Urban Heat Island Technical Report

RESILIENT CAMBRIDGE

Table of Contents

Urban Heat Island

1. Introduction

This technical report details the urban heat island (UHI) analysis completed as part of the City of Cambridge Climate Change Preparedness and Resilience (CCPR) Citywide Plan. It describes the development of the UHI model as a part of the City's Climate Change Vulnerability Assessment (CCVA) and its use in various phases of the City's CCPR planning process. The input data sources and modeling methodology used for this latest round of UHI modeling are identified in Section 2 of the memo. Data from previous and concurrent analyses were used in UHI modeling, including data from the City's Urban Forest Master Plan[1] (UFMP), the CCPR technical memo "Recommendations for Stormwater Strategies for Flood Mitigation" and the NASA Develop team's roof albedo study[2]. The urban heat island (UHI) analysis completed for the Citywide Plan includes:

- Development of a new citywide temperature baseline corresponding to 2018 conditions to incorporate changes in land cover (**tree canopy, impervious** and **cool roof** area) since the initial UHI model was developed in 2010.
- Development of three future citywide cooling scenarios (**tree canopy, impervious** and **cool roof**) to estimate the extent and magnitude of cooling that could be achieved through implementation of cooling strategies.
- Development of updated **ambient air temperature** and **heat index** scenarios to estimate heat vulnerabilities without the implementation of future citywide cooling scenarios.

Modeled temperature results that show spatial variability in the UHI impacts across the City are presented spatially in citywide temperature maps and are summarized quantitatively in graphs. Model limitations and opportunities for further analysis are presented at the end of the memo.

A concurrent study was conducted in 2019 by the Museum of Science Boston, in collaboration with a group of research partners including the City of Cambridge, which collected data from temperature sensors at different time slices during a hot summer day and modeled extreme heat impacts within Cambridge and the surrounding Boston metropolitan area[3]. Heat was modeled for morning, afternoon, and evening periods for a single day in July 2019 by integrating satellite and ground measurements in a predictive model. The modeling methodology and input data used in this study differs significantly from the model developed as a part of CCPR and detailed in this memo. Due to the differences in modeling methodology these analyses were not compared in detail as part of this memo. However, further analysis may be undertaken in future studies to compare the results of different analyses and to better understand and quantify UHI impacts in Cambridge.

---

[1] *https://www.cambridgema.gov/Departments/PublicWorks/Initiatives/UrbanForestMasterPlan*

[2] *https://thrivingearthexchange.org/project/cambridge-ma/*

[3] *https://www.mos.org/pes-forum-archive/wickedhotboston*

2. Model Development and Calculation Process

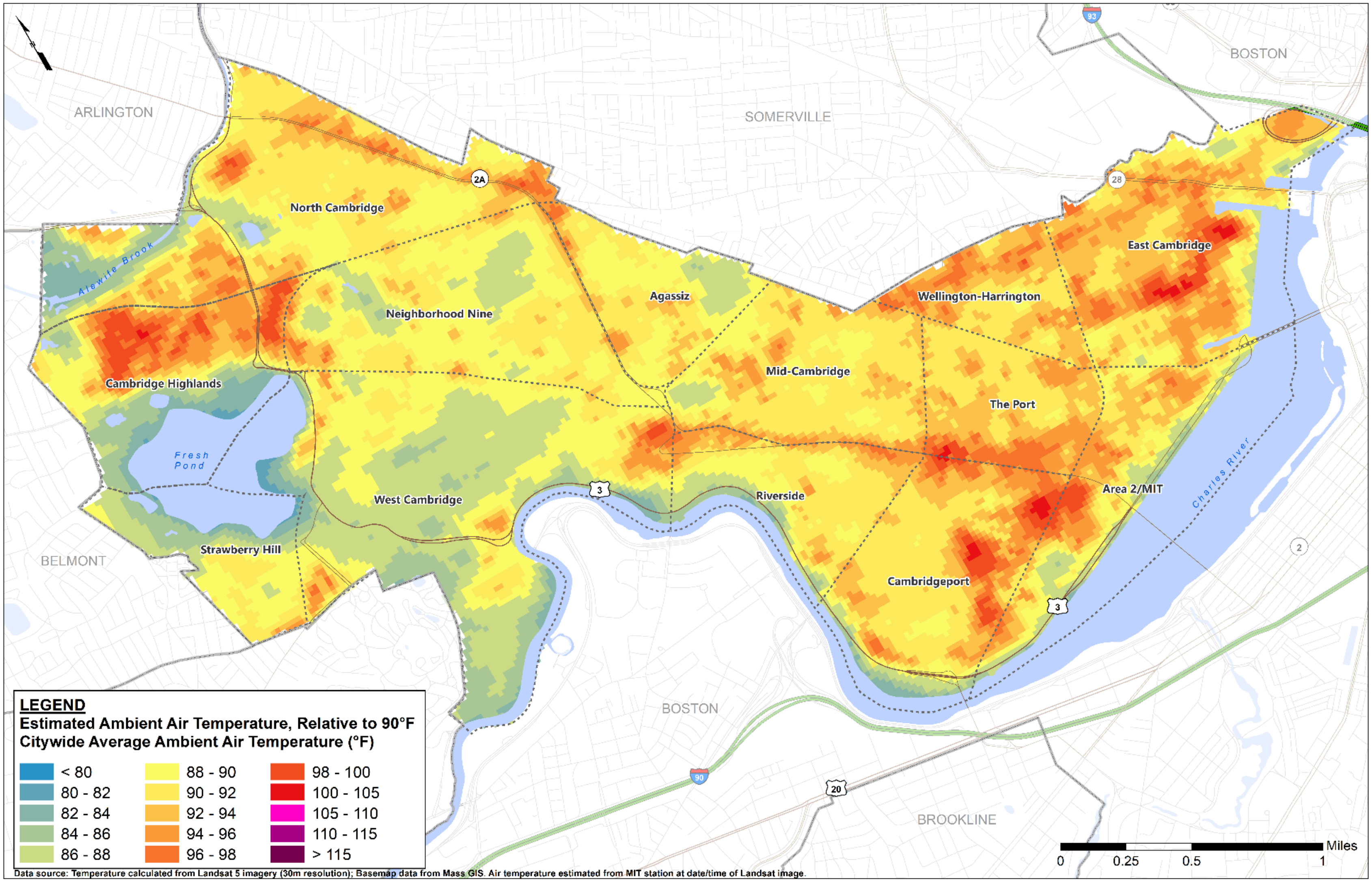
As part of the City's CCVA, Kleinfelder developed an urban heat island model based on using Landsat 5 satellite imagery for the identification of "hot spots". These are areas that experience higher temperatures compared to the City's average temperature. Higher temperatures can be caused by high amounts of impervious area and dark roofs, a lack of canopy, or other weather-related factors. Satellite imagery data was converted to ambient air temperature through a series of conversion steps detailed in CCVA Appendix D Urban Heat Island Protocol for Mapping Temperature Projections[4].

A unique aspect of this model was the conversion of **land surface temperature**, as measured on a surface, to **ambient air temperature** that is the outdoor air temperature. Land surface temperature is typically warmer than the ambient air temperature measured by weather stations. Therefore, land surface temperature was adjusted to estimate ambient air temperature to report extreme heat risk more accurately for the City's population, the main concern for UHI and "hot spots". Ambient air temperature under existing conditions was estimated by establishing a relationship between observed ambient air temperature at weather station locations within the City with the corresponding land surface temperature at these same locations from the model. Ambient air temperature was estimated for representative plausible climate change scenarios by the 2030s and 2070s. This involved multiplying the ambient air temperature values for existing conditions by a scaling factor which was the ratio of average ambient air temperature for future conditions to average ambient air temperature for existing conditions. Similarly, **heat index** was estimated for existing conditions and for representative plausible climate change scenarios by the 2030s and 2070s. Heat index is a more accurate indicator of heat stress for humans. The heat index combines both temperature and relative humidity data to determine the "feels like" temperature that people experience. A day with lower temperatures combined with higher humidity can produce the same level of heat stress as a day with a higher temperature and lower humidity. Future conditions temperature and heat index projections were determined based on a combination of historic extreme heat events in the City and downscaled climate change projections[5]. Figure 1 displays the 2030s baseline temperature grid corresponding to a citywide average temperature of 90°F under 2010 land cover conditions. Ambient air temperature and heat index maps presented in this memo include some corrections to maps presented in CCVA and in the UFMP. Corrections were made to ensure that maps were scaled to the proper citywide average temperature for ambient air scenarios and heat index was recalculated using more realistic values for relative humidity based on observed humidity at weather stations.

---

[4] *https://www.cambridgema.gov/-/media/Files/CDD/Climate/vulnerabilityassessment/ccvareportpart1/climateprojectionsandscenariodevelopment/appendixdurbanheatislandprotocolnovember20151.pdf*

[5] *https://www.cambridgema.gov/-/media/Files/CDD/Climate/CCPR/ccpralewifeappendixbgianalysisanduhimodeling_processed.pdf*



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 1 – Estimated ambient air temperature under 2010 land cover condition.

2.1 Development of Cooling Relationships for Tree Canopy and Impervious Area

Initial cooling relationships were developed to assess the temperature impact of tree canopy and impervious area by intersecting datasets representing these land cover conditions with the UHI temperature grid in GIS. These land cover datasets corresponded to approximately the same timeframe as the UHI temperature grid representing 2010 conditions. The ambient air temperature was plotted against the percentage of tree canopy and impervious area at the 30-meter grid scale, corresponding to the resolution of the source Landsat 5 data. The linear regressions were developed indicated that:

- 1% increase of tree canopy area could yield approximately 0.12°F of cooling[6]
- 1% decrease in impervious area could yield approximately 0.10°F of cooling[7]

These cooling relationships have been used to estimate ambient air temperature and cooling under proposed land cover scenarios in the CCPR Alewife Plan, The Port Preparedness Plan and the City's Urban Forest Master Plan.

The cooling relationships for trees and impervious surfaces have some limitations, mainly that the coefficient of determination (R^2) value for the linear regressions are 0.505 and 0.5696, respectively. This indicates that about half of the variation in temperature can be explained by a single land cover parameter and the remaining variation can be attributed to other land cover parameters and other factors known to impact ambient air temperature. For the purpose of the City's planning efforts, the linear cooling relationships developed were deemed adequate for estimating cooling impacts of implemented strategies. For more information on the development of the impervious area regression refer to CCPR Alewife Appendix B: Green Infrastructure and Urban Heat Island Modeling. For further discussion of the model limitations refer to Section 5 of this memo.

2.2 Development of Cooling Relationship Cool Roofs

The impact of cool roof surfaces on temperature was also assessed in this analysis. A cool roof is one that has been designed to reflect more sunlight and absorb less heat than a standard roof. A meaningful linear regression for temperature and percentage of cool roof area could not be determined as was done for tree canopy and impervious area. This could be due to several factors, such as the small sample size and area coverage of existing cool roofs in 2010 (approximately 1% of citywide land area), variations in roof material, height and slope of different roofs, and other factors including the weather conditions of the day in 2010 when the satellite data was obtained. For the purpose of this analysis, the same cooling relationship developed for impervious area was applied to cool roof area. This is an approximation and may be investigated

---

[6] *https://www.cambridgema.gov/-/media/Files/CDD/Climate/vulnerabilityassessment/ccvareportpart1/climateprojectionsandscenariodevelopment/appendixdurbanheatislandprotocolnovember20151.pdf*

[7] *https://www.cambridgema.gov/-/media/Files/CDD/Climate/CCPR/ccpralewifeappendixbgianalysisanduhimodeling_processed.pdf*

further in future studies to develop a more accurate empirical relationship between cool roof area and ambient air temperature.

2.3 Model Calculation Process

The calculations performed citywide for each 30-meter grid cell in the UHI model are presented below. The model requires inputs of a "baseline" temperature grid, "baseline" land cover conditions and "scenario" land cover conditions to produce results of UHI and temperature change for a certain scenario. *Equation 1* calculates the percent of land cover for each individual grid cell. The percent land cover is calculated for each of the three land cover types (tree canopy, impervious, cool roof) and for a "baseline" and "scenario" condition for a total of six values calculated.

Equation 1

$$\%\ Land\ Cover = \frac{Area\ of\ land\ cover\ within\ 30\ meter\ square\ grid\ cell}{(30\ meter)^2}$$

Equation 2 calculates the estimated change in ambient air temperature for each individual grid cell. The value is calculated for tree canopy and impervious area using the corresponding cooling coefficients developed empirically from linear regressions for the two land cover types. The value is calculated for cool roof area using the impervious area cooling coefficient as an approximation.

Equation 2

$$\begin{aligned}&\Delta\ Estimated\ Ambient\ Air\ Temp_{land\ cover},\ ^{\circ}\mathrm{F}\\&= (\%\ Land\ Cover_{scenario}\ - \%\ Land\ Cover_{baseline}\ )(Cooling\ Coefficient_{land\ cover})\end{aligned}$$

Equation 3 calculates the estimated scenario temperature assuming temperature change from different land cover changes is simply additive. Note that some model scenarios only evaluated the temperature change resulting from changes in one or two of the land cover parameters (tree canopy, impervious, cool roof), in which case the temperature change was calculated zero.

Equation 3

$$\begin{aligned}&Estimated\ Scenario\ Temp,\ ^{\circ}\mathrm{F}\\&= Estimated\ Ambient\ Air\ Temp_{baseline} + \Delta\ Estimated\ Ambient\ Air\ Temp_{tree\ canopy}\\&\qquad\qquad + \Delta\ Estimated\ Ambient\ Air\ Temp_{impervious}\\&\qquad\qquad + \Delta\ Estimated\ Ambient\ Air\ Temp_{cool\ roof}\end{aligned}$$

3. Updated Temperature Baseline and Data Sources

The original temperature baseline grid, developed as part of CCVA, corresponds to land cover conditions from August 30, 2010. Since this date, land cover in Cambridge has changed as documented below. The cooling relationships developed for tree canopy and impervious cover in Cambridge show that both parameters have an impact on the ambient air temperature. The impact of tree canopy and impervious cover on temperature has been shown in numerous studies. One study by Ziter, et al., evaluated how tree canopy and impervious cover influence daytime and nighttime temperature in the midsize city of Madison, WI. The researchers observed that daytime air temperature increased linearly with increasing impervious cover while temperature decreased nonlinearly with increasing canopy cover, with the greatest cooling when canopy cover exceeded 40%.[8] While an empirical cooling relationship could not be developed between cool roof area and temperature in Cambridge, the impact of cool roofs on temperature has been shown in other studies. A study by Mackey, et al. evaluated changes in Landsat temperature measurements in Chicago, IL and concluded that temperature changes were more strongly correlated with albedo increases, from strategies such as cool roofs, than with increases in normalized difference vegetation index (NDVI), from strategies such as green roofs and tree planting[9]. While research into the effects of land cover changes on temperature is still ongoing, it is clear from the existing scientific literature that land cover influences temperature. As part of this analysis the original temperature baseline grid was updated to incorporate changes in **tree canopy, impervious area,** and **cool roofs**.

