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Research Paper

Assessing the tree health impacts of salt water flooding in coastal cities: A case study in New York City

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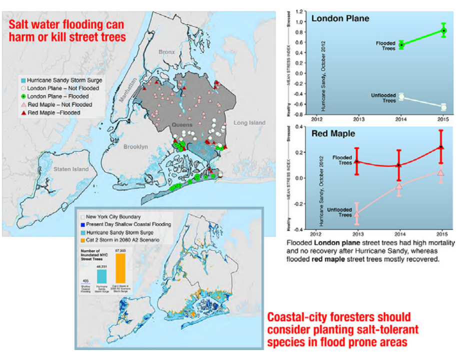
GRAPHICAL ABSTRACT



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ABSTRACT

Hurricane Sandy was the second costliest hurricane in United States (U.S.) history. The category 2 storm hit New York City (NYC) on the evening of October 29, 2012, causing major flooding, wind damage, and loss of life. The New York City Department of Parks & Recreation (NYC Parks) documented over 20,000 fallen street trees due to the physical impact of wind and debris. However, salt water flooding may have caused additional stress to approximately 48,000 street trees located in the storm's inundation zone. Early in the first growing season following Hurricane Sandy (June 2013), NYC Parks staff examined these street trees and found that 6,864 of the flooded trees had a significant proportion of their crown fail to leaf out. Thirty percent of those trees did not leaf out at all. The most commonly affected trees were London plane (*Platanus × acerifolia*) and maple species (*Acer* spp.). Here we show that red maple (*Acer rubrum*) is negatively impacted by salt water flooding but can recover over time. London plane trees, on the other hand, experience high mortality and show no signs of recovery 3 years post Sandy. We demonstrate that by 2080 a similar storm could impact almost 100,000 of NYC's street trees. These findings have global implications for coastal urban forests as we face sea level rise and an increasing frequency and magnitude of coastal storms.

1. Introduction

Hurricane Sandy was the second costliest hurricane in United States (U.S.) history (Blake, Kimberlain, Berg, Cangialosi, & Beven II, 2013). The category 2 storm hit New York City (NYC) on the evening of October 29, 2012, causing major flooding, wind damage, and loss of life. The New York City Department of Parks & Recreation (NYC Parks) documented over 20,000 fallen street trees due to the physical impact

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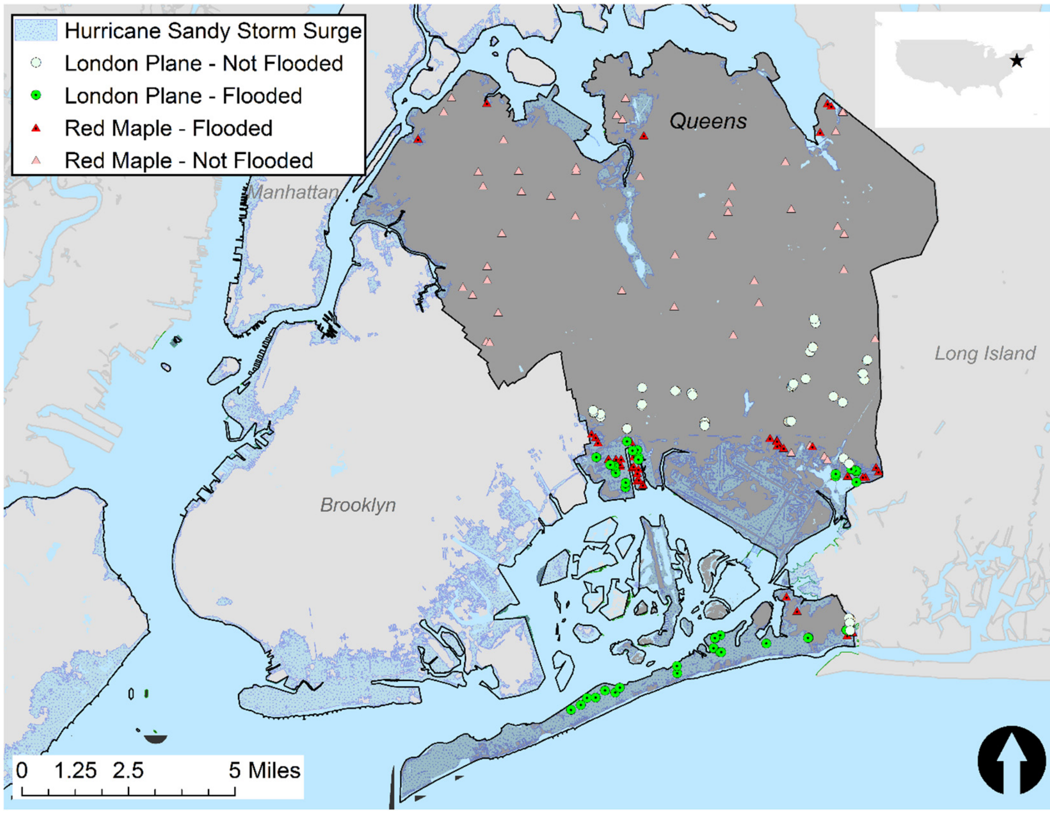

