Climate Change Vulnerability Assessment for the Urban Forest in Cambridge

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City of Cambridge, Massachusetts

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Highlights:

- We use a series of event scenarios to visualize vulnerability of tree species to extreme weather events and pest infestations.
- Cumulative responses from all scenarios highlight species resistance.
- Analysis can inform effective management of the urban forest to climate-driven stressors.

ABSTRACT

City ordinances for Cambridge, Massachusetts recognize the value of in the city's urban forest in terms of air quality, lower wind speeds, aesthetics, energy conservation, noise pollution, habitat, decreased runoff, and bolstering of local businesses and property values. The number, composition and location of trees within the urban forest will be influenced by future climate-related extreme events. The vulnerability of the City's urban forest to climate change has been assessed by evaluating the effects of possible scenarios on the composition and abundance of trees; the assessment shows the potential impacts of each of these scenarios on the premise that they are increasingly probable. The scenarios considered were a hurricane/tropical storm similar to tropical storm Sandy in 2012, an increase in heat stress, an early or late snow or ice event (e.g. loss of tree limbs), Asian longhorn beetle or emerald ash borer pest infestations, and the cumulative effect of all these scenarios. The sensitivity of tree species to each threat was collected from the literature, and a rule to determine the anticipated loss was derived. The results are a reasonable indication of the most tolerant tree species in Cambridge and their locations. This vulnerability assessment can inform proactive management of the urban forest.

1. Introduction

Our changing climate will impact the number and species of trees that thrive in different locations. The Northeast Climate Impacts Assessment (Frumhoff et al. 2007) concludes that New England can expect significantly warmer temperatures, earlier springs and a shorter snow season. Downscaling by Hayhoe et al. (2008) indicate that inland and higher latitudes are expected to have the largest increase in temperature, but that coastal areas could be most prone to changes in the precipitation pattern. The Massachusetts assessment of climate impacts predicts 30-60 days above 90℃ annually by the end of the century, up from 5-20 days currently (Massachusetss Climate Change Adaptation Advisory Committee, 2011). Although other projections may differ in the specific number of hot days, the trend of more days anticipated to exceed 90℃ translates into a greater potential for heat waves which are considered as 3 or more consecutive days with temperatures exceeding 90℃. The New England Regional Assessment provided a detailed assessment of the potential impacts of climate on specific sectors, including regional forests (NERAG, 2001).

Several assessments and studies suggest the mechanisms and impacts of changing climate on forests. A recent article in the Atlantic suggests Western forests are at risk due to encroachment, drought, pests, changing patterns of snow fall, and an expanding burn season (Garland, 2013). The New England Regional Assessment (NERAG, 2001) suggests that air quality, nutrient depletion, ice storms and species migration, including pest species, will all contribute to changing composition and location of forests. The Northeast Climate Impacts Assessment (NCIA) projects “dramatic” changes in northeastern forests this century (Frumhoff et al. 2007). The NCIA analysis suggests a near complete loss of spruce/fir forest under high CO_2 emission scenarios. A severe reduction in hemlock stands is also projected due in part to the expanded habitat for the fatal woolly adelgid hemlock pest.. Vermont’s Agency of Natural Resources developed a series of white papers on climate change, including a review of the impacts on Vermont’s Forests (Wilmot, 2011). Vermont’s projection includes the replacement of northern hardwood forests with oak and pine species. Also noted are increased risk from pests, specifically woolly adelgid, emerald ash borer (EAB) and Asian long-horned beetle (ALB). This analysis also mentions the potential for more frequent short-term droughts, which may limit tree growth.

Managed forests have additional capacity for change and a means of coping with threats related to climate. For example, Vermont’s analysis specifically mentions reduced growth rate from increasingly common short-term droughts. However, urban forests can actively combat short-terms droughts with watering campaigns or devices. Coping strategies developed for forests include altering its structure and composition to reduce vulnerability and developing recovery strategies that reduce the length of the disturbance (Dale et al. 2001). These two classes of management strategies have also been described as resistance and resilience strategies, respectively (Millar et al. 2007).

Here we describe an assessment of effects of possible climate-driven scenarios on the composition and abundance of trees in the context of the urban forest located in the City of Cambridge, MA. Cambridge places a high value on their trees for a number of reasons which include enhanced air quality, lower wind speeds, aesthetics, reduced energy consumption, reduced noise pollution, habitat provisioning, decreased runoff, and increased property values. We have developed a vulnerability assessment which identifies the potential response to a number of events having increased likelihoods, and the City of Cambridge Department of Public Works street and park tree database to display the outcomes of those events as a GIS overlay. The results of the vulnerability assessment inform how the City may manage their urban forest to reduce the impacts of extreme events.

2. Study area and data

The Depart of Public Works for the City of Cambridge, MA, has developed and maintained a comprehensive tree inventory of public street and park trees (Cambridge Department of Public Works, 2011). The report includes a catalogue of all of the city's public trees, including species, diameter at breast height (DBH), number of trunks, and general condition. The GIS layer, "DPW_StreetTrees", is available online (Cambridge MA, 2014). Using these data we determined the species that encompass at least 90% of the identified trees in Cambridge: 34 species have been included in the vulnerability assessment. In total, there are 20,507 trees in the DPW data base, of which 1,810 (8.8 %) were species infrequent enough to be assessed. Of the included trees, 923 (4.5%) were characterized in the database as "unknown" species; these trees were also not assessed.

3. Methods

The scenarios that have the potential to impact the integrity of trees has been identified and compared to previous studies on the sensitivity of each of the 34 most common species (Table 1) found in Cambridge. The composite of the tree response functions for each threat define the urban forest response to each scenario (Table 2). Geospatial analyses were performed in ESRI ArcGis® v10.1, and projected in the Massachusetts State Plane Feet coordinate system (NAD 1983). Data were obtained online from the Massachusetts Office of Geographic Information System (MassGIS, 2014) and from the City of Cambridge Information Technology Department (ITD), Division of Geographic Information, (Cambridge MA, 2014). The maps presented here show mortality of a percentage of all susceptible trees; therefore, "hot spots" of tree mortality represent a random percentage of a specific species. The spatial results will change with each trial based on the location of different species.

3.1 Hurricanes and Tropical Storms

The devastating effects of tropical storms in recent years have documented New England's vulnerability to such systems. As the climate warms, studies have indicated that the frequency of severe weather events will increase (Frumhoff et al. 2007) . In 2012, Hurricane Sandy made landfall in Atlantic City, NJ as a Category I hurricane. Had the storm centered closer to Massachusetts, at high tide, six percent of Boston would have been flooded according to the Boston Harbor Association's *Preparing for the Rising Tide* report (Douglas et al. 2013). Factoring in projected sea-level rise, the cost of damage resulting from storm surges is expected to increase. Although, rising sea level is not including in the modeling of these storms; it does represent a severe scenario. Consequences of this magnitude will be increasingly likely with rising sea level.