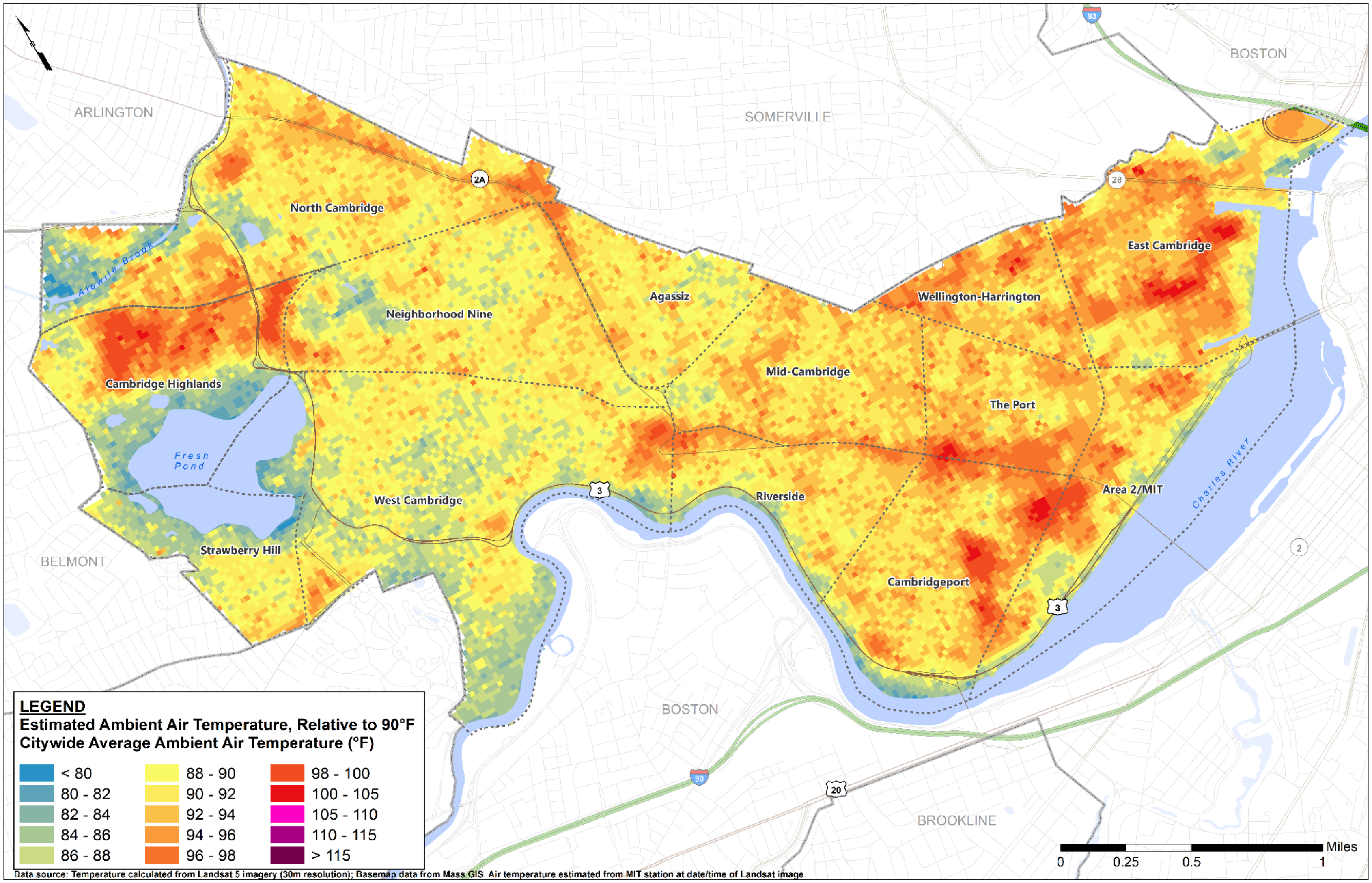
3.1 Tree Canopy Data Sources

GIS datasets representing tree canopy area were obtained from the City of Cambridge for 2009 and from Applied Ecological Services (AES) for 2018. The tree canopy area dataset for 2018 was developed for the City's Urban Forest Master Plan and was the latest available dataset for observed tree canopy conditions at the time of the analysis. Overall citywide tree canopy area decreased by 163.4 acres from approximately 1219.6 acres in 2009 to 1056.2 acres in 2018. Figure 2 shows the updated UHI ambient air temperature for 2018 relative to a citywide average temperature of 90°F and considering only the change in tree canopy area from 2009 to 2018. Figure 3 shows the estimated ambient air temperature change from 2009 to 2018 considering only the change in tree canopy area. These figures were developed as a part of the City's Urban Forest Master Plan. Overall, the decrease in canopy resulted in estimated ambient air temperatures increasing citywide and in localized areas. In some areas, such as areas within Danehy Park and North Point Park, canopy coverage did increase from 2009 to 2018 resulting in some estimated cooling in localized areas as shown in Figure 3.

---

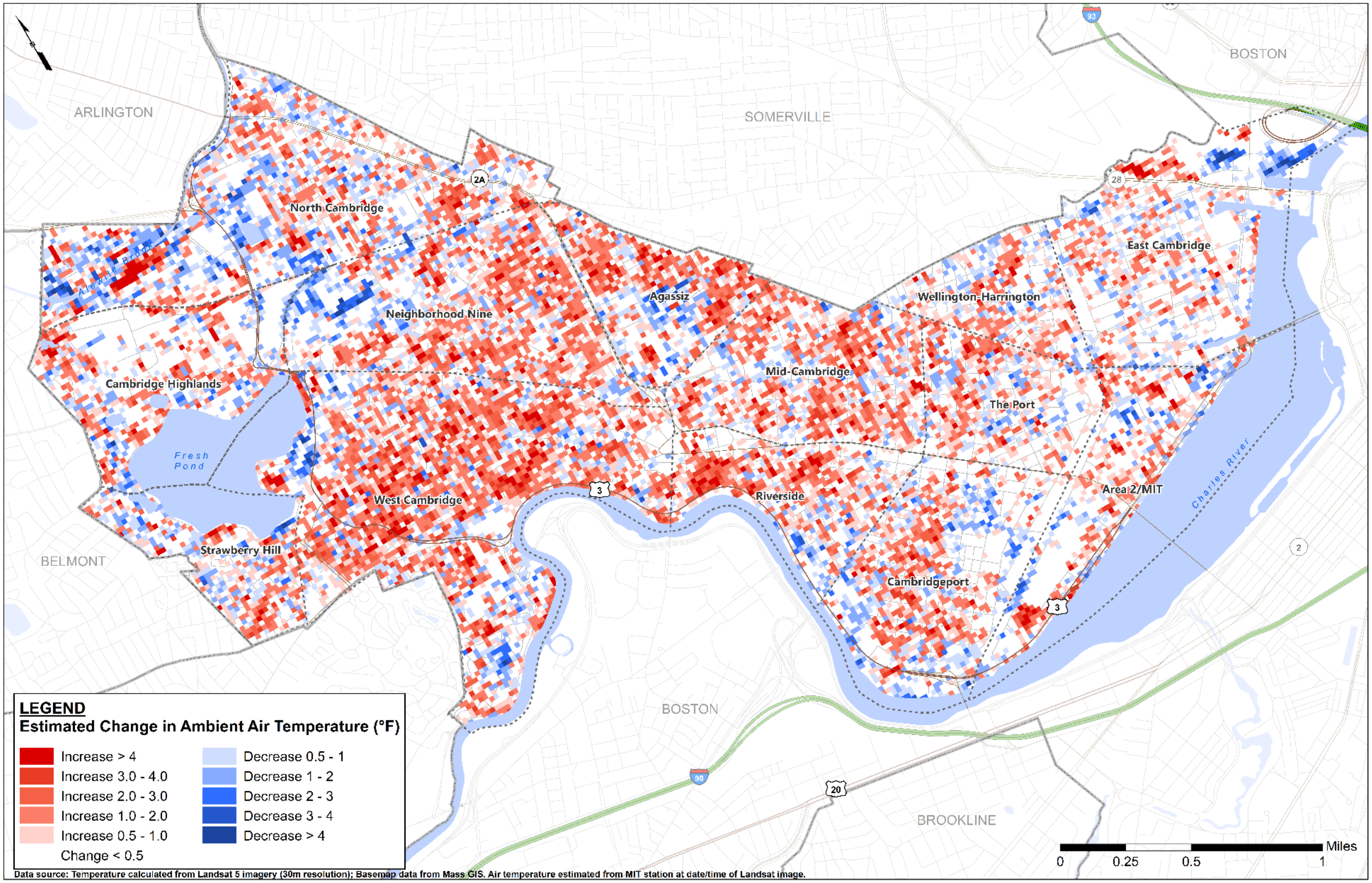
[8] *Ziter, Carly D; Pedersen, Eric J; Kucharik, Christopher J; Turner, Monica G. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. Proceedings of the National Academy of Sciences of the United States of America, 09 April 2019, Vol.116(15), pp.7575-7580*

[9] *Mackey, Lee. "Remotely Sensing the Cooling Effects of City Scale Efforts to Reduce Urban Heat Island." Building and environment 49 (March 2012): 348–358.*



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 2 – Estimated ambient air temperature adjusted for 2018 tree canopy conditions.



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 3 –Estimated ambient air temperature change from 2009 to 2018 considering changes in tree canopy conditions.

3.2 Impervious Area Data Sources

Datasets representing impervious area were obtained from the City of Cambridge GIS data dictionary for 2010 and from Reed Hilderbrand for 2018. The impervious area dataset for 2018 was developed as part of the City's Urban Forest Master Plan and represents the latest available dataset for observed impervious area conditions. Overall, citywide impervious area remained mostly consistent and only increased slightly from approximately 2561.6 acres in 2009 to 2603.9 acres in 2018.

3.3 Cool Roof Data Sources

The datasets representing cool roof areas within Cambridge were created by Kleinfelder with input from the NASA Develop team through an albedo study of the City's roofs conducted in spring and summer 2020[10]. Kleinfelder first used USGS satellite imagery and building footprint datasets from 2009 and 2018 to select building footprints that appeared white in color based solely on visual observation of satellite imagery. Kleinfelder then compared these datasets to datasets created with input from the NASA Develop team's albedo study. The NASA Develop team used high resolution orthoimagery from 2010 and 2018 to calculate median albedo for every roof in Cambridge.

Albedo is a measure of the reflectance of a material. The reflectance of a material combined with the thermal emittance or emissivity of the material is used to determine the material's solar reflectance index (SRI). SRI is a composite measure of a material's ability to reject solar heat and is referenced in LEED recommendations for building and site material limiting UHI. Although SRI is dependent both on a material's reflectance (albedo) and thermal emittance, reflectance (albedo) can be used generally as a proxy to distinguish between cool roofs and non-cool roofs. Kleinfelder used the albedo datasets obtained from the NASA Develop team to create a second dataset representing cool roof area for 2010 and 2018. Kleinfelder used an albedo threshold of 0.8, corresponding to a standard white surface used to calculate SRI.[11] Roofs with median albedo values of 0.8 or greater were classified as cool roofs.

For both time periods, the cool roof dataset created by visual observation was similar to the dataset created using the albedo threshold with few variations. Some buildings were included in one dataset and excluded in another, but generally the two datasets were consistent in identifying cool roofs. To capture all roof area that could potentially be classified as a cool roof, the two datasets were merged to create a single dataset representing the maximum combined cool roof extents. These combined datasets for 2010 and 2018 were used for modeling.

Overall, the citywide cool roof area increased from approximately 35.6 acres in 2009-2010 to 109.3 acres in 2018. This is consistent with the NASA Develop team's study which found that average roof albedo increased citywide from 2010 to 2018 primarily due to an increased number of cool roofs. Note that these values assume that 75% of total building footprint area can be

---

[10] *https://thrivingearthexchange.org/project/cambridge-ma/*

[11] *Muscio, Alberto. "The Solar Reflectance Index as a Tool to Forecast the Heat Released to the Urban Environment: Potentiality and Assessment Issues." Climate (Basel) 6, no. 1 (February 15, 2018): 12–.*

considered cool roof area to account for roof area occupied by mechanical equipment or other material that does not reject solar heat well. Figure 4 summarizes the changes in land cover conditions citywide from the 2009-2010 timeframe to 2018. Land cover values are reported in terms of percent of citywide land area and in acres.

