Health Effects During Extreme Heat Events in New Brunswick: Developing an Evidence-Base to Enhance Adaptation Planning

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Project Data
Research analytic outputs were produced using platform data accessed through the New Brunswick Institute for Research, Data and Training (NB-IRDT) at the University of New Brunswick, along with data provided by the Regional Health Authorities and the Government of New Brunswick, Department of Health under a contract with NB-IRDT, open-source weather data obtained directly from Environment and Climate Change Canada and data on green and blue spaces from the Canadian Urban Environmental Health Research Consortium (CANUE). The following data sets were accessed via the CANUE Data Portal: MODIS - Growing Season Mean, Tree Canopy Coverage and Proximity to Water Bodies (DTW_A_YY).

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Executive Summary

Exposure to extreme heat has been linked to negative health outcomes, including increased need for health services and, in severe cases, death[1]. Climate change events are becoming more frequent. For instance, the occurrence of extremely hot days is expected to more than double in the near future[2]. As a result, there is a growing need to study, understand and protect against the impacts of extreme heat on health outcomes. This is especially true in New Brunswick, which has an aging population with pre-existing health conditions and is therefore more vulnerable to extreme heat.

This study is a comprehensive analysis of heat-related health impacts in New Brunswick over the years 2007 to 2021. Using linked data (including population-level administrative health data, demographic data and daily weather data) accessed through the New Brunswick Institute for Research, Data and Training (NB-IRDT), it estimates the impacts of temperature, humidity and heatwaves on three main health outcomes:

1. Mortality (death)
2. Hospitalization
3. Emergency department (ED) visits

Incorporating environmental data on green spaces (i.e., vegetation, like parks and trees) and blue spaces (i.e., water, like rivers and lakes), it also examines whether living close to these areas has a mitigating, or protective, effect on negative health outcomes related to heat. Overall, this study aims to explore which heat thresholds (i.e., which temperatures or humidity levels) pose the greatest health risk. Its goal is to help improve New Brunswick's Heat Alert and Response System (HARS) and guide interventions to protect New Brunswickers during heat events.

Highlight of Findings

Findings suggest that extreme heat events heighten the impact on public health in New Brunswick for all three health outcomes.

- In the seven days following an extreme humidex of 36 or higher, risk of death is heightened by 5%, and risk of hospitalization and ED visits each rise by 2%. This is referred to as cumulative risk.

While the greatest negative effects were immediate, there was evidence for delayed health risks that persist for up to 7 days following extreme heat exposure, long after heat has subsided.

- Results show a 'harvesting effect,' in which the most vulnerable individuals face greater immediate risk (i.e., on the day of extreme heat exposure), with an apparent observed temporary decline in risk in subsequent days (i.e., the first few days after heat exposure).

- However, increases in risk of mortality and ED visits re-emerged three or more days following exposure to extreme heat.

Prolonged extreme heat events (i.e., heatwaves) were found to have a greater negative impact on health outcomes than single-day heat events.

- Longer heatwaves (2+ days) defined by either extreme temperatures (daytime: ≥30°C, nighttime: ≥18 °C) or extreme humidex (36) are associated with a 14% increase in cumulative risk of death, and a 4% increase in cumulative risk of ED visits.

Temperature and humidity, together, contributed more to heat-related health impacts than either metric on its own.

- A 24% increase in mortality risk was found during heatwaves (2+ days) characterized by both extreme temperature and extreme humidex.

- Though, cumulative risk of mortality was found to be greatest (36%) for heatwaves with very extreme temperature (≥36°C) or humidity (≥40).

The risks of negative health outcomes due to extreme heat exposure are more pronounced in urban areas (i.e., the cities of Fredericton, Moncton and Saint John). Larger cities like these often have higher population density, greater socioeconomic challenges, fewer green spaces and infrastructure that 'traps' heat (known as the urban heat island effect). These factors may intensify heat risks.

- While the cumulative risk of death increases 5% province-wide at extreme temperatures, it rises by 11% in urban areas and by 14% among core urban populations.

Living close to 'green space' may have a mitigating or protective effect on the health impacts of extreme heat. However, data quality issues limited our ability to make robust conclusions about proximity to blue space.

- At extreme temperatures, risk of death increases by 8% for individuals living in areas with lower vegetation coverage, compared to an increase of 2% for individuals living in areas with higher vegetation coverage.

This is the first study of its kind to be conducted in New Brunswick. The findings from this study contribute to the growing body of evidence on the health effects of extreme heat in Canada and can support efforts to enhance preparedness and resilience to future heatwaves.

1. Introduction

1.1 Background

With climate change, extreme heat events are expected to occur more often, last longer and become more intense, posing considerable health risks[3]. Regions like New Brunswick (NB), Canada, are expected to experience substantial climate shifts and may be particularly vulnerable as the populations are not well-adapted to such extreme weather. Projections suggest that the annual occurrence of extremely hot days in Canada, including in provinces like NB, could more than double within the next 30 years[2]. This could lead to growing health and economic risks across all population segments.

Extreme heat events have been linked to a range of serious health issues, including heat exhaustion, heatstroke and the worsening of chronic conditions such as respiratory and cardiovascular diseases, all of which contribute to an increased risk of death[1].

Many studies across different regions have found an association between extreme heat and health outcomes, consistently demonstrating the negative effects of heat events[4-6]. Research has examined a variety of health outcomes, overall rates of illness (all-cause morbidity) and death (all-cause mortality), as well as cause-specific morbidity and mortality (i.e., health outcomes due to specific conditions, including those related to heat).

Studies on heat events have addressed multiple dimensions of heat, including intensity, duration and population vulnerability. While some studies[7, 8] have identified a higher risk of death during extreme heat events, others highlight increased risks of emergency department (ED) visits and hospital admissions. The extent of these risks varies depending on population characteristics, infrastructure and public health interventions. Certain groups, such as older adults, individuals with pre-existing chronic conditions and socioeconomically disadvantaged populations, are especially vulnerable during heat events. Fortunately, improvements to infrastructure – such as increased access to air conditioning – and effective public health interventions have been shown to reduce the health risks associated with extreme temperatures[1,9-11].

Research[12] on prolonged heat events (lasting two or more days) consistently indicates that both the duration and intensity of heatwaves contribute to adverse health outcomes, with longer heat events posing higher risks. Several studies[12-15] have identified a 'harvesting effect,' in which there are immediate increases in mortality and morbidity, followed by reductions in risk in the following days. This suggests that the most vulnerable individuals are affected early in a heat event. Additionally, some studies[13] report a delayed effect of extreme heat, where heat exposure contributes to psychological or physiological conditions that lead to death or hospitalization in the days following the heat event.

Urban areas such as cities face compound risks due to the urban heat island effect, through which land covered by asphalt, concrete and limited vegetation leads to significantly more heat retention than surrounding rural areas. This effect is worsened by the lack of cooling mechanisms such as green and blue spaces (e.g., forests or bodies of water), which can help ease the immediate effects of extreme temperatures. While some studies[16-18] have found that living close to green spaces and to water bodies reduces the health risks associated with extreme heat, findings on their mitigating effects remain inconsistent[7,19 20].

As extreme heat events grow in frequency and intensity, governments and public health agencies are actively working on strategies to adapt to and reduce the impact of extreme heat. Evidence that shows how heat events have impacted health in the past can be used to guide policy decisions and inform targeted interventions to reduce heat-related health risks among vulnerable populations in the future. The findings from this study add to the growing body of evidence on the health effects of extreme heat and can support efforts to enhance preparedness and resilience to future heatwaves. This is the first study of its kind to be conducted in NB.

1.2 Study Objectives

Previous research has consistently shown that extreme heat and heatwaves are linked to higher rates of illness and death. While there is growing awareness of the risks posed by extreme heat, there has been limited research on its specific impact in NB. Most Canadian studies have been based in other provinces and have not accounted for the unique demographic and climatic characteristics of NB, which may influence health outcomes differently.

This study aims to enhance the understanding of heat-related health impacts in NB. The findings are expected to act as an evidence-base for public health planning and policy development, providing insights into temperature thresholds that pose the greatest risks and informing tailored interventions to improve the province's Heat Alert and Response System (HARS).

Specifically, this study seeks to:

1. Examine the relationships between temperature, humidity and heatwaves and their effects on health outcomes in NB.

2. Characterize the burden on the healthcare system following extreme heat events.

3. Evaluate whether proximity to green or blue spaces mitigates the negative health impacts of extreme heat events.

2. Methods

2.1 Study Design

A retrospective population-based longitudinal cohort study was developed using linked, pseudonymized person-level administrative data accessible through the New Brunswick Institute for Research, Data, and Training (NB-IRDT).

The study population consists of NB residents who held an active Medicare card during summer months (May to September) in each summer from 2007 to 2021. Cohort information was obtained from the Citizen Database (CD), maintained by the Department of Health, which includes demographic and residential information collected when individuals register for or renew a provincial Medicare card.

The entire provincial population was considered, and each cohort member was linked to their closest weather station based on residential address data during each summer. Addresses were geocoded using six-digit postal codes, processed through Postal Code Conversion Plus (PCCF+ v.7E) to identify corresponding Dissemination Areas (DAs).

According to Statistics Canada, a DA is "a small, relatively stable geographic unit composed of one or more adjacent dissemination blocks with an average population of 400 to 700 persons"[21]. In rural areas, DAs are geographically larger than in urban centres.

Certain groups who are not covered in the CD were excluded from this study. These include members of the armed forces, Royal Canadian Mounted Police (RCMP) personnel, individuals incarcerated in federal prisons and First Nations populations living on reserves.

2.2 Study Variables

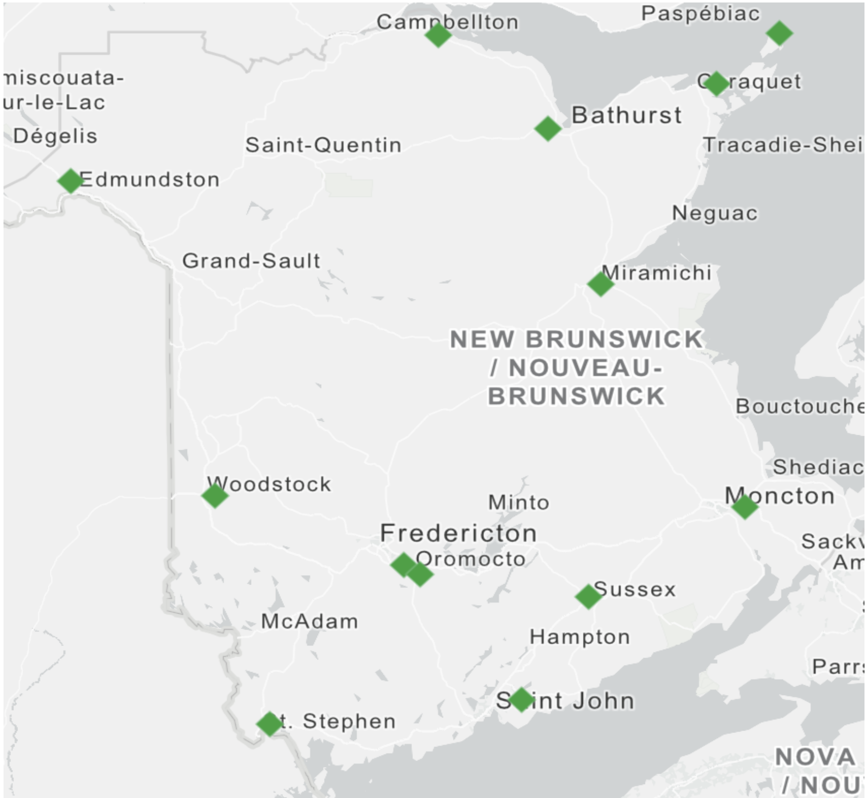
2.2.1 Extreme Heat Exposure

Hourly weather data for 15 years (2007-2021) were obtained from Environment and Climate Change Canada and summarized for each day between May and September, for 13 weather stations that were located in cities that also had a hospital (See Figure 1).