In this study, we considered the impacts of a category 1 storm on the Saffir-Simpson wind scale (119-153 km/h) on Cambridge's urban forest by assessing the loss of trees from wind, salt water inundation, and flooding. The wind speed of Hurricane Sandy at landfall (130 km/h) was used in this analysis. The category

The 2013 MassGIS "Hurricane Surge Inundation Zones" GIS layer, as developed by the New England District U.S. Army Corps of Engineers (USACE), available online from MassGIS (2014), was used to assess potential storm surge inundation areas based upon the best available information at the time of this analysis. Lastly, we assumed inundation would change the salinity of all flooded areas. Salinity tolerance followed the descriptions provided by the National Resource Conservation Service's Plant database (NRCS 2014), where tolerance level is described by the salinity concentration (dS/m) that causes a "slight reduction in growth."

A review of tree damage and mortality from 2007 (Duryea et al. 2007) describes the relative wind resistance of many species and the relative mortality of species with different tolerance levels. Following Hurricane Ivan which hit the Gulf Coast of the United States in 2004, the resulting mortality for species with high levels of wind damage, such as tulip popular and spruce pine, ranged from 50% to 80%. The resulting mortality for species with intermediate levels of wind damage, such as Bradford pear and red maple, ranged from 25% to 50%. Resistant tree species have mortality rates below that. However, Ivan produced winds at a higher velocity (209 km/h) than is expected in the Cambridge scenario. Therefore, the scenario for Cambridge was modeled as expected to result in 50% mortality for highly susceptible species, 25% mortality for species ranked as both high and moderately susceptible, and 15% to moderately susceptible species.

Cambridge is more frequently impacted by Nor'easters (extra-tropical cyclones) than hurricanes. These storms are larger and slower than the hurricane scenario described above. Therefore, the wind and precipitation patterns are likely to be different from these storms. The wind of Nor'easters is less constant and on the average lower in comparison to a Category 1 hurricane. However, the storm may stay longer over one area; therefore, more precipitation may result over this longer period of time as well as snow and ice. Since these wind patterns and inundation maps are not available, the vulnerability to a Nor'easter was not assessed in this analysis.

3.2 Heat Stress

Regional climate projections predict an overall increase in the number of heatwaves (i.e., at least 3 consecutive days exceeding 90°F) as they are defined for New England (Hayhoe 2008; Frumhoff et al. 2007). The number of days above 90°F is projected to be 30-60 by 2100 according to Frumhoff et al. (2007). Hayhoe (2008) projects that, in the 2090's, there will be an additional 20-40 days above the 1990 90th percentile temperature threshold; this temperature differs according to the model used but corresponds to 90-100°F. We will consider a heat stress scenario for Cambridge based on a shift in the American Horticultural Society's Heat Zone map (AHS, 2014). The

City of Cambridge currently resides in Heat Zone 4, which has a minimum of 14 days above 86̊F and a maximum of 30 days above that temperature. The projected conditions differ in specifics according to which model and assumptions are made; however, the annual number of days anticipated to be above 86̊F in the distant future (after 2090) corresponds most closely to the AHS's current heat Zone 7 e.g., minimum of 60 days. Selection of this zone may be considered an extreme case of heat stress. However, we consider susceptible species as those that will not tolerate AHS Heat Zone 7. We assume limited water stress to these trees because of the potential for irrigation provided by the city.

3.3 Early/Late Winter Event (Leaves-on)

Climate predictions for the region indicate an increase in precipitation; the majority of that increase is likely to occur during winter months (Frumhoff et al. 2007). As average temperatures are expected to increase, urban trees are expected to begin leafing out earlier in the year and retain foliage for a longer period of time (Frumhoff et al. 2007). In association with more erratic weather patterns, the potential exists for an increased likelihood of damage from snow and ice loading (Ryan and Kane 2011) as well as frost damage (Cannell and Smith 1986). The susceptibility of tree species to damage from heavy snow or ice was considered. Because the available research describes the susceptibility of tree species as tolerant/intolerant, we will consider up to a 40% loss of vulnerable trees. This level of loss is consistent with the 43% probability of long-term mortality (Tremblay et al. 2005) and the reported 58% loss of damaged trees three years after storm events (Turcotte et al. 2012). The spatial results of this scenario will produce the most change from trial to trial because the loss of trees (40% of vulnerable species) occurs city-wide.

3.4 Severe Rainstorm

In the Northeast, an increase in average precipitation has been anticipated for every season time (Frumhoff et al. 2007). Coupled with more variability in regional rainfall patterns, increased precipitation may result in more frequent flood events. Such storms can either drown roots (Iles and Gleason 2008) or loosen soil to facilitate windthrow (McBride and Leffingwell 2006). Tree species loss will be determined by its relative flood tolerance and its location considering its elevation relative to the 1-percent annual chance of flooding ("100-year flood") zones, as developed by the Federal Emergency Management Agency (FEMA) in their 2013 "FEMA National Flood Hazard Layer (NFHL)" for Massachusetts (MassGIS 2014). A 100-year flood event is likely to increase in frequency with the severity of the progression of climate change; therefore, this scenario serves as a proxy for the impacts of a severe flood with an annual probability of occurrence increasing from 1% in 2009. Because the available research describes the susceptibility of tree species to flooding as tolerant or intolerant (Bratkovich et al. 1993), we will consider a 50% loss of individual trees submerged in the current (as of 2009) 100-year flood scenario.

3.5 Pest Infestation

Although little is currently known about the effects of climate change on herbivorous pests and tree pathogens, it is likely that their impact on the forest will increase through a) direct biological effects on the pest species, b) indirect effects and increased stresses on trees, and c) indirect changes in natural pest predators (Ayres and Lombardero 2000). Two pests currently of concern for New England were chosen as threats: (1)Asian Longhorned Beetle (ALB) and (2)Emerald Ash Borer (EAB). These pests were chosen because of the large number of susceptible trees in Cambridge and the large-scale mortality that an infestation of either type would cause. Because of the severity and spread of an ALB infestation in the northeast, we will assume all hosts and infrequent host species will be removed. In the case of the EAB, we will assume loss of 85% of all host trees (DeSantis et al 2012; Destantis et al 2013).

3.6 Cumulative

Taken together, these scenarios represent an overview of the potential climate change threats posed to the City's urban forest. The cumulative effects of all scenarios were visualized assessed through a compilation of all aforementioned scenarios.

4 Results and Discussion

4.5 Hurricanes and Tropical Storms

Following a storm similar to Sandy (2012), Cambridge's urban forest will suffer tree mortality as a result of such a storm. Our analysis indicates 57% of trees will die as a result of wind-related damage, 8% from salt water inundation, and 16% due to flooding. The wind speed of a Sandy-type hurricane in the Cambridge area would be expected to be in the Category 1 hurricane on the Saffir-Simpson wind scale (119-153 km/h). Based on the composition of each species in Cambridge, pears and red maples are expected to encounter the greatest loss from wind damage. However, there may be loss of oak, ash, London plane tree, and Japanese lilac. Maples, honey locust, and linden are the most common wind resistant trees. The loss from wind-related damage extends across the City, but is most obvious in eastern Cambridge and in areas where the trees are clustered such as Cambridge Cemetery, Danehy Park, and the Fresh Pond area, but this result will vary from trial to trial because of the probabilistic nature of the tree loss.