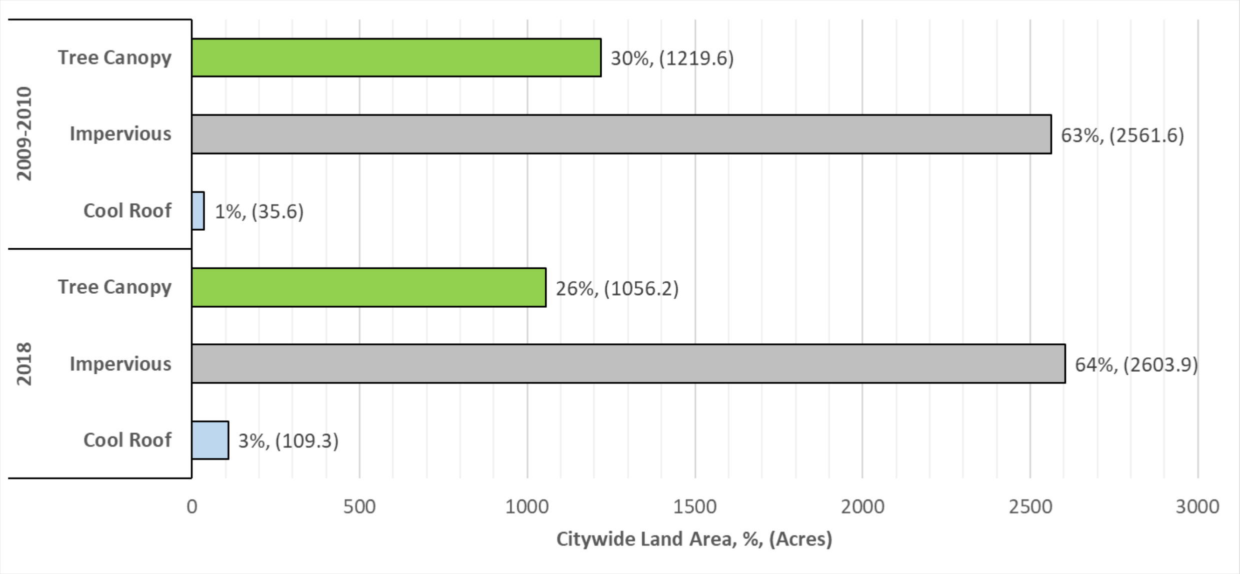
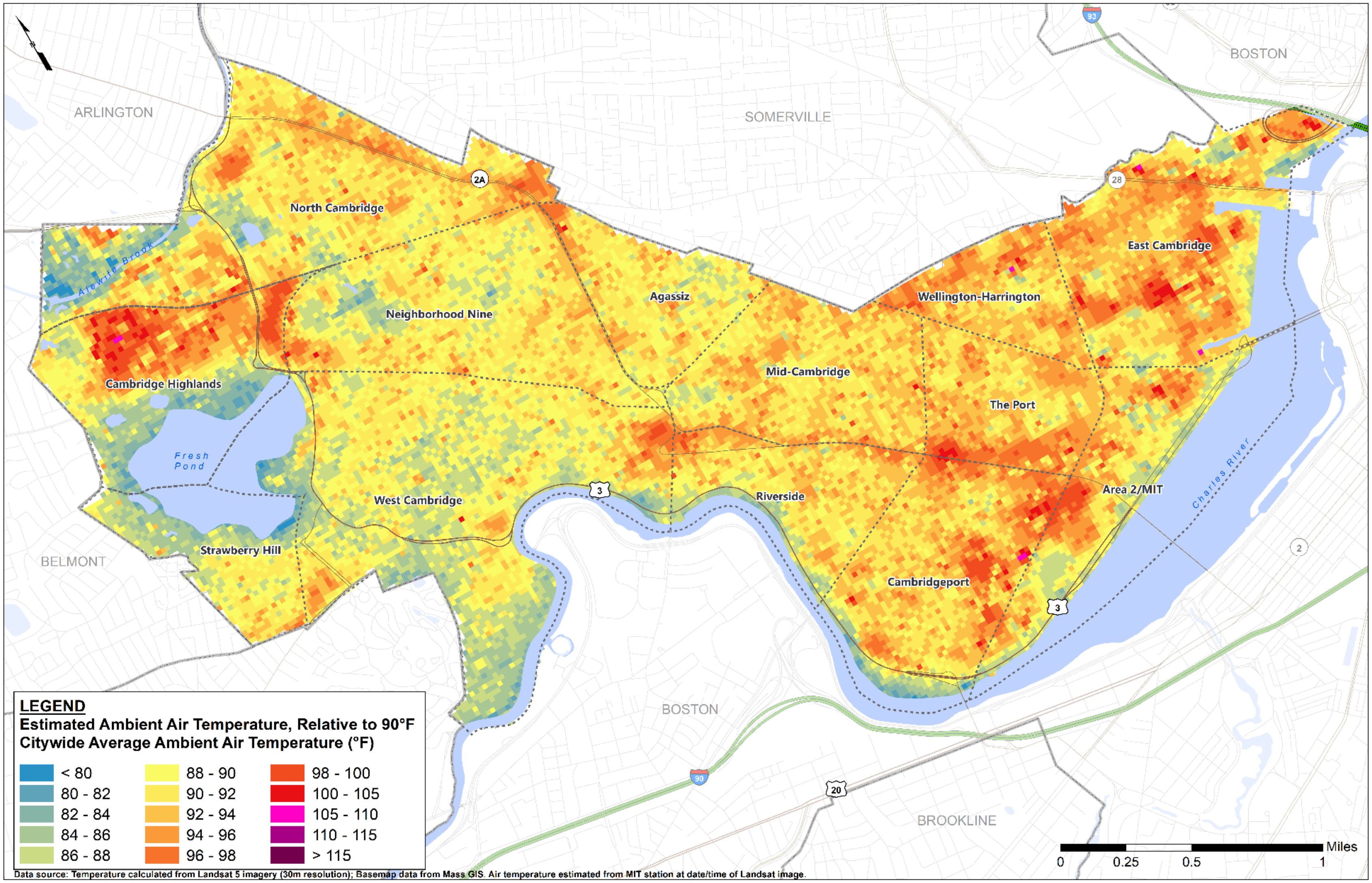


Figure 4 – Citywide Land Cover Changes from 2009-2010 to 2018.

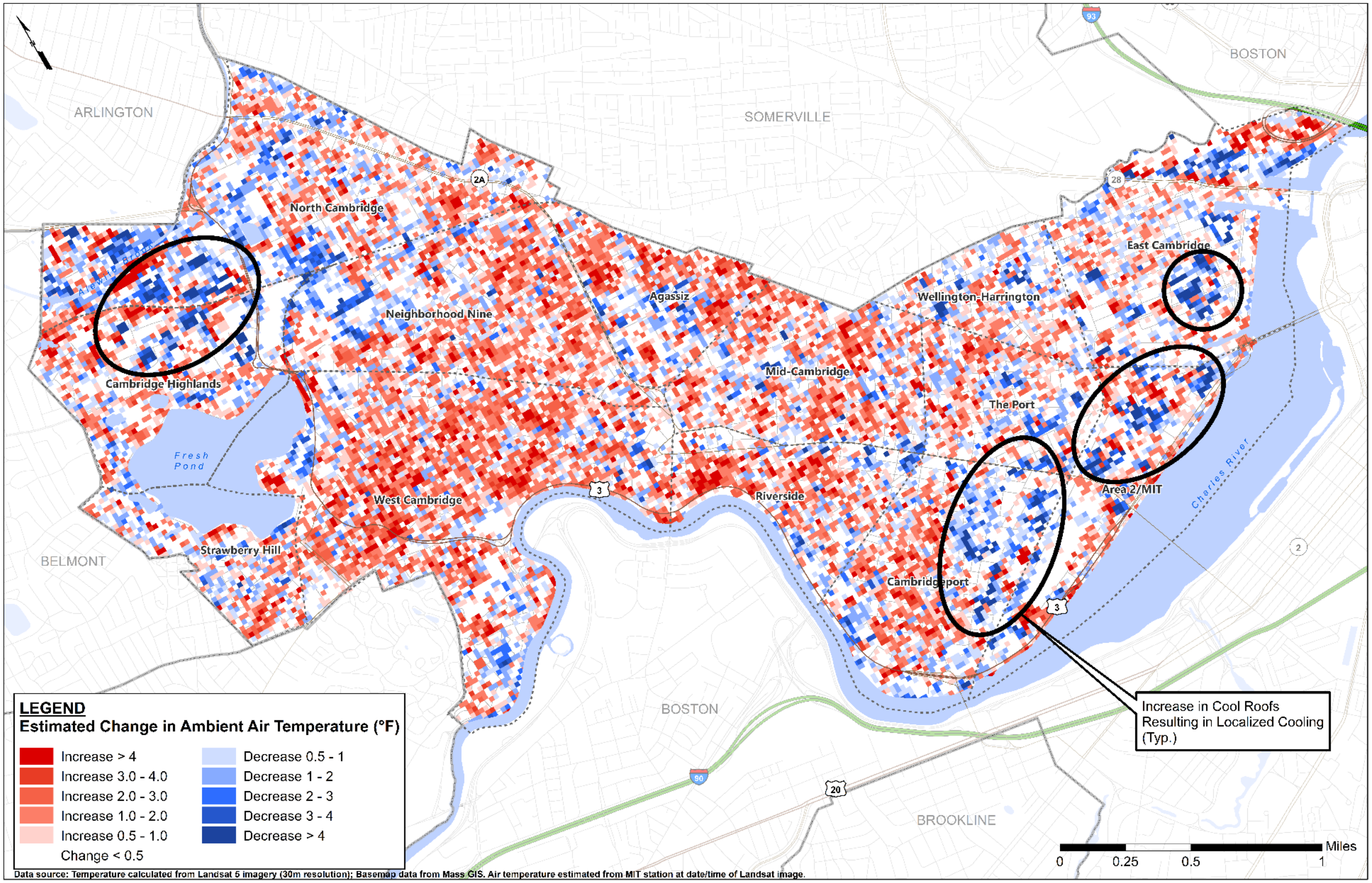
3.4 Updated Temperature Baseline Including Tree Canopy, Impervious and Cool Roof Changes

Figure 5 shows the updated UHI for 2018 relative to a citywide average temperature of 90°F and considering changes in tree canopy, impervious and cool roof areas from 2009-2010 to 2018. Figure 6 shows the estimated ambient air temperature change from 2009-2010 to 2018 considering these changes. Overall, the decrease in canopy and increase in impervious area resulted in estimated ambient air temperature increases citywide and more significantly in specific areas such as West Cambridge. However, in some areas canopy coverage and cool roof area did increase from 2009 to 2018 resulting in some estimated cooling in localized areas. Figure 7 summarizes the estimated ambient air temperature changes from 2009-2010 to 2018 by quantifying the land area experiencing different levels of warming, cooling, or no significant temperature change. A threshold of 0.5 °F temperature change was chosen to represent a significant temperature change. This threshold was chosen primarily for temperature mapping purposes and to partially account for the limitations of the temperature cooling relationships.



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 5 – Estimated ambient air temperature adjusted for 2018 tree canopy, impervious and cool roof conditions.



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 6 – Estimated ambient air temperature change from 2009 to 2018 considering changes in tree canopy, impervious and cool roof conditions.

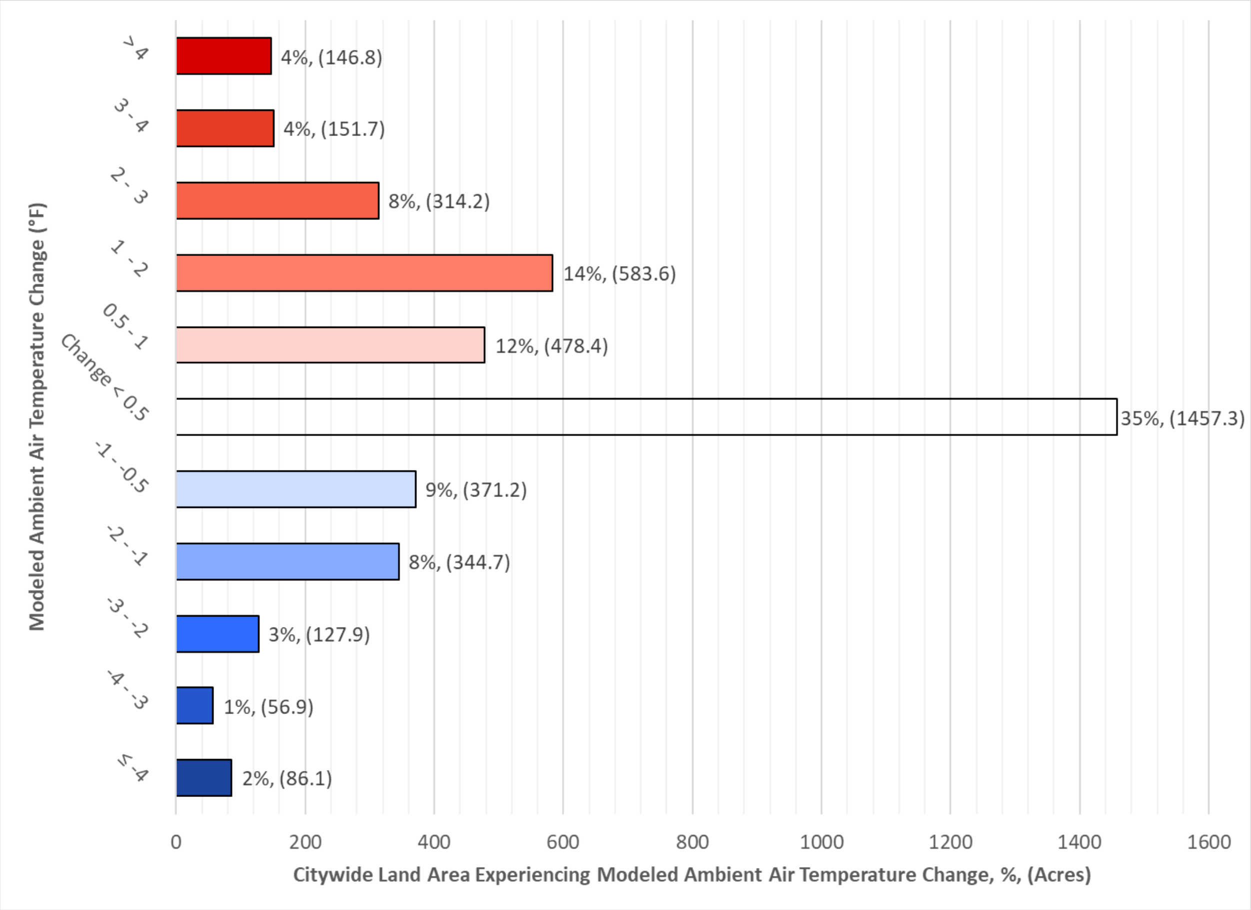


Figure 7 – Citywide Land Area Experiencing Modeled Ambient Air Temperature Changes from 2009-2010 to 2018.

3.5 Key Findings

- Between 2009-2010 and 2018, citywide tree canopy area decreased significantly, impervious area increased slightly, and cool roof area increased significantly.
- From 2009-2010 to 2018, the model projects that 42% of the city area experienced warming greater than 0.5 °F, 23% experienced cooling greater than 0.5 °F and 35% experienced no temperature change or temperature change less than 0.5 °F.
- Between 2009-2010 and 2018, the model reports that estimated average ambient air temperature citywide increased slightly by approximately 0.38 °F. Temperature increases caused by decreased canopy and increased impervious were partially offset by the increase in cool roof area.
- Between 2009-2010 and 2018, the model reports that temperatures increased most significantly in the western and central neighborhoods of the city including West Cambridge, Neighborhood Nine, Agassiz, Mid-Cambridge, and Riverside. However, these neighborhoods are still generally cooler than other city neighborhoods.
- Major UHI hotspot areas identified in previous analyses (including CCVA and the UFMP) largely remain, although the increase in cool roofs has helped somewhat in reducing the

extent and severity of hotspot areas particularly in the Alewife Quadrangle and in portions of Cambridgeport, Area 2/MIT and East Cambridge.

While the model reports that some percentage of the city experienced cooling between 2009-2010 and 2018, a larger percentage of the city experienced warming and the overall citywide average temperature increased. If current land cover trends continue, temperatures will continue to increase as citywide tree canopy decreases and impervious area increases. This is to be further exacerbated by the observed and projected increase in temperature and more frequent extreme heat events caused by climate change. Increasing temperatures impact public health in causing more heat-related mortality and higher building energy use for cooling. The impact of increased temperatures on public health was quantified in the Public Health Assessment completed as a part of CCVA[12]. The Assessment reports excess heat-related deaths for two different climate projection models with temperature changes from the two climate projections ranging from 0.59-1.32 °C (1.06-2.38 °F) and 2.17-2.33 °C (3.91-4.19 °F), respectively. Even for the more conservative temperature change scenario (1.06-2.38 °F) a significant increase in excess heat-related mortality was reported. A University of Massachusetts study compared building energy use within a neighborhood in Worcester, MA before and after a significant removal of trees. The study used data electricity use data from 129 homes for the summer months (mid-June to mid-September) from 2007-2010. The study reported an average 1% decrease in canopy cover resulted in an average 1.2% increase in building energy use (reported in kWh per cooling degree day)[13]. To help mitigate impacts on public health and building energy use, effective cooling strategies must be implemented citywide. The following section presents the citywide cooling scenarios modeled as part of this analysis.

4. Citywide Cooling Scenarios

UHI and temperature change were estimated and mapped for future scenarios for land cover conditions after the implementation of various cooling strategies. A separate future UHI scenario was modeled for each of the three land cover parameters (tree canopy, impervious and cool roof).