These include:

- Bas Caraquet
- Bathurst
- Campbellton
- Edmundston
- Fredericton
- Miramichi
- Miscou Island
- Moncton
- Oromocto
- Saint John
- St. Stephen
- Sussex
- Woodstock

Figure 1: Weather stations included in study analysis



This study uses maximum daily temperature and maximum daily humidex to define heat exposure, modelled as continuous variables. Humidex is a well-known index of perceived temperature used for heat surveillance in Canada. This index measures the combined effect of temperature and humidity and reflects the temperature as perceived by humans. No single 'best' heat exposure metric is proposed, though maximum metrics are commonly used and therefore were adopted in this study. Both average and minimum temperature were examined in sensitivity analyses to explore the potential influence of the selection of heat exposure metrics on main study results.

To account for the impact of persistent extreme heat events, heatwaves were also defined in terms of their duration and intensity. Due to variations in population characteristics and adaptation, there is no universally recognized definition of a heatwave. In this study, we define heatwaves based on the first alert criteria of the NB HARS program (two or more consecutive days where temperatures exceed 30°C and nights do not fall below 18°C, or where humidex is 36 or more).

Using this definition, and considering both the heatwave period and subsequent days, we assessed how the duration of heatwaves adversely affects risk of health service usage and of mortality. Seven different heatwave definitions were examined to determine how heatwave duration and intensity influenced the outcomes of interest (i.e., mortality, hospitalization and ED visits). The following definitions were considered in the analysis:

NB Heat Alert Response System (HARS) based definitions

I. **Heat alert level 1**: Maximum daily and nighttime temperatures exceed 30°C and 18°C, respectively, **or** maximum humidex exceeds 36, for two or more consecutive days.

II. **Heat alert level 1, without nighttime criteria**: Maximum daily temperature exceeds 30°C, **or** maximum humidex exceeds 36, for two or more consecutive days.

More extreme 2-day heatwave definitions

III. **Hot and humid**: Maximum daily temperature **and** humidex exceed 30°C and 36, respectively, for two or more consecutive days.

IV. **Very hot or very humid**: Maximum daily temperature exceeds 36°C, **or** maximum humidex exceeds 40, for at least two consecutive days.

Longer duration heatwave definitions

V. **Heat alert 1 for longer duration (3 days):** Maximum daily and nighttime temperatures exceed 30°C and 18°C, respectively, **or** maximum humidex exceeds 36 for three or more consecutive days.

VI. **Heat alert 1, without nighttime criteria, for longer duration (3 days):** Maximum daily temperature exceeds 30°C, **or** maximum humidex exceeds 36, for three or more consecutive days.

VII. **Hot and humid for longer duration (3 days):** Maximum daily temperature exceeds 30°C, **and** maximum humidex exceeds 36, for three or more consecutive days.

The first four definitions capture effects for heatwaves lasting two or more days. Two definitions capture heatwaves as defined by HARS alert 1 – one definition with and one without the nighttime temperature criteria. The other two 2-day heatwave definitions capture more extreme heatwaves (III) hot (≥30°C) **and** humid (≥36) heatwaves (these thresholds correspond to the 95th percentile of temperature and humidex, which are commonly used in previous studies) or (IV) very hot (≥36°C) **or** very humid (≥40) heatwaves.

The latter three definitions capture heatwaves that last three days or longer, defined based on HARS alert 1, with and without the nighttime temperature criteria, as well as isolating longer hot and humid heatwaves.

The above HARS alert 1-related definitions were slightly modified based on the distribution of the daily weather data. A level 1 HARS alert definition includes daily maximum humidex exceeding 36; however, many days had a humidex of 35. Given similarity in humidex and substantial increase in statical power, a 35-humidex cut-off was used to define HARS alert 1 in the analyses.

To isolate the impacts of persistent extreme heat, the first day of a heatwave was assigned a value of 0, thus considered equivalent to any other summer day, whereas subsequent consecutive 'heatwave' days were assigned a value of 1.

2.2.3 Health Outcomes

Three all-cause health outcomes were examined: mortality, unplanned acute hospitalization (hereafter referred to as 'hospitalization'), and emergency department (ED) visits.

Due to limitations in health claims data coding, it was not feasible to define cause-specific outcomes as a first step. While cause-specific outcomes would provide a more accurate estimate of the effects of extreme heat on related outcomes, examining all-cause outcomes is a common approach used when cause-specific outcomes cannot be defined. Further methodological development is needed to examine cause-specific health outcomes in administrative data in NB. This was not the focus of this present study and will be a focus in future research.

For each day in the study period, the daily number of deaths, hospitalizations and ED visits was summarized for each weather station. Daily death counts were derived from the Citizen Database (CD) for the years 2007 to 2021. The CD is a population-based data set that captures any death in the province. When an NB resident dies, their Medicare card eligibility status is immediately changed to terminated, effective the day after their death, which can be derived from the CD. Although the CD captures whether someone died, it does not capture the cause of their death. For this reason, Vital Statistics – which captures cause of death – is a better data set from which to obtain death records and is a requirement if a cause-specific outcome analysis is to be conducted. However, Vital Statistics data are often delayed by several years, and CD data are transferred to NB-IRDT more regularly.

Daily hospitalization counts were derived from the Discharge Abstract Database (DAD) for the years 2007 to 2020. The DAD contains hospitalization data for discharged patients, including length of stay and reason for hospitalization. To ensure the analysis focused on unplanned hospitalizations, data were refined to focus only on acute hospitalizations and to exclude planned admissions and/or admissions for elective procedures. This approach allowed for a more accurate assessment of outcomes that may be directly associated with extreme heat events. Reasons for hospital admission were not explored as part of this study but are planned as part of future research. If someone was admitted to the ED on the day prior to hospital admission, their hospitalization was considered to have occurred on the date of the ED visit.

Daily counts of ED visits were derived from the Horizon Emergency Department Data and Vitalité Emergency Department Data for the years 2017 to 2021. Horizon Health Network and Vitalité Health Network are NB's two Regional Health Authorities. These data systems were started in 2017 and thus are only available for the last five years of the study period. Since the frequency of ED visits is higher than the frequency of deaths and hospitalizations, and therefore has greater statistical power, it is anticipated to have minimal impact on the results.

2.2.4 Mitigation by Green and Blue Space

The potential mitigating effects of residential proximity to green (vegetation) and blue (water bodies) spaces on heat-related health outcomes were assessed using data available from the Canadian Urban Environmental Health Research Consortium (CANUE). CANUE data are available for geographic regions across Canda and are provided for each six-digit postal code. Green and blue space CANUE data were linked to residential postal codes from the CD.

Vegetation density was measured using the Normalized Difference Vegetation Index (NDVI)[22-24]. There are several NDVI values to select from. To capture vegetation levels during the summer months, the growing season mean value within each postal code was selected. Annual NDVI values are available for each year of the study period, allowing for linkage with health outcomes occurring in the corresponding year. In addition to NDVI, another green space variable was considered in sensitivity analyses that defined tree canopy cover, which is defined as the percent coverage (within a postal code) of vegetation (including leaves, stems, branches, etc.) of woody plants above 5m in height[22,25,26].

To explore the mitigation of green space exposure on negative heat-related effects, cohort members were divided into two groups based on the median NDVI value. Those residing in areas with NDVI values above the median were classified a residing in areas with higher greenness levels, and those below the median were classified as residing in lower greenness areas.

Blue space exposure was assessed by quantifying proximity to various water bodies, including oceans, lakes, tidal rivers, canals and other water sources. The CANUE data provided distance measurements to the nearest water body within a 5-kilometer (km) range of a postal code[27-29]. Data on tidal rivers, canals and other water sources were found to have high missingness, thus limiting our ability to explore their mitigating effects. Data for lakes and oceans appeared more complete. To explore mitigating effects of blue space exposure on negative heat-related effects, analyses were restricted to cohort members who resided within 1km of a lake or ocean and were compared to the main results obtained for the entire NB population. A shorter distance of 500m was also evaluated as part of sensitivity analyses.

2.2.5 Heat-Vulnerable Populations

Heat-vulnerable populations were defined based on demographic, socioeconomic and health-related characteristics. These included children, older adults, those living in socioeconomically deprived areas and individuals with specific chronic conditions. Demographic vulnerability was defined using date of birth data from the CD to include children aged 0–5 years and older adults aged 65 years and older.

Socioeconomic vulnerability was defined using the Canadian Index of Multiple Deprivation (CIMD).[30] The CIMD provides measures on four dimensions of inequality across neighbourhoods, including residential instability, economic dependency, ethno-cultural composition and situational vulnerability. Individuals living in areas in the highest quintile for any of these dimensions were classified as socioeconomically vulnerable. CIMD scores, derived from the 2016

Census, were linked to DAs of residence using PCCF+ and residential address data from the CD. The CIMD was not updated each Census year.

Individuals with specific chronic conditions were defined using data obtained from the NB version of the Canadian Chronic Disease Surveillance System (CCDSS). The chronic conditions included were cardiovascular diseases (stroke, acute myocardial infarction, hypertension, heart failure and ischemic heart disease), respiratory diseases (chronic obstructive pulmonary disease [COPD] and asthma), diabetes, neurological conditions and mental illnesses such as schizophrenia, psychotic disorders, mood disorders, anxiety disorders, personality disorders and/or other mental health diagnoses. Any individual meeting one or more of the above criteria was classified as part of the heat-vulnerable population.

2.2.6 Control Variables

Several variables were included as controls in the analysis to account for potential confounding factors, and they were selected based on confounders included in previous studies[13]. Day of the week and statutory holidays were used to account for institutional and behavioural effects. Seasonality and underlying time trends were controlled for using natural splines, an analytical tool that helps model complex trends over months and years. To account for spatial variations, a weather station indicator was included to reflect regional differences across NB. Pollution data were not included as short-term data were not available at the time of the analysis; however, given the low levels of pollution in the province, and because pollution has had minimal impact on main effects in other studies, the anticipated bias on estimates is expected to be negligible.

2.3 Statistical Analyses

Distributed Lag Nonlinear Models (DLNM) and Poisson regression models are well-established statistical methods for assessing the association between heat, heatwaves and health outcomes. Relative risk (RR) and corresponding 95% confidence intervals (CI) that describe cumulative effects were derived from the model estimates and are presented throughout. All statistical analyses were performed using the R statistical computing language.