Fig. 1. Study area in Queens, NY showing red maple (red triangle) and London plane (green circle) study trees. Trees located in light blue areas within the NYC boundary were inundated with salt water during Hurricane Sandy. All other trees were not impacted by salt water. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of wind and debris. However, salt water flooding may have caused additional stress to approximately 48,000 street trees located in the storm's inundation zone. Early in the first growing season following Hurricane Sandy (June 2013), NYC Parks staff examined these street trees and found that 6864 of the flooded trees had a significant proportion of their crown fail to leaf out. Thirty percent of those trees did not leaf out at all. The most commonly affected trees were London plane (*Platanus* × *acerifolia*) and maple species (*Acer* spp.). Here we show that red maple (*Acer rubrum*) is negatively impacted by salt water flooding but can recover over time. London plane trees, on the other hand, experience high mortality and show no signs of recovery 3 years post Sandy. We demonstrate that by 2080 a similar storm could impact almost 100,000 of NYC's street trees.

Hurricane Sandy was an unusual storm and one analysis suggests that the conditions that propelled Sandy into the east coast of the U.S. are not likely to occur again (Barnes, Polvani, & Sobel, 2013). On the other hand, the world's largest port cities are expected to experience increased exposure to coastal flooding due to sea level rise and storm surge during the next 50 years (Hanson et al., 2011). Increased coastal flooding of urban landscapes will also impact our cities' trees, yet little is known about the tolerance of urban street trees, park trees, and forests to salt water inundation.

The projected increase in urban coastal flooding comes at a time when cities, both large and small, in the U.S. and around the world are engaging in urban greening projects (Pincetl, 2010). The increased effort and investment in urban green infrastructure reflects a broad based recognition that trees provide valuable ecosystem services (Seamans, 2013) and are important to the health and wellbeing of urban populations (Kardan et al., 2015). The hope is that street trees planted today will still be alive, healthy and reaching their peak value in terms of ecosystem services they provide in approximately 50 years. A greater understanding of different tree species' tolerance of periodic salt water inundation can inform urban greening strategies in cities' flood prone areas.

NYC Parks survey data provided initial evidence that salt water flooding during Sandy may have impacted the health of all street trees located in the flood zone. Although we are not aware of research specifically looking at the effects of salt water flooding on urban trees, there is extensive literature about the negative effects of flooding and salinity on non-halophyte plants. Soil inundation causes many physiological changes in woody plants not adapted to flooding, including: suppression of leaf formation and expansion; premature leaf abscission and senescence; shoot dieback; inhibition of photosynthesis and carbohydrate transport, macronutrient absorption, root formation and growth (Kozlowski, 1997). Salinity induces a separate suite of symptoms, including: leaf scorching, leaf shedding, twig dieback, and decreased metabolic functions leading to inhibition of vegetative growth (Kozlowski, 1997; Paludan-Müller, Saxe, Pedersen, & Randrup, 2002). Combined flooding and salinity decrease tree growth and survival more than either stressor alone (Kozlowski, 1997). Tolerance to both flooding and salinity varies widely by tree species and genotype (Allen, Chambers, & Stine, 1994; Kozlowski, 1997; Paludan-Müller et al., 2002).