The scenario for future **tree canopy** used a future planting layer developed in GIS by Reed Hilderbrand as part of the City's Urban Forest Master Plan. This future planting scenario assumes that the 2018 tree canopy is maintained, and a significant amount of new tree canopy area is added in both the public right-of-way and on private property. While these are optimistic assumptions, the future planting scenario represents an ideal goal for future tree canopy citywide. The future planting scenario essentially meets the long-term goals of the Urban Forest Master Plan including 30% canopy coverage citywide and at least 25% canopy coverage in each

---

[12] *https://www.cambridgema.gov/-/media/Files/CDD/Climate/vulnerabilityassessment/ccvareportpart1/vulnerabilityandriskassessmentstechnicalreports/publichealthassessmentnovember2015.pdf*

[13] *Burncoat Neighborhood Tree Removal/Energy Use Study Worcester, MA. Report prepared by University of Massachusetts, Amherst*

city neighborhood. The future planting scenario is only slightly below 25% canopy coverage in East Cambridge (23%) and Area 2/MIT (24%).

The scenario for future **impervious area** used input data from the CCPR technical memo "Recommendations for Stormwater Strategies for Flood Mitigation" including stormwater subcatchment boundaries and classifications. This memo classified each stormwater subcatchment in the city as one of four general types (Figure 8). Type A subcatchments are areas where implementing green infrastructure has been deemed most effective for flood reduction benefits. Type B and Type C subcatchments are areas where implementing green infrastructure has been deemed less effective for flood reduction benefits. Type D subcatchments are areas were implementing green infrastructure would not have significant flood reduction benefits but would have significant co-benefits including UHI mitigation. If green infrastructure were to be implemented on existing impervious area, the resulting reduction in impervious area would have benefits in terms of UHI mitigation, in addition to providing stormwater benefits. For the future impervious area scenario, it was assumed that:

- impervious area would be reduced by 20% in Type A and D subcatchments
- impervious area would be reduced by 10% in Type B and C subcatchments

While these assumptions are optimistic, they represent an upper bound goal for assessing what the maximum estimated cooling benefit could be through the implementation of green infrastructure. A lower implementation level was assumed for Type B and Type C subcatchments since green infrastructure is less effective in these areas.

The subcatchment boundaries are different than the 30-m grid boundaries used for modeling UHI. To reconcile this difference, each 30-m grid cell was assigned a stormwater subcatchment type (A, B, C or D) based on what catchment the center of the grid cell is located in. The impervious area within each grid cell under the future scenario was then calculated by reducing the existing impervious area in the grid cell by 10% or 20% depending on the stormwater subcatchment type. This approach does not consider site specific feasibility of implementing green infrastructure at a fine scale. While the Urban Forest Master Plan developed a citywide spatial tree canopy layer representing potential future canopy, a citywide future impervious area layer was never developed in any previous analysis. Without having developed this layer, the approach of assigning catchment types to each grid cell allows for the evaluation of potential cooling from impervious area reduction at high level. This approach also ensures that cooling potential from impervious area reduction is not overestimated in areas with already low impervious cover under existing conditions, for example, existing open spaces.

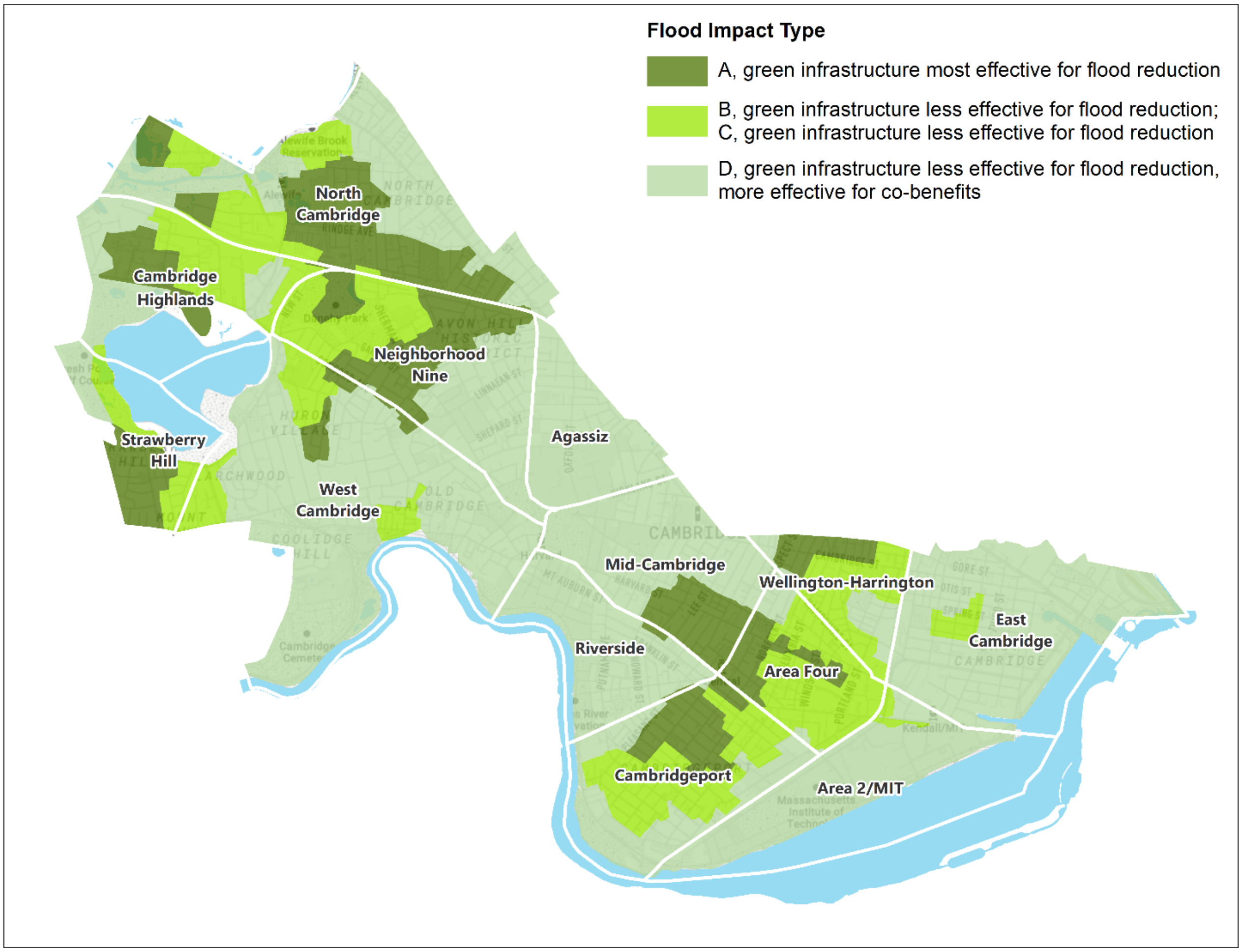


Figure 8 – Stormwater Subcatchments Classified by Flood Impact Type.[14]

The scenario for future **cool roofs** uses the existing cool roof dataset developed for the updated temperature baseline and 2018 building footprint data from the City of Cambridge. For the scenario for future cool roofs it was assumed that:

- 75% of existing buildings without cool roofs in 2018 will be converted to buildings with cool roofs. For the purposes of modeling, a random 75% selection of buildings was chosen. .
- 75% of the total footprint area of each building can be converted to cool roof area to account for building roof area that may be occupied by mechanical equipment or may consist of other material that does not reject solar heat well.

These assumptions are optimistic future goals to be achieved citywide. However, the low cost and ease of implementation compared to increasing tree canopy and decreasing impervious area make the option of implementing cool roofs favorable. Figure 9 summarizes the citywide land cover conditions assumed under the future cooling scenarios compared to land cover conditions

---

[14] *Recommendations for Stormwater Strategies for Flood Mitigation, CCPR Citywide Plan, Kleinfelder.*

in 2009-2010 and 2018. Land cover values are reported in terms of percent of citywide land area and in acres.

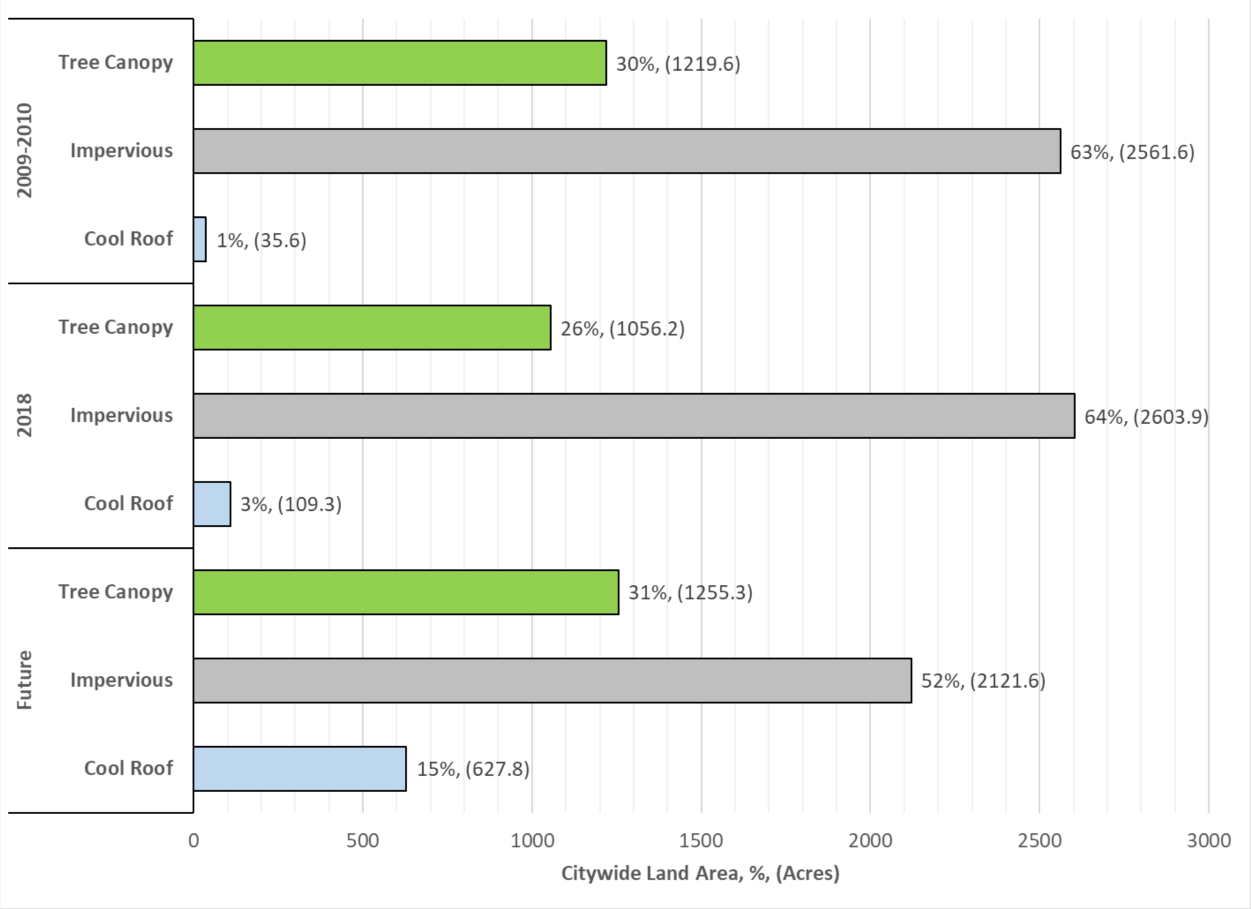
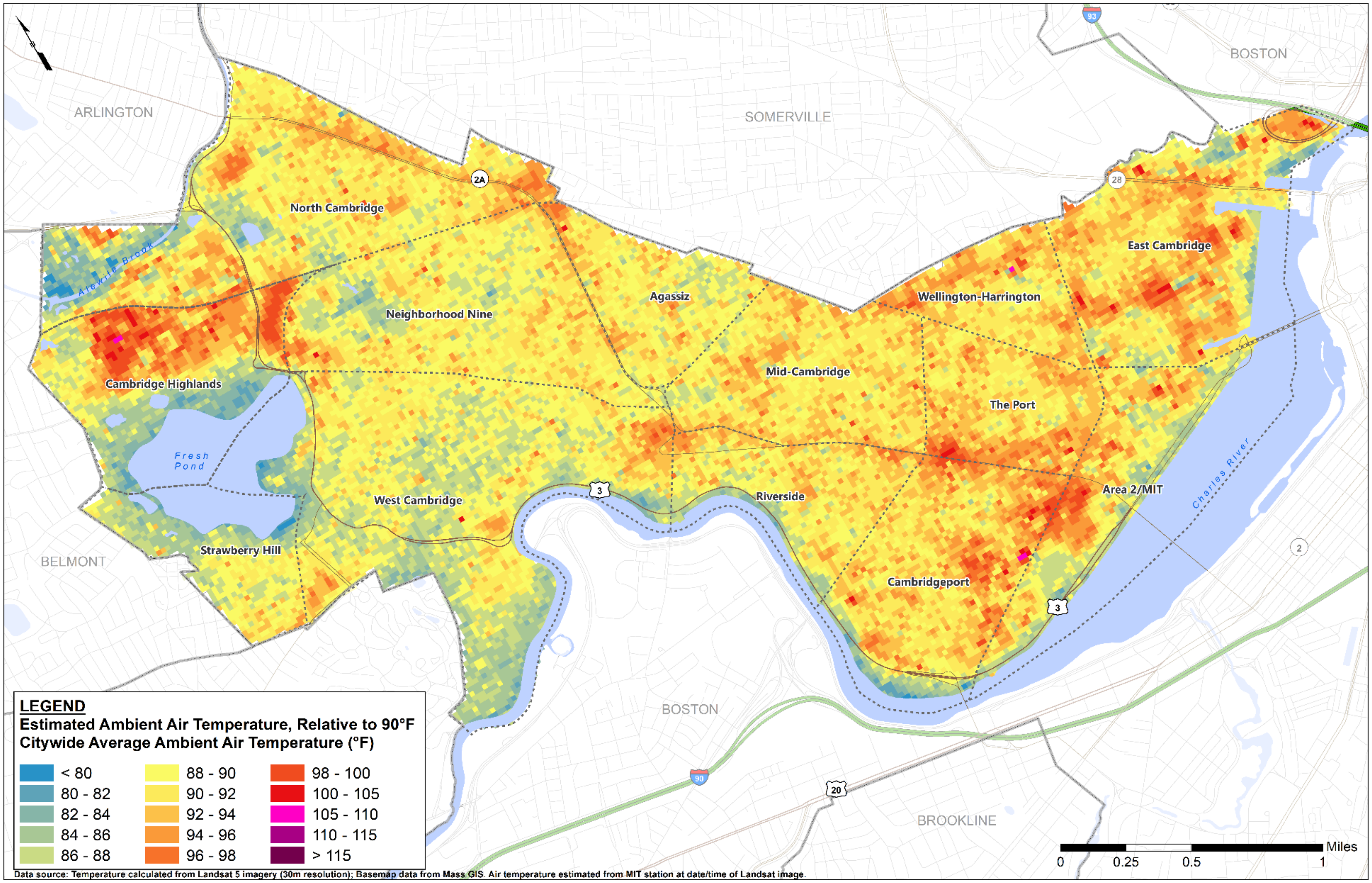


Figure 9 – Citywide Land Cover Under Potential Future Conditions compared to 2009-2010 to 2018 Conditions.