DLNM is a flexible regression modeling approach that allows for simultaneous estimation of non-linear and lagged effects of continuous variables (e.g., temperature and humidex) on health outcomes. Non-linear models are needed as the relationship between continuous measures of heat exposure and health outcomes is not linear. This model was used to estimate cumulative effects of heat exposure over a 7-day lag period. A common value used was a maximum daily temperature of 30°C or maximum daily humidex above 35. Risk of outcomes at these levels was compared with the median value for the summer, which represents a typical summer day.

The effect of heatwaves was estimated using a Poisson regression model, with a binary heatwave variable assigned a value of 1 for heatwave days and 0 otherwise. To account for short-term delayed effects of heatwaves, a 3-day lag term for heatwaves was included.

We stratified our analyses to examine how the risks associated with heat exposure differed among residents of the three main urban areas of NB, those defined as heat-vulnerable and those living in proximity to green and blue space. Two definitions of urban areas were used, one defining those living within 40km of the city centre, and one defining those living within the city core (e.g., Statistics Canada Census Metropolitan Area (CMA) boundaries for Moncton and Saint John, or Census Agglomeration (CA) boundaries for smaller cities (e.g., Fredericton)). Stratified results were compared qualitatively to results of the main analysis (among the entire NB population).

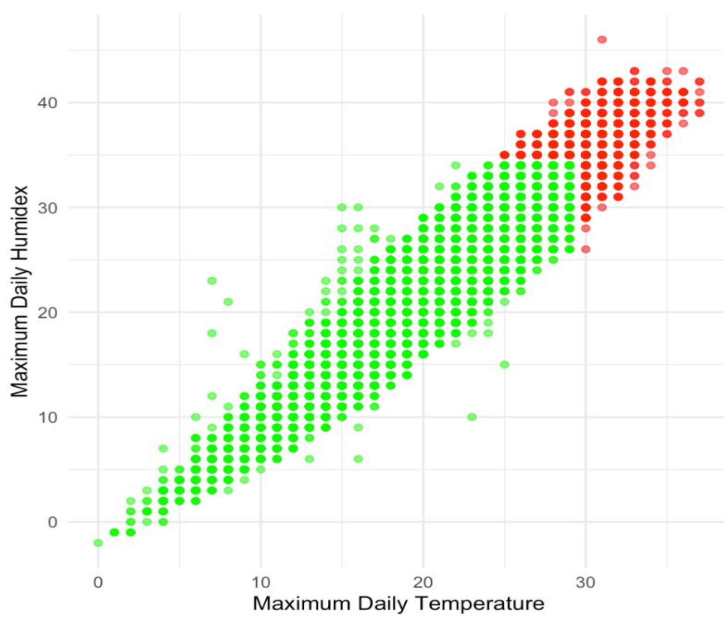
3. Results

Section 3.1 provides descriptive statistics on heat exposure and health outcomes, with the following three sections detailing the results of analyses quantifying heat-related effects across NB (section 3.2), among the three main urban areas (section 3.3) and among heat-vulnerable populations (section 3.4). Section 3.5 describes results on the delayed effects of heat exposure, illuminating sustained effects after heat subsides. Section 3.6 presents a summary of sensitivity analyses conducted to understand the influence of selection of weather metrics. Section 3.7 shows results for various durations and intensity of heatwaves. The last section, 3.8, provides insights into research on the mitigating effects of green and blue space in NB.

3.1 Descriptive Statistics on Heat Exposure and Health Outcomes

Figure 2 illustrates the relationship between maximum daily temperature and maximum daily humidex. Typically, when temperature is high, so is humidex. However, there were days where temperature was high, but humidex was lower, and vice versa.

Figure 2: Scatterplot of the relationship between maximum daily temperature and maximum daily humidex



Between the months of May and September, 2007 to 2021, the average and median for the maximum daily temperature were very similar (21°C and 22°C, respectively), with temperature ranging from a minimum of 1°C to a maximum of 37°C. Similarly, for maximum daily humidex, the average and median were similar (23 and 24), with values ranging from -1 to 46. The 95th percentile, which was commonly used as a threshold in previous studies, was 30°C for maximum temperature and 36 for maximum humidex.

Over the 2007-2021 study period, there were a total of 38,519 deaths, 305,049 hospitalizations and 920,446 ED visits across the province, half of which occurred in NB's three main urban areas (Fredericton, Moncton and Saint John).

Among the population surrounding each weather station, there was on average one death daily, though deaths were three times higher in urban areas (i.e., three deaths daily, nine total across all three cities). There was a daily average of 11 hospitalizations at each station, with more than double the provincial average in the three urban areas (i.e., 24 hospitalizations in each city). Daily ED visits had the highest frequency, with a provincial average of 96 daily and 194 among residents living in urban areas (i.e., ~600 ED visits in total each day across all three cities).

The average age among individuals who died was 76 years, which was higher than the average age of those who were hospitalized (60 years) or who had an ED visit (46 years).

3.2 Cumulative Effects of Extreme Heat Exposure in New Brunswick

The cumulative effects of temperature and humidex over a 7-day period were estimated using the daily maximum temperature and the daily maximum humidex (see Figure 3 and Figure 4 below). The red lines in each figure represent the average effect over seven days, while the shaded area indicates the 95% confidence interval (CI), reflecting the precision of the estimates.

The median values for maximum temperature (21°C) and for maximum humidex (24) were used as the reference point to calculate relative risk (RR) estimates.

Red lines above 1.0 indicate increases in the frequency of the outcome at that temperature/humidex relative to the reference point. On the contrary, those below 1.0 indicate the outcome is less frequent relative to the reference point.

Figure 3: Relative risk estimates for 7-day cumulative effects of daily maximum humidex on outcomes of a) mortality, b) hospitalizations and c) ED visits in New Brunswick. The red line indicates the point estimate, and the shaded area represents 95% confidence interval.

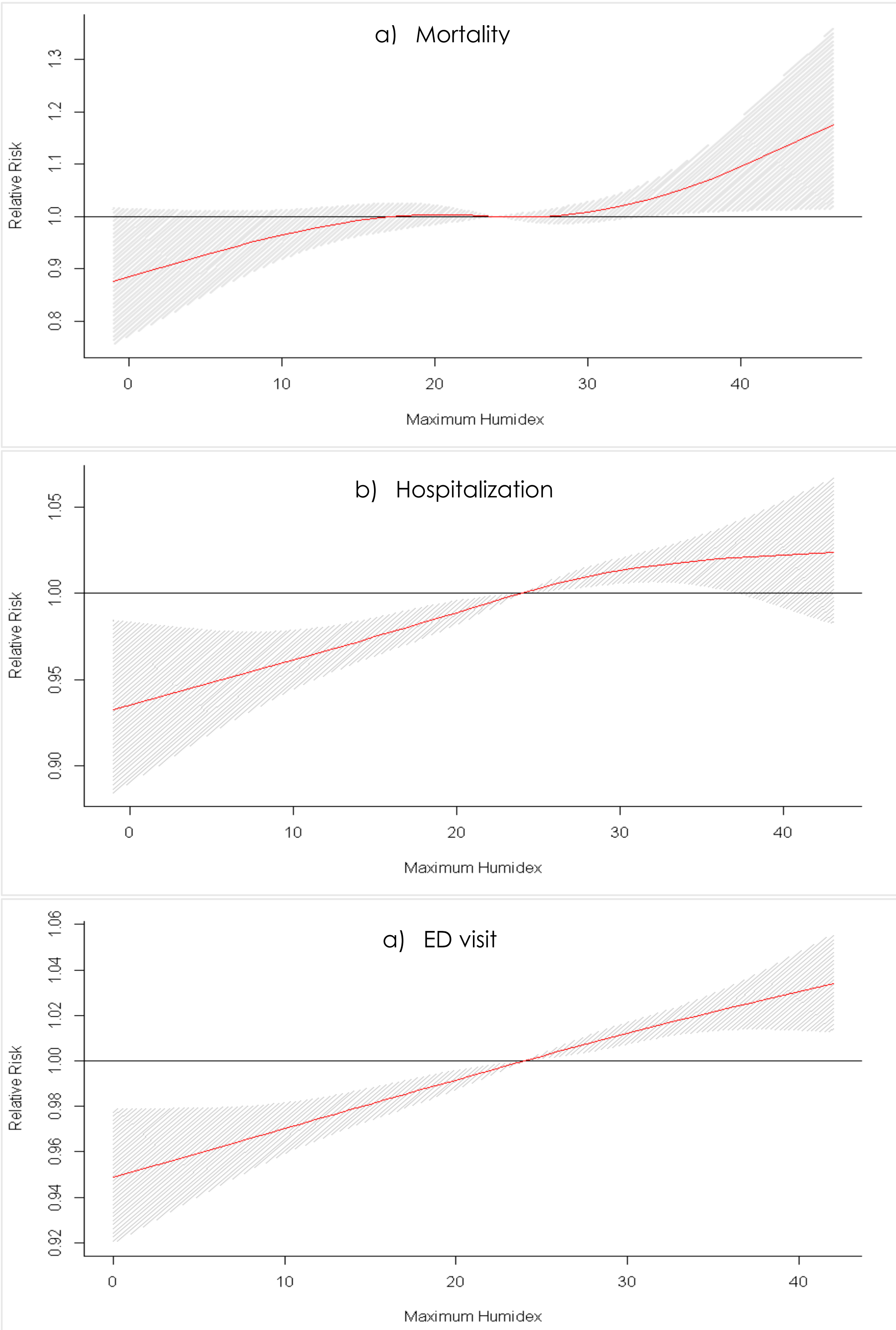
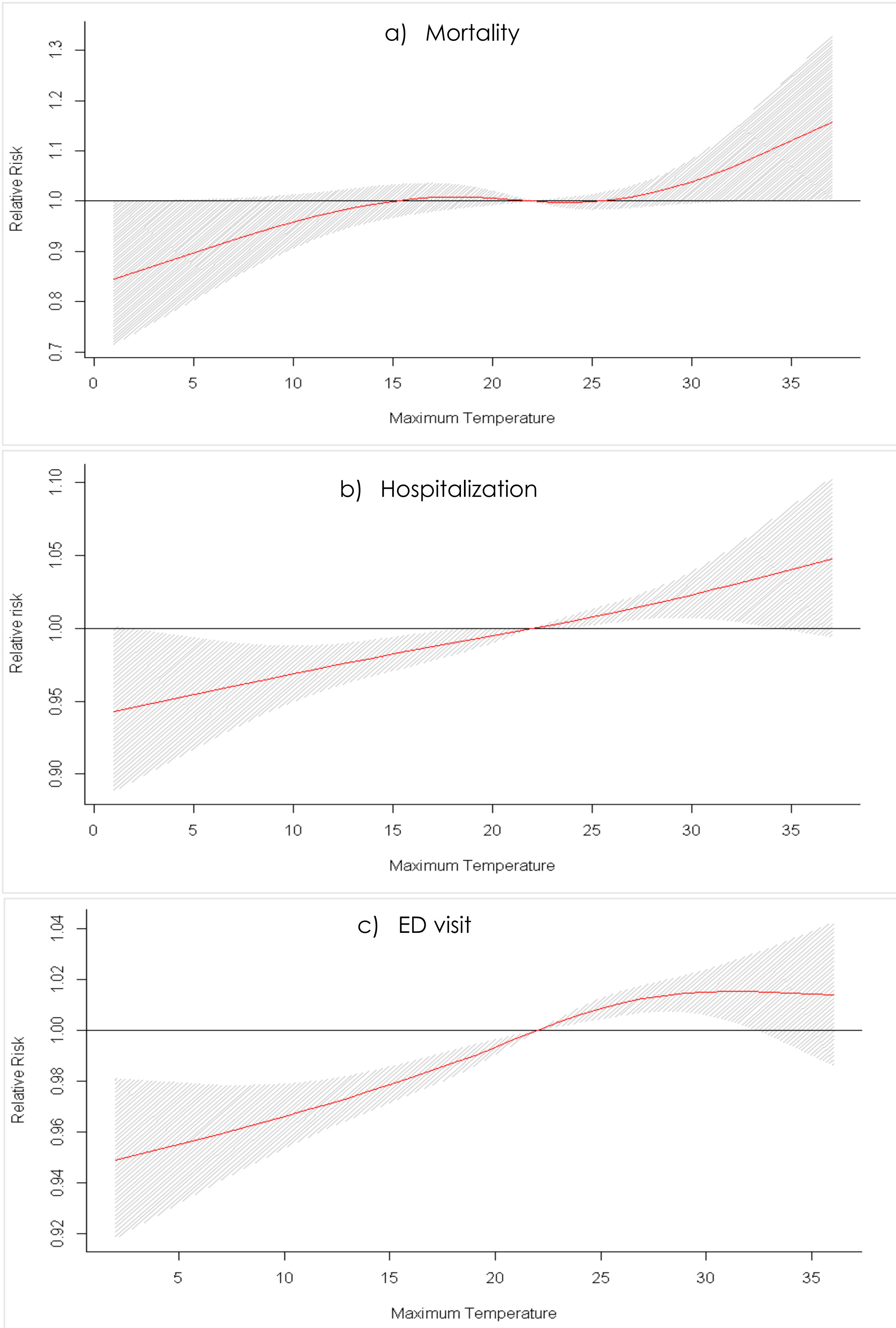


