Climate Change Impacts on Human Health at an Actionable Scale: A State-Level Assessment of Indiana, USA

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Abstract

Climate change is already being felt on local levels, with historical records from the State of Indiana (USA) revealing warmer winters, and more extreme precipitation events. To refine our understanding of climate change impacts on human health, we conducted a state-level assessment of future climate change impacts on human health using outputs from advanced climate model projections for this century. Future projections show a steep increase in extreme heat events, leading to greater potential vulnerability to heat disasters for Indiana communities. Additionally, a 2- to 4-fold increase in days with "uncomfortable night" conditions by the end of the century will strongly impact the cardiopulmonary health of more vulnerable populations (i.e., elderly, those with pre-existing conditions, children, and those with inadequate access to cooling).

Continued trends for warmer winters and more flooding suggest a much greater risk for the expansion and virulence of a number of vector-borne diseases, such as Lyme disease, West Nile Virus, and "tropical" diseases for which the mosquito vectors will thrive. Higher temperatures will also drive more frequent and severe harmful algal blooms in lakes and reservoirs, with implications for human and animal health. Food systems will

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also be impacted, particularly with increased risk of contamination by bacteria and mycotoxins due to elevated heat and humidity.

1. Introduction

Climate change is already negatively impacting human health and well-being, and these impacts are expected to worsen with future climate change (Luber and McGeehin, 2008; Bell et al., 2017). Evidence of the links between climate and health range from extreme heat event morbidity and mortality analyses (e.g., Luber and McGeehin, 2008; Hess et al., 2014; Saha et al., 2015; Lay et al., 2018) to extreme precipitation effects (Pendergrass and Knutti, 2018; Witze, 2018). Studies have also increasingly used regional models of future climate change through 2100 to predict, and potentially better prepare for, future conditions at the local level (e.g., Johnson et al., 2012; Schramm et al., 2014; Conlon et al., 2016; Moulton and Schramm, 2017). In general, these regional climate projections tend to include higher general temperatures and particularly higher numbers of extreme heat days (Lulla et al., 2015; Conlon et al., 2016) as well as greater intensity of precipitation in any given rainfall event (e.g., Prein et al., 2017; Liu et al., 2017; Patricola and Wehner, 2018; Witze, 2018).

Adverse health impacts from climate change are generally related to the direct consequences of temperature and precipitation patterns, such as heat stroke and flood injuries and mortalities, and indirect effects, such as changes in the growing seasons for allergen sources and expanding mosquito population (Ebi et al., 2018). A series of climate change reports prepared through the Congressionally-mandated US National Climate Assessment process (e.g., Melillo et al., 2014; USGCRP, 2017, 2018) break climate impacts and projections into regional and sectorial analyses. Projections for the Midwest are particularly grim, with estimates that heat-related deaths will increase more in this region than anywhere else in the country (Ebi et al., 2018). Given this backdrop, a reasonable next stage in this granularity of outcomes and impacts is to move toward state-level assessments, given that in the US at least, much of the infrastructure and health services responses that will be most closely coupled to climate change require state-level actions.

Some efforts have been made to develop these more granular products, such as the CDC BRACE program (CDC, 2018) which supported a number of state and city level vulnerability assessments. Other targeted plans have either been conducted (e.g., the City of Chicago's Climate Action Plan largely in response to the deadly 1994 heat wave) or are being developed. But all these plans depend largely on the regional climate models, rather than on state-level climate projections (e.g., U.S. EPA, 2017a).

As part of a multi-sectorial climate impact assessment, we report on the most relevant impacts of climate change on human health in the State of Indiana, USA. We first discuss temperature, including extreme heat, extended heat waves, and the impacts that this has on human health via heat stress, air quality, and the interactions between extended warm seasons and proliferation of noxious weeds and pests. We then cover the role that extreme precipitation has on direct flooding impacts on communities as well as the role that ponded water plays in the lifecycles of disease vectors such as mosquitoes. This analysis may provide an effective approximation more broadly for the Midwest region as a whole, which largely has a similar topography (moderate to low relief), hydrogeology (glacially-modified and till-dominated surface runoff and aquifer systems), and population structure (widely distributed and low density urban centers separated widely among largely agricultural landscapes).

II. Methods

Climate Analysis

We adapted a full-spectrum approach to our analysis of climate change and human health from the Human Health section of the Fourth National Climate Assessment report (Ebi et al., 2018), which includes climate drivers, exposure pathways, and health outcomes. Future climate projections presented here are based on averages from 10 global climate models that are the most likely outcomes for a given emissions scenario for Indiana (Byun and Hamlet, 2018; Angel et al., 2018; Hamlet et al., 2019). The 30-year climate projection windows are the 2020s (2011 to 2040), 2050s (2041 to 2070) and 2080s (2071 to 2100). Two future greenhouse gas concentrations were considered as most meaningful to bracket climate trajectories over this century— "low" and "high," following Representative

Concentration Pathways (RCPs) 4.5 and 8.5, respectively, which have been used to develop many existing projections summarized by the Intergovernmental Panel on Climate Change (IPCC). RCP4.5 (“low”) projects net greenhouse gas (GHG) emissions peaking in 2040 and declining after then and end of century temperatures reaching 2.4°C over pre-industrial levels. RCP8.5 (“high”) projects emissions continuing to rise throughout the 21st century and end of century temperatures reaching 4.9°C over pre-industrial levels (Moss et al., 2010; Rogelj et al., 2012). The lowest-bound scenario, RCP2.6 which assumes that emissions peak between 2010 and 2020 and decline substantially thereafter, is not modeled here as it was considered unlikely given current high and increasing carbon emission rates toward the end of this “peak assumption window” (Hamlet et al., 2019).

Temperature, Ozone and Volatile Organic Compounds Analysis

We created a map of the Indianapolis area urban heat island at a census tract level to visualize the spatial distribution of max land surface temperature using a 30x30m resolution Landsat 8 imagery data downloaded from the USGS EarthExplorer website (http://earthexplorer.usgs.gov/). We aggregated the image pixels to census tract polygons and overlaid this map with the VOC maps to identify specific non-mobile sources of VOCs within Indiana and Marion. Unlike the MODIS products which capture images daily, but at a worse spatial resolution (1km), the Landsat imagery is captured at 30x30m resolution every 16 days. This is important for the spatial granularity of urban heat island effects in a city. Specifically, we downloaded all Level 1 GeoTIFF data products for June-August in 2014 from specific satellite bands, which cover Marion County. We re-projected these Landsat raster images in ArcMap to convert to the NAD 1983 StatePlane Indiana East FIPS 1301 Feet projection. Using a method similar to that described in the MODIS Land Surface Temperature Products Collection 5 Users' Guide, the six raster images taken during the 3 months from band 10 were used to create a composite of a nearly cloud-free image. We repeated the same process for the 6 raster images from band 11. The resulting two cloud-free raster images were then combined using a split-window algorithm similar to that used to create the MODIS land surface temperature product areas of higher total VOC concentrations from all sources.