Due to the presence of Amelia Earhart Dam along the Mystic River (elev. 11.55 ft) and the projected CAT 1 storm surge elevation of 11.5 ft, it is unlikely that the City will be inundated as a result of one of these storms. In anticipation of potential flooding (e.g., storm surge occurrence during highest high tide or dam failure), the most vulnerable areas were identified and tree species' vulnerability were assessed accordingly under the flooding and salinity scenarios. Note, although these inundation maps do not directly include a factor for future sea level rise as expected at the end of the century, they do represent an extreme event scenario. Under these assumptions, inundation associated with a category 1 hurricane covers the northeast quadrant of the City between Fresh Pond and the Cambridge Turnpike. Given category I landfall as high tide with increasing sea level or failure of the Amelia Earhart, the geographic area expected to be flooded is the Mystic river valley shown in Figure 1 (hatched area). The primary description of tree species flood intolerance was defoliation or death following submersion under 4-10 inches of water for 10 days (U. S. Forest Service 2002). The scenario of Cambridge specifies 50% mortality of intolerant tree species in the inundation area. The most common intolerant species include Norway maples and pear trees; the most common tolerant species include honey locust, red maple and oak. The overall pattern of loss from flooding is highest around Fresh Pond. Sea level rise could result in a larger area of impact and/or an increase in the severity of impacts in the inundated area.

Since certain species of trees have little or no salt water tolerance, a hurricane-induced inundation may severely impact salt intolerant species. In this scenario, we have specified a loss of 20% of salinity intolerant species below the inundation line, and 10% of the species characterized as slightly tolerant. Red maple, linden and London plane tree will be adversely impacted by salinity, while Norway maple and pear (spp.) are not expected to be impacted. The response to salinity results in tree losses in the Alewife area and around Lusitania Field.

The anticipated overall loss of trees from windthrow, inundation and salinity following a Category I hurricane is 13.2% and is shown in Figure 1. This image shows the distribution of tree mortalities across the City. Because of the limited geographic area impacted by saltwater inundation, the majority of the effect is windthrow.

4.2 Heat Stress

Heat stress is anticipated to have minimal impact on the City's trees. None of the species that make up 90% of the urban forest have a AHS maximum heat zone rating of 6. Many can tolerate up to AHS heat zone 8 or 9. A few species, notably honey locust, are reported in heat zone 7. However, these trees are expected to suffer no increased mortality for the projected time period considered, which would extend until at least 2090.

4.3 Early/Late Winter Event (Leaves-on)

Snow and ice loading and associated tree limb damage is likely to occur in the spring after leaf out, or before defoliation in mid-late fall. Among the most susceptible trees are linden, cherry and elm species. The response to snow or ice loading results in the sporadic loss of trees, or 11% of vulnerable species (Figure 2). However, there is a concentration of anticipated tree loss in mid- Cambridge and along Massachusetts Ave. near the Charles River.

4.4 Severe Rainstorm

Flooding impacts the urban forest through the loss of tree species intolerant to submersion for a specific number of days. As described in the hurricane inundation scenario above, the most common flood-intolerant species are the Norway maple and pear sp.; the most common tolerant species are honey locust, red maple and oak sp.. The 2013 FEMA NFHL denotes locations in City residing in the special flood hazard zone area “AE”. This zone is subject to flooding by the 1% annual chance flood and the flood water surface elevation has been determined. A 25-ft buffer was applied to the AE zones to account for boundary DPW trees residing within these zones. Areas at risk under the 100-year flood follow the banks of the Charles River and the Alewife Brook Parkway area. Flooding resulted in the projected loss of 15% of vulnerable species in both areas (Figure 3). The loss is most intense in the dense tree growth area along the Charles River towards the Lechmere Canal Park.

4.5 Pest Infestation

Infestation, and subsequent control measures (e.g., culling infected species), will have profound effects on the urban forest. Ash species will be destroyed by both EAB and ALB; many of these are located in Danehy Park or along Putnam Avenue (Figure 4). An ALB infestation would also require the removal of elm sp., maple sp. and London plane trees. Overall, removal of trees as a result of ALB infestation results in a massive loss of tree across the city (41%), especially in the Mt. Auburn area (Figure 5). To a much lesser extent, only 4% of trees are expected to be lost due to the EAB.

4.6 Cumulative

Together, these scenarios represent an overview of the potential threats posed to the City’s urban forest exacerbated by climate change. Although these scenarios are not expected to occur together, they each highlight vulnerabilities. Considering a cumulative response allows the identification of the most resilient species and locations in Cambridge. Assessment of the cumulative response to all scenarios shows widespread tree loss, or 58% (Figure 6), however pockets of viable street trees are noticeable in central Cambridge. Honey locust, pin oak, and sycamore are among some of the more common and more resilient species to these specific threats.

5 **Conclusions**

This vulnerability assessment of the urban forest of Cambridge MA anticipates the loss of tree species in response to a set of climate-driven scenarios, specifically a category 1 hurricane, warmer climate, flooding, a late or early season snow or ice event, pest infestations, and the cumulative effect of all scenarios. No climate change projections were made in this study. Rather, the relevance of the scenarios to the future of Cambridge's urban forest was justified using a subset of the existing climate projections. Each of the results presented provide a picture of the composition of today's forest following one the extreme event scenarios. Most of the scenarios have been projected to become increasingly frequent with time (1-3), and therefore, the results are become increasingly probable. However, these specific scenarios are not predicted to occur or have impacts in any specified time frame. One exception is the application of AHS's heat zone tolerance; Cambridge's climate is not likely to correspond to AHS heat zone 7 until the end of the century at the earliest. However, heat stress is not anticipated to effect Cambridge's urban forest composition, regardless of the timeframe over which the AHS heat zone 7 scenario is relevant. Generally, because these scenarios are expected to become increasingly common over time, effective management is key to minimizing the impact of any extreme event.

The loss of trees and tree species in response to climate-associated extreme events shows the most severe impact from culling of trees following an ALB infestation. Other impacts are limited to a specific area, such as the FEMA 100-year flood zone. Tree mortality following an ice storm or a heavy snow event is scattered across the city but impacts a smaller percentage of trees than an infestation. Recommendations for individual tree species which are tolerant to many of these conditions can be developed and vetted by the City's arborist and development division. Pin oak and honey locust are all relatively resilient to the scenarios presented here. Maple sp. are robust with the exception of susceptibility to the ALB. Pine sp. are resilience to all the scenarios if they are planted outside potential salt water inundation areas. With further investigation, these species may be incorporated more frequently into the City's planting program and use to replace trees that are lost in storms or other extreme events.

According to Cambridge Municipal Ordinances, the urban forest functions to conserve energy by providing shade and evaporative cooling through transpiration; improve local and global air quality by absorbing carbon dioxide, ozone, and particulate matter, and producing oxygen; reduce wind speed and direct air flow; reduce noise pollution; provide habitat for birds, small mammals, and other wildlife; reduce storm runoff and the potential for soil erosion; increase real estate property values; and enhance visual and aesthetic qualities that attract visitors and businesses. The loss of trees under each scenario will impact the aforementioned functions to a certain degree.