In this study we set out to understand street tree response to salt water inundation by using fine-scale tree health metrics designed to assess physiological stress of trees (Pontius & Hallett, 2014). Our questions were: 1) How much does salt water flooding during a major storm surge event affect the health of street trees? 2) Do flooded street trees recover from stress caused by salt water inundation and how long does recovery take? 3) Are some tree species more sensitive to salt water flooding than others?

1.1. Methods

We chose red maple and London plane street trees for this study because they are among the most common NYC street trees. Red maple is one of the top ten most commonly planted street trees in NYC, making up about 3.5% of the citywide population (City of New York Parks & Recreation, 2006). London plane trees are the most common street tree in NYC (City of New York Parks & Recreation, 2006), making up 15.3% of the citywide street tree population. In addition, the two species may have different physiological tolerances to salt water inundation. We hypothesized that red maple would be more tolerant to salt water inundation because of its ability to grow "on a wider range of soil types, textures, moisture, pH and elevation than any other forest species in North America" (Burns & Honkala, 1990). We expected London plane to exhibit a greater sensitivity to salt water inundation, as it has been found to be more susceptible to damage from road salt than other street tree species (Gibbs & Palmer, 1994).

Red maple and London plane street trees in Queens, New York were selected from Hurricane Sandy inundation zones using spatial data from the Federal Emergency Management Agency's (FEMA) Hurricane Sandy impact analysis (FEMA Modeling Task Force (MOTF), 2014) overlaid with the NYC street tree map based on the city's 2005 tree census (City of New York Parks & Recreation, 2006) (Fig. 1). In 2013, fifty flooded red maple trees were selected along with an equal number of red maple trees that were outside the inundation zone. In 2014 we added similar cohorts of London plane trees to the study.

For red maple, unflooded trees were selected from anywhere in Queens, while for London plane, unflooded trees were selected from zip codes adjacent to flooded trees (Fig. 1). All London plane trees were adjacent to single family housing land use; however, some sampled red maple trees were in residential-commercial zones or industrial zones. All surveyed trees were mature (7.9–92.7 cm diameter at breast height (DBH) for red maples, 23.4 – 108.0 cm DBH for London plane trees) and were planted in sidewalk tree pits.

Tree health assessment of red maples took place in July 2013, July 2014, and August 2015. London plane trees were assessed in September 2014 and August 2015. Tree health assessment methods were adopted from Pontius and Hallett (Pontius & Hallett, 2014). Ocular estimates of leaf discoloration, fine twig dieback and crown vigor were made for each tree. Crown transparency was assessed using a digital camera (Pontius & Hallett, 2014) and chlorophyll fluorescence measurements were taken for five leaves from each tree using the Handy PEA (Plant Efficiency Analyzer) chlorophyll fluorescence meter (Hansatech Instruments Ltd., England United Kingdom). Leaves were dark adapted for 30 min prior to measurement. We used performance index (PI) and Fv/Fm for our analyses. PI is a measure of how efficiently a leaf can use light for photosynthesis (Hermans et al., 2003) and Fv/Fm is a measure of the efficiency in photosystem II.

To compare street tree health inside and outside the flood zone, Z-scores were calculated for leaf discoloration, fine twig dieback, crown vigor, PI and Fv/Fm and then averaged to create a stress index value for each tree (Pontius & Hallett, 2014). Low values represent healthier trees and high values represent trees that are showing signs of severe decline. The index was calculated separately for red maple and London plane trees. Trees that were dead or removed in between sampling visits (presumably due to poor health or death) were assigned maximum values for leaf discoloration, fine twig dieback and crown vigor. This gave dead or removed trees a maximum stress index value and allowed us to include them in the analysis.

We used a repeated measures completely randomized experimental design and tested the effects of Hurricane Sandy flooding on tree stress using repeated measures mixed-effects models followed by Tukey HSD for means separation (JMP v12.2.0). Red maple and London plane were analyzed separately. To test for effect of land use and spatial location for red maple, we used land use and associated interactions in the red maple model and found that it was not significant and AICc increased, hence land use is not included in our models. Results with $\alpha \leq 0.05$ were accepted as statistically significant.

PRISM spatial datasets of modeled growing season (June, July, August) precipitation and maximum temperature at 800 m resolution (Prism Climate Group., 2016) for 2013, 2014, and 2015 were compiled for red maple trees in the study. Precipitation was summed across the growing season and mean maximum temperature was calculated to facilitate comparison between years.