Ozone (O_3)concentrations were predicted by O_3 formation potential conversion, using amount and type of Volatile Organic Compound (V0C) obtained at the census tract level from the EPA Toxic Release Inventory database from (2005-2015). We used a total of 13 ambient VOC concentrations, including both mobile and non-mobile sources, and summed for O_3 formation potential after calculating the photochemical reactivity weighted concentration for each VOC.

Health Impacts Approach

The approach used in this study considers climate variables temperature and precipitation, both as independent variables as well as interacting variables. From the perspective of air quality and health, temperature impacts cardiovascular systems via heat stress, allergies and asthma via plant allergen season length, pulmonary disease (asthma, etc.) via O_3, carbon monoxide (CO), and to some extent particulate matter production (Ebi et al., 2018). Precipitation impacts flood-related morbidity and mortality, mental health through disaster-related stress, water quality degradation, mold production, and the population levels of mosquitos (e.g., U.S. EPA 2017b). Table 1 illustrates the two climate variables considered in hindcasting recent climate change and forecasting future change based on state-specific climate model outputs.

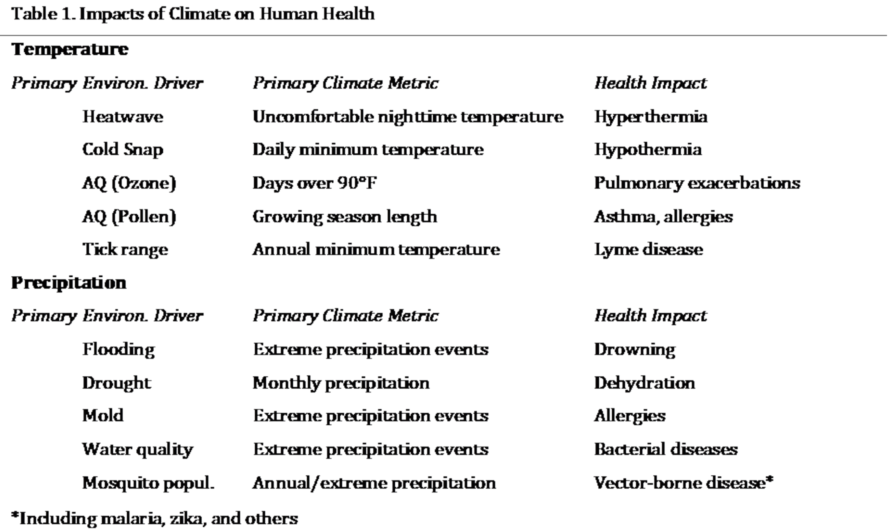


Table 1. Impacts of Climate on Human Health

Temperature		
Primary Environ. Driver	*Primary Climate Metric*	*Health Impact*
Heatwave	Uncomfortable nighttime temperature	Hyperthermia
Cold Snap	Daily minimum temperature	Hypothermia
AQ (Ozone)	Days over 90°F	Pulmonary exacerbations
AQ (Pollen)	Growing season length	Asthma, allergies
Tick range	Annual minimum temperature	Lyme disease
Precipitation		
Primary Environ. Driver	*Primary Climate Metric*	*Health Impact*
Flooding	Extreme precipitation events	Drowning
Drought	Monthly precipitation	Dehydration
Mold	Extreme precipitation events	Allergies
Water quality	Extreme precipitation events	Bacterial diseases
Mosquito popul.	Annual/extreme precipitation	Vector-borne disease*

*Including malaria, zika, and others

3. Temperature Impacts on Health

3.1 Historical records

The observed record of temperature in Indiana since 1895 collected from National Oceanic and Atmospheric Administration (NOAA, Climate at a Glance Database, 2017) provides an important context with which to view future climate change. The annual average temperature has increased 0.4°F/decade since 1960 (Widhalm et al., 2018). Average summer temperatures have also increased, by 0.2°F/decade since 1960, although overall there is no detectable trend for the entire record from 1895 to 2017 (Widhalm et al., 2018). Average summer temperatures for Indiana vary around a long-term average of 72.5°F, with some five-year intervals as low as 71°F and others reaching 74.5°F (Frankson et al., 2017). Heat-stress-related morbidity and mortality are related most strongly to extreme heat events, particularly events where evenings remain very warm for several days in a row (Sheridan and Lin, 2014). The historical record in Indiana reveals an average of about 2 days per year when nighttime temperatures do not drop below 75°F. The 1930's were exceptionally warm in the context of 20th century, experiencing 4-5 days per year with excessive heat. This was before the widespread adoption of air conditioning, and thus would likely to have had an impact on human health, although little analysis has been done on this issue. More recently, the late 1990's and 2005-15 saw 2.5-3.5 days per year of very warm evenings, slightly over the 2.0-day historical average. Very warm nights occurred at or above the long-term norm in every interval but one since 1980 (Frankson et al., 2017).

Several observations arise from the historical temperature record (Widhalm et al., 2018):

- Observed spring temperatures have largely been substantially higher than normal since 1990
- The spring warming signal is the strongest among all the seasons.
- Warming trends have accelerated in the latter half of the record (annually and in all seasons).
- Overnight/minimum temperatures are warming more quickly than daytime/high temperatures.

- Frost-free period is lengthening, with the majority of the extension happening in the spring.
- In latter half of the record (since 1960), declines occurred in extreme cold but no trend is present in extreme heat.

Based on the historical temperature record, we observed a pattern of warmer spring temperatures, with the highest values of the record occurring from 2010-2015 and earlier onset of spring based on last frost dates (Frankson et al., 2017). These trends have resulted in a longer spring allergy season with the lengthening of the ragweed pollen production season (Ziska et al., 2011), as well as other nuisance allergens. Moreover, Chiu et al. (pers. communication) found a total lengthening in the frost-free season in Indiana by more than 2 weeks from 1960-2013, with much of that extension occurring in the spring.

One "natural" driver of pest control is very cold winter temperature, which kills pests and offspring living in the surface soil. The historical record reveals an average of about 5 days per year with minimum temperatures below 0°F (Frankson et al., 2017). There has been one to almost three fewer very cold nights (minimum temperatures below 0°F) than average since 1990, which should result in more pests overwintering successfully into the next spring and summer. Of particular concern is the number and range of pests that are disease vectors, such as mosquitoes and ticks. Climate conditions can affect over-winter survival of both the bacterium that causes Lyme disease as well as the tick that serves as its vector (Beard et al., 2016). The US Midwest and Northeast have seen a significant increase in the number and geographic extent of reported Lyme disease incidence, with cases increasing about 300% nationally over the past 15 years (USGCCRP, 2016). Projected changes include an increased range of transmission, lengthened season of transmission, and higher tick densities (Luber et al., 2014). Southwestern Indiana may be most affected by extended tick habitats; however, impacts on Indiana are projected to be relatively small compared to those in other parts of the Midwest such as Illinois or Kentucky (Brownstein et al., 2005).