Further analysis should determine the relationship between tree species and location with each function. Then the loss of functionality can be calculated for each scenario. Here we only attempt to display the potential degradation of the forest under different extreme events. It is possible that some tree loss may enhance functionality (for example, habitat value). From the cumulative loss of tree species from all scenarios, we assume that there will be at least some loss in function of the urban forest throughout the City. However, effective management of trees may compensate for these anticipated losses.

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Table 1. Species sensitivity to each aspect of the identified scenarios

		Hurricane			Heat	Early/Late Winter Event	Rain	Pests	
	Threat	Wind	Flooding	Salinity	Temp Stress	Ice/Heavy Snow	Flooding	Asian Longhorn Beetle (ALB)	Emerald Ash Borer (EAB)
	Score Description	1 = high levels of wind damage; 2 = intermediate levels; 3 = low levels	10 days under 4-10 inches of water	0=none, 1=low, 2=medium, 3=high	Maximum AHS Heat Zone	3 = highly susceptible, 2 = moderately susceptible; 1 + relatively tolerant	10 days under 4-10 inches of water	0=no, 1=occasional host, 2=preferred host	0=no, 1=host
	REFERENCE	Duryea, Kampf and Littell 2007	"Flooding and its effect on Trees", Forest Service 2002	Natural Resources Conservation Service PLANT database	AHS Encyclopedi a of Plants and Flowers (2011)	Sisinni, et al. 1995; Tremblay, et al. 2005	Forest Service 2002	Cambridge Tree Inventory	Cambridge Tree Inventory
RANK	SPECIES								
33	arborvitae	3*	tolerant*	2	7	1*	tolerant*	0	0
8	ash, green	2	tolerant*	1	9	1.6	tolerant*	1	1
21	ash, white	3	tolerant*	2	9	1.6	tolerant*	1	1
18	cherry spp	2	intolerant	2*	7*	2.8	intolerant	0	0
22	cherry, sargent	2	intolerant	2*	9	2.8	intolerant	0	0
15	crabapple spp	2*	tolerant	2*	8	1	tolerant	0	0
17	elm spp	3	tolerant*	2*	9*	2.4	tolerant*	2	0
25	elm, American	3	tolerant*	1	9	2.4	tolerant*	2	0
32	elm, lacebark	3	tolerant*	0	9	2.4	tolerant*	2	0
12	ginkgo	2*	intolerant*	2*	9	1	intolerant*	0	0
2	honey locust	3*	tolerant	2	7	2	tolerant	0	0
13	lilac, Japanese tree	2*	intolerant*	2*	8	1*	intolerant*	0	0
9	linden, American	3	tolerant	0	8	2.8	tolerant	0	0
5	linden, little leaf	3	tolerant	0	8	2.8	tolerant	0	0
26	maple, hedge	3*	tolerant	2*	8*	1.85	tolerant	2	0
1	maple, Norway	3*	intolerant	2	7	1	intolerant	2	0
3	maple, red	1;3	tolerant	0	9	2	tolerant	2	0
23	maple, silver	3*	tolerant	1	8	1.85	tolerant	2	0

14	maple, sugar	3	intolerant	0	8	1.7	intolerant	2	0
27	maple, Nwy crim kg	3*	intolerant	2	7	1	intolerant	2	0
4	oak, pin	2;3	tolerant	1	8	2	tolerant	0	0
11	oak, red	1;3	tolerant	2	9	2	tolerant	0	0
30	oak, swamp white	2;3	tolerant	0	8	1	tolerant	0	0
6	pear spp	1*	intolerant*	2*	8*	1.1	intolerant*	0	0
28	pear, Bradford	1*	intolerant*	1	8	2*	intolerant*	0	0
29	pine, austrian	3*	intolerant*	2	7	1*	intolerant*	0	0
31	pine, red	2;3	intolerant*	0	7	1*	intolerant*	0	0
16	pine, white	2;3	intolerant*	1	9	1*	intolerant*	0	0
7	plane tree, London	2*	tolerant*	0	8	1.2	tolerant*	1	0
34	serviceberry(common)	3*	tolerant*	1	9	1*	tolerant*	0	0
20	sophora (japonica)	3*	tolerant*	2*	9	3	tolerant*	0	0
24	sweet gum, American	3	tolerant*	0	9	1	tolerant*	0	0
19	sycamore (American)	2;3	tolerant	0	8	2.5*	tolerant	0	0
10	zelkova, Japanese	2;3*	tolerant*	0	9	2*	tolerant*	0	0
		*Additional references: Forests for Oregon, Spring 2009; University of Florida, The Urban Forest Recovery Program, 2007; eHow "Deciduous Small trees for Windy Conditions, " "Trees and Shrubs for Windbreaks," "Trees that Withstand Wind," and "Wind Resistant and Tolerant Trees" as well as the references within.	*Additional references: "Flood Tolerant Trees," Michigan State University extension; "Flooding Effects of Trees," University of Minnesota extension; "Shade and Flood Tolerance of Trees," University of Tennessee extension	*Additional references: "III. Trees observed to have some salt tolerance" Cornell University Extension; "Native Florida Plants Tolerant of Occasion Salt Water Flooding," Sanibel-Captiva Conservation Foundation	Additional references: Arbor Day Foundation (many cherry species); for pear and elm, zone was assumed to be the same for all species.	*Additional references: Shortle et al . 2003; Nebraska Statewide Arboretum 2007; Turcotte et al. 2012			

Table 2. Scenarios and tree mortalities based on the severity of each threat as identified by literature review.

	Threat	Conditions	Outcome	Justification
Hurricane	Wind	Sandy at landfall was 130 km/h	1 = 50% mortality, if two scores then 1= 25% mortality; 2 = 15% mortality	Duryea, Kampf, & Littell, 2007 - Following Ivan (209 km/h), tree mortality for group 1 = 50 - 80%, group 2 = 25 - 50%, 3 = <20%
	Flooding	Raster maps for storm surge maximum of maximum (MOM) water levels	Loss of 50% intolerant tree under 10 inches of water or more	"Flooding and its effect on Trees", Forest Service 2002 describes "intolerant" as defoliation or death of trees under 4-10 inches of water for 10 days.
	Salinity	Inundation is salt water for hurricane scenario	If 0 salinity tolerance and below inundation, then 20% mortality, if 1 salinity tolerance and under 10 inches, then 10% mortality	"Tolerance to a soil salinity level is defined as only a slight reduction (not greater than 10%) in plant growth." NRCS PLANT database (plants.usda.gov/charinfo.html)
Heat	Temp Stress	Projections of 30-60 days above 90℃ by 2100 (Massachusetts Climate Change Adaptation Report)	Loss of trees with maximum heat zone tolerance from 1-6	Heat Zone 7 corresponds to 60 to 90 days above 87℃ (American Horticultural Society)
Early/Late Winter Event	Ice/Heavy Snow	Loading to limbs from ice and snow	Loss of % susceptible species according to level (0% = 1, 10% >=2, 40% = 3)	Up to 30% of sensitive species from Ice (Sisinni, Zipperer and Pleninger 1995); Probability of Long Term Mortality (PLTM) upt to 43% from Ice (Tremblay, Messier and Marceau 2005)
Rain	Flooding	Current FEMA 100-year flood maps	Loss of 100% intolerant trees under 10 inches of water or more	"Flooding and its effect on Trees", Forest Service 2002 describes "intolerant" as defoliation or death of trees under 4-10 inches of water for 10 days.
Pests	Asian Longhorn Beetle (ALB)	Infestation	Infestation of ALB affecting the entire city and requiring removal of all hosts and occasional hosts	Requires removal of "host" species, generally, within 1/2 mile of infection (USDA ALB response guidelines)
	Emerald Ash Borer (EAB)	Infestation	Loss of ash species	Loss of 85% of host species by 2060 (DeSantis et al. 2012)
Cumulative	All		Remaining trees following all scenarios	

Figure Legends

Figure 1. The cumulative loss of trees from a Category 1 hurricane, including windthrow, salinity and inundation. Note, the inundation map does not include the protection of the City from the Amelia Earhart Dam. At current sea level, it is unlikely that a Category I hurricane would overtop the dam; however, it would be overtopped with an additional 6 inches of sea level rise. The hatched area indicates the inundation zone should the dam fail.

