advantaged areas, residents in low income areas tend to be reluctant to engage in voluntary tree planting programs—the type of which might increase tree density and diversity (Donovan and Mills, 2016). This may be because maintaining a tree long-term requires a significant investment and there are more immediate needs. The impact from a storm such as Hurricane Harvey can be compounded if low income residents need to choose between replacing personal belongings and watering a tree, for instance.

Study Parameters

Urban FIA data collected before and after Hurricane Harvey were analyzed to determine the effects of the associated flooding on trees. Species level mortality and damage were quantified in flood impacted areas. Exotic invasive species prevalent throughout Houston (comprising over 25% of the trees in the city) were given special attention, as was ash, with EAB invasion likely to occur in the future. Additionally, the flood-mitigating effects of trees were investigated.

The study area initially focused on the Houston city limits. This is both where flooding was most intense and where there is the most available data (flood extent and depth, lidar-based canopy, and forest inventory plots). A total of 37 Urban Forest Inventory & Analysis plots that both experienced flooding and contained trees were revisited in 2020 to assess damage to trees from the flood. Data on species composition, size of trees, standing live/dead, amount of foliage and other attributes were compared pre- and post-Harvey. Data from plot measurement were evaluated across two size classes, 1 to 4.9 inches and 5 inches in diameter and larger. This corresponds with FIA measuring protocol and underscores potential regeneration and sapling survivability since the previous measuring cycle.

Preliminary results suggested that rainfall associated with Hurricane Harvey was so extreme that trees had little influence on flood intensity. Two of the most heavily forested areas of the city are designated inundation areas designed to absorb flooding impact. Since they are intended to be flooded, they were not included in the effect of canopy on flooding analysis. Initially, this analysis took a pixel-based approach of intersecting canopy and inundation. Given that a tree's impact on flooding on the landscape does not correspond exactly with the area directly beneath its crown, the analysis was expanded to the watershed scale, comparing watershed land cover composition to the percent of the watershed that experienced flooding. Additional watersheds that experienced flooding to a lesser extent were also included. The overall study area is defined by the San Jacinto River basin, and the city study area is the overlapping area between the San Jacinto River basin and the 2010 U.S. Census boundary for the city of Houston (Figure 1).

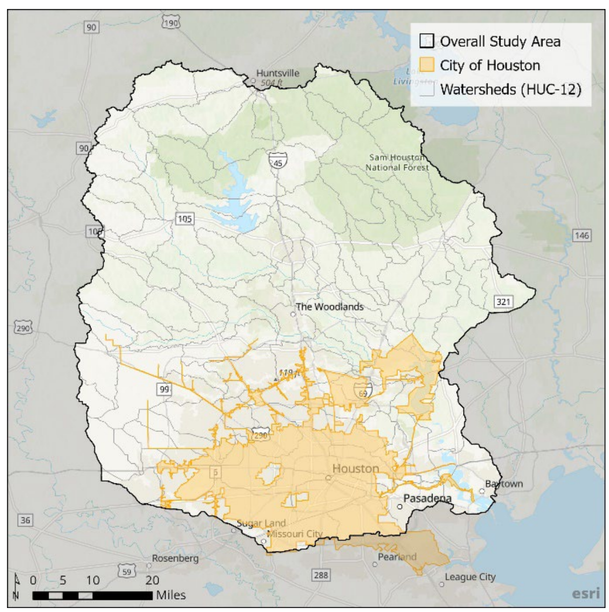

Figure 1. Map of the study area: the San Jacinto River basin, including the majority of the City of Houston, and all HUC-12 watersheds within the basin.