3.2 Temperature projections and health impacts

The extreme heat projections for both low and high atmospheric concentrations show substantial increases over the century (Fig. 1). The modeled baseline (1915-2013) of summer days with temperatures above 95°F ranges from 0-12 across the state. This number increases to 26-66 days for low emissions and 30 to over 100 days for high emissions by 2071-2100. Note that the increase is substantial even in the 2020's projection (Fig. 1), indicating that heat stress is not a distant scenario but rather a more immediate one. Furthermore, the number of consecutive days with Tmax above above 86°F (one measure of heat wave duration) rises from 3-5 in the historical record to 6-9 by mid-century (Bowling et al., 2018). This increase is a critical factor, given the links between prolonged heat and heat wave-induced morbidity and mortality events (e.g., the Chicago Heat Wave of 1995).

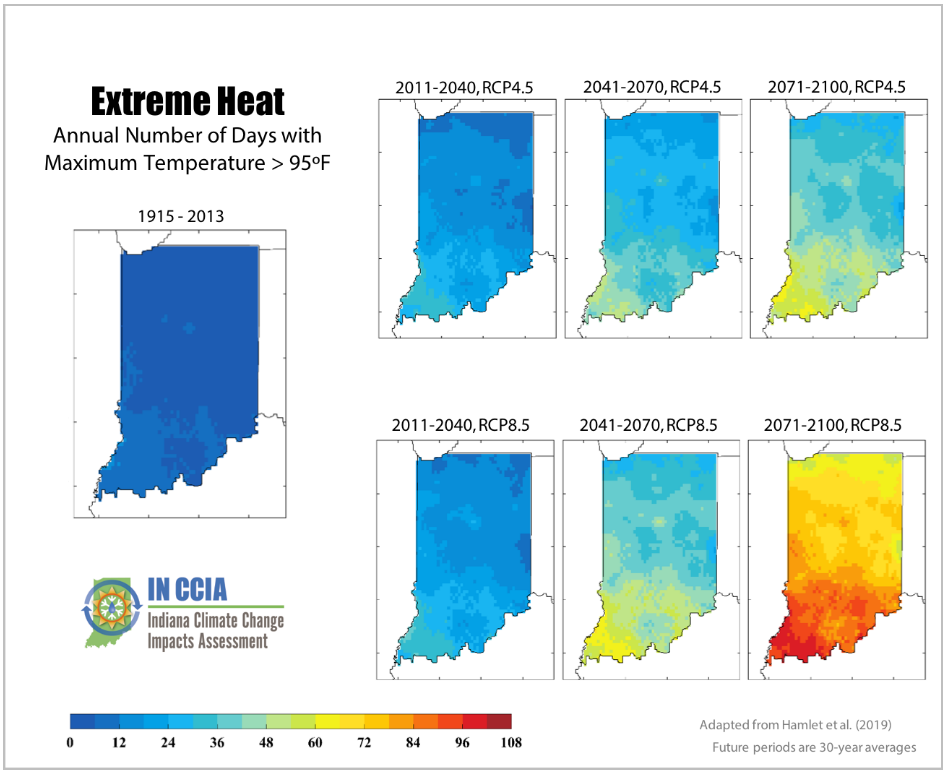
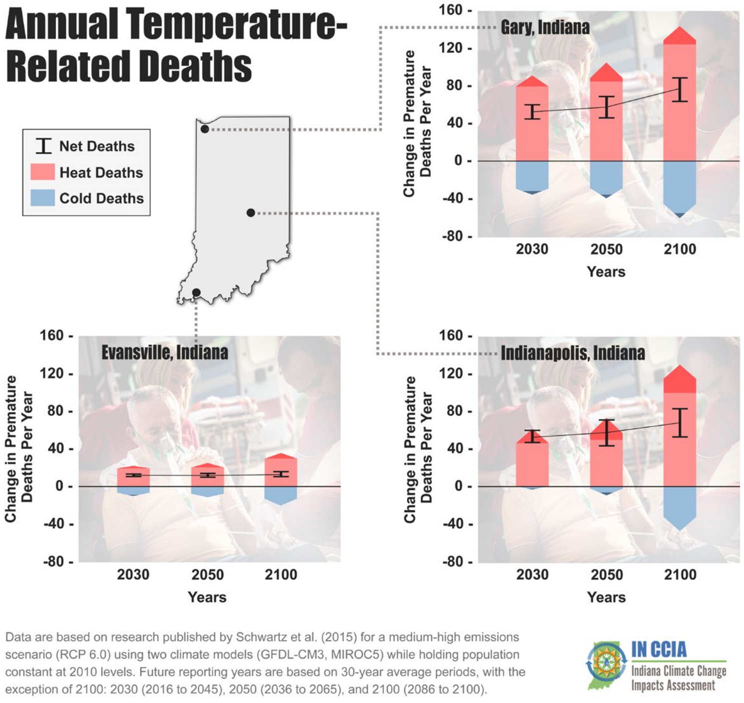


Figure 1. Spatial variability of projected ensemble extreme heat days based on RCP4.5 (top row) and RCP8.5 (bottom row) for 2020s (left column), 2050s (middle column) and 2080s (right column) relative to the historical baseline period (1915-2013).

Another key parameter for heat stress and cardio-pulmonary morbidity and mortality are evening temperatures, and thus we examined the projected occurrence of “uncomfortable nights” (days with minimum temperatures above 68°F). Uncomfortable nights are dominated by higher temperatures and typically high humidity, making most passive cooling systems (i.e., open windows) ineffective. The modeled baseline (1915-2013) for this parameter ranges from 10-40 days across the state (Hamlet et al., 2019). This increases to 40-80 days for low emissions and 60-110 days for high emissions by the end of the 21st century. This increase poses clear health risks, especially for vulnerable populations (i.e., elderly, those with pre-existing conditions, children, and those with inadequate access to cooling). Based on research by Schwartz et al. (2015), the number of heat deaths in the U.S. will increase by 10,000-15,000 individuals by 2050 and 20,000-27,000 by 2100. These increases in heat deaths will be somewhat offset by decreases in cold deaths, but the net will still be significantly higher mortality incidences from climate change impacts on temperature (Figure 2). Narrowing in on Indianapolis, Schwartz et al. (2015) calculated a net annual increase in deaths of 81.9 by 2100 due to warming (Figure 2).



Data are based on research published by Schwartz et al. (2015) for a medium-high emissions scenario (RCP 6.0) using two climate models (GFDL-CM3, MIROC5) while holding population constant at 2010 levels. Future reporting years are based on 30-year average periods, with the exception of 2100: 2030 (2016 to 2045), 2050 (2036 to 2065), and 2100 (2086 to 2100).