Figure 2. The distribution of tree species susceptible to damage from snow and ice loading. The percentage of trees anticipated to be impacted is low and scattered. However, more susceptible individuals are seen in the eastern part of the city.

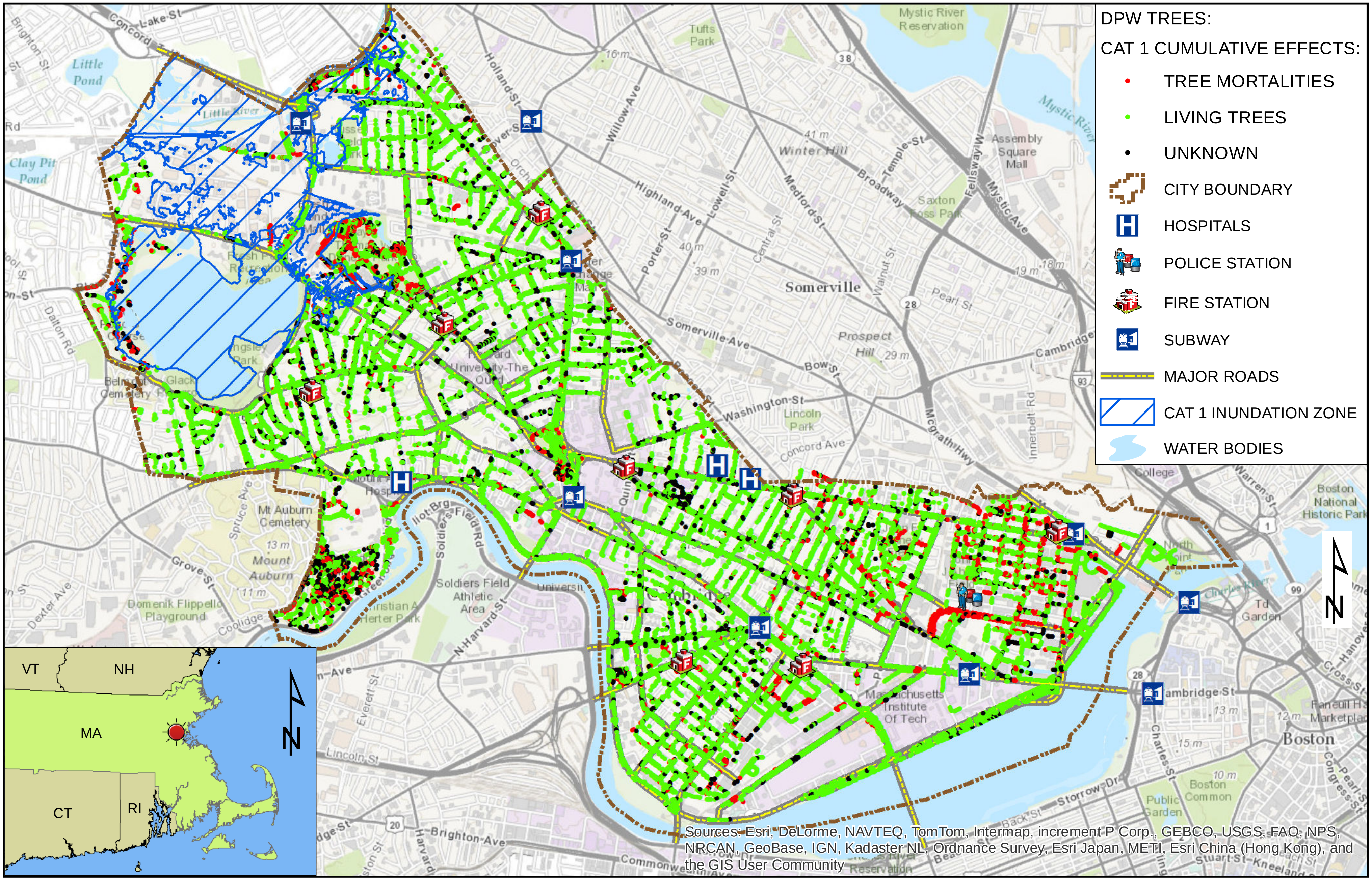
Figure 3. Current 100-year FEMA flood zones (hatched) are overlaid with anticipated loss of trees following a flood. With increasing precipitation patterns and sea level rise, flooding of this magnitude is expected to become increasingly frequent in the next century. The flood risk is the highest along the Charles River and the Alewife Brook area. Anticipated loss of trees is the most intense south of Lechmere Canal Park.

Figure 4. The Emerald Ash Borer (EAB) and its anticipated impacts on the urban forest; ELB would precipitate the loss of all ash hosts: clusters of ash are observed in the Danehy Park area as well as the south central neighborhoods.

Figure 5. Host species vulnerable to Asian Longhorn Beetle (ALB) infestation. In this scenario, we have assumed that all host and occasional host would be impacted or removed. Note the uniform distribution of host across the city, and the substantial number of trees lost.

Figure 6. The cumulative loss of trees in response to all the scenarios. Note the widespread loss of trees across the City, which is mostly due to the loss following EAB infestation. Flood and hurricane inundation are shown as hatched areas on the east and west of the map. Street trees in the center of the city are among the most resilient.