Findings

City of Houston – Impact of Flooding on Trees

The composition of live trees remained relatively stable with a few notable exceptions. Of the 25 species found on remeasured plots, 20 exhibited little change in total number present (see Tables 1 and 2). For live trees at least 5 inches in diameter, the maple genus (primarily *Acer negundo*) decreased from 4.7% of the observed trees to 1.0%, while elms (*Ulmus spp., primarily U. alata, U. americana, U. crassifolia, U. parvifolia*) jumped from 5.0% to 9.7%. For live trees 1 to 5 inches in diameter, holly (primarily *Ilex vomitoria*), sparkleberry (*Vaccinium arboreum*), and maples decreased (56.3% to 52.5%, 2.3% to 0.0%, and 4.6% to 2.5%, respectively) while tallow and elms increased (13.8% to 18.8% and 8.0% to 11.3%, respectively).

Table 1. Composition of live trees at least 5 inches in diameter, pre- and post-Harvey

	Pre-Harvey (2016)	Post-Harvey (2020)
Acer	4.7%	1.0%
Carpinus	1.0%	0.7%
Carya	1.7%	1.7%
Catalpa	0.3%	0.3%
Celtis	5.3%	5.0%
Crataegus	0.7%	0.3%
Cupressus	0.0%	0.7%
Fraxinus	16.9%	17.7%
Ilex	0.0%	0.3%
Juniperus	0.3%	0.3%
Lagerstroemia	0.7%	0.7%
Ligustrum	0.0%	0.3%
Liquidambar	5.0%	4.3%
Nyssa	0.0%	0.3%
Pinus	8.6%	8.7%
Platanus	0.3%	0.3%
Prunus	0.3%	0.3%
Quercus	20.9%	21.1%
Sabal	1.0%	1.0%
Salix	0.3%	0.3%
Sideroxylon	0.3%	0.3%
Tilia	0.3%	0.3%
Triadica	26.2%	24.1%
Ulmus	5.0%	9.7%

Table 2. Composition of live trees 1-4.9 inches in diameter, pre- and post-Harvey

	Pre-Harvey (2016)	Post-Harvey (2020)
Acer	4.6%	2.5%
Crataegus	4.6%	5.0%
Cupressus	1.1%	0.0%
Fraxinus	2.3%	1.3%
Ilex	56.3%	52.5%
Ligustrum	0.0%	1.3%
Liquidambar	0.0%	1.3%
Morus	1.1%	1.3%
Prunus	1.1%	1.3%
Quercus	4.6%	3.8%
Triadica	13.8%	18.8%
Ulmus	8.0%	11.3%
Vaccinium	2.3%	0.0%

Of the 301 live trees at least 5 inches in diameter that were present before Harvey, 81% remained alive, 16% died, and 3% were removed. Looking just at genera with a minimum of 10 observations at least 5 inches in diameter, maples fared the worst proportionally, with 71% (10 trees out of 14) succumbing, and tallow fared the worst by quantity, with 30 trees dying (38%); 15 live elms were observed pre-Harvey and all 15 were also alive post-Harvey.

Sparse crown is an indicator of poor tree health due to both abiotic and biotic stressors, including insects and disease. Trees were assessed for amount of absent foliage at both time periods. The average foliage absent on trees at least 5 inches in diameter that were alive both before and after Harvey went from 6.4% prior to the storm to 36.0% following Harvey, with ash seeing the greatest impact and sweetgum seeing the least (Figure 2). At least one kind of damage was observed on 57% of these surviving trees, with stem decay observed on 20% of trees, foliage diseases observed on 18% of trees, and flooding/high water indicators observed on 18% of trees.