Figure 2. Climate change-driven mortality projections for three cities in Indiana (data from Schwartz et al., 2015). The projected increase in deaths due to warming in the summer months (April-September), the projected decrease in deaths due to warming in the winter months (October-March), and the projected net change in deaths compared to a 1990 baseline, using two climate models (CFDL-CM3, MIROC5; medium emissions RCP 6.0 scenario)

3.3 Temperature and health impacts of air quality

Climate change will affect air pollution, and thus potentially human health, through several processes. In the last few decades, air pollution has been identified as a key cause of mortality and morbidity in the U.S. and worldwide. It is estimated that about 200,000 premature deaths in the U.S. are caused by fine particulate air pollution and about 10,000 deaths are caused by O_3 pollution air pollution every year (Caiazzo et al., 2013). The prediction of the effects of climate change on air pollutant concentrations is complex because they are affected by many factors, including natural sources of air pollutants and precursors which themselves may be impacted by climate change, as well as direct anthropogenic sources such as pollutant emissions rates. In the case of fine particulate matter smaller than 2.5 microns in diameter (PM2.5), the emissions are primarily those from combustion processes taking place in vehicle engines and power plants. In the case of O_3, the emissions of importance are the nitrogen oxides (NOx) and volatile organic compounds (VOCs) emitted by vehicle engines and industrial processes which are the precursors for O_3 formation in the atmosphere (Ebi et al., 2018). These emissions are themselves determined by a variety of factors including the state of the economy, systems of individual and mass transportation, and regulatory policies and enforcement (Landrigan et al., 2018).

Increased loss of life due to worsening air quality is highly likely (Filippelli and Taylor, 2018; Filippelli et al., 2020), but estimates differ on how many deaths will occur. One study predicted 4,000 more annual U.S. deaths by 2050 due to increased PM 2.5 and another 300 deaths from increased O_3 exposure (Tagaris et al., 2009), coming to about 82 and six for Indiana, respectively. Another study suggested PM2.5 and O_3 together will lead to 2,000 to 4,000 more deaths per year throughout the country for every 1°C (1.8°F) of warming, or about 42- 84 more per year in Indiana (Jacobson, 2008).

Still another approach examined the United States on a county-by-county basis and estimated all deaths tied to O_3 exposure during summer months. In Indiana, this comes to between 32 and 130 deaths per year by 2050 (Alexeeff et al., 2016), with the range accounting for uncertainties between O_3 and health effects and potential future O_3 concentrations under a high emission scenario.

Controlling precursor emissions, primarily NOx and VOCs, is one of the most essential elements for limiting ground-level O_3 formation. VOCs, methane (CH_4), and CO react with the hydroxyl radical (OH) to form intermediate species that interact with NOx, ultimately producing ground-level O_3. (Murazaki and Hess, 2006). Mobile fossil fuel combustion in the urban environment generates large amounts of NOx and, with elevated surface temperatures in the urban environment due to climate change, VOC volatilization from natural sources and anthropogenic activities may be elevated, as well. Additionally, locally higher temperatures due to urban heat island can lead to shallow mixing heights in the atmosphere which has been linked to increased ground-level O_3 formation.

To illustrate that elevated urban heat could potentially lead to higher levels of O_3, thus exacerbating pulmonary issues, we demonstrate that census tracts located in an urban heat island within Indianapolis have higher VOC emissions from both mobile and non-mobile sources. Higher total VOC emissions are mostly in downtown and in urban heat islands with high temperature, thus these areas may have more intense O_3 formation. As global temperature in urban environment arises, more O_3 will be formed in general. Thus, these areas have higher O_3-forming potential given the important role of VOCs as a precursor in O_3 formation (Fig. 3). Our analysis demonstrates the correlation between elevated temperature in urban heat islands and potentially higher O_3 formation (Fig. 3).

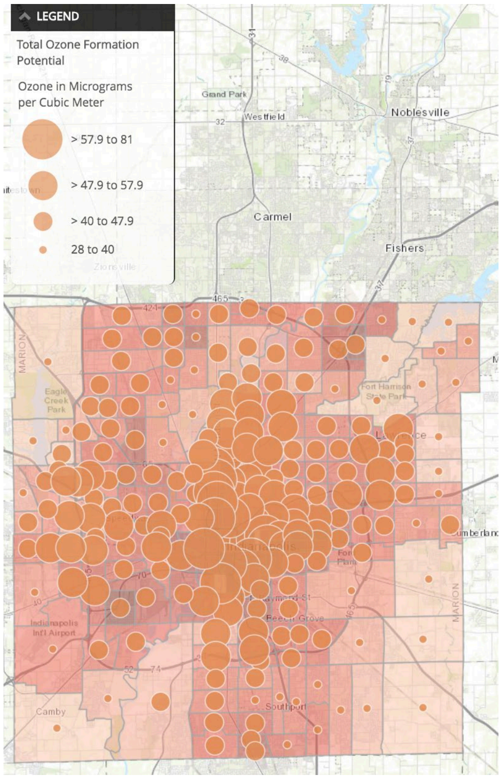


Figure 3. Predicted O_3 concentrations (circles) overlain on a map of Indianapolis maximum land surface temperature. Larger circle size indicates higher O_3 concentration, and darker colors indicate higher temperatures.

It is important to note that climate change-related health outcomes will not impact all individuals from Indiana evenly. Negative health impacts from worsening air quality will especially affect children because their lungs are still developing (Black et al., 2017). Children also have relatively faster breathing rates, which increase their exposure to air pollutants such as O_3 and PM 2.5. Adults with chronic, pre-existing health conditions will also face more risk, as will those who live in heavy transit corridors or near industrial activity.

4. Precipitation Impacts on Health

4.1 Historical records

One of the most significant changes in Indiana climate has been in the amount and intensity of precipitation over the past 25 years and longer. Total annual precipitation averaged 40 inches over the historical record but has consistently been about 5-15% higher than the long-term average since 1990 (Frankson et al., 2017; Widhalm et al., 2018). Higher precipitation coupled with warmer temperatures over longer periods could offer better conditions for mosquito abundance in general. But probably even more concerning is the increasing trend in precipitation intensity. Importantly from a flood-control perspective, the number of extreme precipitation events has increased from the long-term average of about 1.8 per year to 2.0-2.7 events per year (Frankson et al., 2017). Extreme precipitation was also the focus of the Indiana state-specific assessment (Hamlet et al., 2019). In this case, the number of days that exceed 25 mm was the metric used for this parameter, and exhibited a historical baseline (1915-2013; effectively a century of record starting when accurate measurements began and ending with the final complete reported year of data before the model runs were initiated) that ranged from 9 days in the northern part of the state to 12.5 days in the southern part.

