Public Health Assessment

Climate Change Vulnerability Assessment

City of Cambridge, Massachusetts

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Public Health Report

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1. Heat-related mortality

Heat has been the largest single weather-related cause of death in the US since NOAA began reporting data for heat in 1988. In addition, heat impacts on health are the most well understood, measureable, and yet preventable impacts of climate change.

Heat - key concepts

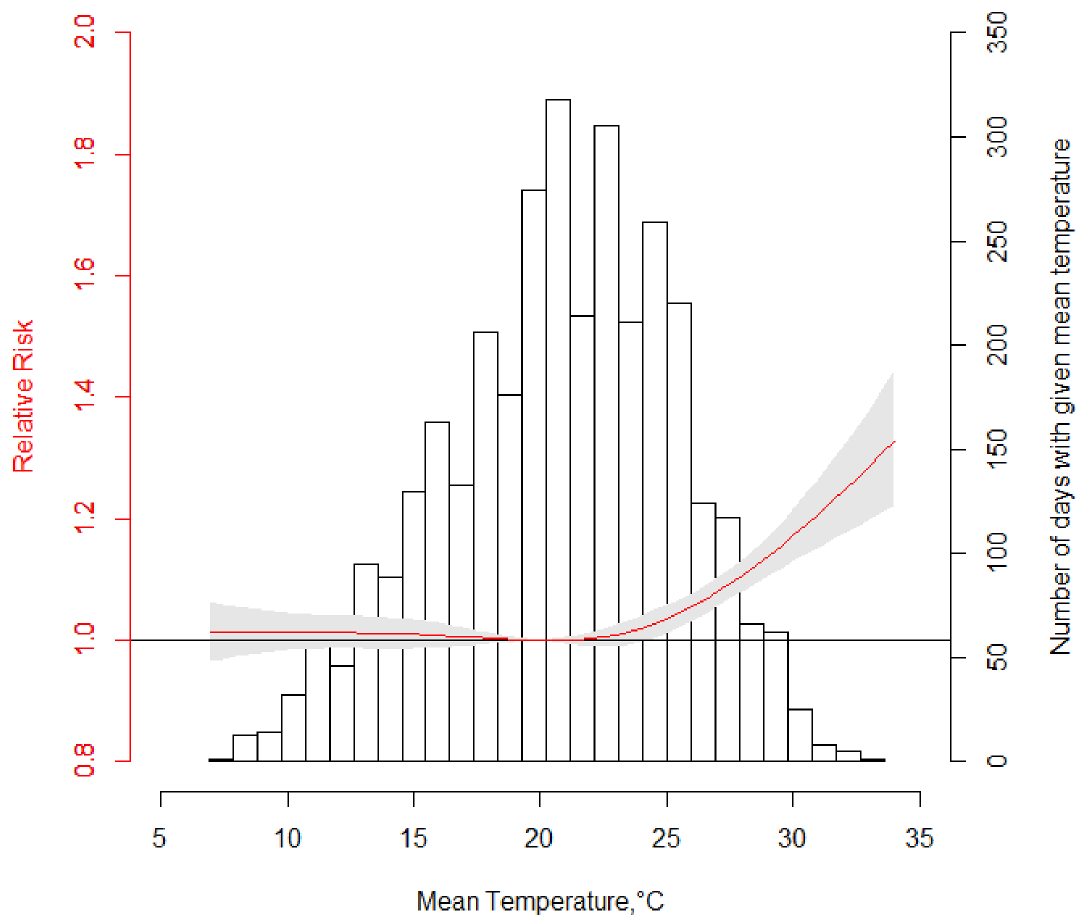
Heat exposure metrics
Various exposure metrics such as minimum, mean or maximum temperature or composite indices of temperature, humidity and/or other meteorological variables have been utilized in the literature to quantify the effects of heat on mortality and morbidity. In a recent analysis, various exposure metrics performed similarly as predictors of heat-related mortality in New York City (Metzger et al., 2010).

Heat waves vs. daily temperature
Heat waves are broadly defined as periods of unusually hot weather over an extended period of time, relative to local conditions. For example, New York City defines a heat wave as a period of at least 3 consecutive days with temperatures > 90°F (32°C). However, it is worth noting that health risks can also occur when one or two days of very elevated temperatures are experienced.

Like other cities in the Northeastern US, Cambridge is vulnerable to adverse health impacts of heat and will face challenges in the years to come. Both mortality (deaths) and morbidity (e.g., hospital visits or reported illnesses) can be affected by extreme heat. Factors that contribute to vulnerability in cities include the urban heat island effect that can amplify the impacts of rising temperatures, areas with minimal tree canopy, and a relatively high proportion of older housing stock that may be poorly adapted to hot weather and lack air conditioning compared to many southern U.S. cities. In addition to hotter summers expected in the years to come, Cambridge is aging as a community. For many, simply being older, obese, diabetic are risk factors for heat-related morbidity and mortality (Basu and Samet, 2002). It is also recognized that those with respiratory or circulatory disease face greater physiological challenges during extreme or prolonged heatwaves (Anderson and Bell, 2009).

A large number of studies have characterized health responses during and following severe heat waves such as the European heat wave of 2003 (Vandentorren et al., 2004) and the 1995 heat wave in Chicago. More recent studies have assessed health responses in relation to less severe but more frequent temperature extremes. These more recent studies usually fit an exposure-response function that can be used to quantify the excess mortality that occurs when temperatures rise above certain levels. An example of a temperature exposure-health response function for Boston is reproduced in Figure 1 (Petkova et al., 2013).

Figure 1. Curve showing the risk of premature death (legend on left axis) vs. mean summer daily temperature for Boston, based on analysis of daily data from 1985 to 2006. See text for details on methodology. Also shown is the histogram of observed temperatures (legend on right axis).



Most studies investigating the impacts of heat have focused on premature deaths (i.e., mortality) (Barnett, 2007, Curriero et al., 2002, Medina-Ramón and Schwartz, 2007). Heat has a direct impact on total daily deaths, with most deaths occurring on the same day or shortly after exposure to heat. Most heat deaths occur at home, but studies have also reported an increase in emergency room visits and hospital admissions for heat-sensitive diseases during heat episodes (Knowlton et al., 2009, Lin et al., 2009). Exposure to elevated temperatures may also have an impact on birth outcomes. For example, a study reported an association between high ambient temperature and preterm births (Basu et al., 2010).

Morbidity and mortality effects of heat may be especially severe if electric power is lost during an extreme heat event because air conditioning provides protection from exposure to heat. Blackouts are more likely during heat waves due to the increased demand for electric power for air conditioning, an effect that places stress on the systems that supply and deliver electricity. When blackouts occur, exposure to heat increases, with a corresponding increase in health risks. As a result of higher summertime temperatures and increased electricity usage, more frequent blackouts could occur in the future.

Estimating the current and future burden of heat-related mortality in Boston and Cambridge

To estimate the current and potential future burdens of heat-related deaths, scientists analyze historical data on daily deaths and temperature in a given locale, and then use those historical relationships, in conjunction with future climate projections, to estimate potential future impacts in a changing climate. We carried out such an analysis for the cities of Boston and Cambridge to assess current and future impacts of heat on premature mortality.

We started by characterizing the summer heat–mortality relationships between observed daily deaths and mean daily temperature using data from 1985 to 2006. To represent Boston, we used mortality data for Suffolk County, MA. Daily mean temperature data for the same period for Boston were obtained from the U.S. National Climatic Data Center. The distributed lag non-linear module in R was used to model the summer heat–mortality relationship (see Figure 1 above).