We quantified the kilometers of roads susceptible to salt water inundation by overlapping both 1) US Census Bureau Core Metropolitan Statistical Areas (CMSAs) (US Census Bureau., 2014; US Census Bureau., 2015) adjacent to the Atlantic Ocean and 2) NOAA's shallow coastal flooding GIS layer (NOAA., 2016) in ArcGIS 10.1. This shallow coastal flooding layer delineates areas commonly flooded under current sea level and climate conditions during high tides. We also examined the effects of coastal flooding during Hurricane Sandy (FEMA Modeling Task Force (MOTF), 2014) and future storm conditions (Gilmer & Ferdana, 2012) (2080 A2 scenario, with a Category 2 storm). Similarly, we quantified the number of NYC street trees susceptible to salt water inundation by overlaying the NYC street tree map based on the city's 2005 tree census (City of New York Parks & Recreation, 2006) with the aforementioned coastal flooding layers.

2. Results

2.1. Red maple

Time since flooding and flooding status significantly impacted tree health for red maple (Table 1). One growing season after Hurricane Sandy, flooded red maple street trees exhibited significantly poorer health than those that were not flooded. Two and three growing seasons after Hurricane Sandy, unflooded trees became more stressed and the flooded trees exhibited no change in their overall stress index value (Fig. 2). There were no significant differences in overall red maple tree health between flooded and unflooded trees during the second and third growing seasons after Sandy.

Two years post Hurricane Sandy; PI was higher for flooded trees indicating greater photosynthetic efficiency in the new leaves. However, leaf discoloration, dieback, and vigor were still higher for flooded trees (Table 2). Red maple mortality was 2% for unflooded trees and 10% for flooded trees by the end of year three. There was a decreasing trend in PI for unflooded trees post Hurricane Sandy indicating lower photosynthetic efficiency in trees that were not impacted by salt water flooding (Table 2).

2.2. London plane

Flooded London plane trees exhibited greater signs of stress two and

Table 1
A repeated measures mixed effects modeling technique was used to understand the effects of salt water flooding (flooding), year and the interaction between flooding and year on red maple and London plane tree stress. Year compares years after hurricane Sandy (October 2012) for 100 trees of each species. Red maples were assessed in 2013, 2014 and 2015 and London plane were assessed in 2014 and 2015. Surrounding land use was not included in the red maple model due to lack of significance and a higher AICc. London plane sample trees were all located within the single-family home land use.

Whole Model	Red Maple Stress Index $R^2 = 0.72$, n = 300		London Plane Stress Index $R^2 = 0.83$, n = 200	
Effect	F	P > F	F	P > F
Flooding	4.2	0.043	177	< 0.001
Year	6.1	0.003	0.9	0.335
Flooding × Year	2.1	0.119	16	0.0001