4.2 Precipitation projections

Flooding and extreme weather events are usually associated with negative public health consequences, especially when there is evacuation and population displacement (WHO, 2017). Flood-related health problems range from immediate health impacts resulting from violent direct physical effects on humans (drowning, traumas, hypothermia, and animal bites) to longer term effects associated with health care services (personnel, drugs and supplies) and infrastructure (Ahern et al., 2005; Du et al, 2010). Among these longer term effects are poor mental health, poisoning, starvation, infected wounds, and transmission of water-associated diseases (related to disruption in the infrastructure of sanitation and water supply). These diseases are classified by the World Health Organization (WHO) in four categories: water-borne, water-washed, water-based, and water-related (Coussens, 2009). We will focus most of our analysis here to water-related health impacts, namely those linked to ponded water and warmer conditions, resulting in both the proliferation of pests (e.g., mosquitos) and ideal growing conditions for harmful algae.

Total annual precipitation for Indiana shows substantial increases over the century (Figure 4; Hamlet et al. 2019). The modeled baseline (1915-2013) of precipitation ranges from 40-52 inches across the state (note that Hamlet et al. intentionally use a precipitation gauge undercatch bias correction, and thus baseline is slightly different from that of Frankson et al., 2017). This number increases to 44-54 inches for low emissions and 44-58 inches for high emissions by 2071-2100. This projects that seasonal precipitation will increase by 17% in spring and 32% in winter in the high emissions projection for 2071-2100 (Hamlet et al, 2019). For Indianapolis, this represents an increase of 2.5-5 inches of annual precipitation by 2100. Given the low elevation relief of Indiana, and particularly the flat topography in the northern half of the state (Barrett, 1912), these increases suggest a higher potential for flooding, possibly resulting in direct overall damage to property and the health care industry (including emergency medical services) as evidenced by past records (Ho-Oh et al., 2010), as well as indirect impacts related to standing water, to be detailed next.

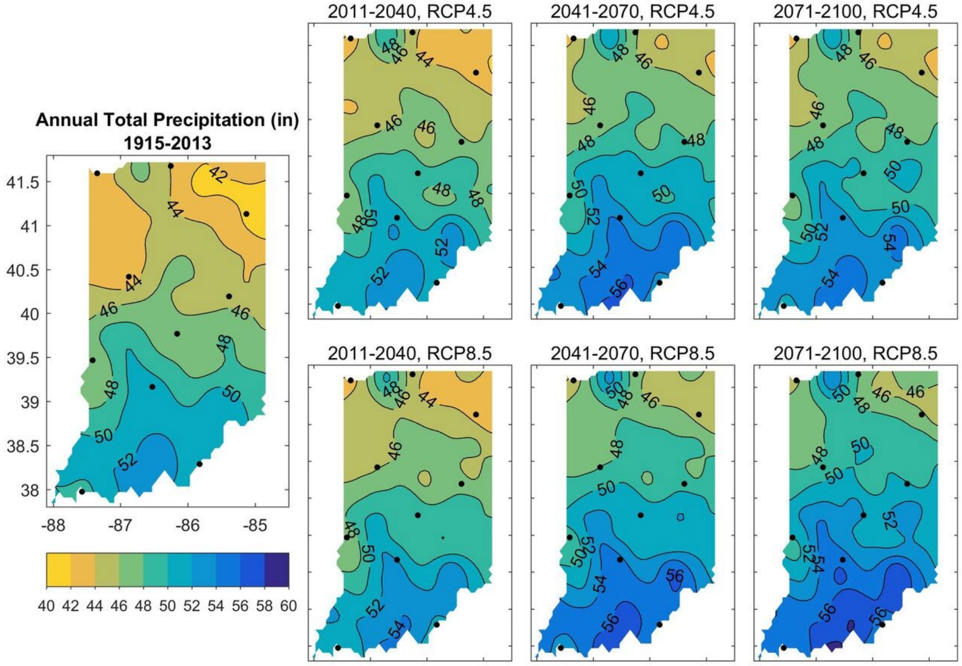


Figure 4. Total annual precipitation for Indiana based on atmospheric GHG concentrations under RCP4.5 (top row) and RCP8.5 (bottom row) for 2020s (left column), 2050s (middle column) and 2080s (right column) relative to the historical baseline period (1915-2013), using a precipitation gauge undercatch bias correction (Hamlet et al., 2019.

4.3 Climate Impacts on Disease Vectors

Although literally the term vector could be applied to any living organism transmitting an infective pathogen, it conventionally refers to insects such as mosquitoes, ticks, and fleas. The term 'water-related' is used by the WHO to refer the diseases caused by the pathogens transmitted by such vectors as mosquitos, which require water as a breeding media or have some connection with water during their life cycle (Coussens, 2009). Mosquito abundance and transmission of the pathogens they carry are conditions likely sensitive to flooding and extreme weather events for several reasons such as increased stagnant waters and disruption of health and housing infrastructure (Porphyre et al, 2005). Diseases such as Malaria and Yellow Fever were endemic in the United States in the past (Patterson 2009), and a host of other diseases are still endemic in Latin America and Southeast Asia, such as dengue, chikungunya or Zika (Paixão et al, 2018). Many of these would be unlikely to take hold in the United States today (or remerge in the case of Malaria and Yellow Fever) because of better socioeconomic conditions and public health infrastructure, but could eventually be a concern if the protective effect of good housing and health infrastructure gets compromised as a result of floods or other disasters (Moreno-Madriñán and Turell, 2017; 2018).

A present concern in regard to mosquito-borne viruses are zoonotic diseases such as West Nile Virus (WNV) since their cycles can be completed in animals such as birds despite the protective effect of good living conditions and health infrastructure for humans (Moreno-Madriñán and Turell, 2018). The most concerning climate change factor influencing the prevalence of West Nile Virus (WNV) are increased temperatures. Depending on the optimal window of temperature for the mosquito vector and the virus, climatic change may differently affect parameters such as larval development, extrinsic incubation period, and the duration of the gonotrophic cycle (Rueda et al., 1990; Dodson et al., 2012; Garcia-Rejón et al., 2008). In general, for conditions of Indiana, more rapid development of these processes and shorter periods between mosquito bites are expected with warmer temperatures (Garcia-Rejón et al., 2008; Hartley et al., 2012). Such conditions translate into more efficiency of the mosquito as vectors (more vectoral capacity), resulting in more epidemic potential (Dohm et al., 2002; Reisen et al., 2006).

Based on results from all mosquito species collected from 20 light traps during the 1981-2016 time period by the Mosquito Control Department of Marion County, Indiana, an increase occurred over this time period (Supplementary Information). This increase is consistent with historical changes in annual precipitation, extreme precipitation, and temperature in Indiana noted earlier. Given model projections for these factors over this century, it is likely that these increases in mosquito populations, and thus potential for mosquito-borne disease transmission, will persist into the future (Patterson, 2009; (Kraemer et al., 2015a, b; Messina et al., 2016; Monaghan et al., 2016). For example, under the high emission scenario for Indiana, the number of days over 25 mm of precipitation was expected to increase by about 20% uniformly across the state (Hamlet et al., 2019). This could even be a more serious trigger for mosquito-transmitted diseases as compared to just a growing amount of precipitation because floods can affect the housing infrastructure and lifestyle, making people more exposed to mosquito bites. It is estimated that good housing and sanitation, and not climate, are currently the main protective factors against transmission of anthroponotic mosquito-transmitted diseases such as dengue, Yellow fever, chikungunya and Zika virus in the Unites States (Moreno-Madriñán and Turel, 2017).