Figure 4: Relative risk estimates for 7-day cumulative effects of daily maximum temperature on outcomes of a) mortality, b) hospitalizations and c) ED visits in New Brunswick. The red line indicates the point estimate, and the shaded area represents 95% confidence interval.



We observed similar patterns of association between humidex/temperature with health outcomes. Overall, the results suggest that exposure to extreme heat (higher temperature and humidex) is associated with increases in daily numbers of deaths, hospitalizations and ED visits.

The highest increases were found for the most extreme levels of temperature and humidex; however, the imprecision of these estimates was large due to the limited number of days with extreme temperatures and humidex. With a longer observation period through more research, more precise estimates of risk can be made. Based on current estimates, more negative outcomes are anticipated with more extreme heat.

While not the focus on the current analysis, there were also days that had very low temperature and humidex during the summer months, and the risk of mortality, hospitalization and ED visits on these days was found to be lower relative to the reference points.

Increasing humidex was accompanied by a consistent increase in risk for all outcomes (Figure 3). In the seven days following a day with a maximum humidex of 36, there was a 5% increase in the number of deaths compared to a day with a typical summer humidex value (RR: 1.05 (95% CI: 1.01–1.10)). At a humidex level of 36, there was a 2% increase in the number of hospitalizations and ED visits (RR: 1.02 (95% CI: 1.00–1.04)) and 1.02 (95% CI: 1.01–1.03), respectively).

Similarly, increasing temperature was also accompanied by a consistent increase in risk for all outcomes (Figure 4). In the 7 days following a day with a maximum temperature of 30°C, there was a 4% increase in the number of deaths compared to a day with a typical summer temperature value (RR: 1.04 (95% CI: 1.00-1.08)). At this same temperature, there was a 2% increase in the number of hospitalizations (RR: 1.02 (95% CI: 1.01-1.04)) and a 1% increase in ED visits (RR: 1.01 (95% CI: 1.01-1.02)).

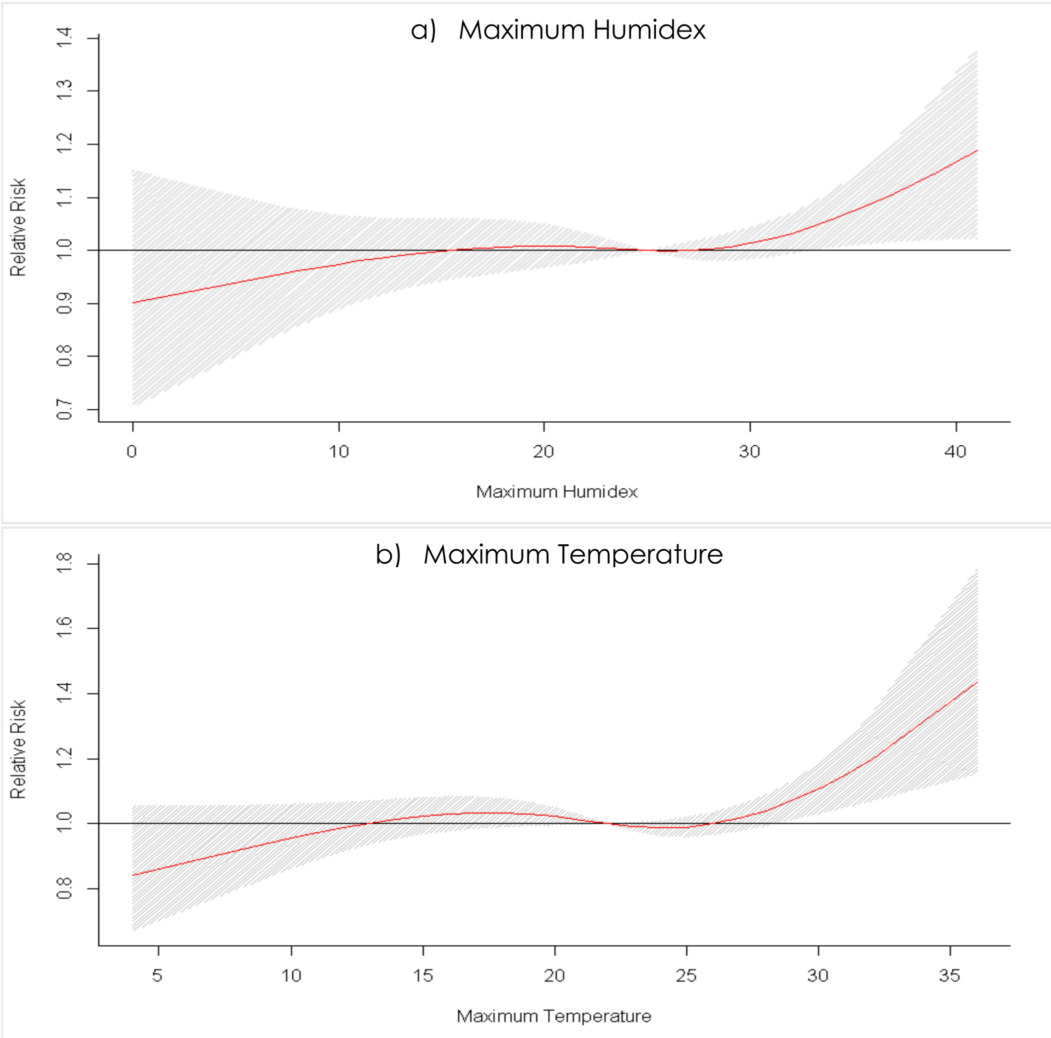
When considering more extreme temperature and humidex values, average increases in health outcomes were more pronounced, but confidence intervals were also wider. At a more extreme humidex level of 40, risk of mortality increased by 10% (RR: 1.10 (95% CI: 1.01–1.18)), while at a maximum temperature of 35°C, risk increased by 12% (RR: 1.12 (95% CI: 1.01–1.25)). Similarly, the risk of an ED visit at a humidex level of 40 increased by 3% (RR: 1.03 (95% CI: 1.01–1.05)).

3.3 Cumulative Effects Among the Three Main Urban Areas

The same analyses were repeated but were restricted to residents living in one of the three main urban areas of NB: Fredericton, Moncton or Saint John.

In Figure 5, the effect of extreme heat exposure on health outcomes appears more pronounced than the estimates obtained for the whole province (section 3.2). For a maximum temperature of 30°C, there was an 11% cumulative increase in the number of deaths (RR: 1.11 (95% CI: 1.03–1.19)), as compared to 4% provincially (reported in section 3.2).

Figure 5: Relative risk estimates for 7-day cumulative effects of daily a) maximum humidex and b) maximum temperature on mortality among the three main urban areas in New Brunswick. The red line indicates the point estimate, and the shaded area represents 95% confidence interval.



Similar results were observed for maximum humidex, with the effect in the urban areas found to be greater. A maximum humidex of 36 was associated with a 9% increased risk of death (RR: 1.09 (95% CI: 1.01–1.17)), as compared to 5% provincially.

When restricting urban areas to their core populations, the cumulative effect of maximum temperature was higher (RR: 1.14 (95% CI: 1.04–1.25)), whereas the effect for maximum humidex was nearly identical (RR:1.09 (95% CI: 1.00-1.20)). These findings indicate an increasing risk of mortality in increasingly urban areas in the province.

For the other two outcomes (hospitalizations and ED visits), estimated effects were more similar to provincial estimates. It should be noted, though, that health system capacity limits may play a role in the different results observed for mortality as compared to the health service utilization outcomes.

While not an objective of the study, we compared the cumulative effects in each of the three main urban areas, as well as a group of weather stations in smaller cities in the northeastern region of NB, which included the stations in Bathurst, Campbellton and Miramichi.

There were interesting differences among the three urban areas, with Moncton having particularly higher rates, which warrants further research. Meanwhile, the results in the northern region were similar but had wider confidence intervals. This was anticipated given the lower frequency of outcomes, since the population in the northern region is substantially smaller than in the three main urban areas. Further stratifying results by station will be important in future research to characterize and better understand the local context with regards to preparing for and protecting against the effects of extreme heat events.

3.4 Cumulative Effects Among Heat-Vulnerable Populations

This study uses a definition of heat-vulnerable populations as identified through a previous phase of this study (report forthcoming), which includes individuals meeting at least one of the following criteria: demographic vulnerability (i.e., children or older adults), socioeconomic vulnerability (classified as being in the highest quantile of any Canadian Index of Multiple Deprivation [CIMD] subscales) or having a chronic condition (cardiovascular diseases, mental illness, neurological disorders, diabetes or respiratory conditions).

According to this broad definition, most individuals who died (97%), were hospitalized (85%) or had an ED visit (91%) were classified as heat-vulnerable.