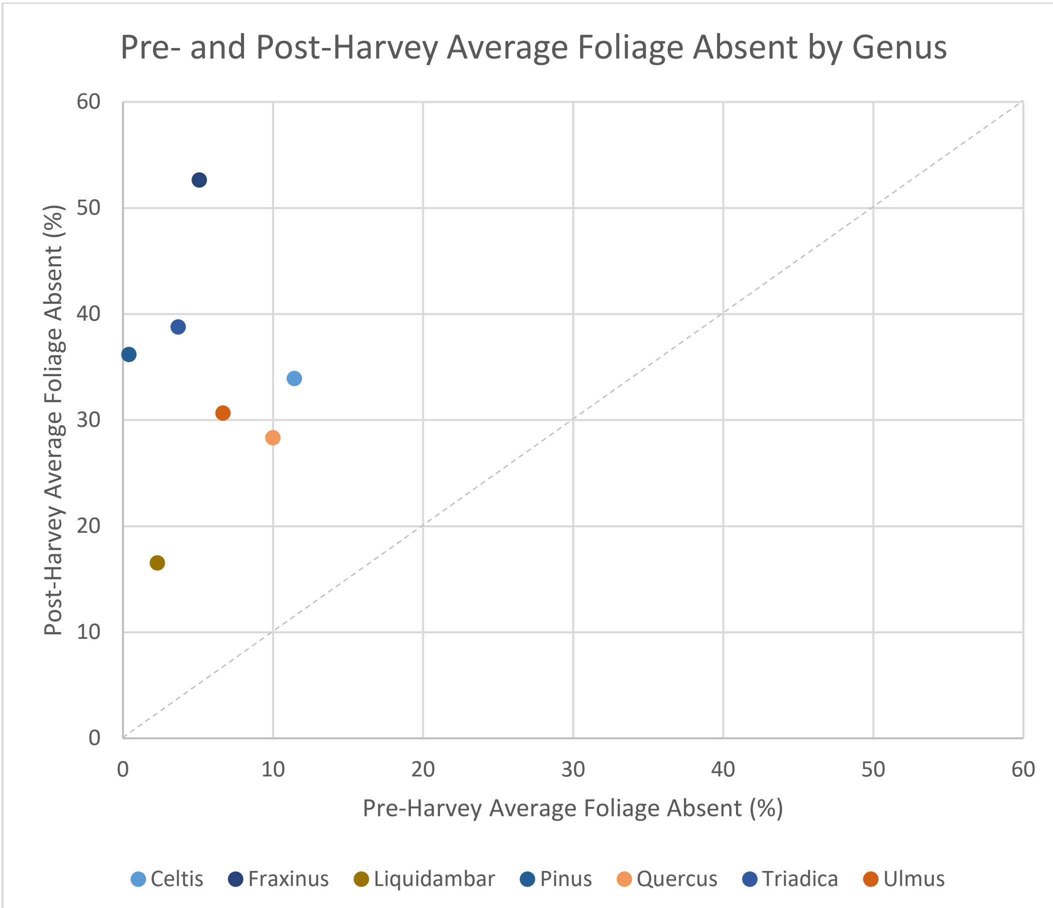

Figure 2. Average foliage absent of live trees at least 5 inches in diameter pre- and post-Harvey for genera with at least 10 observations

Although total ash trees remained relatively consistent following Hurricane Harvey, stress from inundation was apparent based on the general conditions of their crowns. There was a slight increase in live ash trees greater than 5 inches in diameter, from 16.9% to 17.7%, but a decrease (2.3% to 1.3%) in live trees 1 to 5 inches in diameter. There were 51 live ash trees at least 5 inches in diameter present prior to Hurricane Harvey and 53 alive post-Harvey. While these trees averaged only 5.1% absent foliage pre-Harvey, post-Harvey rates increased to greater than 50%.

Disparity of impacts across socioeconomic classes was less straightforward. More trees were present in less socially vulnerable areas as well as in areas of average to higher income levels (www.mycitystrees.com, 2020). The least socially vulnerable class sustained the most tree mortality (34%). This class accounted for 28% of all the trees tallied prior to and 58% of all trees that died following Harvey (Table 3). When looking at income level, the most trees (50%) were in the middle income class, which also sustained the most mortality, accounting for 90% of trees that died. Nearly 30% mortality was observed in this class, compared to the overall mortality of 16%. Two sizeable U.S. Army

Corps of Engineers stormwater control facilities, Addicks and Barker Reservoirs, comprise a large portion of land that falls in this income class. These forested reservoirs are designed to collect and hold stormwater, and as such, trees were inundated for a longer duration than trees located elsewhere, likely accounting for the higher mortality in this class.