Projecting potential future health impacts from warming temperatures involves linking together projections about future climate, the underlying health status of the population, the size and age distribution of the population, and the exposure-response function. We did this separately for Boston and for Cambridge. The Boston results were based on the published work of Petkova et al., 2013. The Cambridge results represent new work carried out for this report.

For the Boston analysis, projections for future temperature were developed using downscaled outputs from 33 global-scale general circulation models (GCMs) used in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5), in conjunction with two greenhouse gas emissions scenarios based on representative concentration pathways (RCPs). For this analysis, we selected the two RCPs most used by the climate modeling community, RCP 4.5

and RCP 8.5, which represent relatively low and high greenhouse gas projections, respectively. GCM outputs were downscaled to the Logan Airport weather station using a statistical downscaling method. This yielded a set of 66 future temperature projections for daily mean temperature (T*mean*) in each city from 2010 to 2100 based on the three 30-year time slices, the 2020s, 2050s and 2080s, and for a baseline period 1971-2000. We held both population and baseline mortality rates constant based on data from the year 2000 (Table 1).

The temperature-mortality relative risk estimate for Boston was applied to the daily downscaled temperature projections until 2100 in order to compute estimates of warm-season heat-related mortality.

Results

Temperature, population and mortality summary statistics for Boston are presented in *Table 1*.

Table 1. Population, mortality and temperature statistics for Boston (Suffolk Co)

City	Population (2000)[1]	Annual/Daily Mortality Rate per 100,000 (2000)[1]	Mean Summer[2] Temperature (˚C)[3]	Mean Annual Temperature (˚C)[3]
Boston	689,807	795/2.18	19.6	10.9

[1] *Population and mortality rates obtained from the CDC Wonder Database*

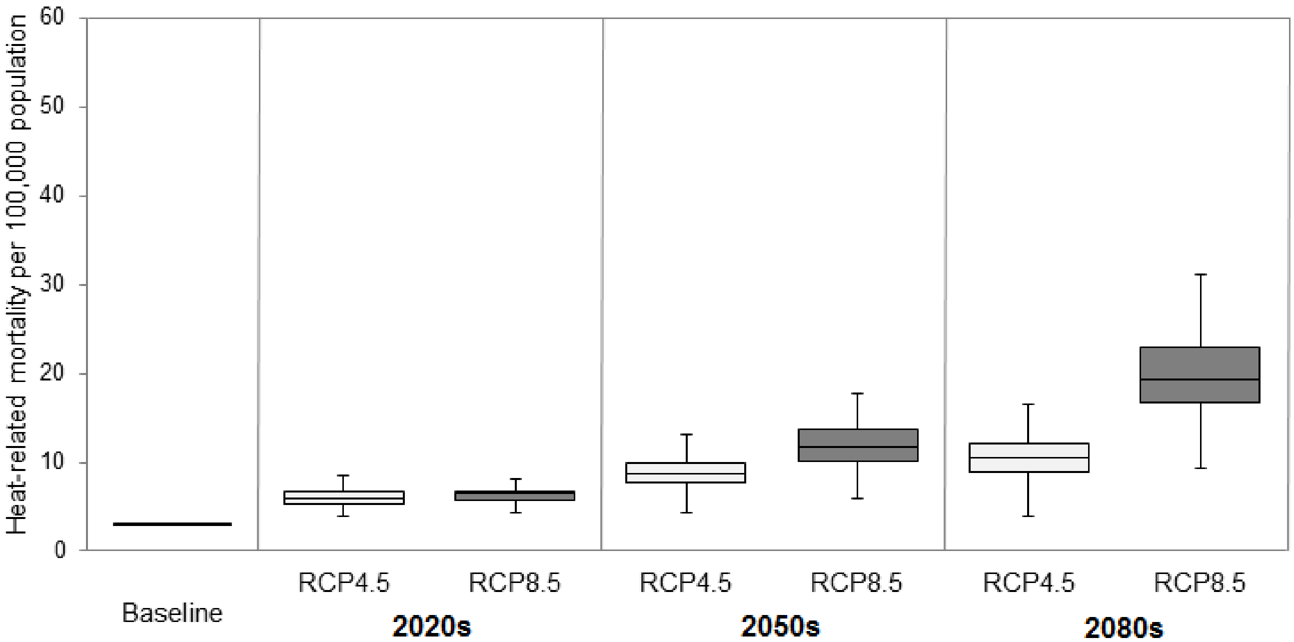
[2] *Includes data for May, June, July, August and September*

[3] *Temperature data obtained from the U.S. National Climatic Data Center*

Annual current and projected future heat-related mortality rates for Boston are presented in *Figure 2.* Baseline heat-related mortality rates were 2.9 per 100,000 persons in Boston. During the 2020s, median heat-related mortality rates calculated across all models and the RCP 4.5 and RCP 8.5, respectively were 5.9 and 6.5 per 100,000. In the 2050s, Boston was projected to experience median mortality rates of 8.8 and 11.7 per 100,000, for RCP 4.5 and RCP 8.5, respectively. By the 2080s, projected median heat-related mortality rates across all models and the RCP 4.5 and RCP 8.5 were 10.5 and 19.3 per 100,000. These findings reflect the impacts of gradually increasing temperatures due to climate change. They do not directly address changes in extremely high temperatures, since climate models are not able to predict those with confidence.

By the 2080s under RCP 4.5, the calculated heat-related mortality rates represent a nearly four-fold increase. By the 2080s under RCP8.5, these rates represent a nearly seven-fold increase. It should be noted that the time slices and climate model data used for the Boston heat-mortality assessment are different from those developed for the CCVA, since they come from a separate, published study. In spite of this caveat, these data provide a useful perspective on potential future heat-related mortality impacts in Boston.

Figure 2. Projected annual heat-related mortality rates during the 2020s, 2050s and 2080s for Boston during the baseline period (1985-2006) with variations according to 33 global climate models and two greenhouse gas scenarios. Box plots illustrate the minimum, lower quartile, median, upper quartile and maximum values across the GCMs. Also displayed are the annual heat-related mortality rates computed for the baseline period between 1985 and 2006, based on observed temperatures.



Heat-related mortality projections for the City of Cambridge:

It is likely that the exposure-response function relating daily temperatures to daily deaths would be similar in Cambridge to what we observed in Boston, given the similarity of climate and population across the two municipalities. For example, Petkova et al., 2013 showed that the function for Boston was similar to those obtained in NYC and Philadelphia, and it is likely that Cambridge would be even more similar to Boston. To estimate impacts in Cambridge, we thus used the exposure-response function for Boston, as well as a prior published exposure-response function for Boston from Curriero et al., 2002 (as a sensitivity analysis). These exposure-response functions were then combined with several alternative estimates of future climate and population in Cambridge. We assumed a reference annual baseline mortality rate (due to all causes) of 567.9 per 100,000 (from recent Cambridge data) to derive estimates of current and future heat-related mortality burdens.