CAMBRIDGE URBAN FOREST: CAT 1 HURRICANE FLOODING, SALINITY, & WINDTHROW MORTALITIES



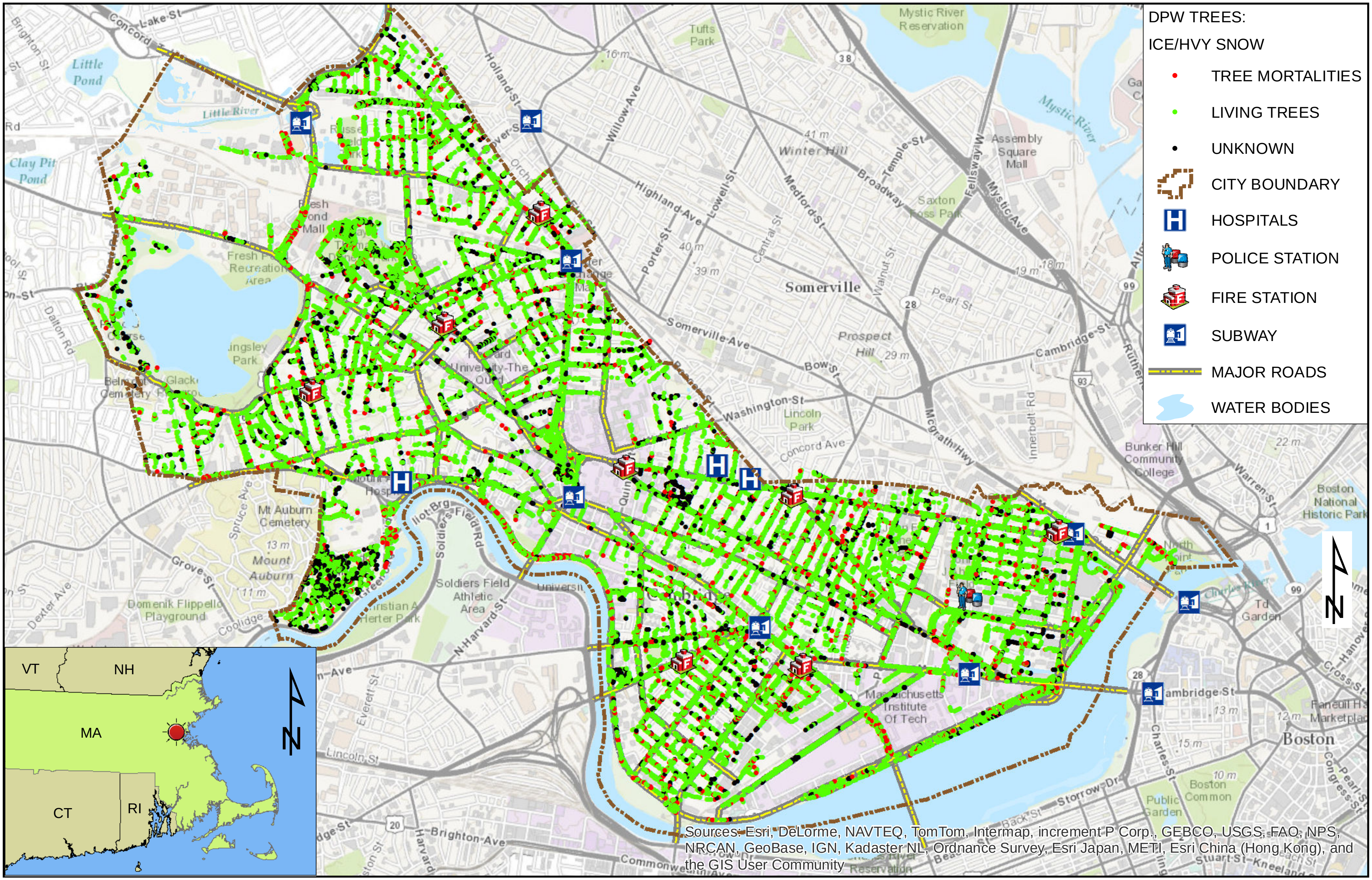
US ARMY CORPS OF ENGINEERS
ENGINEERING RESEARCH & DEV. CNTR
MA SPF, NAD 83
DATE: 3/3/2014

0 0.5 1 2 Miles

1 inch equals 3,000 feet

SOURCES:
ESRI ARCGIS ONLINE
CAMBRIDGE GIS/DIV. ITD
FEMA, NOAA, MASS GIS

CAMBRIDGE URBAN FOREST: ICE& HEAVY SNOW MORTALITIES



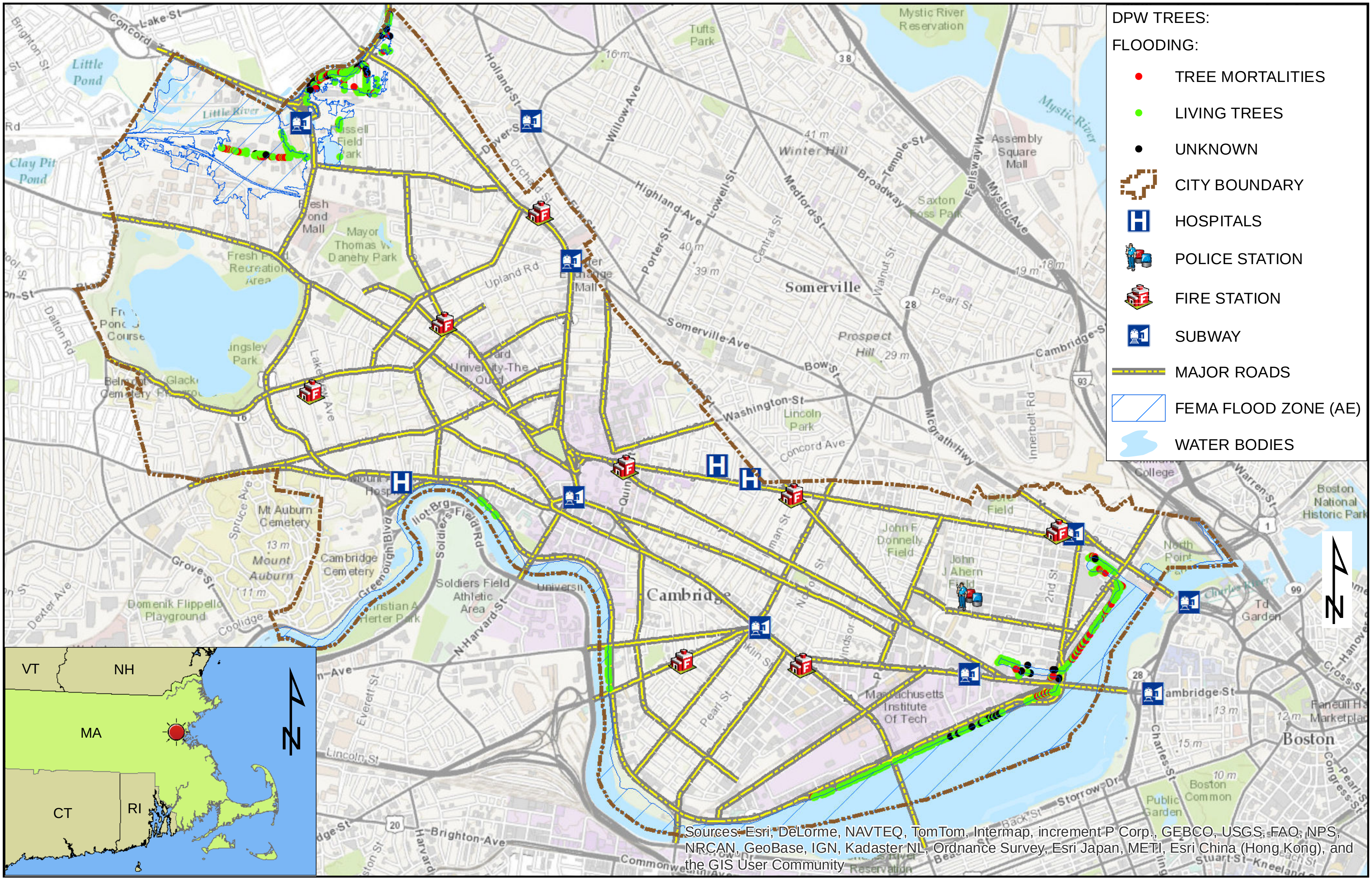
US ARMY CORPS OF ENGINEERS
ENGINEERING RESEARCH & DEV. CNTR
MA SPF, NAD 83
DATE: 2/27/2014