Considering just size of trees and associated tree benefits, loss tended to be of larger trees at the lower income and more vulnerable classes. The average diameter of dead trees in the second lowest income level was 14.2 inches and in the most vulnerable class was 12.4 inches. With an already lower number of trees in these classes, loss of mature shade trees means a proportionately higher loss in social, environmental, and economic benefits provided by trees in these areas.

Table 3. Tree mortality from Hurricane Harvey relative to social vulnerability and income classes

Geographic Classification	Pre-Harvey Proportion of Total Trees	Tree Mortality (Percent of Total)	Average Diameter of Dead Trees (Inches)
Most Vulnerable*	15%	8%	12.4
Highly Vulnerable	3%	0%	--
Somewhat Vulnerable	0%	0%	--
Slightly Vulnerable	53%	33%	8.6
Least Vulnerable	28%	58%	7.3
$35,000 and less Income	5%	2%	6.8
$35,001 - $50,000 Income	12%	6%	14.2
$50,001 - $65,000 Income	50%	90%	7.9
$65,001 - $100,000 Income	23%	0%	--
$100,001 and more Income	10%	2%	5.1

*Social Vulnerability Index (Centers for Disease Control)

Tallow lost the greatest number of larger trees to flooding, but increased in number of live saplings from pre- to post-Harvey. We can infer from this that tallow is highly opportunistic, with young trees rapidly colonizing areas following storms and other disturbances. Maples, often considered adapted to wet soil conditions, did not fare well with extended inundation, sustaining losses to both young and mature trees. Elms fared the best, with all larger trees surviving and both diameter classes increasing in number, suggesting that growth and regeneration have been vigorous post-Harvey.

As noted earlier, pore structure influences a species' efficiency in water use, with the larger earlywood pores found in ring-porous species conferring resilience to fluctuating conditions. Of the five species in this study showing notable pre- and post-Harvey differences, elm is ring-porous and the remainder are diffuse or semi-diffuse porous. This study supports the consideration that efficiency in water transport could translate to atypical inundation tolerance in mature specimens. It may be simply the result of having the facility for speedy compensatory growth of new wood in the post-flood response stage (a ring-porous characteristic).

City of Houston – Impact of Trees on Flooding

Excluding the two large flood-control areas (covering a combined 25,000 acres) in the western portion of the city that were designed to collect and hold stormwater, 76,000 acres, or 24% of the city's total area, experienced flooding from Harvey (Figure 3). Of these 76,000 acres, 42% had tree canopy, and 58% did not. More than 20,000 acres were flooded to five feet or greater in depth.