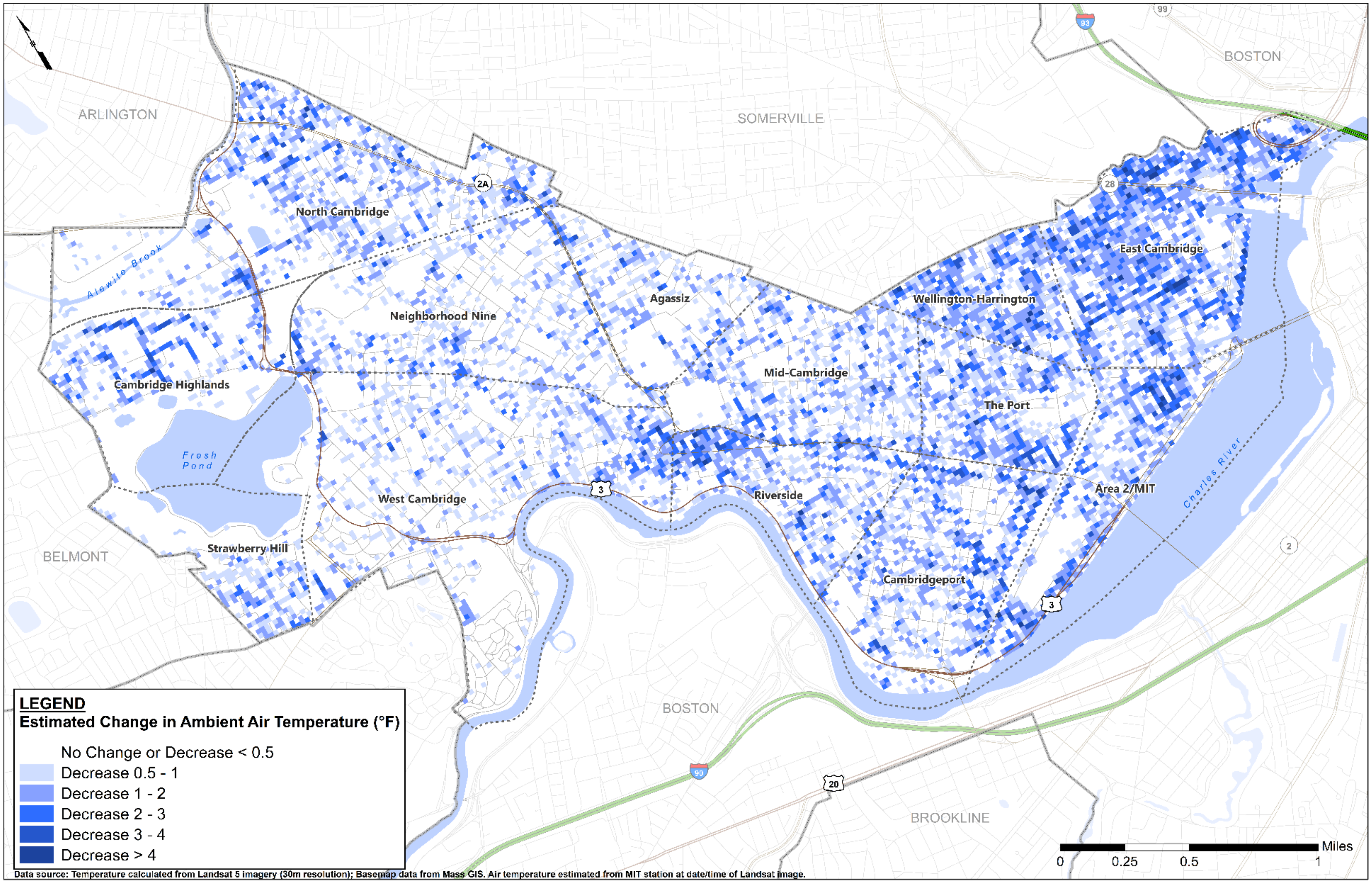
Figure 10 shows the updated UHI for the future planting scenario relative to a citywide average temperature of 90°F. Note that this figure was developed as part of the City's Urban Forest Master Plan and does not incorporate changes in impervious and cool roof area from 2009-2010 to 2018. Figure 11 shows the estimated ambient air temperature change from 2018 to the future planting scenario.

Figures 12 through 15 show modeled UHI citywide for the future impervious area and cool roof scenarios as well as the estimated ambient air temperature change from 2018 conditions for each of the future scenarios. Figure 16 summarizes the estimated ambient air temperature cooling under the future scenarios by quantifying the citywide land area experiencing different levels of cooling.



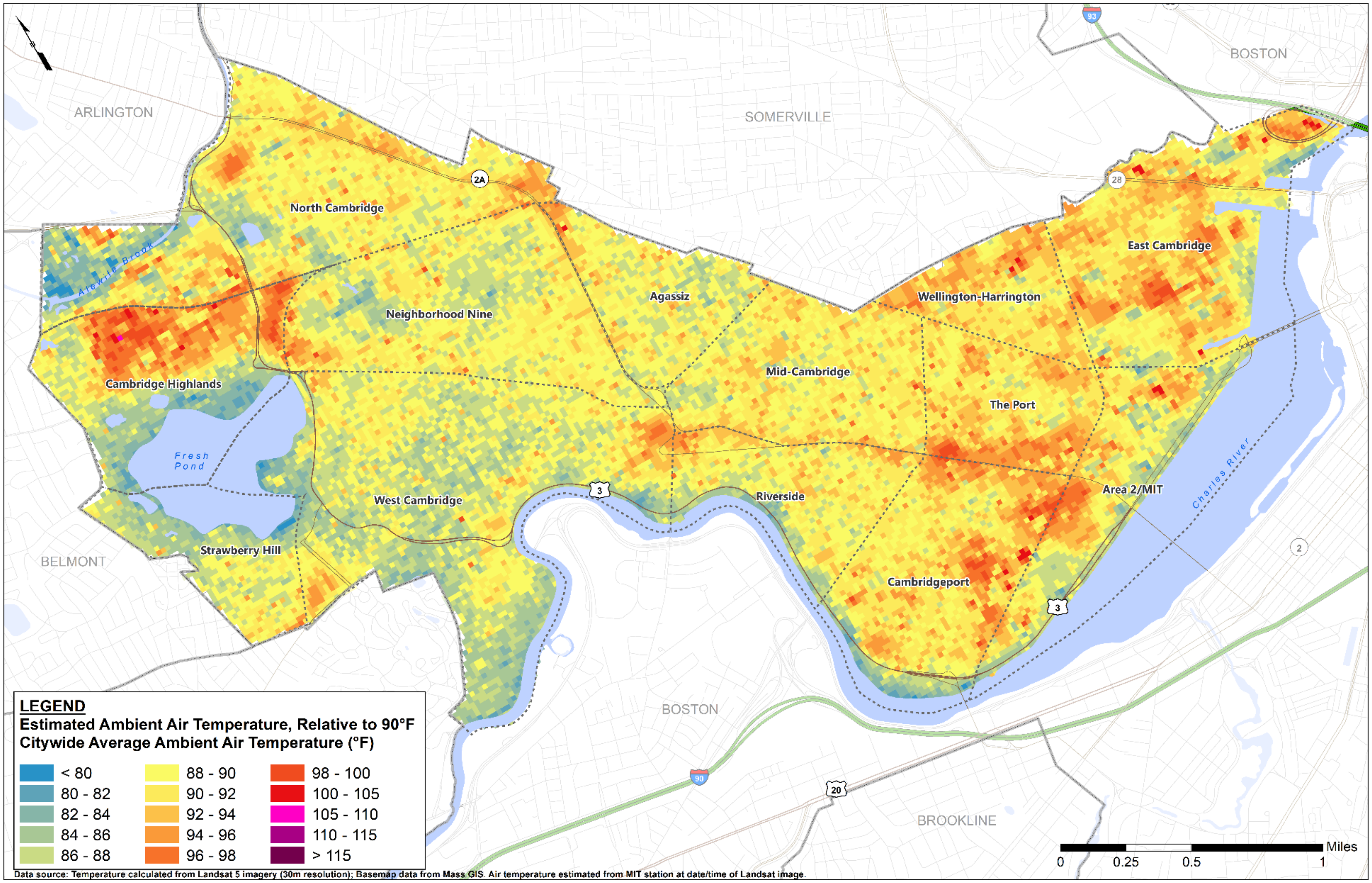
Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 10 –Estimated ambient air temperature for future tree canopy conditions.



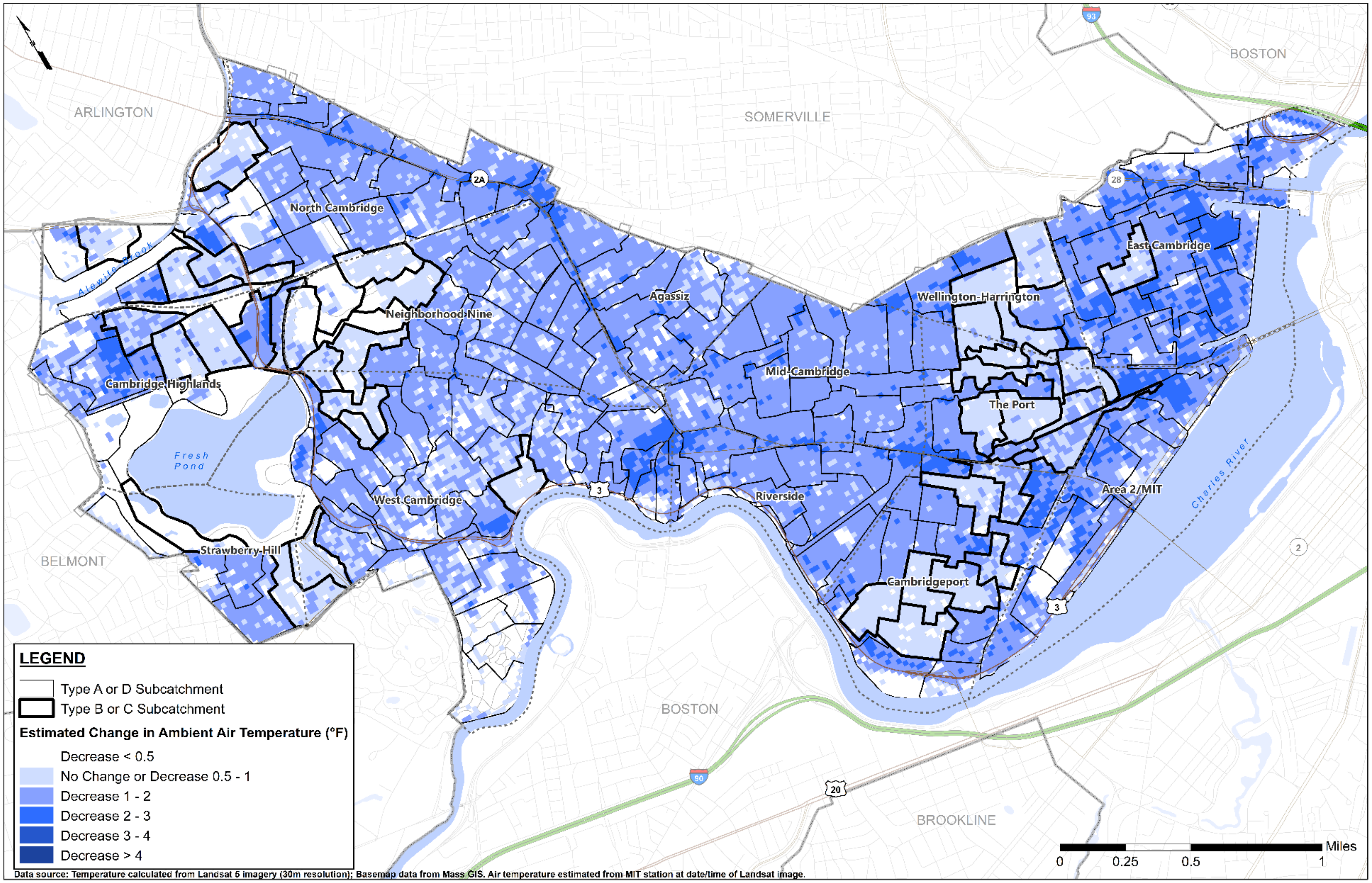
Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 11 – Estimated ambient air temperature change from 2018 to future tree canopy conditions.



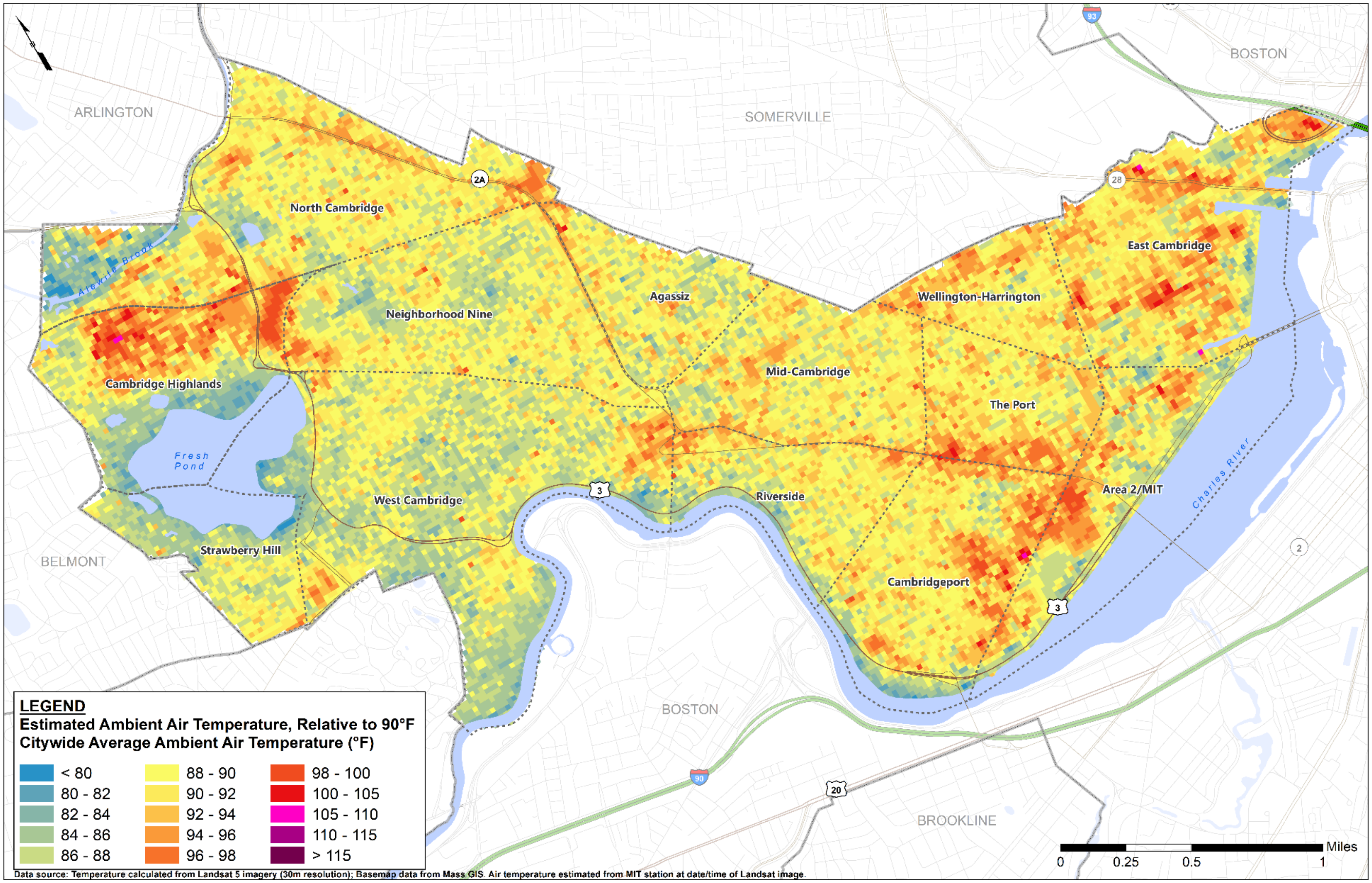
Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 12 – Estimated ambient air temperature for future impervious conditions.