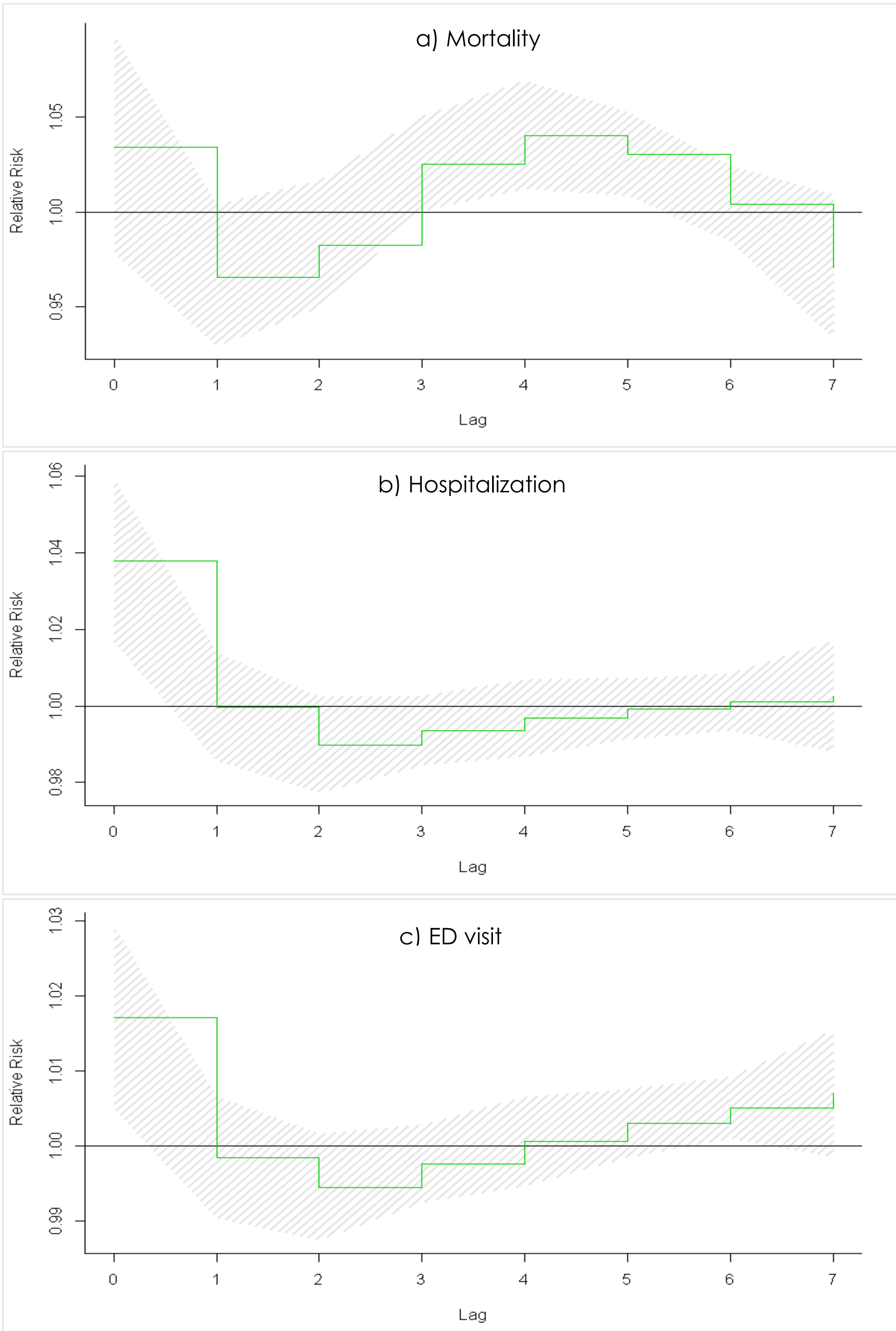
Given the substantial overlap in outcomes between the two samples, the cumulative effects of heat exposure among those who were defined as heat-vulnerable were nearly identical to those observed for the entire study population. These results suggest that negative effects of heat exposure are primarily limited to those who are defined as heat-vulnerable.

3.5 Delayed Effects of Extreme Heat Exposure

When modelling cumulative effects of heat exposure over time, the distribution of delayed effects is evaluated as part of the analysis. The models used allow for the evaluation of both immediate effects (day 0) and delayed effects (days 1-7).

Figure 6 presents relative risks and 95% CI for each lag (0-7 days) for a maximum humidex of 36.

Figure 6: Relative risk estimates for 7-day delayed effects of heat exposure at a humidex of 36 on outcomes of a) mortality, b) hospitalizations and c) ED visits. The green line indicates the point estimate, and the shaded area represents 95% confidence interval.



The findings reveal a sharp immediate increased risk in each outcome on the day of extreme heat exposure (day 0), followed by a decline in risk in the subsequent days (e.g., lag day 1 and 2). This pattern is commonly referred to in epidemiological literature as a harvesting effect. This effect suggests that the most vulnerable individuals, who may have had the outcome in the following days in the absence of heat, are affected earlier due to the heat exposure, which then results in an apparent reduction in risk in subsequent days.

Expanding the window of observation to seven days revealed important increased effects that persist in the later days following extreme heat exposure, implying that heat-related effects do not immediately subside after the immediate peak, and increases in outcomes may continue to occur up to seven days later.

Different lagged patterns were observed for each outcome, though similar patterns were found for temperature and humidex. While harvesting effects were observed during the days following immediate exposure for all three outcomes (mortality, hospitalizations and ED visits), delayed effects were found for mortality and ED visits but not for hospitalizations.

For mortality (Figure 6a), increases were found on the day of extreme heat (day 0, immediate effect), followed by reductions in the risk of death on lag day 1 and day 2 (harvesting effect), whereas on days 3-5, higher risk of mortality was found, with the highest risk found on lag day 4. The same pattern was found for humidex 36 as for temperature 30°C, as shown in Figure 6a.

For hospitalizations (Figure 6b), impacts were only found for immediate effects (on the day of extreme heat). There was some evidence of harvesting effects on lag days 1-3; however, no further delayed effects were observed beyond this period.

The lagged pattern for ED visits (Figure 6c) had similarities to the other outcomes. Like hospitalizations, ED visits also had the highest impacts associated with immediate effects. There was a reduced effect in the subsequent days, followed by evidence for some marginal delayed effects in later days, like the results observed for mortality.

3.6 Comparison of Temperature Metrics of Heat Exposure

Maximum weather metrics (maximum temperature/humidex) were used in the main analysis. To better understand how selection of different metrics may have affected the estimated heat-related effects, the average and minimum daily temperature metrics, in comparison to maximum temperature, were examined.

Average daily temperature may be a more valid measure of true exposure, given it may better capture the typical temperature experienced throughout the day, and the maximum may only reflect a very brief peak of extreme heat rather than sustained high temperatures. However, the results indicate that the effects of average daily temperature were nearly identical (graph not shown) to those of maximum daily temperature (Figure 4).

Minimum daily temperature, which reflects heat experienced during nighttime hours, was found to have an overall similar relationship as maximum and average temperature with health outcomes. Taken together, results suggest that maximum temperature may be a reliable temperature metric to use in examining heat-related effects in NB.

3.7 Cumulative Effects of Heatwave Duration and Intensity

The cumulative effect of heatwaves for each definition (described in the Methods section), including heat events that lasted for at least two days or three days, as well as those with different intensities, are presented in Figure 7.

Tables 1 and 2 in the Appendix provide detailed estimates for lagged results, as well as the frequency of heatwave days and the number of health outcomes during those days, as classified using each heatwave definition.[1]

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[1] Definition I: **Heat alert 1**: Maximum daily and nighttime temperature exceeds 30°C and 18°C, respectively, for two or more consecutive days, **or** maximum humidex exceeds 36 for two or more consecutive days.

Definition II: **Heat alert 1, without nighttime criteria**: Maximum daily temperature exceeds 30°C, **or** maximum humidex exceeds 36, for two or more consecutive days.

Definition III: **Hot and humid**: Maximum daily temperature **and** humidex exceed 30°C and 36, respectively, for two or more consecutive days.

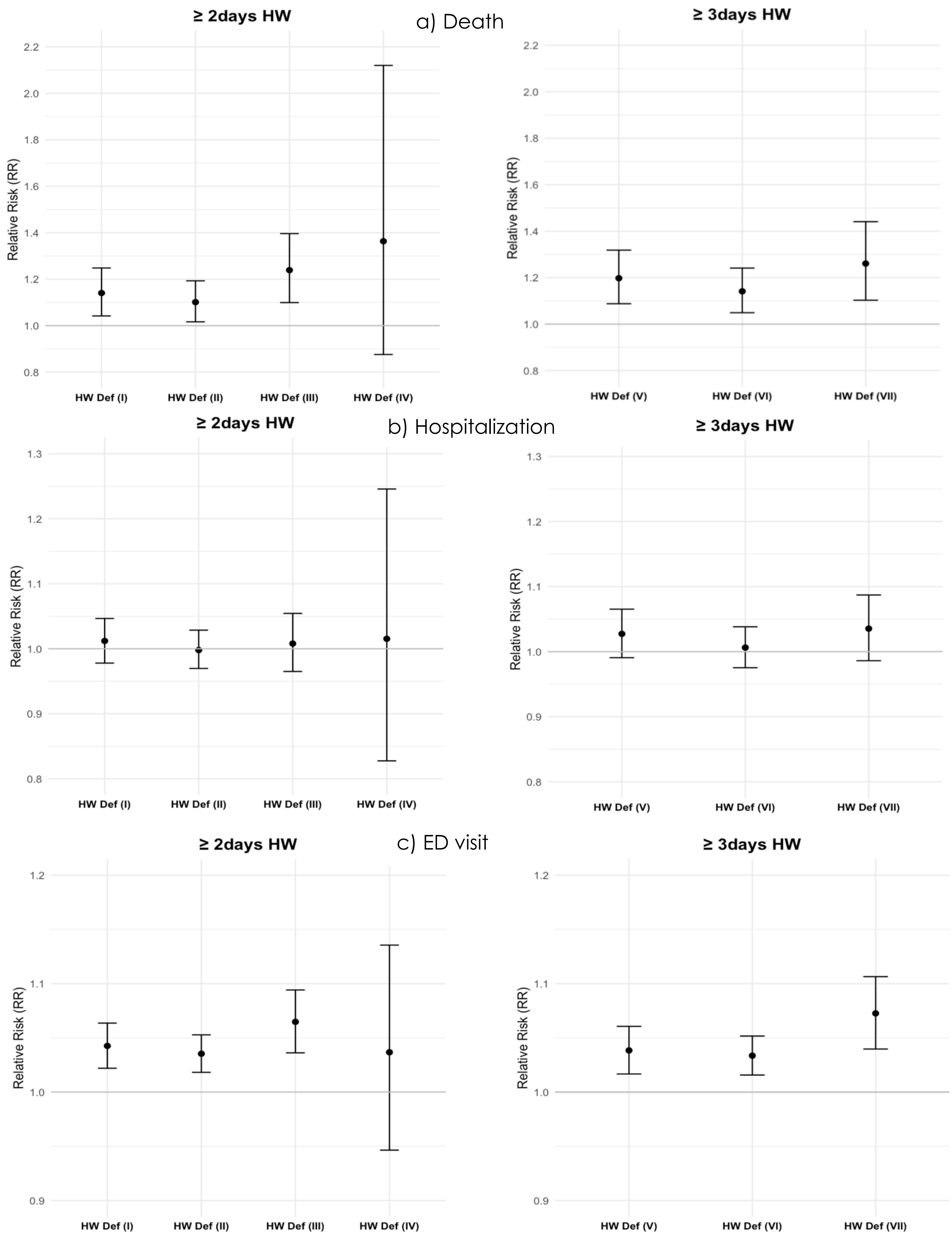
Definition IV: **Very hot or very humid**: Maximum daily temperature exceeds 36°C, **or** maximum humidex exceeds 40, for at least two consecutive days.