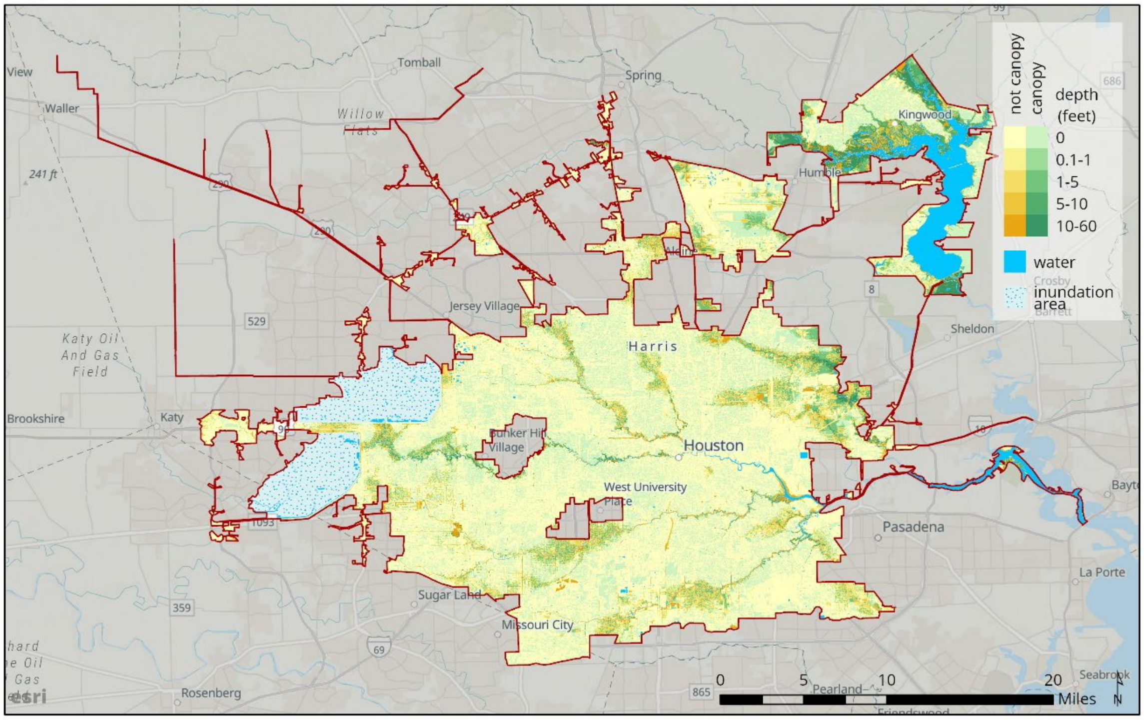

Figure 3. Tree canopy of Houston and flood inundation from Hurricane Harvey

While the flooded area had less area of canopy than non-canopy, so did the non-flooded area (31% of the non-flooded area had tree canopy and 69% did not). Since flooding tends to be most prevalent in low-lying areas near waterways, which may also correspond to areas with high tree cover, this is not necessarily surprising. This reasoning is at least partially supported by the data, as the areas within 100 meters of waterways had 38% tree canopy, while the areas more than 100 meters from waterways had 33% tree canopy. Of areas with tree canopy within 100 meters of waterways, 68% experienced flooding, while 26% of the tree canopy area beyond 100 meters was flooded. Areas without tree canopy also experienced less flooding in areas more than 100 meters from waterways, but with not as great of a difference (48% flooded within 100 meters of waterways versus 19% flooded beyond 100 meters). The spread between areas with tree canopy and those without decreased from 20 percentage points within 100 meters of waterways to 7 percentage points more than 100 meters from waterways.

In the immediate Houston area, a clear relationship between tree canopy and flooding did not emerge from the analysis. In addition to tree cover tending to be high near waterways, this result is likely due to the extremity of the event and the fact that a tree's impact on flooding on the landscape does not correspond exactly with the area directly beneath its crown. For these reasons, the analysis was expanded to the watershed scale, comparing watershed land cover composition to the percent of the watershed that experienced flooding.

San Jacinto Basin – Impact of Land Cover on Flooding

As previously noted, the study area is comprised of two main ecoregions: East Texas Pineywoods and the Gulf Coastal Plain. Not accounting for urban influence, forest cover is highly variable within these two ecoregions. Forest cover ranged from 0% to 90% in the 98 watersheds that encompass over 2.6 million acres and are included in this portion of the analysis (Figure 4). Average cumulative precipitation from August 23 through August 30, 2017, in these watersheds ranged from 21 to 42 inches. Inundation as a consequence of Hurricane Harvey ranged from 0% to 61%.