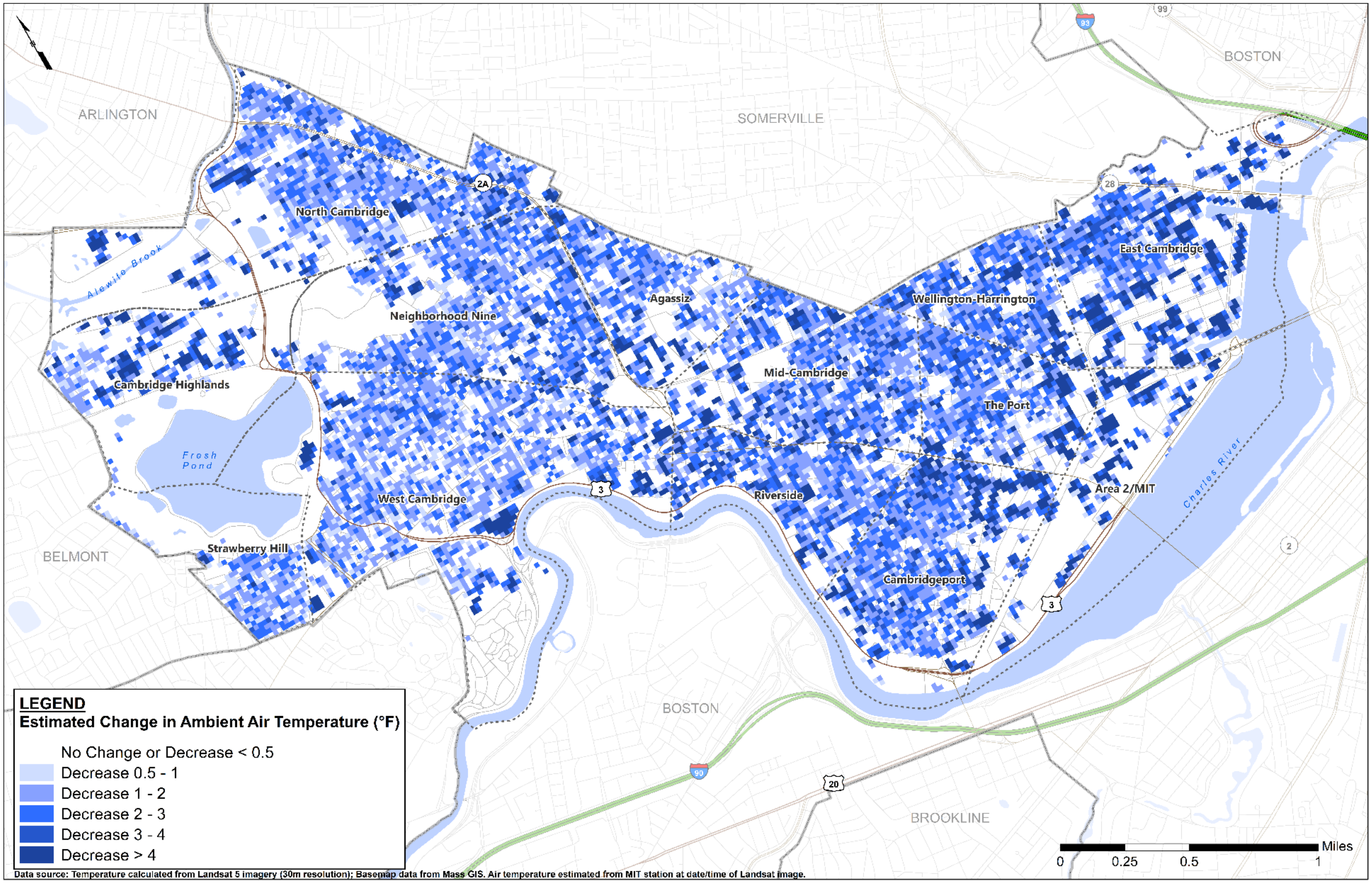
Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 13 – Estimated ambient air temperature change from 2018 to future impervious conditions.



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 14 – Estimated ambient air temperature for future cool roof conditions.



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 15 – Estimated ambient air temperature change from 2018 to future cool roof conditions.

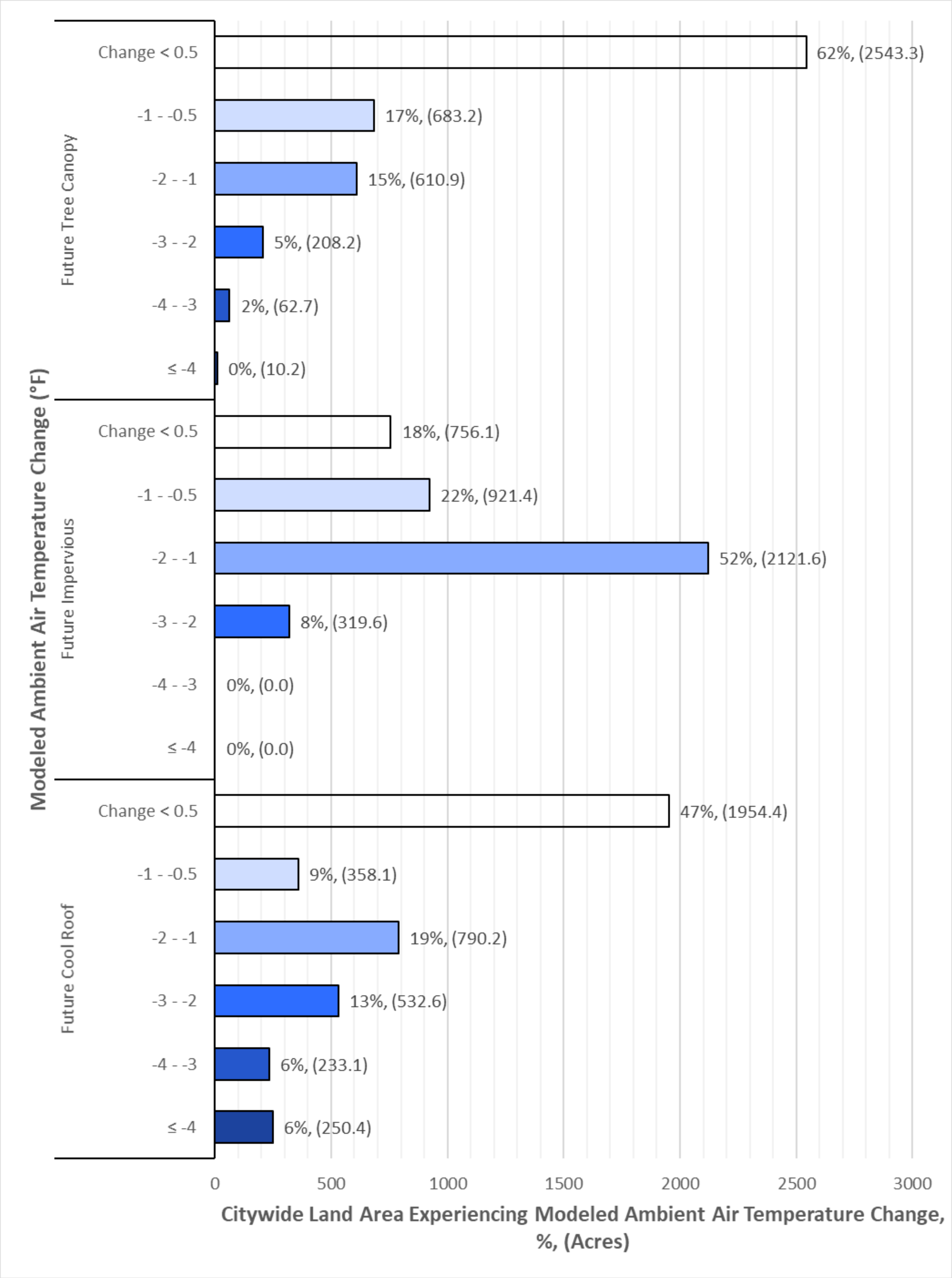


Figure 16 – Citywide Land Area Experiencing Modeled Ambient Air Temperature Changes from 2018 to Future Conditions.

4.1 Key Findings

- Under the future tree canopy scenario, 38% of the city is projected to experience cooling greater than 0.5 °F, with 22% of the city projected to experience cooling greater than 1.0 °F compared to 2018 land cover conditions. The average citywide temperature is projected to decrease by approximately 0.5°F.
- Under the future impervious scenario, 82% of the city is projected to experience cooling greater than 0.5 °F, with 60% of the city projected to experience cooling greater than 1.0 °F compared to 2018 land cover conditions. The average citywide temperature is projected to decrease by approximately 1.1°F.
- Under the future cool roof scenario, 53% of the city is projected to experience cooling greater than 0.5 °F, with 44% of the city projected to experience cooling greater than 1.0 °F compared to 2018 land cover conditions. The average citywide temperature is projected to decrease by approximately 1.2 °F.
- Under the future scenarios, the extent and severity of hotspot areas have been reduced particularly in the Alewife Quadrangle and in portions of Cambridgeport, Area 2/MIT and East Cambridge.

The future tree canopy scenario achieves the lowest level of cooling in terms of percent citywide land area experiecing cooling and citywide average temperature decrease. This was expected considering the assumed level of implementation for this scenario was less than for the impervious and cool roof scenarios in terms of acres of land cover change. The future impervious scenario results in the greatest percentage of citywide land area experiencing cooling, however all of this cooling is lower magnitude cooling less than 2.0°F. The level of cooling would ultimately depend on how the impervious area reduction would be distributed citywide. The future cool roof scenario achieves the greatest decrease in average citywide temperature. While these results are tentatively promising, it should be noted that there are limitations and assumptions to the modeling approach for cool roofs that may overestimate the anticipated cooling benefit.

If cooling is assumed to be simply additive, the three future cooling scenarios can be aggregated into a single combined scenario. Under this combined scenario the average citywide temeprature decrease would be the sum of the individual future scenarios which is approximately 2.9°F (Figure 17). Note that the sum is not exact due to rounding. In many localized areas the project cooling would be significantly above the average of 2.9°F. This is a significant level of estimated cooling that could be achieved under a combined scenario with optimistic implementation assumptions. Ultimately the level of cooling achieved under future land cover conditions will be dependent on the level of implementation level and on the spatial distribution of various cooling strategies. The implementation of cooling strategies in existing hotspot areas will have the greatest benefits in terms of human comfort, reducing heat-related mortality and decreasing building energy use. Where feasible the implementation of cooling strategies in existing hotspot areas should be prioritized.

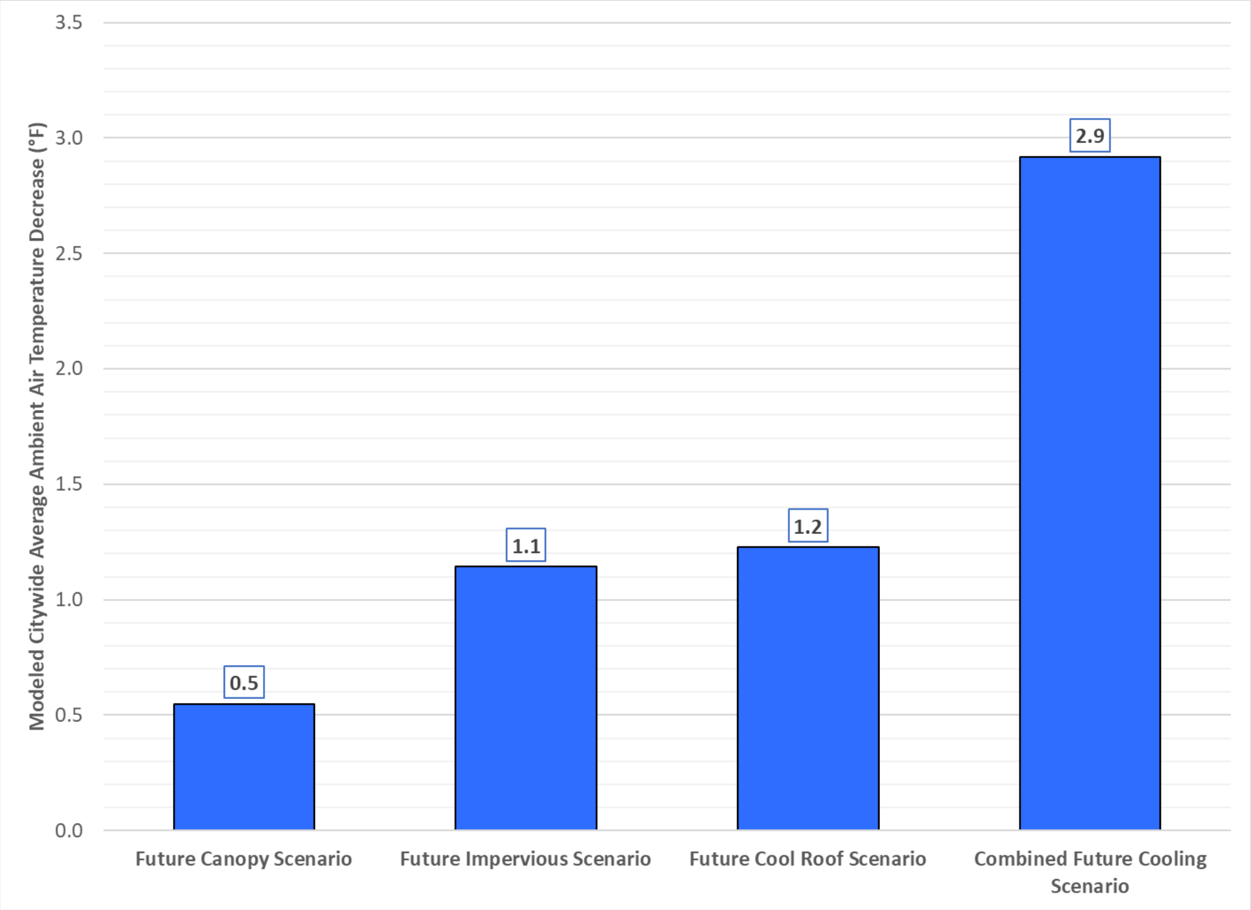


Figure 17 – Modeled Citywide Average Ambient Air Temperature Decrease Under Future Scenarios.