0 0.5 1 2 Miles

1 inch equals 3,000 feet

SOURCES:
ESRI ARCGIS ONLINE
CAMBRIDGE GIS/DIV. ITD

CAMBRIDGE URBAN FOREST: 1% ANNUAL CHANCE OF FLOODING & INUNDATION MORTALITIES



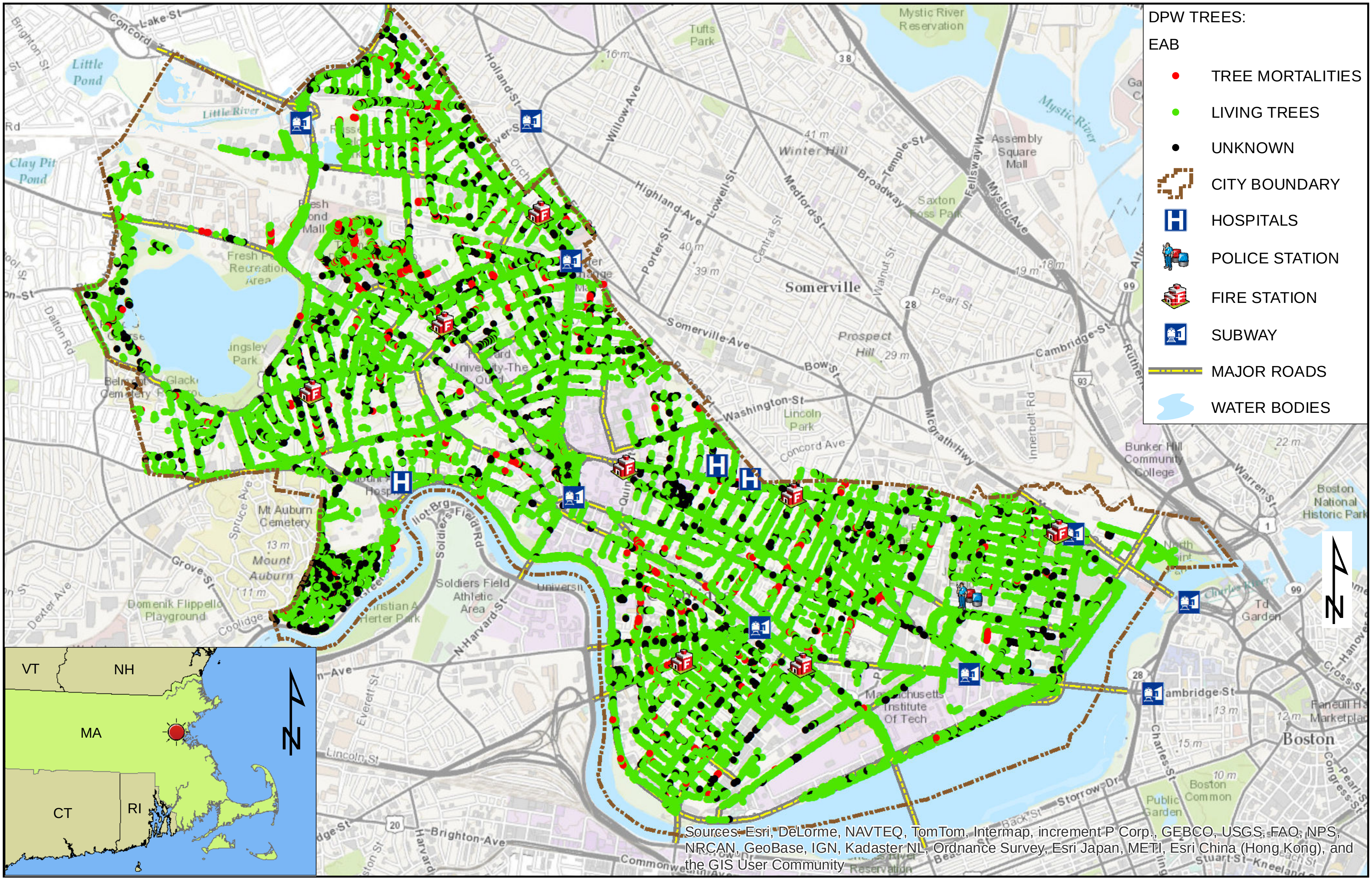
US ARMY CORPS OF ENGINEERS
ENGINEERING RESEARCH & DEV. CNTR
MA SPF, NAD 83
DATE: 2/27/2014