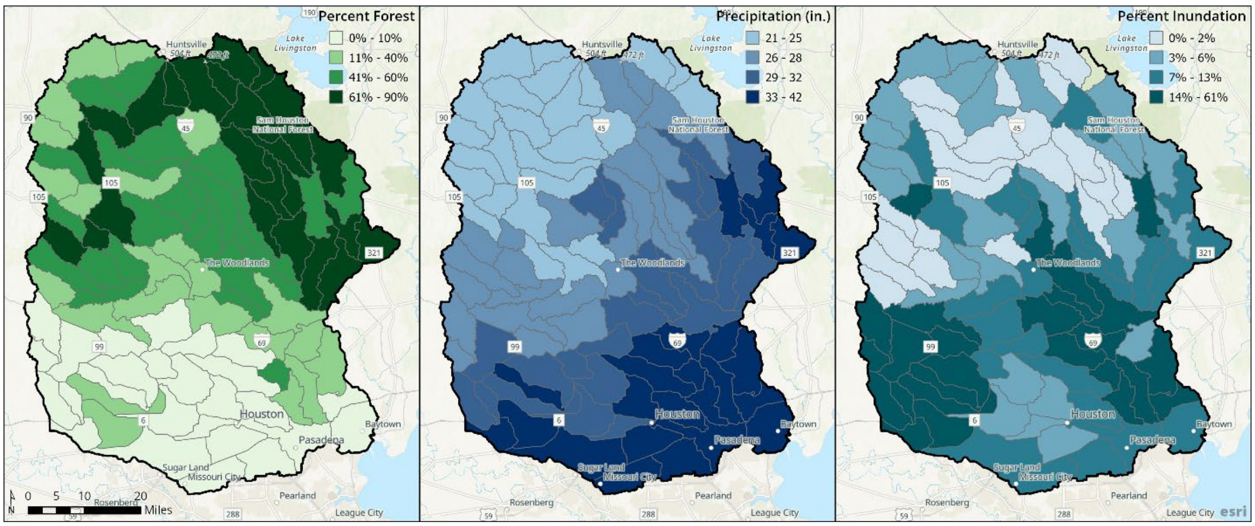

Figure 4. Percent forest, average precipitation, and percent inundation by watershed.

Both the mean and the range of inundation percent by watershed decreased with increasing forest cover (Table 4), while a high percentage of impervious cover tended to correspond with greater areas of inundation.

Table 4. Watershed inundation from Hurricane Harvey relative to forest cover

	Inundation of Watershed			
Percent Forest Cover	Mean	Min	Max	Range
0-10	18.5%	3%	61%	58%
11-40	15.0%	1%	54%	53%
41-60	8.3%	1%	21%	20%
61+	3.1%	0%	8%	8%

To check for statistical significance in the differences between forest cover groups, we used a Kruskal-Wallis test (non-parametric method used when within-group variances are not equal). The Kruskal-Wallis test showed that at least one group differed, so we followed up with pairwise comparisons to identify which groups significantly differed from each other. The group with over 60% forest was significantly different from the two lowest forest cover groups (0-10% and 11-40%), and the 41-60% group was significantly different from the 0-10% group (Figure 5).