Projection of future population in Cambridge, MA

The population projections for 2025-2035 were taken from the MAPC Metro Future report, which provides regional population projections for two growth scenarios up to 2040 (2010–2040). The two growth scenarios 'Status Quo', and 'Stronger Region', represent 6.6% and 12.6% growth respectively over the next 30 years. Since the MAPC projection only covered the period 2010-2040, we used these population projections in conjunction with climate projections from CCVA and from the US EPA. For projections based on climate data from the 33 downscaled climate models and two scenarios discussed above for Boston for 2020, 2050, and 2080, we used alternative future population projections from the Integrated Climate and Land-Use Scenarios (ICLUS) project. The ICLUS population projections consisted four IPCC Special Report on Emissions Scenarios population growth scenarios (A1, A2, B1, B2). The population projections for Cambridge were estimated using the ICLUS population projections for Middlesex County and the percentage of Cambridge population in Middlesex County in 2010. While these population projections provide illustrations of possible future impacts related to population change, they are highly uncertain.

Table 2 shows the estimated heat-related excess mortality in 2030s climate compared with baseline climate in Cambridge using two different climate models. Using the CESM-WRF-CMAQ downscaling model and three RCPs generated smaller temperature changes (0.59-1.32 ˚C) compared with using the ATMOS report (2.17-2.33 ˚C). Under the status quo population scenario, in each year of the 2030s, Cambridge was projected to experience excess deaths of 11.8, 9.1, and 20.2 for RCP4.5, RCP6.0, and RCP 8.5, respectively. The excess heat-related deaths were much higher for the CCVA scenarios ranging as high as 38/year under a high population scenario and the Curriero exposure-response.

Table 2. Heat-related excess mortality in 2030s due to climate change using different climate projection models in warm season (May-September), Cambridge, MA (deaths per year)

Population projection*	Source of CRF coefficient#	2025-2035 vs. 1995-2005[c]			2015-2044 vs.1971-2000[d]	
		RCP4.5	RCP6.0	RCP8.5	CCVA-Low	CCVA-High
Status Quo scenario	Curriero et al.(2002)	11.8	9.1	20.2	33.3	35.8
	Petkova et al. (2013)	3.6	2.8	6.3	10.3	11.1
Stronger Region scenario	Curriero et al.(2002)	12.6	9.7	21.7	35.7	38.4
	Petkova et al. (2013)	3.9	3.0	6.7	11.0	11.9

[a] Population projection based on the developed by MAPC for 2010-2030.
[b] The concentration-response function (CRF) in Boston, MA was applied in the calculation.
[c] The downscaled CESM-WRF-CMAQ model used in this report, RCP stands for representative concentration pathways.
[d] The summertime temperature projections were derived from the ATMOS report, Climate Change & Vulnerability Assessment (CCVA), October 2013.

Table 3 shows that in the 2020s, the median heat-related deaths calculated across all models (Petkova et al, 2013) were 4.5 and 5.0 deaths per year under the status quo population scenario.

In the 2050s, Cambridge was projected to experience median annual mortality of 6.5-6.8 and 8.7-9.0 deaths per year across all four ICLUS population scenarios for RCP 4.5 and RCP 8.5, respectively. By the 2080s, projected median heat-related mortality across all ICLUS population scenarios and the RCP 4.5 and RCP 8.5 were 7.8-8.1 and 14.3-14.8 deaths per year.

Table 3. Projected heat-related annual mortality during the 2020s, 2050s, and 2080s for Cambridge under the two Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5.[a]

Population projection	2020s		2050s		2080s	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Status Quo scenario [b]	4.5	5.0	/	/	/	/
Stronger Region scenario [b]	4.7	5.2	/	/	/	/
ICLUS-A1 scenario [c]	4.4	4.8	6.5	8.7	7.8	14.3
ICLUS-A2 scenario [c]	4.5	5.0	6.7	8.9	8.0	14.7
ICLUS-B1 scenario [c]	4.5	4.9	6.7	8.9	8.0	14.6
ICLUS-B2 scenario [c]	4.5	5.0	6.8	9.0	8.1	14.8

[a] The projected heat-related annual mortality rates in Boston, MA (Petkova et al, 2013) were applied in the calculation.
[b] Population projection based on the developed by MAPC for 2020.
[c] Population projection based on the average of four scenarios (A1, A2, B1, B2) in the ICLUS population projection.

Thus, a range of future estimates of heat-related mortality were obtained using a range of alternative inputs to the calculations. None should be viewed as the right answer. However, taken as a whole, it is clear that Boston and Cambridge will face potentially greater risks of heat-related mortality in future decades, more so later in the century and more so for higher climate change and population growth scenarios. These analyses do not take into account future aging of the population (and attendant increasing vulnerability) nor future adaptation (and attendant decreasing vulnerability). Also, these statistical analyses cannot anticipate the state of our future healthcare delivery system nor our economy. They are based on documenting historical health impacts, and projecting those into the future based on future climate. However if future heat waves are much higher or longer than those observed in the past, past experience may not be a reliable guide to future health impacts.

2. Local/Regional Air Quality

Ozone and fine particles (PM2.5) are the two pollutants of greatest health concern at concentrations typically observed in Cambridge. Based on current scientific understanding of exposure-response relationships for each of these pollutants, there is no known threshold level below which health effects disappear. Thus, incremental improvements in air quality are expected to lead to incremental improvements in population health, even for concentrations below EPA air standards. These standards are determined by federal law and through the rule-making process within federal regulatory agencies.

Climate Change and Air Quality

Studies of future ozone concentrations in the presence of climate change suggest that climate change alone (absent changes in pollution precursor emissions) could lead to increases in ozone episodes in polluted areas of the northeastern US, leading to increasing health risks. The literature for PM2.5 is smaller and less robust than for ozone, but suggests that PM2.5 could become a bigger problem in some areas, holding pollution emissions constant. These findings imply that more aggressive emissions reductions may be needed to meet air quality targets in the future.

To examine the possible influence of future climate change on air quality in the Boston region, we reviewed findings from recent climate-air quality modeling studies that have examined future ozone concentrations in the New England region (see Table 4 below). In general, these studies suggest ozone concentrations could increase on average by as much as 5 ppb over the region covering Cambridge with climate change, though results vary depending on the study period, scenarios, and climate and air quality models used.

Ozone-Related Deaths in Cambridge Under Future Climate Scenarios

To further explore the potential health impacts of climate change on ozone in the region, we obtained new ozone projections for eastern Massachusetts at a 36 km grid scale from the US EPA, and have mapped these data to GIS layers depicting possible future ozone concentrations under scenarios of climate change.

To model climate change, U.S. EPA used the Community Earth System Model (CESM) driven by three different greenhouse gas emissions scenarios, or RCPs: RCP4.5, RCP6.0, and RCP8.5. The numbers refer to the globally averaged radiative forcing in watts per square meter at the year 2100. The CESM data were downscaled to a 36 km × 36 km grid cells over most of North America using the Weather Research and Forecasting (WRF) model. These meteorological fields were then used as input to the Community Multiscale Air Quality (CMAQ) model in order to model changes in air quality.

Air pollution is dependent on both the climate (meteorology) and on the emissions. Here we used the U.S. EPA projections of anthropogenic emissions at 2030 that took into account regulations that have already been adopted (i.e., the Cross-State Air Pollution Rule and the Tier 2 emissions standards for motor vehicles). Biogenic emissions were modelled using the downscaled meteorology. 36 km gridded daily maximum 1-h ozone and daily maximum 8-h ozone concentrations (ppb) in the warm season (May-September) were obtained for two 11-year time slices: the 1995-2005 period from the historical experiment, as well as the future period 2025-2035.
Since Cambridge only has a total area of 18 km^2, ozone projected concentrations in the 36-km grid cell that covers the whole area of Cambridge were used as the ozone pollution level for Cambridge.