Definition V: **Heat alert 1 for longer duration (3 days)**: Maximum daily and nighttime temperatures exceed 30°C and 18°C, respectively, for three or more consecutive days, **or** maximum humidex exceeds 36 for three or more consecutive days.

Definition VI: **Heat alert 1, without nighttime criteria, for longer duration (3 days)**: Maximum daily temperature exceeds 30°C for three or more consecutive days, **or** maximum humidex exceeds 36 for three or more consecutive days.

Definition VII: **Hot and humid for longer duration (3 days)**: Maximum daily temperature exceeds 30°C, **and** maximum humidex exceeds 36, for three or more consecutive days.

Figure 7: Relative risk estimates for 3-day cumulative effects for various heatwave definitions on health outcomes of a) mortality, b) hospitalizations and c) ED visits



Overall, the findings provide evidence that more intense and prolonged extreme heat exposure is associated with increased risk of mortality, hospitalizations and ED visits in NB. As expected, when compared to the effects of a single day of extreme heat exposure, the effects of heatwaves were found to be greater in magnitude, with evidence suggesting increased risk during longer and more intense heatwaves.

Among the different definitions examined, the estimated effects with the greatest magnitude were found for death during heatwaves characterized by both hot **and** humid days. Heatwaves defined as hot and humid were found to be associated with increases of 24% (≥2 days) and 26% (≥3 days) in the number of deaths (Definition III: 1.24 (95% CI: 1.10-1.40); Definition VII: 1.26 (95% CI: 1.10-1.44)).

While effects for the definition characterized by very hot or very humid days (Definition IV: 1.36 (95% CI: 0.88-2.12)) were highest, the confidence intervals were very wide as there was a small number of days that met this definition (n=38 days over 15 summers). These results imply that extended heat events characterized by both high temperatures and high humidity may pose a greater health risk as compared to heat events characterized by high temperature or high humidex alone.

HARS alert 1 criteria (hot **or** humid for 2 consecutive days) were associated with a 14% increase in risk of death (Definition I: 1.14 (95% CI: 1.04–1.25)), which was higher but very similar to the effect estimated when eliminating the nighttime HARS criteria (Definition II: 1.10 (95% CI: 1.02-1.19)). Based on the distribution of nighttime temperatures, which had an average of 17°C, 1° below the HARS nighttime criteria, there is an opportunity to better understand the impacts of nighttime temperatures to align with population risk. This was not the focus of this study but should be explored in future research.

When comparing effects for heatwaves lasting longer than two vs. three days, effects were similar for events characterized by hot **or** humid days (Definition I vs. Definition V: 14% vs 20% increase; RR: 1.20 (95% CI: 1.09-1.32)). Similarly, results were consistent when removing the nighttime temperature from the definition (Definition II vs. Definition VI: 10% vs. 14% increase: RR: 1.14 (95% CI: 1.05-1.24))

For the other two outcomes (hospitalizations and ED visits), a similar pattern was observed; however, effect estimates were smaller in magnitude (Table 1). Heatwaves characterized by hot **and** humid days showed potential for the greatest effects, with those lasting for a longer duration also demonstrating evidence of the potential for heat-related impacts.

Heatwaves lasting three or more consecutive days were associated with a slightly higher risk of mortality and health service use. Specifically, when temperature and humidex exceeded 30°C and 36, respectively, the relative risk of death was 1.26 (95% CI: 1.10–1.44), for hospitalization it was 1.04 (95% CI: 0.99–1.09), and for ED visits, it was 1.07 (95% CI: 1.04–1.11).

Delayed effects were also defined for heatwave days; however, the recommended approaches to model heatwaves do not accurately capture the lags in a way that was possible for single-day extreme heat events. As a result, the relative risk estimates for lag days were not conclusive, though there appears to be more of an immediate effect on heatwave days.

3.8 Exploring Mitigating Effects by Residential Proximity to Blue and Green Space

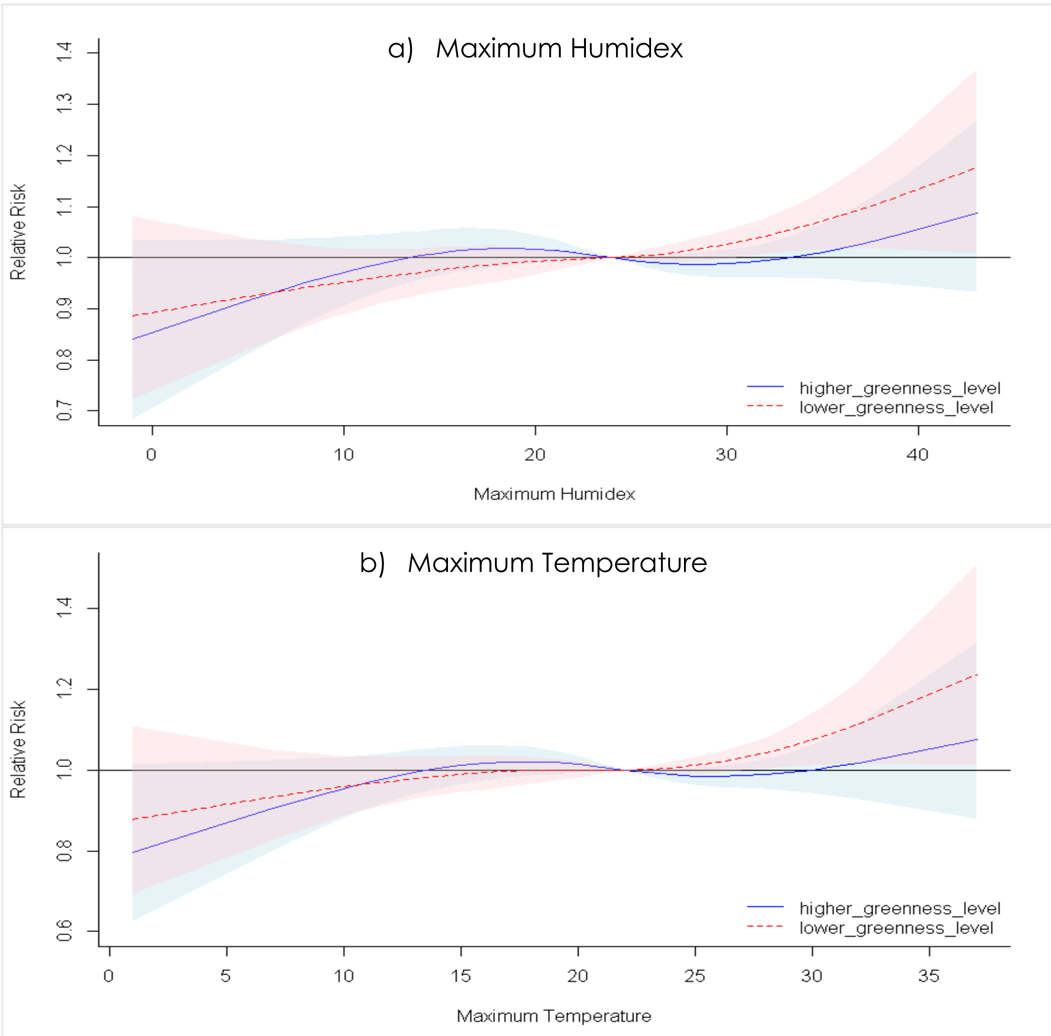
3.8.1 Green Space Analyses

Mitigation of negative heat-related effects by residential proximity to green space was examined through stratified analysis using the Normalized Difference Vegetation Index (NDVI), which is a measure of greenness based on vegetation, ranging from -1 to +1, with higher values indicating more greenness. Overall, NB has a very high NDVI, with little variability. The narrow range in greenness made it difficult to properly explore mitigating effects. Provincially, the mean and median NDVI values were both 0.51, which ranged from -0.21 to 1.

Results indicate, on average, that increased risk of mortality on hotter days was lower in areas with more vegetation coverage compared to those with less (Figure 8). While the confidence intervals for the estimates overlapped, the cumulative relative risk (RR) of mortality at a humidex of 36 was 1.02 (95% CI: 0.96–1.09) in higher-greenness areas, compared to 1.08 (95% CI: 1.02–1.15) in lower-greenness areas. Similar results were obtained when restricting to the three main urban areas. For hospitalizations and ED visits, no clear trends were found when comparing areas with higher and lower greenness.

Sensitivity analysis using tree canopy, instead of NDVI, to define greenness showed similar but more precise results. The cumulative RR of death at a humidex of 36 for those living in areas with lower tree canopy cover was 1.08 (95% CI: 1.02-1.15), while for those in areas with higher tree canopy cover, it was 1.01 (95% CI: 0.95-1.08). This provides additional evidence for the potential mitigating effects of green space on heat-related health outcomes.

Figure 8: Relative risk estimates for 7-day cumulative effects of daily a) maximum humidex and b) maximum temperature on mortality in New Brunswick in areas with Normalized Difference Vegetation Index (NDVI) above (high-greenness) and below (low-greenness) the provincial median



3.8.2 Blue Space Analyses

Results generated through the blue space analyses were inconclusive and therefore were unable to inform on potential mitigation of heat-related effects.

NB has a large system of tidal rivers for which blue space data were largely unavailable; only residential proximity to lakes and oceans was possible to examine. Additionally, there may be important confounding biases and information biases in the data. Individuals living near lakes and oceans may have a different profile (e.g., higher proportions of older adults given properties near the ocean are more expensive). Due to limitations in the modeling framework used in this study, adjusting for these additional factors was not feasible.

Relying on residential data also has important limitations. For instance, during summer months, individuals may be more likely to spend time at a cottage near the lake or ocean, for which location data are not available. Due to these limitations, the results for the blue space analyses did not provide consistent or reliable results and therefore are not presented in detail in this report.

4. Discussion

Section 4.1 presents a summary of the key findings of this study, and Section 4.2 follows with a discussion of the findings in the context of existing scientific literature. Section 4.3 presents the strengths and limitations of the study, and Section 4.4 provides concluding remarks and opportunities for future research.

4.1 Summary of Findings

This study examined the impact of extreme heat events on health outcomes – specifically, mortality (death), hospitalization and emergency department (ED) visits.

To do so, it employed a population-based time-series analysis over 15 years using pseudonymized administrative health data sets. It addresses a significant gap in the literature as the first study of its kind conducted in NB, a province with a higher prevalence of heat-vulnerable population characteristics compared to other regions in Canada.

Overall, results suggest that heatwaves are accompanied by notable increases in negative health outcomes, with the largest increase found for death. The study results also demonstrate evidence of a 'harvesting effect' occurring in NB, where the most vulnerable individuals are impacted early in the exposure period (i.e., on the day of extreme heat exposure), leading to a temporary decline in risk in subsequent lags (i.e., in the days following extreme heat exposure).

Yet, results also show that health risks continue for several days following heat exposure, even after heat has subsided. Based on these results, there appear to be two phases to heat risk: immediate risk and delayed risk. The negative effects of extreme heat appear to be more pronounced in NB's three major urban areas: the cities of Fredericton, Moncton and Saint John.

Heatwaves, particularly those characterized by both high temperatures ***and*** humidex levels, were found to pose the greatest health risks, with the largest associations also found for death. Analyses restricted to heat-vulnerable populations help confirm that the vast majority of those who died, were hospitalized or were admitted to the ED were considered heat-vulnerable.