5. Model Limitations and Further Analysis

The cooling relationships developed for tree canopy and impervious areas have some limitations. The coefficient of determination, defined by the R^2 values of the linear regressions correlating the land cover percentage to temperature, were 0.505 and 0.5696 for tree canopy and impervious area, respectively. This indicates that about half of the variation in temperature can be explained by a single land cover parameter and the remaining variation can be attributed to other land cover parameters and other factors known to impact ambient air temperature such as elevation and wind velocity. A study by Ziter, et al., observed that temperature change with respect to land cover changes was not strictly linear depending on the scale of the evaluation and could increase if the land cover percentage was above a certain threshold value.[15] Further analysis of UHI could take into consideration this threshold by using a bilinear regression for the cooling relationship or developing some other non-linear cooling relationship. The cooling relationship used for cool roofs is still an approximation as described in Section 2 of this memo.

---

[15] *Ziter, Carly D; Pedersen, Eric J; Kucharik, Christopher J; Turner, Monica G. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. Proceedings of the National Academy of Sciences of the United States of America, 09 April 2019, Vol.116(15), pp.7575-7580*

While the results of the future cool roof scenario are tentatively promising, it is important to note that estimated cooling anticipated from cool roof implementation may be overestimated and should be investigated further.

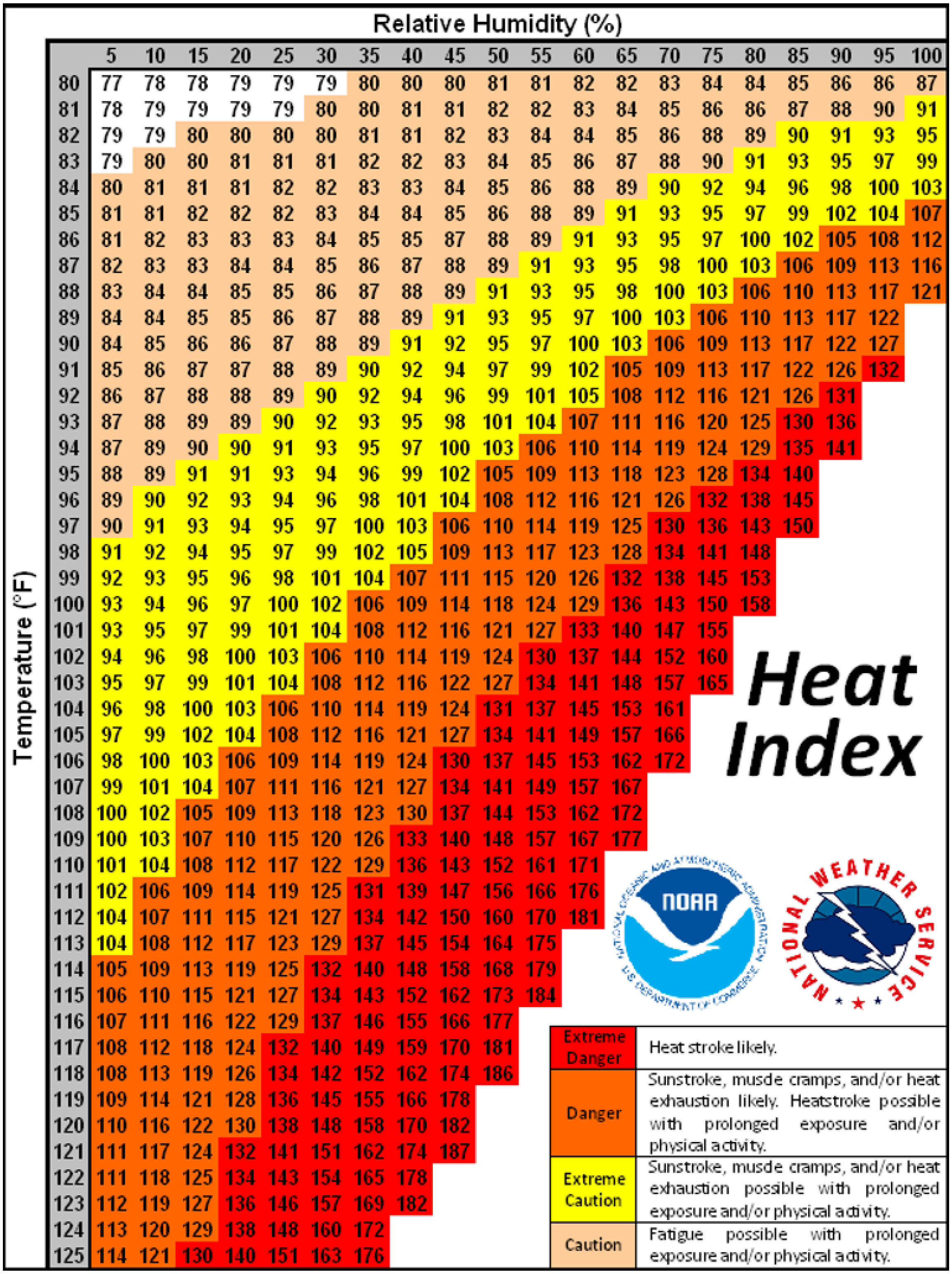
The combined future cooling scenario assumes that cooling is additive between the individual cooling scenarios. Cooling likely is not exactly additive and could be less than the sum of cooling scenarios in some cases and potentially greater than the sum of cooling scenarios in other cases. For example, new tree canopy planted over existing impervious area could have an added benefit of shading this area and producing additional cooling compared to new tree canopy planted over existing pervious area. Assuming that cooling is additive between the cooling scenarios is a simplifying assumption for the purposes of high-level planning.

Further analysis could involve creating a new temperature baseline from more recent Landsat data instead of adjusting the 2010 temperature map based on land cover changes and using approximate empirical relationships for temperature change. The conversion of raw Landsat data to an ambient air temperature map is a detailed and time-consuming process as outlined in CCVA Appendix D. However, the United States Geological Survey (USGS) recently developed a new Landsat data product for land surface temperature which performs some of the steps in this conversion process. The conversion from land surface temperature to ambient air temperature would still be required to generate UHI maps. Landsat observations made within the summer months of multiple years could potentially be processed and compared to see if trends can be observed. A new 2018 temperature map based on observed satellite data could also be compared to maps developed as part of the Museum of Science Boston study and the updated 2018 baseline generated in this analysis.

6. UHI Scenarios for the HeatViewer

Ambient air temperature is the measured air temperature. Climate projections track how ambient air temperature might change moving forward. This important indicator establishes overall baseline and trends, as well as provides some indication of whether there may be impacts to heat-sensitive infrastructure and population. The UHI maps presented in previous sections of this memo are all relative to a temperature baseline grid where the citywide average ambient air temperature is 90°F. However, by 2070 there could be as many as 68 days per year with ambient air temperature greater than 90°F, of which there could be as many as 16 days greater than 100°F.

Additionally, these maps also only represent ambient air temperature and not heat index which is a more accurate indicator of heat stress for humans and combines both temperature and relative humidity data to determine the “feels like” temperature that people experience. A day with lower temperatures combined with higher humidity can produce the same level of heat stress as a day with a higher temperature and lower humidity. The Heat Index Chart, as published by NOAA, in Figure 18 below, illustrates that relationship. Heat stress affects the body’s ability to maintain its normal temperature and may damage vital organs. Extreme heat causes more deaths in the U.S. than floods, hurricanes, lightning, tornadoes, and earthquakes. But heat-related deaths are preventable.



Relative Humidity (%)

Temperature (°F)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
80	77	78	78	79	79	79	80	80	80	81	81	82	82	83	84	84	85	86	86	87
81	78	79	79	79	79	80	80	81	81	82	82	83	84	85	86	86	87	88	90	91
82	79	79	80	80	80	80	81	81	82	83	84	84	85	86	88	89	90	91	93	95
83	79	80	80	81	81	81	82	82	83	84	85	86	87	88	90	91	93	95	97	99
84	80	81	81	81	82	82	83	83	84	85	86	88	89	90	92	94	96	98	100	103
85	81	81	82	82	82	83	84	84	85	86	88	89	91	93	95	97	99	102	104	107
86	81	82	83	83	83	84	85	85	87	88	89	91	93	95	97	100	102	105	108	112
87	82	83	83	84	84	85	86	87	88	89	91	93	95	98	100	103	106	109	113	116
88	83	84	84	85	85	86	87	88	89	91	93	95	98	100	103	106	110	113	117	121
89	84	84	85	85	86	87	88	89	91	93	95	97	100	103	106	110	113	117	122	
90	84	85	86	86	87	88	89	91	92	95	97	100	103	106	109	113	117	122	127	
91	85	86	87	87	88	89	90	92	94	97	99	102	105	109	113	117	122	126	132	
92	86	87	88	88	89	90	92	94	96	99	101	105	108	112	116	121	126	131		
93	87	88	89	89	90	92	93	95	98	101	104	107	111	116	120	125	130	136		
94	87	89	90	90	91	93	95	97	100	103	106	110	114	119	124	129	135	141		
95	88	89	91	91	93	94	96	99	102	105	109	113	118	123	128	134	140			
96	89	90	92	93	94	96	98	101	104	108	112	116	121	126	132	138	145			
97	90	91	93	94	95	97	100	103	106	110	114	119	125	130	136	143	150			
98	91	92	94	95	97	99	102	105	109	113	117	123	128	134	141	148				
99	92	93	95	96	98	101	104	107	111	115	120	126	132	138	145	153				
100	93	94	96	97	100	102	106	109	114	118	124	129	136	143	150	158				
101	93	95	97	99	101	104	108	112	116	121	127	133	140	147	155					
102	94	96	98	100	103	106	110	114	119	124	130	137	144	152	160					
103	95	97	99	101	104	108	112	116	122	127	134	141	148	157	165					
104	96	98	100	103	106	110	114	119	124	131	137	145	153	161						
105	97	99	102	104	108	112	116	121	127	134	141	149	157	166						
106	98	100	103	106	109	114	119	124	130	137	145	153	162	172						
107	99	101	104	107	111	116	121	127	134	141	149	157	167							
108	100	102	105	109	113	118	123	130	137	144	153	162	172							
109	100	103	107	110	115	120	126	133	140	148	157	167	177							
110	101	104	108	112	117	122	129	136	143	152	161	171								
111	102	106	109	114	119	125	131	139	147	156	166	176								
112	104	107	111	115	121	127	134	142	150	160	170	181								
113	104	108	112	117	123	129	137	145	154	164	175									
114	105	109	113	119	125	132	140	148	158	168	179									
115	106	110	115	121	127	134	143	152	162	173	184									
116	107	111	116	122	129	137	146	155	166	177										
117	108	112	118	124	132	140	149	159	170	181										
118	108	113	119	126	134	142	152	162	174	186										
119	109	114	121	128	136	145	155	166	178											
120	110	116	122	130	138	148	158	170	182											
121	111	117	124	132	141	151	162	174	187											
122	111	118	125	134	143	154	165	178												
123	112	119	127	136	146	157	169	182												
124	113	120	129	138	148	160	172													
125	114	121	130	140	151	163	176													

Extreme Danger	Heat stroke likely.
Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity.
Extreme Caution	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity.
Caution	Fatigue possible with prolonged exposure and/or physical activity.

Figure 18 – Heat Index Chart (Source: National Weather Service NWS, NOAA).

To assess citywide heat vulnerabilities more thoroughly, three additional heat scenarios were modeled in addition to the updated baseline scenario presented earlier for a total of four scenarios. The four scenarios modeled for existing 2018 land cover conditions are:

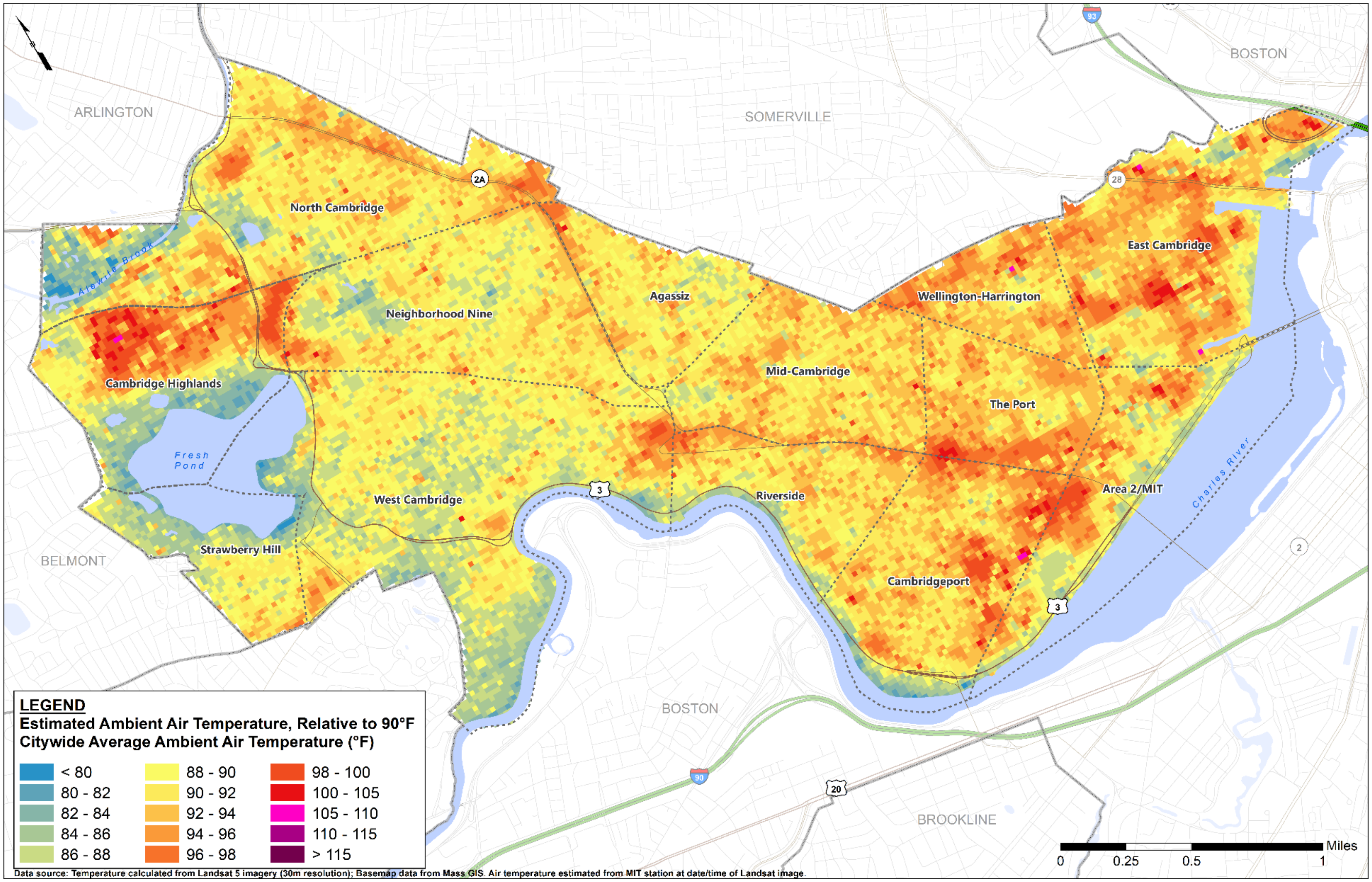
- Ambient air temperature for a citywide average ambient air temperature of 90°F.
- Ambient air temperature for a citywide average ambient air temperature of 100°F.
- Heat index for a citywide average ambient air temperature of 90°F and an average relative humidity of 44%, resulting in an average heat index of 93°F.
- Heat Index for a citywide average ambient air temperature of 100°F and an average relative humidity of 34%, resulting in an average heat index of 106°F.