Projection of future population in Cambridge, MA
The population projections for 2025-2035 were taken from the MAPC Metro Future report, which provides regional population projections for two growth scenarios up to 2040 (2010–2040). The two growth scenarios ‘Status Quo’, and ‘Stronger Region’, represent 6.6% and 12.6% growth respectively over the next 30 years.

Excess mortality due to ozone exposure
We estimated the change in excess mortality as follows:

$$\Delta y = \text{Pop} \times MR \times \left(\exp^{\beta \times \Delta c} - 1\right)$$

where Δy is the excess number of deaths due to changes in ozone concentrations (Δc); Pop is the 2025-2035 population in Cambridge; MR is the baseline mortality rate; β is the coefficient of the concentration-response function (CRF) for ozone, derived from four independent epidemiological studies (Table S1). Here we used the overall mortality rate in Cambridge in 2009 (567.9 deaths per 100,000 population) as the baseline mortality rate and kept it constant in 2025-2035.

Results
Table 5 shows concentration changes estimated for ozone and PM2.5 from the model in the grid cell covering Cambridge, MA. Also shown are changes in temperature derived from the model. For ozone, concentrations increase very slightly under RCP4.5 and somewhat more so for RCP8.5. Surprisingly, RCP6.0 resulted in small decreases in mean ozone.

Figure 3 shows the spatial distribution of ozone concentrations in the historical (1995-2005) and the future years (2025-2035) under three different RCPs. The largest increase of ozone concentration was 1.13 ppb for MDA8 (daily maximum 8-hour average) and 1.37 ppb for MDA1 (daily maximum 1-hour average) in RCP8.5 scenario (Table S2).

Table 6 shows the estimated ozone-related excess mortality changes between 2025-2035 and 1995-2005 under three RCPs. The very small changes in ozone concentrations, combined with the small population of Cambridge, resulted in negligible annual mortality impacts of future ozone changes (less than 1 death per year). However, it is important to note that these results come from a single climate and air quality model, and it is known that findings can vary substantially across models and across different configurations of individual models. In light of the findings from previous studies suggesting average increases in ozone concentrations up to 5 ppb under future climate scenarios (table 4), and the fact that changes in extreme values are likely to be larger, ozone and related health effects remains a key concern for related to climate change in Cambridge.

Table 4. Studies of the effect of climate change on regional ozone air quality covering Cambridge, MA.

Reference	Domain	Scenario [a]	Time horizon	Period [b]	Metric [c]	GCM [d]	RCM [e]	CTM [f]	Regional grid /km	Surface ozone and changes (ppb) in region covering Cambridge
Climate change only, assuming constant anthropogenic emissions										
(Hogrefe et al., 2004)	Eastern U.S.	A2	2020/2050/ 2080 vs. 1990	JJA[a]	MDA8[b]	GISS AO	MM5	CMAQ	36	50-55(1990s), +1.5-4.5(2020s), +1.5-4.5(2050s), +5.0(2080)
(Bell et al., 2007)	U.S.	A2	2050 vs. 1990	JJA	MDA	GISS GCM	MM5	CMAQ	36	<4%
(Kunkel et al., 2008)	Global/northeastern U.S.	A1F1, B1	2090 vs. 1990	JJA	MDA8, mean	PCM	MM5	SAQM	30	Boston, MA: +13-21%(A1F1), -1-+7%(B1)
(Tagaris et al., 2009)	U.S.	A1B	2050 vs. 2000	JJA	MDA8	GISS GCM	MM5	CMAQ	36	-0.71 - +0.71
(Wu et al., 2008)	Global	A1B	2050 vs. 2000	JJA	MDA8	GISS GCM	-	GEOS-Chem	4°×5°	60-70(2000); -1 - +1(2050)
Combined changes in climate and emissions										
(Chen et al., 2009)	U.S.	A2	2050 vs. 1990	annual	MDA8	PCM	MM5	MOZART-2/CMAQ	36	+4-6
(Gao et al., 2013)	U.S.	RCP4.5, RCP8.5	2057 and 2059 vs. 2001-2004	annual	MDA8	CESM/CAM-Chem	WRF	CMAQ	12	RCP4.5: -4 - -2(spring),-10 - -8(summer),-5 - -7(fall), +6-8(winter); RCP8.5:+2-4(spring),-5 - -3(summer),+6-8(fall),+9-10(winter)
(Gonzalez Abraham, 2013)	Global	A1B	2050 vs. 2000	annual	MDA8	ECHAM5	WRF	CMAQ	36	67-70(2000),70-74(2050)
(Pfister et al., 2014)	U.S.	RCP8.5	2030 vs.2000	JJA	MDA8	CCSM	WRF	WRF-Chem	12	60-68(2000),36-40(2030)
(Penrod et al., 2014)	U.S.	A1B	2030 vs. 2000	JJA, DJF	MDA8	CCSM	WRF	CMAQ	36	-2 - -1(summer); +2-3 (winter)
(Kim et al., 2015)	U.S.	RCP4.5, RCP8.5	2057 and 2059 vs. 2001-2004	annual	MDA8	CESM/CAM-Chem	WRF	CMAQ	12	-2.99-0.00(RCP4.5), +3.01-6.00(RCP8.5)
(Fann et al., 2015)	U.S.	RCP6.0, RCP8.5	2025-2035 vs. 1995-2005	MJJAS	MDA8	CESM, GISS	WRF	CMAQ	36	RCP6.0:+0.2-1.14; RCP8.5:+1.15-5.0

[a] Socio-economic scenario for the 21st century GHG emissions: A1B, A1F1, A2, B1 are scenarios from the IPCC SRES.

[b] Simulated months: JJA stands for June-July-August; JJAS stands for JJA and September; DJF stands for December-January-February.

[c] Reported ozone metric: MDA8 is maximum daily 8-h average; MDA is the maximum daily average; 1500LT is the ozone concentration at 1500 local time, where most locations in California exhibit peak ozone concentrations; Afternoon mean is the mean ozone concentration from noon to 5 pm local time.
[d] Global climate model: GISS AO is the NASA Goddard Institute for Space Studies (GISS) Atmosphere-Ocean Global Climate Model; PCM is the parallel climate model; ECHAM5 is the fifth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology (MPIM); CCSM is a coupled Global Climate Model developed by the University Corporation for Atmospheric Research; CESM is the Community Earth System Model developed by the National Center for Atmospheric Research (NCAR).
[e] Regional climate model: MM5 is the Pennsylvania State University/National Center for Atmospheric Research mesoscale regional climate model; RegCM is the Regional Climate Model system originally developed at the National Center for Atmospheric Research (NCAR).
[f] Chemical transportation model: CMAQ is the Community Multiscale Air Quality model; SAQM is a modeling component of the San Joaquin Valley Air Quality Study/Atmospheric Utilities Signatures, Predictions and Experiments Study (SJVAQS/AUSPEX) Regional Modeling Adaptation Project; MOZART-2.4 is Model for Ozone and Related Chemical Tracers, version 2.4; CHIMERE is a multi-scale CTM model that runs over a range of spatial scale from the regional scale (several thousand kilometers) to the urban scale (100-200 km) with resolutions from 1-2 km to 100 km; GEOS–Chem is a global three-dimensional model of tropospheric chemistry driven by assimilated meteorological observations from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling Assimilation Office.