0 0.5 1 2 Miles

1 inch equals 3,000 feet

SOURCES:
ESRI ARCGIS ONLINE
CAMBRIDGE GIS/DIV. ITD
FEMA, MASS GIS

CAMBRIDGE URBAN FOREST: EMERALD ASH BORER (EAB) MORTALITIES



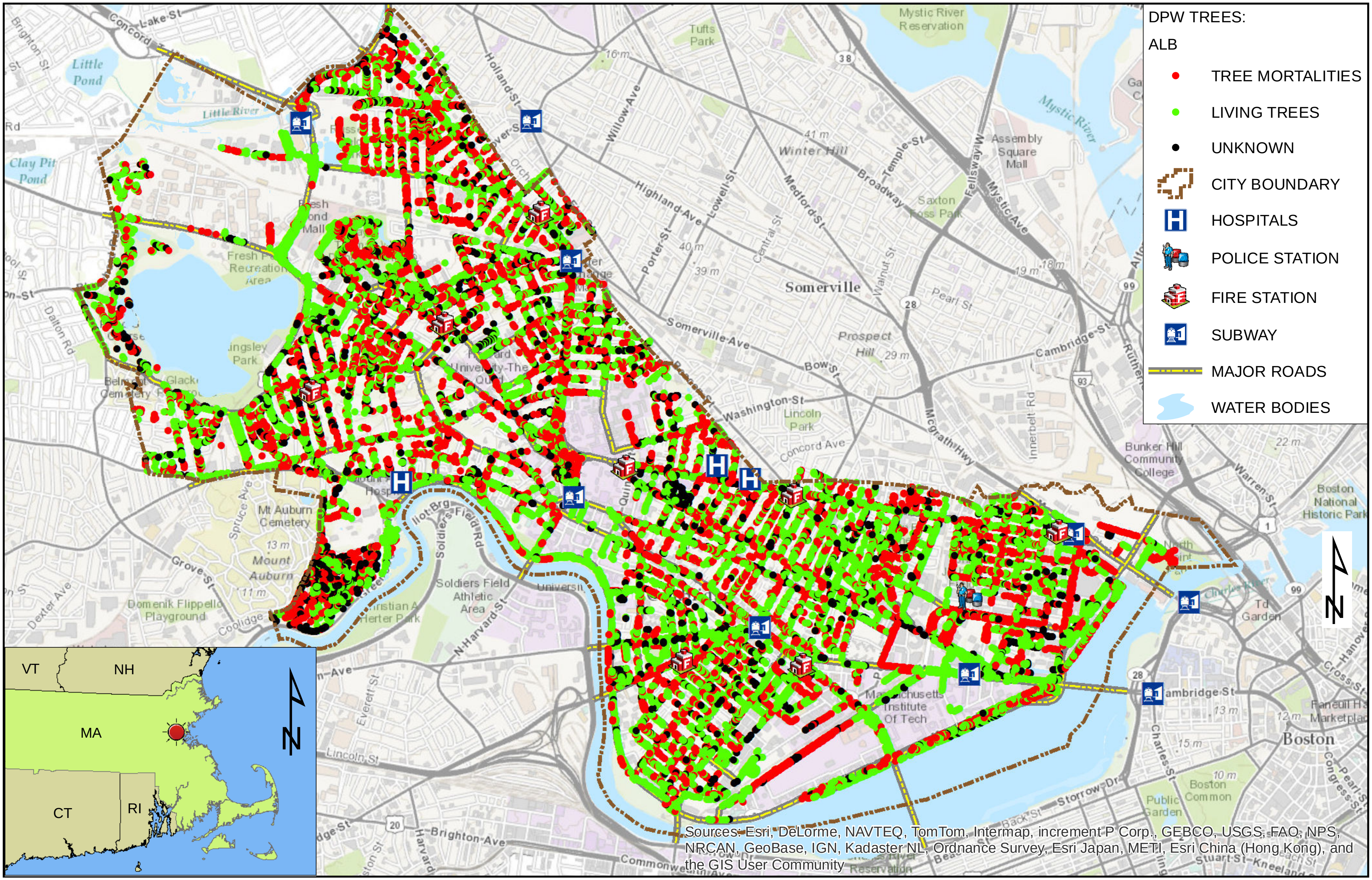
US ARMY CORPS OF ENGINEERS
ENGINEERING RESEARCH & DEV. CNTR
MA SPF, NAD 83
DATE: 2/27/2014

0 0.5 1 2 Miles

1 inch equals 3,000 feet

SOURCES:
ESRI ARCGIS ONLINE
CAMBRIDGE GIS/DIV. ITD

CAMBRIDGE URBAN FOREST: ASIAN LONGHORN BEETLE (ALB) MORTALITIES



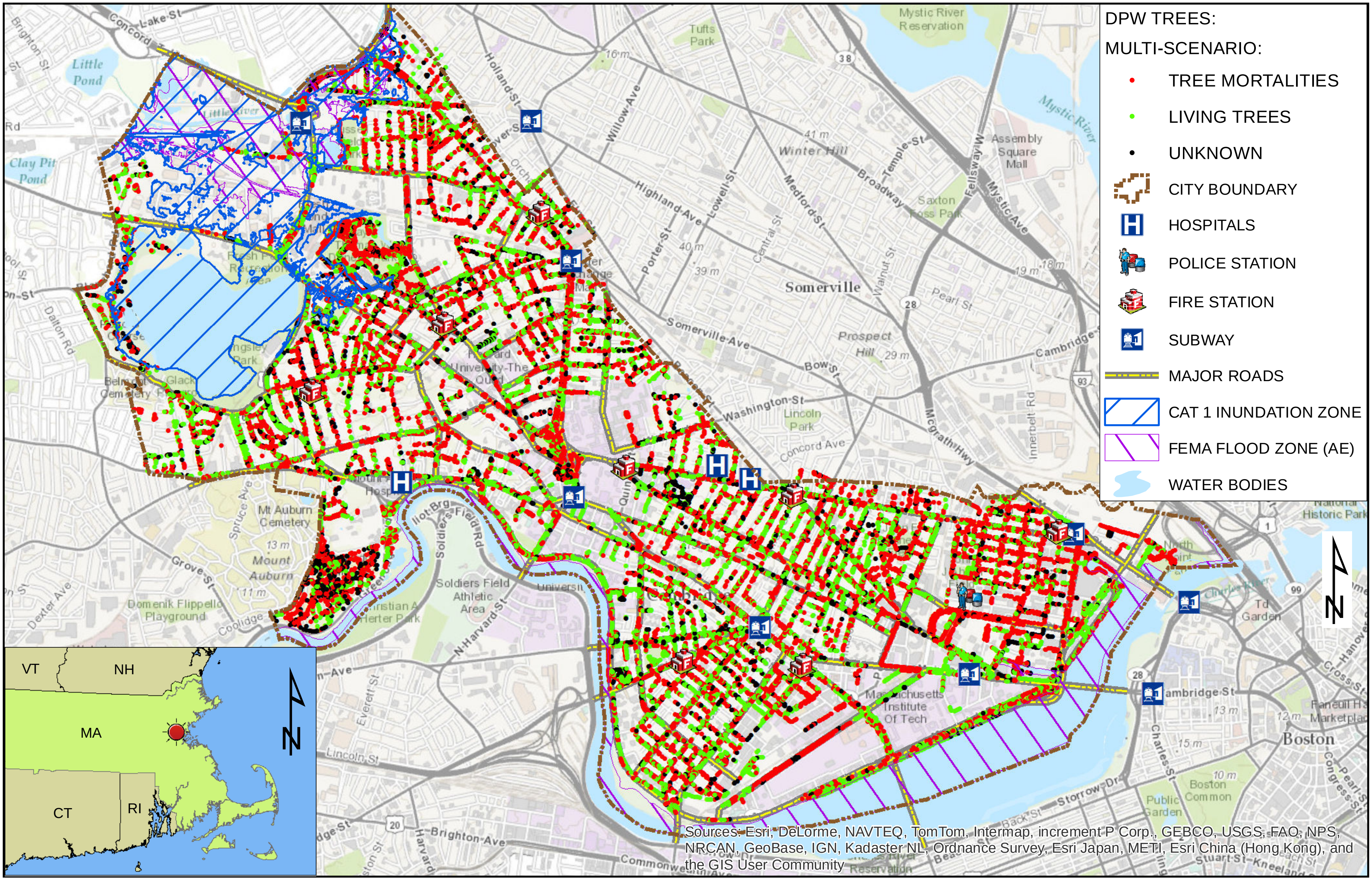
US ARMY CORPS OF ENGINEERS
ENGINEERING RESEARCH & DEV. CNTR
MA SPF, NAD 83
DATE: 2/27/2014

0 0.5 1 2 Miles

1 inch equals 3,000 feet

SOURCES:
ESRI ARCGIS ONLINE
CAMBRIDGE GIS/DIV. ITD

CAMBRIDGE URBAN FOREST: TREE MORTALITIES BASED ON CUMULATIVE EFFECTS



US ARMY CORPS OF ENGINEERS
ENGINEERING RESEARCH & DEV. CNTR
MA SPF, NAD 83
DATE: 3/3/2014

0 0.5 1 2 Miles

1 inch equals 3,000 feet

SOURCES:
ESRI ARCGIS ONLINE
CAMBRIDGE GIS/DIV. ITD
FEMA, NOAA, MASS GIS