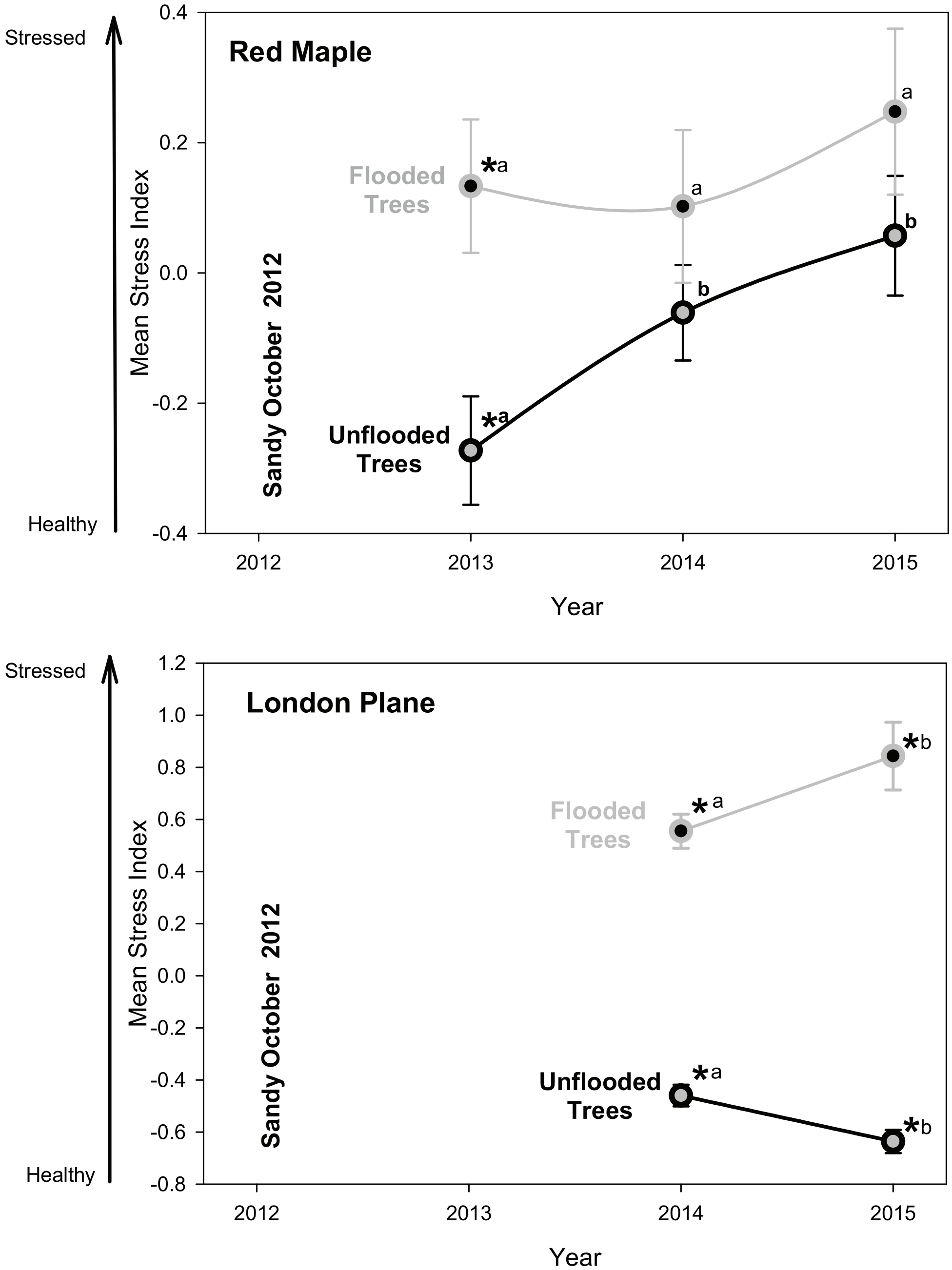

Fig. 2. Mean stress index for flooded and unflooded trees. Error bars are ± 1 SE. Significant differences (α ≤ 0.05) between flooded and unflooded trees denoted with an *. Year to year differences (within flooding status) are significant if marked with a different lower-case letter. Flooded red maples 1-year post Hurricane Sandy are significantly less healthy than unflooded trees. Flooded and unflooded red maple health does not differ in subsequent years. Flooded red maples show no significant changes in health over time while unflooded red maples become more stressed 2 and three years post Hurricane Sandy. Flooded London plane trees are more stressed than unflooded trees two and three years post Hurricane Sandy. Flooded London plane trees are less healthy in 2015 than in 2014 while unflooded London plane trees are healthier in 2015 than 2014.

three years post Hurricane Sandy (Fig. 2, Table 2). In addition, flooded London Plane trees exhibited 56% mortality while unflooded London Plane trees did not experience any mortality by the end of year three (Table 2). Transparency, discoloration and dieback were all greater for flooded trees than unflooded trees in both years. Unlike red maples, London plane tree health continued to decline for flooded trees and improved for unflooded trees. Our mixed-effects model confirmed that flooding status was a significant factor in the health of London plane trees (Table 1).

2.3. Climate

To understand why unflooded red maples had increasing stress levels over time (Fig. 2) we set out to determine whether they experienced different climatic conditions than their flooded counterparts given their spatial distribution (Fig. 1). Growing season (June, July, August) precipitation and temperature can impact tree health if they deviate from norms. Total growing season precipitation in 2013 was 369 mm (mm), which was 60 mm higher than average (1961–1990 mean). In 2014, precipitation was 29 mm below average, and in 2015, precipitation was just 7 mm above average. Mean maximum temperature for the growing season in each of the three years was within one degree Celsius of the average mean high of 28∘C (1961–1990). Unflooded red maples experienced higher mean maximum temperatures than flooded but the difference was only 0.2 °C.