Table 5. Historical and projected future concentrations of ozone and PM2.5 over Cambridge, MA, using CESM-WRF-CMAQ and US.EPA projections of anthropogenic emissions at 2030.

11 year average	o3max8h(ppb)	o3max1h(ppb)	Tmax(°C)	Tmin(°C)	Tavg(°C)	$PM_{2.5}$
Historical: 1995-2005	50.63	53.9	29.36	19.02	23.82	4.48
RCP4.5:2025-2035	50.9	54.08	30.19	19.82	24.58	4.48
RCP6.0:2025-2035	50.52	53.73	29.98	19.56	24.41	4.62
RCP8.5:2025-2035	51.76	55.27	30.85	20.3	25.14	4.64

Table 6. Ozone-related excess mortality due to future climate change (2025-2035) compared with baseline climate (1995-2005) under different Representative Concentration Pathways (RCPs) in warm season (May-September), Cambridge, MA (deaths per year with 95% CI)

Metric	Source of CRF coefficient	Status Quo population scenario			Stronger Region population scenario		
		RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5
MDA8	Ito et al.(2005)	0.08(0.05,0.12)	-0.03(-0.04,-0.02)	0.35(0.21,0.49)	0.09(0.05,0.13)	-0.03(-0.05,-0.02)	0.37(0.22,0.52)
	Levy et al. (2005)	0.08(0.05,0.11)	-0.03(-0.04,-0.02)	0.33(0.23,0.44)	0.09(0.06,0.11)	-0.03(-0.04,-0.02)	0.36(0.24,0.47)
	Schwartz (2005)	0.04(0.01,0.06)	-0.01(-0.02,0.00)	0.15(0.05,0.25)	0.04(0.01,0.06)	-0.01(-0.02,0.00)	0.16(0.05,0.27)
	Bell et al. (2005)	0.06(0.03,0.09)	-0.02(-0.01,-0.03)	0.24(0.11,0.36)	0.06(0.03,0.09)	-0.02(-0.04,0.00)	0.26(0.12,0.39)
MDA1	Ito et al.(2005)	0.04(0.02,0.06)	-0.04(-0.05,-0.02)	0.32(0.19,0.45)	0.04(0.03,0.06)	-0.04(-0.06,-0.02)	0.34(0.21,0.48)
	Levy et al. (2005)	0.04(0.03,0.05)	-0.04(-0.05,-0.02)	0.30(0.21,0.39)	0.04(0.03,0.06)	-0.04(-0.05,-0.03)	0.33(0.22,0.43)
	Schwartz (2005)	0.02(0.01,0.03)	-0.02(-0.03,0.00)	0.13(0.04,0.22)	0.02(0.01,0.03)	-0.02(-0.03,-0.01)	0.14(0.04,0.24)
	Bell et al. (2005)	0.03(0.01,0.04)	-0.03(-0.04,-0.01)	0.22(0.11,0.33)	0.03(0.01,0.05)	-0.03(-0.04,-0.01)	0.23(0.11,0.36)

Note: Population projection based on the developed by MAPC for 2010-2030.

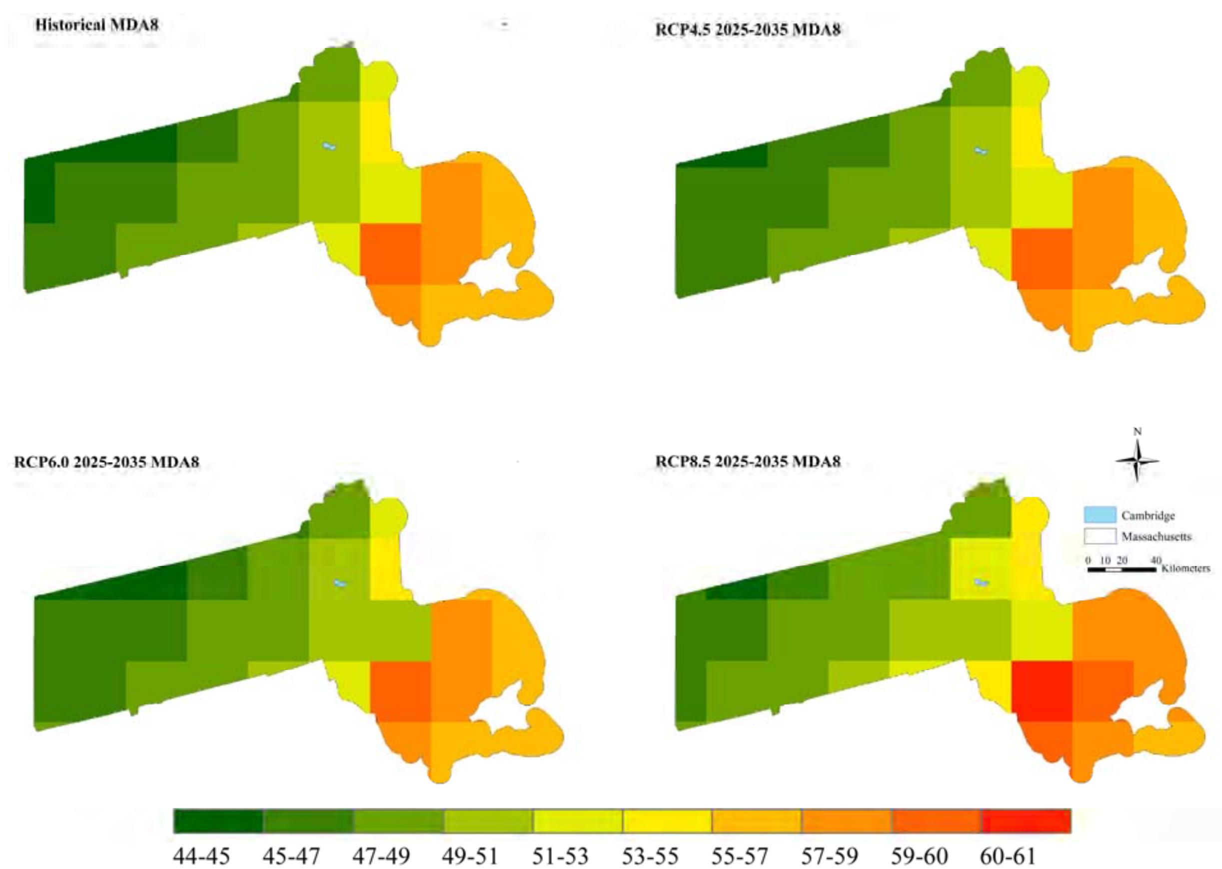
Table 7. Ozone-related excess mortality due to future climate change (2025-2035) compared with baseline climate (1995-2005) under different Representative Concentration Pathways (RCPs) in warm season (May-September), Cambridge, MA (deaths per year)

	Source of CRF coefficient	RCP4.5	RCP6.0	RCP8.5
MDA8	(Ito et al., 2005)	0.08	-0.03	0.33
	(Levy et al., 2005)	0.08	-0.03	0.32
	(Schwartz, 2005)	0.03	-0.01	0.14
	(Bell et al., 2005)	0.05	-0.02	0.23
MDA1	(Ito et al., 2005)	0.06	-0.02	0.25
	(Levy et al., 2005)	0.06	-0.02	0.24
	(Schwartz, 2005)	0.03	-0.01	0.11
	(Bell et al., 2005)	0.04	-0.02	0.17

Note: Population projection based on the average of four scenarios (A1, A2, B1, B2) in the ICLUS population projection.