Of particular concern is the recent arrival of non- *Ae. aegypti* mosquito strains in Indiana. *Aedes albopictus* (Skuse)*,* arrived into the United States in 1987 (Moore and Michell, 1997) and has been reported to be present in Indianapolis by the Marion County mosquito control program. In laboratory studies, this mosquito has been a more competent vector than *Ae. aegypti* for both dengue (Brady et al., 2014) and chikungunya (Turell et al., 1992) viruses. Furthermore, it was the main chikungunya vector during the 2004-2007 major outbreak on islands in the Indian Ocean. Other studies have shown this mosquito to be a competent vector for Zika virus (Wong et al., 2013; Aliota et al., 2016; Chouin-Carneiro et al., 2016). Due to its better adaptation to colder temperatures, *Ae. albopictus* is expected to reach further north than *Ae. aegypti* (Kraemer et al. 2015a, b). *Aedes japonicus* (Theobald) is another recently introduced species of mosquito that is a competent vector of dengue and chikungunya viruses (Schaffner et al., 2011). It was first detected in New York and New Jersey in 1998 (Peyton et al., 1999). Fortunately, despite the better suitability to carry, replicate, and transmit dengue, chikungunya and Zika viruses (vector competency), these two mosquitos have less vectoral capacity as compared with *Ae. aegypti* as they are less likely to feed repeatedly on humans (Richards et al., 2006, Lambrechts et al., 2010) and the three viruses cannot complete their cycles in animals other than humans.

4.4 Climate impacts on water-associated diseases

The occurrence of blue-green algae, also known as cyanobacteria, in aquatic systems is a growing environmental and public health concern. If the environment is favorable, cyanobacteria can form harmful algae blooms (HABs), which consequently increase their biomass forming scum on the water surface (Paerl and Huisman, 2008). Although HABs are responsible for the loss of aesthetic conditions and production of taste and odor compounds, the main public health concern is related to their capability to produce toxins known as cyanotoxins that have been a worldwide concern for human and environmental health (Carmichael et al., 2001; Funari and Testai, 2008).

Since future climatic scenarios are predicting heavy rainfall and warm temperatures for Indiana, HABs are also expected for Indiana's aquatic systems. Recently a framework using different climate change projections, two greenhouse gas concentrations, and two cyanobacterial scenarios showed that for all possible combinations, cyanobacteria will increase in the state of Indiana (Chapra et al. 2017). Therefore, the evaluation of how HABs will respond to climate variability is an important concern for human and environmental health. To analyze this in one Indiana-relevant system, we used data from the Indiana Department of Environmental Management from Brookville Lake, Indiana, from 2012-2016. We found several climate-related trends in algae cell counts and HAB concentrations, namely positive linear trends in temperature, cyanobacterial cell counts, and concentrations of the algal-produced toxin Microcystin-LR (supplementary information). These observations agree with Paerl and Huisman's (2008) findings in which cyanobacteria growth is related to the increase of air temperature, and add to this finding an increased propensity for toxin production. Although the effects of microcystin on human health are not well understood, research suggests that the main target organ in mammals is the liver (Sivonen and Jones, 1999; Azevedo et al., 2002).

5. Climate Impacts on Food and Food Safety

Our food system is a highly complex, global network; much of the food we eat is grown in other countries or even continents. Thus, impacts of food production around the globe are likely to impact the food supply and food security within Indiana. Although the exact impacts are difficult to predict, in general, researchers agree that reductions or uncertainties in food production on a global scale are anticipated to result in increased variability of decline in crop yields (Porter and Semenov, 2005), which can result in decreased food availability and increased prices (Wheeler and von Braun, 2013). These, in turn, may lead to food insecurity (Coleman-Jensen et al., 2017). Meanwhile, studies from Australia suggest drought-related financial stress may be associated with poor mental health and suicide among farmers (Ellis and Albrecht, 2017; Austin et al., 2018). Several lines of evidence suggest that Indiana agricultural communities may already be at risk: Indiana farmers' income has been decreasing (Hurt 2017) and suicide rates in rural areas have been increasing faster than in metropolitan areas (Ivey-Stephenson et al., 2017).

Food quality may also be reduced due to climate change. Increasing evidence suggests that increased atmospheric CO_2 levels results in reduced concentrations of iron, magnesium, zinc, and other micronutrients (Ziska et al., 2016; Loladze 2014) and protein (Ziska et al., 2016; Taub et al., 2007) in plants. Nutritional deficiencies are already of concern in Indiana. An estimated 7% of Indianans already had limited access to healthy foods in 2015 (County Health Rankings, 2018). Iron deficiency is already of concern among children and women of childbearing age in the United States, with even higher rates among non-Hispanic blacks and Mexican Americans (U.S. Centers for Disease Control and Prevention, 2012). In 2003, the prevalence of anemia was 13.2% among white Indiana children and 23.5% among black Indiana children (Indiana State Department of Health, 2018).

Food pathogens are highly dependent on temperature, precipitation and extreme weather (Ziska et al., 2016), which are all anticipated to increase in Indiana from climate change. It is important to remember that food systems are complex, and contamination of the food supply can occur at several different points, including production, transportation, storage, and preparation (Ziska et al., 2016). Microbial contamination of food by

Salmonella, E coli, and Campylobacter is a leading cause of foodborne illness, a situation that tends to increase with increased temperature and humidity (Patz et al., 2008; Kim et al., 2015). Additionally, floodwaters can be contaminated with sewage or manure and then travel to groundwater or irrigation water, providing another route for contamination of the food supply (Patz et al., 2008). As noted earlier, increased flooding is predicted in Indiana as a result of climate change.

Mycotoxins are toxic chemicals produced by molds growing on crops; mycotoxins result in a variety of health effects including renal disease and cancer (Wu et al., 2014). Conditions of increased temperature and humidity are likely to increase the risk of fungal growth and mycotoxin production (Cotty and Jaime-Garcia, 2007; Paterson and Lima, 2010). Corn, the top agricultural crop produced in Indiana, is particularly susceptible to mycotoxin production (Cotty and Jaime-Garcia, 2007). Although routine screening of foods for mycotoxins does occur in the United States and in Indiana, it is of some concern that climate change could increase the risk of mycotoxin contamination.