2.4. Future salt water flooding scenarios

The eastern U.S. has over 5794 km of urban roadways susceptible to salt water inundation from shallow coastal flooding under typical weather conditions (NOAA, 2016). Of this extent, 42 km are present in NYC. Coastal storms, like Hurricane Sandy, can increase the number of roads and street trees impacted by salt water inundation. For instance, during Hurricane Sandy 1426 km of roads were flooded in NYC, over 33

Table 2
Average stress index values and individual tree health assessment variables that are used to create the stress index. Standard error in parentheses. To test for differences in stress index between year and flooding status we used a repeated measures mixed effects model with Tukey HSD (JMP v12.2.0). Bolded values denote significant differences ($\alpha \leq 0.05$) between flooded and unflooded trees of the same species within a given year. Differences between year (within flooding status) are significant if marked with different lower-case letters. Percent mortality is the cumulative proportion of initial sample trees that died.

Year	N	Mortality	Z-score		Transparency		FvFm		PI		Discoloration		Dieback		Vigor	
Red Maple																
Unflooded																
2013	49	NA	**−0.273a**	(0.08)	**21.04%a**	(0.9%)	**0.773**	(0.006)	5.59a	(0.36)	1.22	(0.16)	8.2%	(2.0%)	2.4	(0.17)
2014	49	0%	−0.061ab	(0.07)	24.50%b	(1.1%)	0.776	(0.007)	**2.59b**	(0.30)	**1.16**	(0.16)	**7.1%**	(1.4%)	**2.3**	(0.17)
2015	49	2%	0.057b	(0.09)	22.06%ab	(1.5%)	0.781	(0.008)	1.92b	(0.19)	1.33	(0.14)	12.4%	(2.8%)	2.7	(0.16)
Flooded																
2013	51	NA	**0.133**	(0.10)	**27.13%a**	(1.4%)	**0.744**	(0.011)	4.91a	(0.34)	1.59	(0.17)	14.5%	(2.7%)	2.9	(0.16)
2014	51	6%	0.102	(0.12)	23.13%b	(1.0%)	0.755	(0.010)	**5.70a**	(0.42)	**1.63**	(0.16)	**18.5%**	(3.5%)	**2.9**	(0.17)
2015	51	10%	0.248	(0.13)	20.12%b	(1.2%)	0.762	(0.010)	2.13b	(0.24)	1.41	(0.15)	22.7%	(4.2%)	2.7	(0.19)
London Plane																
Unflooded																
Year	N	Mortality	Z-score		Transparency		FvFm		PI		Discoloration		Dieback		Vigor	
2014	50	NA	**−0.460a**	(0.04)	**28.05%a**	(0.9%)	**0.825**	(0.002)	1.20a	(0.07)	**1.40a**	(0.07)	**4.0%**	(0.9%)	**2.2a**	(0.14)
2015	50	0%	**−0.636b**	(0.04)	**18.46%b**	(0.7%)	0.828	(0.001)	1.64b	(0.10)	**1.20b**	(0.07)	**6.1%**	(0.8%)	2.5b	(0.10)
Flooded																
2014	50	NA	**0.555a**	(0.06)	**48.9%a**	(2.2%)	**0.810a**	(0.004)	1.12a	(0.09)	**2.96a**	(0.03)	**49.7%a**	(4.3%)	**3.9a**	(0.04)
2015	50	56%	**0.843b**	(0.13)	**71.0%b**	(4.9%)	0.822b	(0.003)	1.52b	(0.13)	**2.40b**	(0.12)	**68.9%b**	(5.3%)	4.3b	(0.13)