(Ito et al., 2005)	Non-accidental mortality	warm (Apr. to Sep.)	MDA8	1.17(0.7-1.63) per 10 ppb
		warm (Apr. to Sep.)	MDA1	0.88(0.53-1.23) per 10 ppb
(Levy et al., 2005)	All-cause mortality	warm (May to Oct.)	MDA8	1.12(0.76-1.47) per 10 ppb
		warm (May to Oct.)	MDA1	0.84(0.57-1.10) per 10 ppb
(Schwartz, 2005)	Non-accidental mortality	warm (May to Sep.)	MDA8	0.49(0.15-0.83) per 10 ppb

Figure 3. Maximum daily 8-hour ozone concentrations historically and in the 2025-2035 period under three different RCP scenarios. The City of Cambridge is depicted as the light blue area contained within a single 36 km model grid box. This illustrates the potential benefit of future studies that model air pollution at much finer spatial scales.



3. Indoor Air Quality/Mold

Indoor air quality is an important issue in the current climate and could be impacted by future changes in climate. People spend on average at least 90 percent of their time indoors. The quality of the air indoors thus has a large bearing on health status. Indoor air quality is most impacted by indoor sources of pollution but also is influenced by the penetration of outdoor pollutants. Indoor air quality is adversely affected by combustion sources that emit indoors, such as cigarette smoking, cooking with gas, and burning of candles and incense. Indoor air quality is also impacted by emission of volatile organic compounds (VOCs) from numerous materials including paints, wallboard, carpet and consumer products. In fact, for most VOCs, indoor concentrations far exceed those measured outdoors. Another important factor for indoor air quality is moisture, including air humidity as well as dampness of building materials due to leaking pipes or flooding from outdoors. Indoor dampness has been known for a long time to be a cause of adverse respiratory effects, including symptoms of cough and wheeze among persons of all ages.

Climate has an influence on indoor air quality via effects on ventilation – e.g., opening of windows or use of air conditioning - and via effects on indoor dampness. To the extent that warming outdoor temperatures lead to changes in building ventilation, corresponding changes in indoor air quality could occur, either increases or reductions depending on the direction of change. Behavioral changes will also play a role. More relevant and potentially more concerning will be potential increases in exposures to dampness, flooding and resulting indoor mold and bacterial growth and exposure. This risk is exacerbated in buildings that are adjacent to poorly drained soils, have poorly sealed exterior windows and roofs, and those that utilize forced hot air, which can become a conveyor of air from damp basement areas. Climate change will lead to higher sea level, larger and more impactful coastal storms, and more intense rainfall events in general, all of which could lead to more frequent and/or severe flooding problems in Cambridge. Any residential or commercial structures that experience flooding will face potential long-term challenges related to mold growth and resulting respiratory problems. Mapping of flood zones will assist in characterizing neighborhoods, streets, and individual units that may be at greatest risk, and for which mitigation and flood-resiliency measures will be warranted.

4. Vector-Borne Disease

Mosquitoes and the diseases they carry are climate sensitive especially to temperature, rainfall, and humidity, evidenced by the seasonality of mosquito borne diseases (Reiter, 2001; Khan et al., 2011). Rain collects, providing still water for mosquitoes to breed while extended drought conditions decrease survival for all life stages; temperature influences the rate of larval development, adult feeding behavior, the rate of pathogen replication within the mosquito; and humidity influences adult mortality (Hales, 2002; Arrivillaga and Barrera, 2004; Honorio et al., 2009; Johansson et al., 2009; Knowltron et al., 2009). Temperature may limit disease transmission in areas where the vector is present but the temperature precludes efficient transmission (Westbrook, 2010). Because these climactic factors influence the number of disease infected mosquitoes, climate directly relates to the risk of disease transmission. Global warming and associated warmer, wetter conditions may increase the risk of vector borne disease infection if these conditions fall within the optimal growth rates of both the vectors and arboviruses. However human manipulation of the environment, especially urbanization, and human behavior complicate the relationship between mosquitoes and climate.

Climactic factors associated with heightened transmission of WNV in the Northeastern USA include consistently high spring and summer temperatures and lower precipitation rates over this same time period. Warmer winter temperatures may increase overwintering survival and therefore increase the number of *Culex* mosquitoes that emerge in the spring (Han & DeMaria, 2012).

EEE transmission is linked to precipitation patterns that affect the overwintering survival of larvae and, in part, predict adult abundance the following season. Two consecutive years of excess average rainfall have accounted for EEE outbreaks in the past (Grady et al., 1978). Increased abundance of the enzootic vector, *Culiseta melanura*, leads to increased amplification of the virus, increased risk that the virus will be picked up by a bridge vector that bites both birds and mammals, and an increased risk of transmission to humans. Periods of increased rainfall and warm summer temperatures indicate periods when surveillance should be intensified.

Cold winters currently prevent the establishment of *Ae. albopictus* (tiger mosquito) in much of the Northeastern USA (Andreadis 2009) however *Ae. albopictus* is present in an increasing number of cities in the Northeastern USA and has been observed at least as far north as New Bedford, MA (a tire recycling facility) in recent years . This species is associated with transmission of dengue and the expansion of its range is likely to increase the transmission risk of this pathogen. Jetten and Focks (1997) modeled the influence of 2º and 4º Celsius warming in temperate cities of North America and found that warming would increase the number of weeks for potential transmission of dengue.

Climate and tick borne diseases

The host seeking density of *Ixodes scapularis* (eastern deer tick) has been positively correlated with Lyme disease incidence (Mather et al., 1996; Stafford et al., 1998; Hubalek et al., 2003). Climate variables are linked to the distribution and abundance of *I. scapularis.* Temperature and humidity regulate tick survival and ground measured minimum, maximum, mean temperatures as well as vapor pressure predict the ability of various stages of *I. scapularis* to transmit pathogens (Brownstein et al., 2003). While cold winter and autumn temperatures may decrease vector populations (Ogden et al., 2004; Rand et al., 2004) or inhibit host seeking behavior (Schulze & Jordan, 2005), warm spring temperatures may increase development speed and lead to earlier emergence of nymphs (Lindsay et al., 1995).

Projected climate change and vector-borne diseases in the Northeastern USA

A suitable climate underlies the distribution of vector-borne diseases. Global warming and associated warmer, wetter conditions may increase the risk of vector borne disease infection. The projected increases in warm days, decreases in cold nights, increased precipitation, and increased heat waves/warm spells in the northeastern USA (IPCC, 2012) portend conditions that may increase the abundance of vectors and their ability to transmit diseases in the northeastern USA. However a decrease in soil moisture may have a negative impact on mosquito and tick borne diseases, but this was projected with low confidence (IPCC, 2012). Extreme weather events associated with climate change such as floods and droughts will also influence vector borne diseases. Flooding disrupts water, sewer, and sanitation services. Extreme weather events can damage windows and doors or damage screens that cover them. Flooding may contaminate water sources and cause inadvertent storage of standing water that persists long enough to support larval growth. Extreme weather events including heat waves can cause power outages and expose people to vector borne diseases if they open their windows rather than relying on Air Conditioning. Current state housing code does not require the installation of window screens above the third floor, so the exposure to adult mosquitoes would be potentially exacerbated.