A greater risk of metal and chemical contamination of food is anticipated with climate change via extreme weather, increased temperatures, and changing agricultural practices. In situations where chemicals are not securely stored, extreme weather and flooding can introduce these compounds into the food chain through mechanisms similar to above or from remobilization of historical pollutants within soils (Ciszewski and Grygar, 2016; Luber et al., 2014). Chemical and microbial contamination of the food supply was observed due to flooding from Hurricane Katrina (Presley et al., 2006). Chemicals that can readily enter the food chain include polychlorinated biphenyls, persistent organic pollutants, pesticides, and heavy metals (Foulds et al., 2014; Carrie et al., 2010; Umlauf et al., 2002).

Methylmercury is a neurotoxicant that can affect adult and child neurodevelopment, even at low levels of exposure (Karagas et al., 2012). The most common route of exposure to methylmercury is through fish and seafood. This is part of a complex process: elemental or inorganic mercury is released into the environment and eventually finds its way into water bodies, where specialized bacteria in water convert the mercury into methylmercury, which is then incorporated into fish and seafood. The presence of mercury in Indiana waters is well documented; in some areas, concentrations are already high enough to pose health concerns if fish from these waters are consumed (Filippelli et al., 2015). Higher water temperatures may result in increased uptake of methylmercury into tissues, thus potentially increasing toxic levels in fish consumed by humans (Carrie et al., 2010; Dijkstra et al., 2013).

6. Conclusions and Recommendations

Climate change has affected and will continue to affect a number of processes that ultimately result in human health impacts over this century. On balance, the net direct impact on human health from extreme heat events will be moderate so long as cooling options are available for vulnerable populations, whereas secondary processes that impact pest ranges and activity, and air quality, will likely have a substantial, and negative, impact on human health in Indiana. Additionally, changes in precipitation patterns will result in greater chances of flooding, which can directly impact people, as well as secondary impacts on ponded water, which increases mosquito populations and thus the potential for expansion in the range of vector-borne diseases. Degraded water quality has the potential to cause increased rates of contact-related diseases. Increased extreme precipitation causes myriad direct and indirect health issues.

Given these climate projections, it is important to consider building protective measures into environmental health, health access, and food distribution systems to make Indiana residents and communities more resilient to climate. Several strategies should receive priority at the state and local level to build resilience. First priorities should include the development of robust extreme heat plans, particularly for the southern portion of the state and any of the urban centers, which will see extreme heat event impacts first. Additionally, infrastructure and systems should be implemented for transporting and housing residents at risk during substantial precipitation events, particularly in the more vulnerable northern portion of the state. Finally, a robust early warning system should be adopted to identify vector-borne diseases outbreaks and HABs before they become major public health events.

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Supplementary information for:

Climate Change Impacts on Human Health at an Actionable Scale: A State-Level Assessment of Indiana, USA

Filippelli, G.M.[1,2,3], Freeman, J.L.[4], Gibson, J.[1,5], Jay, S.[1,6], Moreno-Madriñán, M.J.[1,6], Ogashawara, I.[2], Rosenthal, F.S.[4], Wang, Y.[1,6], and Wells, E.[4]

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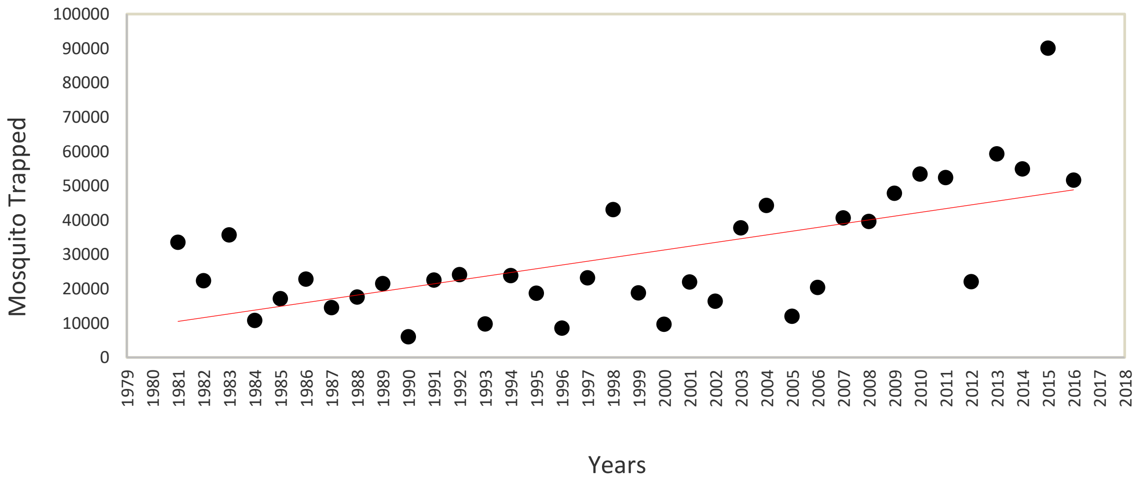

Figure 1. 1981-2016 temporal trend line of mosquito trapped in 20 light traps during the 1981-2016 time period in Marion County, Indiana (data from Marion County Public Health Department).