Based on the analyses in NB, only limited conclusions could be drawn about impact of green and blue spaces mitigating against risk of mortality during extreme heat.

4.1.1 Heat Exposure Impacts on Mortality

This study shows that exposure to extreme heat and heatwaves imposes a greater health burden in terms of mortality compared to other health outcomes (i.e., hospitalization and ED visits).

At extreme temperatures, the cumulative risk of mortality increases by 5%, with even higher risks observed in urban areas and core urban populations, where risk of mortality rises by 11% and 14%, respectively.

Prolonged extreme heat events, classified as heatwaves lasting at least for two days, were found to have a stronger negative impact on health outcomes than single hot days. The effect is more pronounced when heatwaves are defined by both high temperatures ***and*** humidex levels (Definition III), leading to a 24% increase in mortality risk. In contrast, when heatwaves are defined by either high temperature ***or*** high humidex alone (Definition I), the associated risk of mortality is lower, with a 14% increase.

Longer and more intense heatwaves, those lasting at least three consecutive days that are both hot and humid (Definition VII), are associated with a 26% increase in risk of mortality, highlighting the heightening risks linked to sustained extreme heat. Moreover, very intense heatwaves (i.e., higher temperature or humidex lasting at least two days) could increase the relative risk of mortality by up to 36%. However, because these extreme events occur less often, the estimated risk is less precise.

The findings also suggest that individuals living in areas with higher vegetation coverage experience a lower risk of heat-related mortality compared to those in less green areas. At extreme temperatures, the risk of mortality increases by 8% in lower-greenness areas (e.g., fewer forests and parks), whereas in higher-greenness areas, the increase is only 2%. This indicates a potential mitigating, or protective, effect of vegetation. However, due to missing data on tidal rivers (i.e., 'blue space'), and model limitations in controlling for demographic and socioeconomic factors, the potential protective effect of living near water is not reported.

4.1.2 Heat Exposure Impacts on Health Services

The findings also provide evidence of an increased risk of healthcare utilization, including hospitalizations and ED visits, during extreme heat events.

At extreme temperatures, the risk of hospitalizations and ED visits rises by 2%, with slightly higher or similar effects observed in urban areas. Heatwaves characterized by both high temperatures ***and*** elevated humidex levels are associated with a greater risk of ED visits, with a 6% increase. However, when heatwaves are defined as periods in which either temperature ***or*** humidex was high, the risk increases by only 4%. Longer heatwaves lasting at least three days are linked to a slightly higher ED visit risk of 7%, and to a 4% increase in hospitalizations.

4.2 Discussion of Findings

While the health effects of extreme heat have been extensively studied, the number of studies in Canada remains limited. This discussion of findings focuses on Canadian research only. Most studies have been conducted in Quebec, Ontario or British Columbia, where population size and demographic, socioeconomic and health-related factors differ from NB. These differences, along with variations in study design and health outcomes assessed, may limit the direct comparison of our findings with other Canadian studies. Therefore, we offer general observations about how our results align with the existing literature.

A recent study in Quebec[7] examined the overall health burden of extreme heat and, similar to our findings, reported a higher risk for mortality as compared to other health outcomes. The estimated effects for hospitalization were almost the same as in our study, but the risks for mortality and ED visits were found to be higher in Quebec than in NB. This could be attributed to Quebec's higher population density and the urban heat island effect, which may amplify heat-related health risks. Differences in healthcare system management could also play a role, as ED facilities in NB frequently operate at full capacity, potentially discouraging individuals with less severe conditions from seeking emergency care.

A study conducted in southern Ontario[31] examined the effects of extreme heat over seven years, from 2005 to 2012. The study estimated the relative risk (RR) of mortality by comparing the 99th percentile of maximum temperature (32°C) with the 75th percentile (28°C), which was 1.06 (95% CI: 0.90–1.24). The study suggests that limited statistical power may have contributed to a wide confidence interval, as some regions included in the analysis had relatively few deaths over the study period, which may be more similar to NB than to more densely populated areas like Quebec.

In our study, even though death records in some regions were relatively small, the analysis had sufficient statistical power, as the estimated risk of mortality was found to be statistically significant. However, methodological differences may have led to different conclusions between the two studies. For instance, the reference point in our study is lower (21°C) and is compared to 30°C, the 95th percentile of temperature – a threshold commonly applied in previous research.

A study in Ontario[32] estimated the relative risk of ED visits, showing an increased risk of ED visits for cardiovascular-related reasons among individuals with comorbid diabetes (RR = 1.13 (95% CI: 1.01-1.26)). This is higher than the estimate we obtained for ED visits among all vulnerable populations combined (RR = 1.01 (95% CI: 1.01-1.02)), which includes a population of individuals with comorbid diabetes. We expected smaller effect sizes in our study given we looked at all-cause – rather than heat-specific – outcomes. Future research should examine the reasons for admissions to understand the feasibility of analyzing cause-specific effects in NB.

A study conducted in British Columbia[33] performed an analysis of death over 20 years (2001 to 2021) and attributed 0.42% of all-cause deaths to extreme temperatures. While we did not estimate the attributable risk, which prevents direct comparison, the results obtained in our study can be extended to calculate these values. Future research could focus on estimating the number of heat-related deaths and the health service usage attributable to heat. This would help measure the direct impact of extreme heat exposure on all-cause population health outcomes. In other words, this would help quantify how many deaths or hospitalizations on hotter days occurred due to heat exposure.

The BC study[33] also found that the risk of temperature-related deaths varied across different regions, a trend also seen in the Quebec study[7]. Although this was not a focus of our study, we also found evidence of regional variation. There were stronger associations between extreme heat exposure and mortality when we restricted our analyses to the three main urban areas of NB. When data were further stratified, risk in Moncton appeared to be greatest. Compared to the other urban areas in the province, Moncton is larger and has greater population density and more pronounced urbanization, which may contribute to urban heat island effects, leading to elevated temperatures and risk of heat-related mortality. The combination of higher population density, infrastructure that retains heat and less green space is suggested to amplify the health burden of extreme heat in urban centres.

Another population-based study in Ontario[34] examined temperature extremes in relation to reasons for hospitalization for hypertensive diseases, diabetes and arrhythmia during extreme cold and extreme heat events. The study found a 30% increase in the risk of diabetes-related hospitalizations during extreme heat (1.30 (95% CI: 1.06–1.58)). It also estimated that 11.16% (95% CI: 7.50–14.25) of diabetes-related hospitalizations could be attributed to extreme heat, again emphasizing the importance of examining cause-specific effects among populations with specific diagnoses.

Studies examining the effects of heatwaves generally report stronger effects for multiple days of extreme heat than for single days of extreme heat. A study[35] based on the July 2010 heatwave in Quebec found a significant increase of 33% in mortality and 4% in ED visits. The findings of this study were based on a single heat event from July 4th to 9th, characterized by maximum temperatures of 30°C or higher, minimum temperatures above 20°C and high humidity. Our findings on heatwaves, particularly when defined by both high temperature ***and*** humidex, are similar. A study conducted in Australia[12] reported an average increase of 28% (95% CI: 15%–42%) in mortality during heatwaves, with greater impacts observed during more intense heatwaves in major metropolitan areas. These findings are consistent with the patterns observed in our study.

Canadian studies have mainly evaluated the overall risk of heat exposure without specifically describing patterns of delayed effects. Research studies from other countries[12,14,15] have reported both harvesting and delayed effects, which our study also observed. Harvesting effects refer to high immediate effects, putting those most vulnerable at exceptional risk such that they experience the outcome earlier than they would have otherwise. This results in an observed reduction in risk in the days following extreme heat.

In our study, this trend was most pronounced for mortality. This may be attributed to the demographic profile of NB, where an aging population and a higher prevalence of chronic conditions contribute to increased vulnerability to heat-related mortality. A similar trend was seen for hospitalizations and ED visits, in which immediate effects were observed on the day of extreme heat. For hospitalizations, there was only evidence for immediate effects and none during the subsequent days. This indicates that individuals requiring hospital services seek care immediately, but not after heat has subsided.

In addition to immediate effects, we also observed important delayed effects, well after heat has subsided. For ED visits, we observed some marginal delayed effects in later days (i.e., lag days 5-7). This may be due to certain heat-related illnesses taking longer to manifest or individuals delaying medical attention until symptoms become severe. Capacity constraints in EDs may also contribute to the observed delays, as overcrowding could lead to patients postponing visits until space becomes available. These findings imply that while a HARS alert may end, the impact on the population remains for a longer duration, up to seven days.

Delayed effects were also examined for heatwave days. This appeared to show evidence for stronger immediate effects and less evidence for delayed effects, though we acknowledge potential limitations in the approach suggested in the literature to model heatwaves. This is another area for improvement in future research.

Some studies[36-38] have suggested that during heatwaves, an increase in out-of-hospital mortality may reduce the expected number of hospital admissions during extreme heat events. This could explain why we observed small effects for hospitalizations during heatwaves.

Few studies in Canada have specifically evaluated whether green or blue spaces modify the health impacts of heat exposure. The study in Quebec described above[7] found no mitigating effect of greenness on health outcomes. The researchers assessed greenness at a regional level using a single NDVI value assigned to each health region. Additionally, they used a single NDVI value for the entire study period, assuming greenness exposure remained constant over time. In contrast, our study assigned annual NDVI values to individual postal codes, allowing for temporal variations in greenness over time. This approach also enabled a more precise estimation of individual exposure to greenness based on residential address-specific NDVI values, which provides a more refined assessment of potential mitigation effects.

A study in Alberta and Ontario[39] used a case-crossover design to examine ED visits, which found that increased residential greenness, particularly tree canopy coverage, had a mitigating effect on heat-related ED visits for mental and behavioural disorders. However, the protective effect of NDVI was less clear. This was similar to our study findings, as in our sensitivity analyses, tree canopy appeared to better distinguish between exposure groups.

In our study, we found some evidence of effect modification, indicating a reduction in mortality in areas with higher greenness. However, we did not observe a significant mitigating effect on health service use outcomes (hospitalizations and ED visits). The absence of a strong and consistent protective effect may be due to the fact that NDVI captures all types of vegetation, including grasslands, shrubs and agricultural areas, rather than specifically reflecting tree canopy coverage, which provides direct shade, improved ventilation and cooling. Further analyzing the specific role of tree canopy coverage in mitigating heat-related health impacts also showed more precise results.

Most studies evaluating the effect of blue space have been conducted in other countries. One Canadian study[40] examined the impact of living near lakes, rivers or coastal areas on overall health. However, these researchers did not directly study whether proximity to blue space mitigates heat-related mortality, ED visits or hospitalizations. This may be because other researchers have also identified data quality issues with the available data. In our analysis, we did not find evidence of effect measure modification by blue space, which was likely due to methodological limitations such as missing data on river proximity and limitations in models for confounding adjustments, rather than a true lack of association. With more complete and accurate data, along with design and analytical approaches that account for differences in demographic and socioeconomic factors, future research can better evaluate the potential role of blue space in reducing heat-related health risks.

4.3 Strengths and Limitations

There are several strengths and limitations to our research study that are important to recognize in interpreting its findings.

4.3.1 Strengths

This study used pseudonymized administrative health data and captured the entire provincial population that either died or used health services during the study period. The inclusion of nearly 15 years of data on mortality and hospitalization enabled a large sample size, enhancing statistical power and allowing for subgroup analyses. This extended timeframe strengthens the findings by accounting for temporal trends, long-term climate variability and seasonal factors.