Socio-ecological risk factors

Urbanization can lead to increased risk of disease transmission by affecting both the biology and behavior of humans, reservoir hosts, vectors, and even the pathogens themselves. Urbanization can result in areas of higher density of susceptible hosts; place higher densities of hosts and vectors together as urban areas encroach on natural habitats; and create habitats for adult vectors and breeding habitats that support important certain “container-breeding” disease vectors (Leisnham & Slaney, 2009).

In the USA low-density urbanization has been the dominant trend evidenced by only a 10% increase in total urban population and a 50% increase in outlying areas designated as urban since 1950 (Leisnham & Slaney, 2009). This form of suburban development with a resulting pattern of a matrix of urban and natural areas may promote many of the vector borne diseases in the Northeastern USA. Research on Lyme disease has linked residential development that encroaches on forested areas to risk of transmission. Human risk of Lyme disease at these transitional areas is due to the direct contact of humans with deer ticks. But, these transitional areas of deforestation and fragmentation are also linked to decreased biodiversity (Despommier et al., 2007). The role of biodiversity has been posited to influence tick infection rates. Known as the dilution effect, increased reservoir host biodiversity reduces infection rates in ticks due to the inclusion of hosts that are not as efficient as the white-footed mouse at infecting feeding ticks (Schmidt & Ostfeld, 2001; Allan et al., 2003; Keesing et al., 2006). More recently researchers have applied the theory of the dilution effect on WNV transmission. Increased bird diversity reduces WNV transmission (Allan, 2009). The size of a wetland area within an urban environment is linked to the biodiversity of birds and the number of infected mosquitoes (Johnson et al., 2012), though current risk from WNV is primarily associated with non-wetlands urban breeding sites (e.g. roof gutters, used tires) that support larval development of “container-breeding” species such as *Culex pipiens*.. Birds respond to vegetation composition and structure, and urban areas that retain native vegetative characteristics are posited to retain higher bird diversity (Chace et al., 2004).

Man-made features may be important sources of mosquitoes. At an individual parcel level, clogged roof gutters, used tires, birdbaths, discarded toys, pet bowls, tarps, plant dishes, and rainwater collection containers are examples. At a neighborhood or city parcel level, storm drains and subterranean drainage systems are hospitable breeding grounds for both *Culex* and *Aedes* species especially during times of low surface water availability (Leisnham & Slaney, 2009). Cemeteries, road-work, construction sites, irrigation, urban agriculture, open waste water systems, tire piles, are other recognized sources of mosquitoes.

High living standards and protective factors such as spending less time outdoors and using AC or screens while indoors in cities like Cambridge reduces transmission risk (Reiter et al., 2003), including upper floors of buildings not otherwise required to have screens.

Urban areas experience climate phenomena differently than rural areas. The urban heat island effect is a result of the high proportion of impervious surfaces that absorb and store solar radiation and keep urban areas warmer than rural areas. Higher concentrations of pollutants in urban areas may seed cloud formation and result in more precipitation (Changnon et al., 1981; Bornstein & Lin, 2000; Shepherd et al., 2010) and higher concentrations of carbon dioxide may increase the rate of plant growth in urban areas (Ramirez & Finnerty, 1996). Warmer temperatures, higher precipitation, and increased plant growth are all potential risk factors for increased vector borne disease transmission.

Surveillance, control, & prevention

In 2000, Massachusetts began statewide surveillance of mosquitoes to estimate human risk of infection. **Current practices for mosquito borne disease surveillance** begin with fixed and long-term traps used to generate baseline information and detect trends in mosquito abundance and virus prevalence. Supplemental traps are set when EEE or WNV activity is detected in an area either through virus isolation in mosquitoes, emergence of large numbers of human-biting mosquitoes in an area with a high rate of virus activity, or identification of human or animal cases (Han & DeMaria, 2012). Human surveillance becomes active when routine surveillance data estimate a high risk of human disease. Information on positive surveillance findings is reported to local, regional, and national authorities and then made publically available on the Massachusetts Department of health arbovirus website (www.mass.gov/dph/wnv). In 2007, the Massachusetts department of health began constructing arbovirus risk maps for WNV and EEE integrating historic data with current virus isolations (human, mosquito), weather conditions, and areas of mosquito habitat (Han & DeMaria, 2012). Additionally the Massachusetts Department of Health periodically reviews national and regional surveillance data as well as scientific literature to determine risk of other emerging Arboviruses and defines subsets of mosquito pools will be tested for the presence of emerging arboviruses (Han & DeMaria, 2012).

Notwithstanding the strong surveillance response to the introduction of WNV in 2000, state support for mosquito pool analysis has been significantly reduced and districts now must pay for all testing. The distribution of state-deployed traps appears to be relatively static and oversamples parts of Brookline and Boston while neglecting Cambridge entirely, even as that community became the regional "hot spot" for WNV in 2012. This restriction of support for testing has resulted in fewer pools being tested in many areas of the state, including Cambridge, and advocacy for a more robust financing system for mosquito surveillance is certainly warranted.

Best practice for prevention and control entails comprehensive, integrated pest management (IPM). Fundamental to IPM is an understanding of the biology of the transmission system and regular monitoring to determine if and when interventions are needed to keep pest numbers below disease transmission thresholds (CDC, 2003). Surveillance of mosquitoes as well as human cases is critical to inform IPM.

A **comprehensive mosquito surveillance** program must include larval and adult surveillance, documentation of trends and the creation of maps over time, virus testing, and data analysis (CDC, 2003). Regular trapping over time of adults at representative geographic coverage and subsequent documentation of adult mosquito density infection rates by rapid testing are key. Mapping of larval habitats to facilitate larval control of source habitats and the association of larval production with adult mosquito population density is important. Larval surveillance must include a wide range of aquatic habitats including those known by trained inspectors and surveillance for new sources (CDC, 2003). Timely mosquito testing and infection rate calculation are essential for disease risk estimation and outbreak control efforts. Because of the limited flight range of most mosquitoes, especially in the proximity of high host density, mosquito surveillance reflects the immediate risk and control efforts are effective locally. The spatial and temporal correlation between isolated WNV from collected mosquitoes and subsequent human cases underscores the importance of mosquito surveillance (Andreadis et al., 2004). Periods of increased rainfall and warm summer temperatures indicate periods when surveillance should be intensified for EEE.

For areas with vector borne disease transmission, the CDC recommends active **human surveillance** through the regular contact of physicians and hospitals as well as laboratory based surveillance (CDC, 2003). In addition to active surveillance, special projects may be used to enhance surveillance. Real time computerized syndromic surveillance in emergency departments as well as identifying WNV in pediatric patients are two special projects outlined by the CDC (CDC, 2003).

Source reduction, the alteration or elimination of mosquito breeding habitat, is thought to be the most effective and economical method for long term **mosquito control** (CDC, 2003). Source reduction can occur from the individual to the regional level. Sanitation and water management are cited as the two main areas for source reduction. Sanitation is basically cleaning up garbage and clearing natural and artificial waterways so that they flow freely. Water management of marshes, including impoundment and open marsh water management, involves manipulation of these natural systems so that mosquitoes cannot successfully breed, though urban wetlands are primarily associated with nuisance species in the Boston area. Source reduction from public and private property and treatment of storm drains and other areas with standing water on public and private property are crucial components of a strong municipal/regional prevention program. The MA legislature recently reinstated a public sector waiver to allow only larviciding of public storm drains without having to obtain full pesticide applicator license. From 2000-2007 this "fast-track" temporary applicator licensing program was invaluable in helping communities in MA used to treat public storm drains at an affordable cost. Obstacle to reinstatement of this program with reasonable testing standards for this low-risk activity remain, as the State Pesticide Board must still determine how high a standard they expect municipal employees and seasonal workers to meet before allowing them to distribute these pre-measured materials to urban storm drains. This effort to ease the burden on municipalities should be supported whenever possible.