The four scenarios correspond approximately to the ambient air temperature and heat index scenarios originally modeled in CCVA for the 2030s and 2070s. Corrections were made to ensure that maps were scaled to the proper citywide average temperature for the ambient air scenarios in addition to adjustments made to account for changes in land cover between 2010 and 2018.

Heat index was recalculated citywide for each of the two heat index scenarios as opposed to calculating heat index for one scenario and scaling the calculated heat index for other scenarios as was previously performed in CCVA. Additionally, more realistic values for relative humidity were used in the calculation of heat index. Relative humidity was calculated for each individual grid cell as detailed in CCVA Appendix D to account for the fact that increasing ambient air temperature typically corresponds to a decrease in relative humidity. This results in a range of relative humidity values throughout the city and citywide average relative humidity values of 44% and 34%, respectively, for the 90°F and 100°F scenarios.

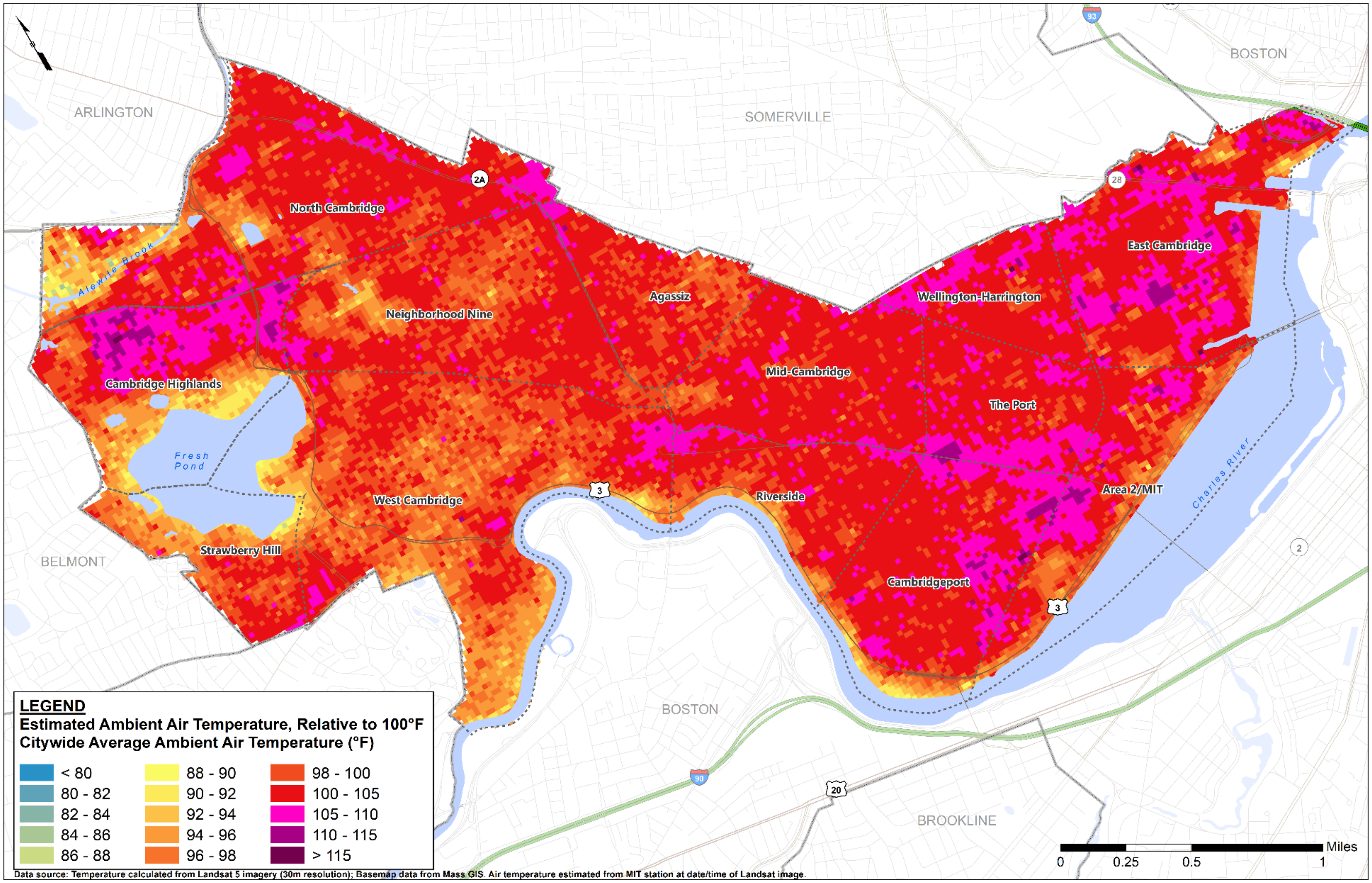
The four modeled heat scenarios are presented in Figures 19 through 22. The four modeled heat scenarios will also be included in the ClimateViewer web application developed by the City. The application will report the following for every parcel in the City:

- Heat risk / vulnerability at the parcel scale under the four extreme heat scenarios like the City's FloodViewer web application
- Land cover metrics relevant to extreme heat that have been identified in this memo (tree canopy, impervious, roof area)
- Links to additional resources detailing potential implementation strategies for mitigating extreme heat impacts (risk to action)



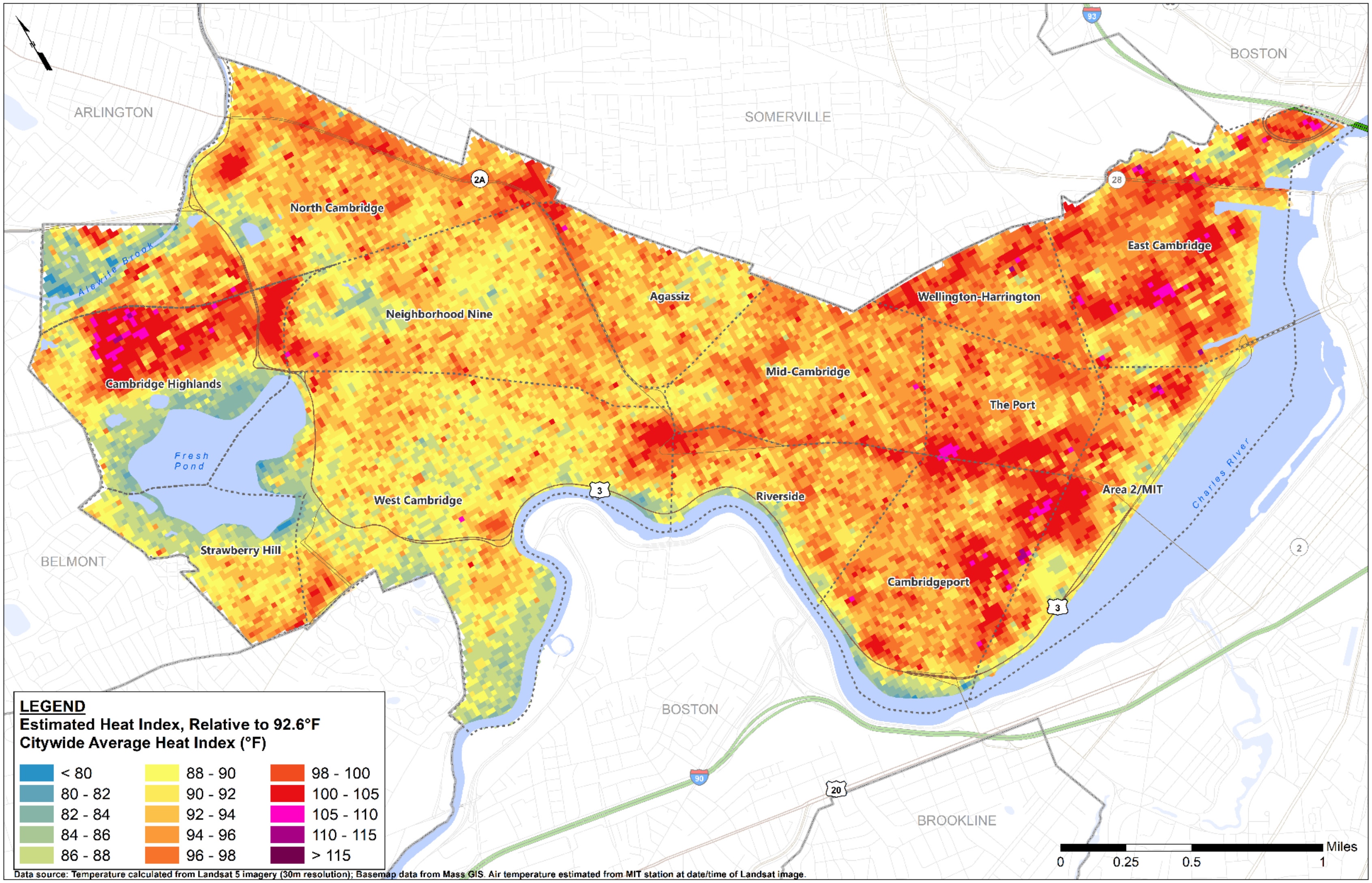
Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 19 – Estimated ambient air temperature relative to 90°F citywide average ambient air temperature adjusted for 2018 tree canopy, impervious and cool roof conditions.



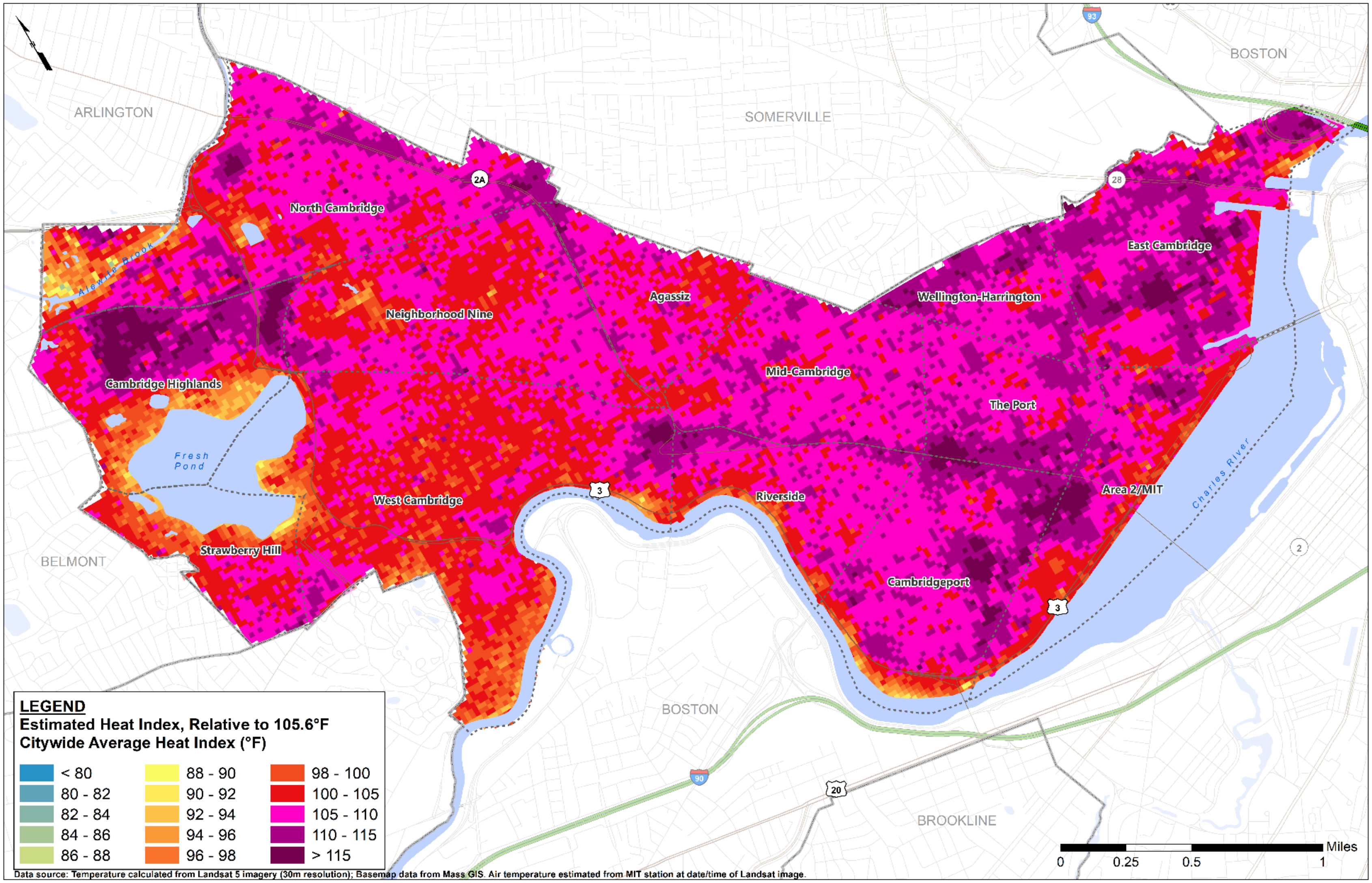
Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 20 – Estimated ambient air temperature relative to 100°F citywide average ambient air temperature adjusted for 2018 tree canopy, impervious and cool roof conditions.



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 21 – Estimated heat index relative to 92.6°F citywide average heat index and adjusted for 2018 tree canopy, impervious and cool roof conditions.



Data source: Temperature calculated from Landsat 5 imagery (30m resolution); Basemap data from Mass GIS. Air temperature estimated from MIT station at date/time of Landsat image.

Figure 22 – Estimated heat index relative to 105.6°F citywide average heat index and adjusted for 2018 tree canopy, impervious and cool roof conditions.