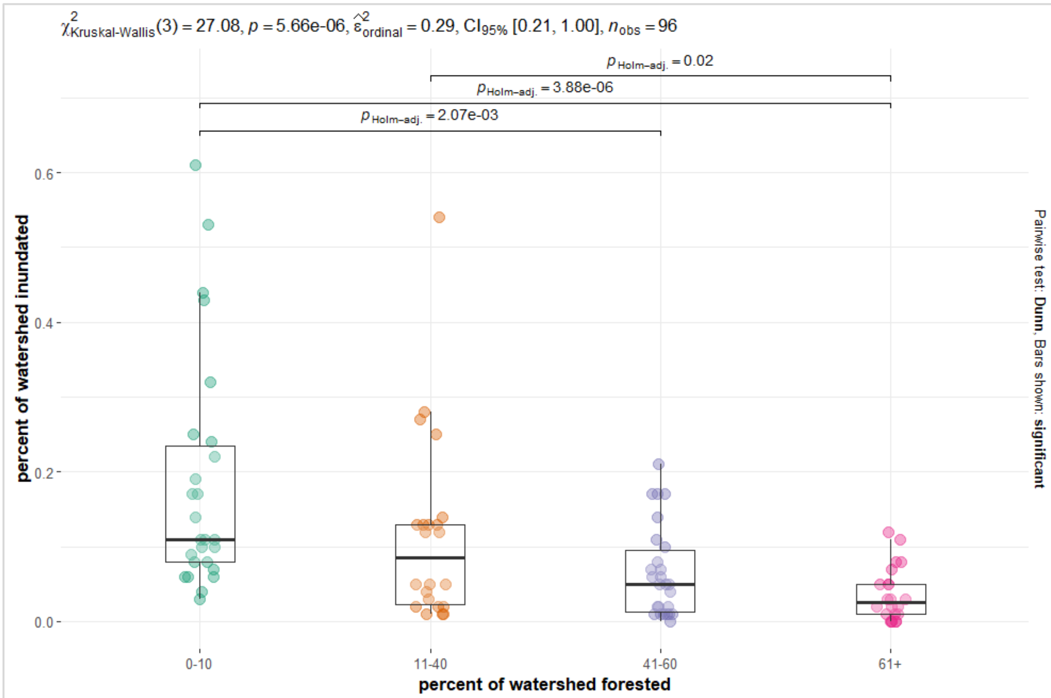

Figure 5. Test for differences in watershed percent inundation by percent forest

Recommendations

From the species level analysis, we may conclude that elms are flood tolerant, maples are not, and tallow will rapidly colonize flood-impacted lands. Ash, while neither gaining nor losing individual specimens due to flooding in this study, likely experiences stress that can ultimately affect its resistance to EAB when it arrives in the area. Because many invasive tree species, as well as ash, are prevalent in flood-prone riparian areas, the relationship of flooding to these issues and management opportunities must be considered. The following are recommendations for planting trees strategically to mitigate the risk of flood damage to trees and property while cultivating environmental equity that incorporates management for invasive species and insects/disease:

- Intensive removal of nonnative invasive tree species in the first 1-3 years following a flood event is critical to stem rapid spread of undesirable species.
- Heighten pest monitoring after storms as infestations may occur following flood events.
- Retain large blocks of forestland within watersheds, ideally a minimum of 40% cover, to reduce downstream flood potential.
- Where possible, plant clusters of trees. Due to partial physical protection and increased leaf and root area, groups of trees tend to be more resilient to storms and more effective at stormwater reduction than individual open-grown trees.
- Elms are fairly flood-tolerant and may be a good choice for treescapes that see periodic flooding such as rights-of-way, easements and parklands, and are a solid choice for disadvantaged

neighborhoods that may not have had previous investment in tree planting as they are aesthetically pleasing, moderately fast-growing shade trees.

- Maples are reportedly tolerant of periodic soil saturation and appear not to handle catastrophic flooding. Therefore, limit planting of maples to areas that have only minor flood potential.
- While baldcypress (*Taxodium distichum*) was not present on study plots, this species thrives in swampy areas and is a good choice for flood-prone areas and irrigated spaces. This deciduous conifer's graceful form and high heat tolerance makes this species a desirable specimen tree for yards and public places. Due to the presence of "knees" that grow from roots, these may be best for unmanicured landscapes such as medians or mulched beds.
- Establishing tree canopy in green stormwater management infrastructure such as bioswales and retention basins will enhance environmental equity by serving as neighborhood treescapes while providing environmental, social, and economic benefits.

Considerations

Storms that result in severe flooding have associated levels of tree mortality and some species are more susceptible than others. This may result in an increase of less desirable species if rapidly colonizing species invade areas where trees are lost. Corresponding environmental, economic, and social benefits of the urban forest are reduced when more vulnerable mature trees that provide greater benefits than young trees are lost. Additionally, these types of storms may have a larger impact on lower socioeconomic urban areas due to the lack of intentional plantings of resilient species. Planting flood-tolerant species and targeted management can help minimize the impact of storms across all socioeconomic classes.