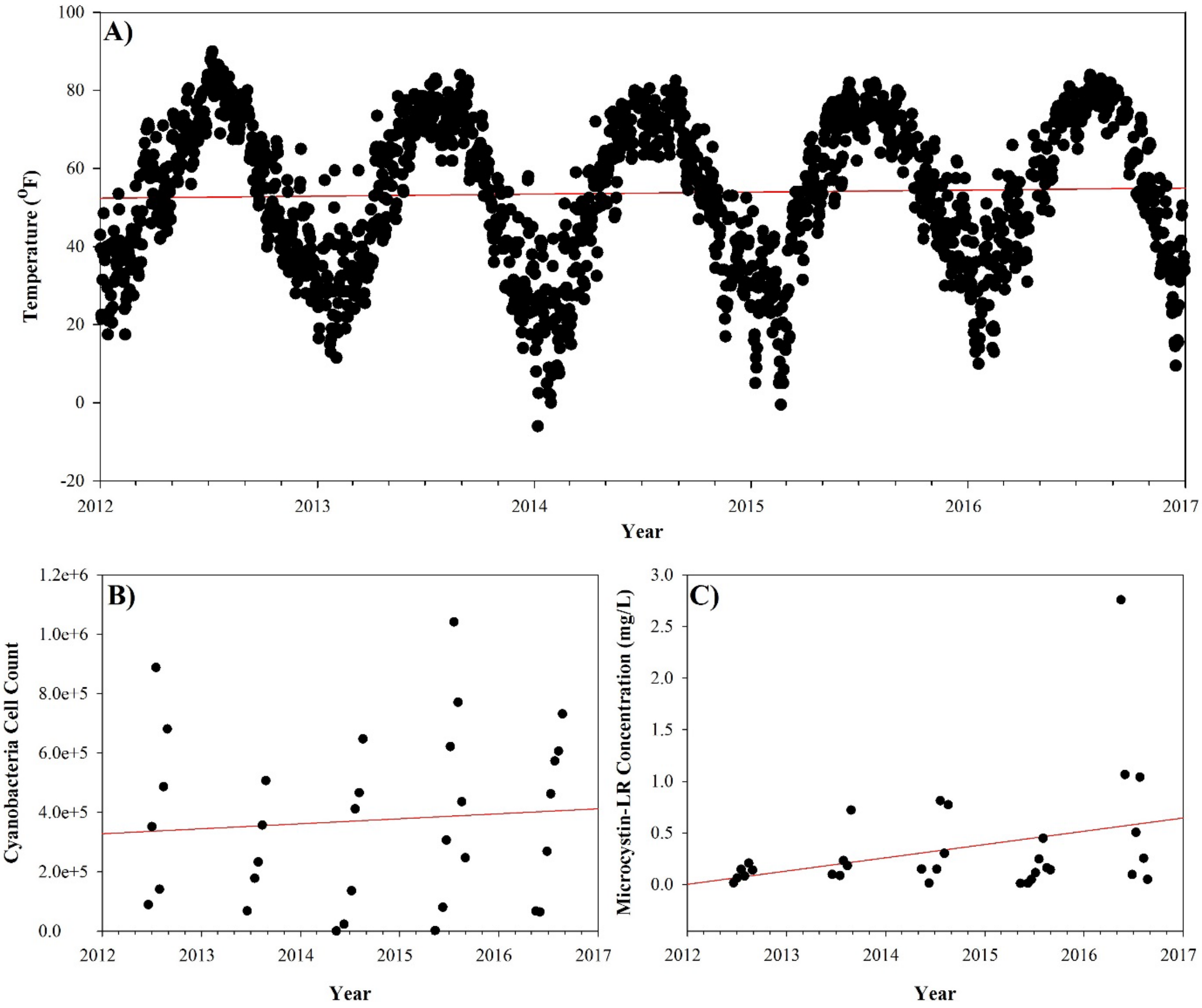

Figure 2, A) Air temperature for the Brookville weather station from 2012 to 2016; B) Cyanobacteria cell count from Brookville Lake collected by IDEM during summer from 2012 to 2016; C) Microcystin-LR concentrations from Brookville Lake collected by IDEM during summer from 2012 to 2016. Data from the Indiana Department of Environmental Management. In the United States, no regulations exist for cyanotoxins levels in the Safe Drinking Water Act (SDWA) or in the Clean Water Act (CWA) (USEPA, 2015a). Since the SDWA provides the authority for the United States Environmental Protection Agency (USEPA) to publish health advisories (HAs) for agents that do not have any national drinking water regulation. Therefore, USEPA is the agency that is responsible for the implementing and enforcing of the guidelines, standards or HAs related to cyanotoxins. Based on this, during summer 2015, the USEPA issued a 10-day HA for two cyanotoxins: microcystin-LR (USEPA, 2015b) and cylindrospermopsin (USEPA, 2015c). For these two cyanotoxins, USEPA recommended HA levels in drinking water at or below 0.3 μg/L for microcystin-LR for children pre-school age (USEPA, 2015b); and 0.7 μg/L

of cylindrospermopsin for the same age range (USEPA, 2015c). These levels are higher for the rest of the population with HA levels for drinking water for microcystins at or below 1.6 μg/L (USEPA, 2015b); and for cylindrospermopsin at or below 3.0 μg/L (USEPA, 2015c). Besides the publication of Federal HAs by the USEPA, some U.S. States have implemented their own guidelines for the monitoring of cyanotoxins.

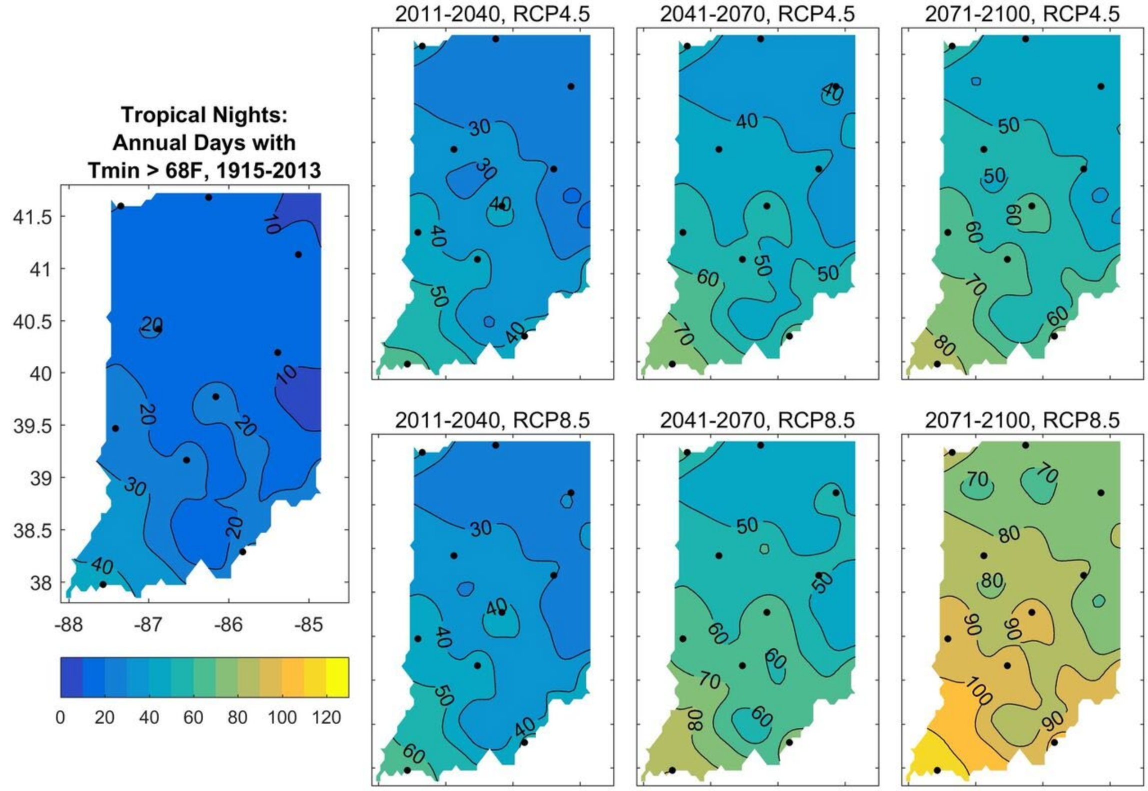

Figure 3. State-wide tropical night projections for Indiana under two climate scenarios. A key parameter for heat stress and cardio-pulmonary morbidity and mortality are evening temperatures, and thus we projected a tropical nights (days with minimum temperatures above 65°F) scenario. These tropical nights are dominated by higher temperatures and typically extremely high humidity, making most passive cooling systems (i.e., open windows) ineffective.

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