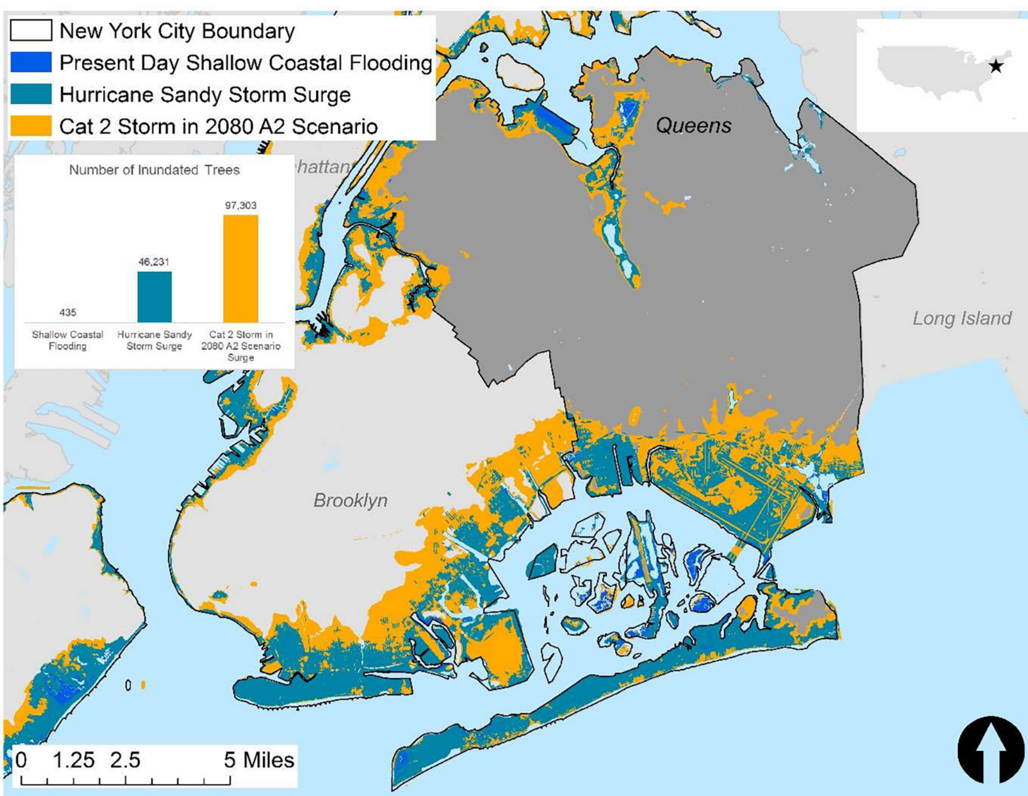

Fig. 3. Study area in Queens, NY showing the extent of current shallow coastal flooding (dark blue), coastal flooding from Hurricane Sandy (teal blue), and the maximum estimated coastal flooding in 2080 during a Category 2 storm, under the A2 IPCC scenario (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

times the modeled present day shallow coastal flooding prediction. Under future climate change scenarios, which include sea level rise, it is likely that kilometers of urban roadways impacted by salt water flooding will increase dramatically (Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013; Hanson et al., 2011). In NYC, kilometers of flooded roads could double during storms under the IPCC A2 scenario in 2080 (from 1426 km to 2766 km) (Fig. 3), impacting over 97,000 street trees, 51,072 more street trees than were flooded during Hurricane Sandy (FEMA Modeling Task Force (MOTF), 2014; Gilmer & Ferdana, 2012; NYC Department of Parks and Recreation, 2005).

3. Discussion

The immediate physical impact of Hurricane Sandy on street trees was not unexpected. However, we did not anticipate that the trees left standing after the storm would experience significant health problems and mortality. Salt water flooding was associated with significant physiological stress to both red maple and London plane street trees. Over half of the flooded London plane study trees died and those that remained alive continued to decline for several years. On the other hand, red maples appear to be more salt tolerant with only 10% of the flooded trees dying and, over time, no change in the physiological stress for living trees. Unflooded red maples showed signs of increased stress over time. We hypothesized that unflooded red maples experienced lower rainfall or higher temperatures than flooded trees because of their geographic distribution. Modeled PRISM data indicated that there was no difference in growing season precipitation between cohorts and only a small difference in mean maximum temperature. Either climate is not a factor in the unflooded tree's increased stress level or we needed finer spatial resolution data to detect a difference.

Questions remain regarding whether flooded NYC street trees will continue to decline or recover over time, but it is clear that salt water inundation has had an adverse effect on street tree health in the Hurricane Sandy flood zone for both red maple and London plane trees. We found evidence that different tree species can have a wide range of tolerance to salt water inundation. More research is needed to rank street tree species as to their level of salt tolerance and to determine whether flooded London Plane trees recover over time.