Central to IPM is **health education** with the goal of changing human behaviors to prevent transmission. Community based vector control is a crucial component of successful vector control. The success of community based vector control interventions is based on the identification of the mechanisms and behaviors that promote vector production and addressing these issues (Elder and Lloyd, 2007). Education and outreach are prerequisite to engaging the public. Communities need to first understand the significance of vector borne diseases and then strategies that are protective. Health education for vector borne diseases should include messaging for prevention at the personal, household, and community levels.

Integrated tick management is a technique of incorporating several methods at once to reduce risk. With 75% of Lyme disease acquired around the home the need to manage ticks in residential landscapes should be a top priority (Stafford, 2004). Landscape practices to reduce tick and host habitat adjacent to homes, the management and treatment of host animals, applications of insecticides to high risk tick areas, and personal protection measures are the main components of integrated tick management (Stafford, 2004). Reducing the habitat for deer as well as white-footed mice in residential areas reduces tick abundance. Predators of mice, including foxes, snakes, and hawks, may have an important role in reducing the risk of tick borne diseases.

Recommendations for vector-borne disease risk reduction

To **improve environmental monitoring**, utilization of GIS and remote sensing to extract environmental and demographic data in conjunction with vector surveillance can highlight areas of risk and even predict risk as these variables change (Knowltron et al., 2009). The City of Cambridge could work to downscale the surveillance and risk mapping efforts underway by the state of Massachusetts. Using remote sensing to augment ground based surveillance of land cover classification, combined with data collection on climate parameters, including temperature, rainfall, and humidity, and surveillance of both mosquitoes and ticks, the city of Cambridge could create its own risk maps for predicting increased risk of transmission to humans.

Multiple trap types should be used to capture the mosquitoes that inhabit a particular area – carbon dioxide baited light traps are used to collect host seeking mosquitoes, gravid traps are used to characterize the ovipositing mosquito population, resting boxes may be used to measure populations of bird-biting mosquitoes, and special attention should be given to day time biting mosquitoes such as *Ae. albopictus* when choosing trap deployment strategies (CDC, 2003). Long-term surveillance of vectors should include areas where they are known to exist but also areas where they are known not to exist currently in order to assess range expansion as well as the introduction of invasive species. Spread and invasion of vectors underlies the risk of emerging vector borne diseases.

Frequency of isolated cases may rise with projected climate conditions and increasing incidence of imported cases. The education of clinicians for the signs and symptoms of imported diseases is important for stopping potential outbreaks and because proper treatment and case management can reduce severity of disease and save lives. **Surveillance** depends not only on the ability of clinicians or other health care providers to recognize and diagnose disease but also on if the patient seeks advice from clinicians. Sentinel surveillance of returning travelers is one way to capture imported cases of diseases like dengue and chikungunya (Knowltron et al., 2009).

Special surveillance efforts should occur after extreme weather events because infrastructure may be damaged, increasing human-vector contact (Knowltron et al., 2009)

Improving vector control is the primary means to reduce the spread of disease. Truck-based pesticide spraying that targets adult mosquitoes is not effective for all mosquito species, especially daytime biting mosquitoes such as *Aedes* species, and is also costly and may result in insecticide resistant mosquitoes (Knowltron et al., 2009). Some field work was conducted in 2001 by CDC researchers in the Boston area indicating that the primary WNV vector in the area, *C. pipiens*, is found in high densities in the canopies of trees and may be less accessible to most ground-based applications of insecticide than previously thought.

The reduction of standing water to reduce breeding sites is the most effective means of control. Education and mobilization of communities to recognize and deal with standing water is important for sustainable mosquito control. Community mobilization activities such as clean up days that engage people with prevention efforts or research activities may be successful in conveying health education, prevention, and control (CDC, 2003).

Prevention campaigns should be targeted to those at high risk. For WNV and EEE, high-risk groups include those over 50, those with outdoor exposure, the homeless, and people without window screens or those who don't have access to AC. Partnerships are important with organizations that communicate with these targeted groups such as the AARP or senior centers for people over 50, union officials, job site supervisors, golf pros, or gardening experts for those who spend a lot of time outside, and other community leaders who may reach a lot of people. Children are at high risk for tick borne diseases; however the elderly and immune compromised are the most likely to have severe disease. It remains important for local and state public health authorities to explain and reinforce the different risks and habitats for mosquitoes associated with EEE vs. WNV. Ongoing confusion about the distinct localities where these two arboviruses are present and what the relative health risks posed by each virus has been reduced and media coverage has become more nuanced and accurate, but this effort will need to continue.

Because it is so important for individuals to reduce breeding sites for mosquitoes and habitat conditions suitable for ticks on their properties, and individuals may not be compliant, **fines** can be given based on untidy yards, standing water for breeding, and/or garbage accumulation.

Conclusions

It seems likely that holding all else equal, climate change could lead to conditions that will increase the risk of vector borne diseases in the Northeastern USA. However all else will not remain equal and independent and associated risk factors will influence vector borne disease risk. Continued surveillance is critical to predicting times and areas of increased disease risk. Surveillance efforts should be aimed to capture emerging vectors and pathogens of public health importance. Mosquito traps that preferentially collect human-biting species should be used and mosquitoes should be tested for diseases including dengue and chikungunya as the presence of these pathogens in regional mosquito populations escalates. There is a need for science to link urban design with human health; methods are needed for architects, urban planners, and citizens to improve their environment (Jackson, 2003). Social changes through education campaigns and community involvement for vector control efforts, making peridomestic and communal areas free of breeding sites for mosquitoes, could greatly reduce source populations of mosquitoes regardless of climactic and ecological changes. Promoting prevention and control now and forming plans for disasters in the future will create resilient communities that will be less vulnerable to worst case scenarios that may involve the breakdown of infrastructure due to extreme heat waves, energy shortages, floods, or droughts.

Supplementary Information

Table S1. List of ozone-mortality risk estimates (and sources) used in the current study.

Reference	Health outcome	Study season	Metric	% increase (95%CI)
(Ito et al., 2005)	Non-accidental mortality	warm (Apr. to Sep.)	MDA8	1.17(0.7-1.63) per 10 ppb
		warm (Apr. to Sep.)	MDA1	0.88(0.53-1.23) per 10 ppb
(Levy et al., 2005)	All-cause mortality	warm (May to Oct.)	MDA8	1.12(0.76-1.47) per 10 ppb
		warm (May to Oct.)	MDA1	0.84(0.57-1.10) per 10 ppb
(Schwartz, 2005)	Non-accidental mortality	warm (May to Sep.)	MDA8	0.49(0.15-0.83) per 10 ppb
		warm (May to Sep.)	MDA1	0.37(0.11-0.62) per 10 ppb
(Bell et al., 2005)	Non-accidental mortality	warm (May to Oct.)	MDA8	0.8(0.38-1.22) per 10 ppb
		warm (May to Oct.)	MDA1	0.6(0.29-0.92) per 10 ppb

Note: MDA8: maximum daily8-hour averaged ozone; MDA1: maximum daily 1-hour averaged ozone.

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