Another strength of this study is the ability to track residential mobility (i.e., where people live over time) using annually updated postal codes, which reduces the risk of exposure misclassification. This approach ensures that individuals' environmental exposures are more accurately linked to their health outcomes. To examine the role of environmental factors, our study incorporates health data linked to postal codes to evaluate neighbourhood greenness and proximity to water bodies. By updating these measures annually, our study captures changes in exposure over time, which provides more precise analysis.

The study also considered multiple heat metrics, including maximum temperature and humidex, which ensured a more comprehensive assessment of heat exposure. Moreover, it evaluated different heatwave definitions, considering variations in heat thresholds, duration and intensity. This allowed for a more detailed understanding of how different experiences of extreme heat can affect health outcomes.

Unlike many Canadian studies that have primarily focused on general temperature effects, our study also examined the impact of heatwaves. In addition to examining the overall effects of extreme heat, it evaluated how health risks change over time by incorporating lagged exposure analysis. This approach allowed for investigation of both the immediate and delayed health impacts of extreme temperatures.

4.3.2 Limitations

There are also several limitations. For this analysis, temperature data at the weather station level were used. While station-level data provide broad spatial coverage and are commonly used in large-scale epidemiological studies, they may not accurately reflect individual exposure, particularly over large areas or for indoor temperatures, where people spend most of their time during extreme heat events.

Incorporating indoor temperature measurements would provide a more precise assessment of actual exposure during heat events; but this is not feasible. Thus, the reliance on ambient temperature data introduces the possibility of measurement bias, which, if present, is most likely randomly distributed across the province. This random distribution would result in an underestimation of the true effect of heat on health outcomes.

Furthermore, temperature exposure was assigned based on the residential location of individuals, which does not account for population mobility, such as commuting, work-related travel or time spent indoors. This limitation also contributes to non-differential exposure misclassification.

The study period for ED visits was limited to five years (2017-2021) due to data availability, while longer study periods were available for mortality and hospitalization. This restriction may limit the ability to assess long-term trends and the full extent of ED visits.

Additionally, this study examined all-cause mortality, hospitalization and ED visits rather than specific heat-related health conditions, such as heat stroke or cardiovascular events. While all-cause outcomes capture the overall health burden, they include outcomes completely unrelated to heat exposure, which dilutes the estimated effect of extreme temperatures and heatwaves, as these events are anticipated to be randomly distributed across all days. The inclusion of non-heat-related deaths and hospital admissions weakens the statistical association that is estimated between heat exposure and health outcomes.

Due to limitations in the modelling approach used in this study, we were unable to adjust for individual-level confounding factors such as income or age when comparing the health effects of heat in different groups. This could introduce bias in observed estimates, which was particularly evident when evaluating the modifying effects of blue space. Additionally, data quality issues affected the analysis, particularly the incomplete availability of postal code proximity data for tidal waters. Given that NB has an extensive network of tidal rivers, missing proximity data limited the ability to assess the mitigating effect of blue space.

Similarly, while the modelling approach used accounts for time trends and seasonal variations, it does not directly measure behavioural changes associated with different temperatures. Warmer summer months typically encourage increased outdoor activity, potentially raising heat exposure and related health risks. Conversely, during more extreme heat, individuals may alter their behaviour by reducing time outdoors or seeking cooler environments. These behavioural adaptations are not captured in our analysis, making them a potential source of residual confounding. As a result, the observed associations between heat and health outcomes may partly reflect unmeasured behavioural factors that vary across different temperature conditions.

Our analysis of green and blue space relied on postal code-level data, which may not precisely capture individual exposure to these environmental factors. Moreover, we were unable to adjust for air pollution, such as particulate matter or ozone, which are considered in similar studies. However, given the lower levels of urbanization and pollution in NB, it is unlikely that this had a significant confounding effect.

Finally, the statistical model used (Distributed Lag Non-Linear Model, DLNM) is complex and involves multiple parameterizations, including decisions on the functional form, knot placements and lag structure of the temperature function. This complexity may increase the risk of overfitting or reliance on specific assumptions, potentially affecting the generalizability of the findings and making interpretation more sensitive to modeling choices. Furthermore, due to the non-linearity and delayed effects of heat exposure, an interaction term between environmental factors (such as green and blue spaces) and temperature metrics could not be incorporated into the model. Instead, a stratified analysis was performed, in which the study population was divided into subgroups. While this approach allowed for the qualitative assessment of effect modification, it may have introduced challenges related to smaller sample sizes within each subgroup, thus increasing imprecision in the estimates.

4.4 Conclusions

Despite the growing global recognition of the health impacts of extreme heat, research on heat-related health risks in Canada remains limited. This study fills a gap in the literature by providing the first comprehensive analysis of heat exposure and heatwaves in NB, a province with distinct demographic and environmental characteristics, and the first in Atlantic Canada.

The findings show that extreme heat events contribute to an increased health burden, particularly for mortality. The risks were more pronounced in urban areas, where factors such as higher population density, socioeconomic vulnerability, infrastructure characteristics and urban heat island effects may intensify heat risks. The results also suggest that the risks associated with heat events are not limited to the day of the event, but additional health effects also re-emerge over the days following a heat event. Additionally, the 'harvesting effect' indicates that the most vulnerable individuals might be affected immediately after heat exposure.

The findings further highlight that heatwaves have a stronger negative impact on health outcomes. Specifically, heatwaves characterized by days that are both hot ***and*** humid were associated with the greatest increase in mortality, suggesting that both temperature and humidity, together, contribute to greatest heat-related health impacts.

Further research should focus on the cause-specific associations between heat exposure and health risks to better understand how heat events contribute to the cause or exacerbation of certain conditions.

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Appendix Tables

Table 1: Relative risk estimates for definitions of heatwaves (HW) of varying intensity, lasting two or more days, for both lagged and cumulative effects on mortality, hospitalization and ED visits

Outcome	>= 2days Heatwave (HW) Definitions			
	HW definition I	HW definition II	HW definition III	HW definition IV
Mortality	**n days=801 n death=1317**	**n days=1023 n death=1661**	**n days=449 n death=749**	**n days=38 n death=75**
HW-lag0	1.08(1.01-1.15)	1.07 (1.01-1.14)	1.10 (1.01-1.19)	1.26 (1.00-1.58)
HW-lag1	1.04 (0.97-1.11)	1.01 (0.95-1.07)	1.06 (0.97-1.16)	1.03 (0.80-1.33)
HW-lag2	1.02 (0.95-1.09)	1.05 (0.99-1.12)	1.01 (0.93-1.11)	0.91 (0.70-1.20)
HW-lag3	1.00 (0.94-1.07)	0.97 (0.91-1.03)	1.05 (0.97-1.14)	1.15 (0.91-1.47)
HW-cum	1.14 (1.04-1.25)	1.10 (1.02-1.19)	1.24 (1.10-1.40)	1.36 (0.88-2.12)
Hospitalization	**n days=704 n hosp.=9307**	**n days=922 n hosp.=12061**	**n days=404 n hosp.=5378**	**n days=26 n hosp.=350**
HW-lag0	1.03 (1.00-1.05)	1.03 (1.01-1.05)	1.03 (1.00-1.06)	1.05 (0.95-1.17)
HW-lag1	0.98 (0.95-1.00)	0.98 (0.96-1.00)	0.94(0.91-0.97)	0.89 (0.79-1.01)
HW-lag2	0.99 (0.96-1.01)	0.98 (0.96-1.00)	1.01 (0.98-1.05)	1.03 (0.91-1.16)
HW-lag3	1.02 (0.99-1.04)	1.01 (0.99-1.04)	1.03 (1.00-1.06)	1.05 (0.94-1.18)
HW-cum	1.01 (0.98-1.05)	1.00 (0.97-1.03)	1.01 (0.97-1.05)	1.02 (0.83-1.25)
ED visits	**n days= 390 n ED = 38330**	**n days= 512 n ED = 51477**	**n days=199, n ED = 20237**	**n days= 22 n ED = 2272**
HW-lag0	1.01 (0.99-1.02)	1.01 (0.99-1.02)	1.01 (0.99-1.03)	1.00 (0.95-1.04)
HW-lag1	1.02 (1.01-1.04)	1.02 (1.01-1.03)	1.02 (1.00-1.04)	1.01 (0.97-1.06)
HW-lag2	1.00 (0.98-1.01)	1.00 (0.99-1.01)	1.01 (0.99-1.02)	0.99 (0.95-1.04)
HW-lag3	1.02 (1.01-1.03)	1.02 (1.01-1.03)	1.03(1.01-1.05)	1.04 (0.99-1.09)
HW-cum	1.04 (1.02-1.06)	1.04 (1.02-1.05)	1.06 (1.04-1.09)	1.04 (0.94-1.13)

Table 2: Relative risk estimates for definitions of heatwaves (HW) of varying intensity, lasting three or more days, for both lagged and cumulative effects on mortality, hospitalization and ED visits

Outcome	>= 3days Heatwave (HW) Definitions		
	HW definition V	HW definition VI	HW definition VII
Mortality	**n days=556 n death=963**	**n days=711 n death=1222**	**n days=271 n death=482**
HW-lag0	1.09 (0.99-1.19)	1.08 (0.99-1.17)	1.16 (1.03-1.31)
HW-lag1	1.12 (1.00-1.24)	1.07 (0.97-1.19)	0.97 (0.83-1.12)
HW-lag2	0.94 (0.84-1.06)	0.99 (0.90-1.10)	1.10 (0.94-1.27)
HW-lag3	1.05 (0.96-1.14)	0.99 (0.91-1.08)	1.03 (0.91-1.16)
HW-cum	1.20 (1.09-1.32)	1.14 (1.05-1.24)	1.26 (1.10-1.44)
Hospitalization	**n days= 494 n hosp.=6652**	**n days= 648, n hosp.=8694**	**n days=257 n hosp.=3599**
HW-lag0	1.03 (1.00-1.07)	1.04 (1.01-1.07)	1.03 (0.98-1.07)
HW-lag1	0.98 (0.94-1.03)	0.97 (0.93-1.01)	0.95 (0.90-1.00)
HW-lag2	1.01 (0.96-1.05)	0.99 (0.95-1.03)	1.04 (0.98-1.10)
HW-lag3	1.01 (0.97-1.04)	1.01 (0.98-1.04)	1.03 (0.98-1.07)
HW-cum	1.03 (0.99-1.07)	1.01 (0.98-1.04)	1.04 (0.99-1.09)
ED visits	**n days= 274 n ED = 27856**	**n days= 365 n ED = 38054**	**n days= 103 n ED = 11787**
HW-lag0	1.01 (0.99-1.03)	1.01 (0.99-1.02)	1.02 (0.99-1.05)
HW-lag1	1.01 (0.99-1.04)	1.02 (1.00-1.04)	1.01 (0.97-1.04)
HW-lag2	1.01 (0.98-1.03)	1.00 (0.98-1.02)	1.02 (0.99-1.06)
HW-lag3	1.01 (0.99-1.03)	1.01 (1.00-1.03)	1.02 (1.00-1.05)
HW-cum	1.04 (1.02-1.06)	1.03 (1.02-1.05)	1.07 (1.04-1.11)