Given that salt water flooding causes chronic stress and even mortality of street trees, we set out to determine the possible extent of urban coastal flooding in the eastern U.S. The eastern U.S. has almost 6000 km of urban roadways that are currently susceptible to shallow coastal flooding. This estimate will be exceeded during storm events. For instance, 42 km of NYC's streets are susceptible to shallow coastal flooding and during Hurricane Sandy, 1426 km of NYC streets were flooded (Fig. 3).

Thus, the number of impacted street trees increased from less than 500 to over 46,000 during Hurricane Sandy. Our focus on street trees means that these numbers represent a minimum of impacted city trees because we are ignoring trees in parks, forests, and trees on private property. More research is needed to understand the impact of salt water flooding on these other urban trees.

Future sea level rise scenarios suggest that the world's largest port cities will experience increased exposure to coastal flooding (Hanson et al., 2011). Fig. 3 shows the projected impacts to NYC's street trees under future sea level rise scenarios. We estimate that in the year 2080 a category 2 storm could flood twice as many kilometers of NYC streets than were flooded during hurricane Sandy, affecting 97,000 street trees, more than double the number of trees flooded by the storm surge in 2012. The frequency of this flooding will likely increase with future climate change (Hallegatte et al., 2013).

We demonstrate that an increasingly large portion of our urban forest resource could be impacted by salt water flooding in the future. The street trees we plant today in urban coastal areas are very likely to be impacted by salt water inundation during their lifespan. This study demonstrates that different tree species have a wide range of tolerance to salt water flooding. This is important information for urban forest land managers to consider as coastal cities around the world prepare for increased flooding over the next several decades. If we can learn more about which species are tolerant to salt water flooding, cities that are seeking to replace trees in flood prone coastal zones can choose species that are more likely to survive in these areas.

Another possible strategy for increasing the resilience of our coastal urban forests is to identify genotypes of salt tolerant tree species that are hyper-tolerant to salt in their environment. Red maple is a species with a high degree of genetic variability and corresponding variation in flood tolerance (Anella & Whitlow, 1999). If we can identify red maple genotypes that are hyper-tolerant to high saline conditions, they would make good candidates for planting in coastal flood prone areas. For a strategy like this to be viable, multiple tree species need to be evaluated for salt tolerance and further work needs to be done to identify hyper-tolerant genotypes within the most tolerant tree species. Allen et al. states that there is reason for "cautious optimism" about the prospects for increasing salt tolerance of forest tree species (Allen et al., 1994). Subsequent work has shown that some *Populus* spp. clones are salt tolerant and can be used in phytoremediation of high saline soils (Zalesny, Zalesny, Wiese, Sexton, & Hall, 2008). Application of these methods and principles to developing salt tolerant urban street trees would go a long way to improving the resilience of our coastal urban forests over the next century.

4. Conclusions

Trees in cities are important because of their ability to cool the environment, the ecosystem services they provide, and their aesthetic value. Cities around the world are investing in planting and caring for urban trees and forests to increase urban tree canopy cover. Healthy trees grow faster and have a greater impact on improving the urban environment. This study makes it clear that coastal flooding, especially from storm surge, has significantly damaged New York City's trees. It has not damaged them equally, however. Some species such as red maple are less stressed and can recover better than other species when inundated by salt water.

The city of New York, like many coastal cities, is in the midst of planting to replace trees that have been lost to storms. It's crucial that planting decisions take into account new knowledge about tree species that will survive better in a changing climate, one in which coastal flooding increases in likelihood. It's also important for scientists and urban planners to understand the significance of continuing to study how species respond to an increasingly likely stressor such as storm surge.

On a larger, scale, however, this study is of greatest significance not for New York City, but for how it acts as a case study for how other coastal cities may want to monitor their trees' response to coastal flooding. There may be other tree species which, like red maple, are less stressed by salt water flooding than other species. Certainly, there will be important decisions about planting and re-planting in all the world's coastal cities. Climate change projections make it clear that the likelihood of coastal flooding is only going to increase. This study opens the door to a host of shared studies than can help cities around the world make more responsive, informed decisions about urban forest management.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2018.05.004. These data include Google maps of the most important areas described in this article.

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