While the mitigating effects of tree canopy on flooding itself appears to be limited when flooding is of catastrophic intensity, trees provide water quality benefits, an important consideration when protecting drinking water from contamination associated with floods, and may influence increased financial support for urban forests.

These findings inform the public on issues such as urban forest diversity, the relationship between trees and stormwater, impacts to community forest composition following storms, and strategies to support environmental equity both before and after storms. The socioeconomic findings along with species and invasive information can facilitate recovery and preparedness efforts by partners in Houston and other cities affected by storms. Further, the methods and process can be of use to other urban areas around the country, even if the challenges differ.

This project was supported by a USDA Forest Service National Urban and Community Forestry Challenge Grant and addresses key interests of cities that face natural disasters. It demonstrates that a resilient and sustainable urban forest necessitates a management approach that considers all aspects of the ecosystem.

References

Berland, A., Shiflett, S., Shuster, W., Garmestani, A., Goddard, H., Herrmann, D., Hopton, M. (2017, Feb). The role of trees in urban stormwater management. *Landscape and Urban Planning, 162,* 167-177.

Copini, P., den Ouden, J. Robert, E., Tardif, J., Loesberg, W., Goudzwaard, L., Sass-Klaassen, U. (2016) Flood-Ring Formation and Root Development in Response to Experimental Flooding of Young *Quercus robur* Trees. *Frontiers in Plant Science,* 7, 775.

Donovan, G., Mills, J. (2016). Environmental Justice and Factors that Influence Participation in Tree Planting Programs in Portland, Oregon, U.S. *Arboriculture & Urban Forestry,* 40(2), 70-77.

Emeraldashborer.info. (2018). Information Network Page. Accessed 20 April 2018. http://emeraldashborer.info/

Frey, N. (2016). Equity in the distribution of urban environmental amenities: the case of Washington, D.C., *Urban Geography, 38*(10), 1534 1549, https://doi.org/10.1080/02723638.2016.1238686

Landry, S, Chakraborty, J. (2009, Nov). Street Trees and Equity: Evaluating the Spatial Distribution of an Urban Amenity. *Environment and Planning,* 41(11)*,* 2651-2670. https://doi.org/10.1068/a41236

McCullough. D., Poland, T., Cappaert, D. (2009) Attraction of the emerald ash borer to ash trees stressed by girdling, herbicide, or wounding. *Canadian Journal of Forest Research,* 39, 1331–1345

Mercader, R., Siegert, N., Liebhold, A. and McCullough, D. (2011). Influence of foraging behavior and host spatial distribution on the localized spread of the emerald ash borer, *Agrilus planipennis*. *Population Ecology,* 53, 271–285.

Nowak, D., Bodine, A., Hoehn, R., Edgar, C., Riley, G., Hartel, D., Dooley, K., Stanton, S., Hatfield, M., Brandeis, T., Lister, Tonya. (2017). Houston's Urban Forest, 2015. *Resource Bulletin SRS–211. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.*

Sadof, C., Hughes, G., Witte, A., Peterson, D., Ginzel, M. (2017, Jan) Tools for Staging and Managing Emerald Ash Borer in the Urban Forest. *Arboriculture & Urban Forestry,* 43(1), 15-26

Scharenbroch, B., Morgenroth, J., Maule, B. (2016, Jan). Tree Species Suitability to Bioswales and Impact on the Urban Water Budget. *Journal of Environmental Quality,* 45*,* 199-206.

U.S. Environmental Protection Agency. (n.d.). Environmental Justice Program. Retrieved April 2018 from https://www.epa.gov/environmentaljustice.

Xiao, Q., McPherson, E.G. (2016, Jan). Surface Water Storage Capacity of Twenty Tree Species in Davis, California. *Journal of Environmental Quality,* 45, 188-198.