SPATIAL AND TEMPORAL CHANGES IN GROUNDWATER MANGANESE AND INFANT MORTALITY IN NORTH CAROLINA

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ABSTRACT

Angela Kathleen Bittner Penny: Spatial and Temporal Changes in Groundwater Manganese and Infant Mortality in North Carolina
(Under the direction of Marc Serre)

Manganese is ubiquitous in North Carolina, with well users at risk for excess exposure. Previous studies didn't consider long-term infant mortality rate variability or total worker health exposure in agricultural settings. In this study, manganese concentrations and infant mortality rates are evaluated throughout North Carolina from years 2000 through 2019, assessing spatiotemporal changes using Bayesian Maximum Entropy (BME) analysis. Manganese concentrations exceeded established adverse effect limits and showed variability overlooked in studies sampling for limited years. Manganese concentrations are autocorrelated over 1.25 degrees and 3.3 years while infant mortality rates are autocorrelated over 0.6 degrees and five years. Infant mortality rates were evaluated using BME interval estimation, resulting in regional maximums of up to one infant death per thousand live births attributable to manganese in the North Carolina Coastal Plain. Increased testing and advisories for private well users will aid in identifying and mitigating manganese exposure and related infant mortality.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS AND SYMBOLS

AF	Attributable Fraction
AI	Adequate Intake
BME	Bayesian Maximum Entropy
DALY	Disability-adjusted life-years
Delta Y (ΔY)	Infant Mortality Attributable to Manganese
EPA	United States Environmental Protection Agency
L	Liter
mg	Milligram
mn	Manganese
SMCL	Secondary maximum contaminant levels
ug	Microgram
ULs	Tolerable Upper Intake Levels
USGS	United States Geological Survey
WHO	World Health Organization
YLD	Years lived with disability
YLL	Years of life lost

CHAPTER 1: INTRODUCTION

Manganese is a transition metal and the twelfth most abundant element in the Earth's crust. It is found in ground and surface waters as well as soils and its presence in the environment is due to both geogenic and anthropogenic sources. Manganese occupational exposure can occur through manufacturing, mining, and agricultural activities and can enter the environment via industrial discharge, fertilizer and biosolids, and natural leaching from weathering (World Health Organization, 2020).

Considered a threshold chemical, low doses of manganese can have beneficial health effects in bone formation and immune response. It is an essential element for health and is found in dietary supplements and many food sources including spinach, whole grains, and nuts. Manganese deficiency is rare due to the presence of many dietary sources, and adequate intake (AI) levels for manganese average approximately 2.0mg/day for adults with absorption ranges between 1 and 5% for ingested manganese (Freeland-Graves et al. 2016, Martins, 2020). AI for manganese vary by age and sex, with infants less than 6 months of age AI equal to 0.003mg/day (or 3ug/day) (Martins, 2020). The Tolerable Upper Intake Levels (ULs) for manganese dietary consumption in adults is approximately 11mg/day. While infant ULs are not established, it's noted that breast milk, formula, and food should be the only sources of manganese for infants (National Institutes of Health, 2021). Any concentration of manganese ingested via drinking water is then in excess of beneficial levels for infants. Although manganese overexposure occurs more often in chronic exposure, infants are vulnerable to effects of high manganese acute exposure as well. Infants can absorb as much as 20 percent of manganese ingested as they retain more and excrete less manganese compared to adults (Maine Center for Disease Control and Prevention, 2018). The health advisory limit for infants is 300ug/L for ten-day acute exposure due to infants having higher absorption rates and multiple intake routes including formula and human milk (Coetzee et al, 2016). Manganese toxicity can occur from drinking water with high manganese concentrations that affect the central nervous system and increase risk of neurodegenerative disease and infant mortality (National Institutes of Health, 2021).

Manganese in drinking water is considered a secondary contaminant by the EPA where testing is only required on a voluntary basis. Secondary maximum contaminant levels (SMCL) are established for non-mandatory water quality standards. Problems associated with secondary contaminants primarily include aesthetic, cosmetic, and technical effects. The SMCL for manganese is 50ug/L, with noticeable effects above this limit including black staining, metallic taste, and black to brown coloration in the water (Du, 2004; Murosky, 2010). The EPA established the health advisory level for manganese at 300ug/L in drinking water to prevent neurotoxic effects of chronic exposure. (NCDHHS, 2022). The EPA health advisory level is equal to the acute exposure limit for infants (300ug/L). The World Health Organization drinking-water guideline for manganese is 400ug/L and this standard is widely used in global studies of infant mortality and groundwater manganese (World Health Organization, 2020).

Manganese is mobilized by a variety of factors in the environment and is dependent upon local conditions. In the Piedmont of North Carolina, manganese is naturally occurring within the Carolina Slate Belt in the saprolite layer present above bedrock. Reducing and acidic conditions can reduce manganese to the 2+ state, the most stable in groundwater. As manganese is mobilized in the 2+ state, it can travel through bedrock fissures to groundwater supplies (Polizzotto et al, 2015). McMahon et al found that manganese concentrations can cluster at the water table and groundwater recharge near the water table can mobilize concentrations. Infiltration and elevated dissolved organic carbon into aquifers can increase manganese concentrations in the acidic shallow groundwater near the water table (McMahon et al, 2019). Groundwater manganese concentrations decrease with an increase in well depth, indicating that the mobilization factors influencing high manganese concentrations are occurring near the surface at shallow depths. The Coastal Plain in the eastern portion of the state features shallow well depths (Huffman, 1996) and greater groundwater recharge occurs which raises the water table (Alley, 2009). Greater variability in manganese concentrations will occur at shallower depths and precipitation events can raise the water table and mobilize manganese. Manganese concentrations were found to be higher in humid climates with high precipitation, which create anoxic groundwater conditions. Anthropogenic nitrogen fertilizer in soils can create acidic groundwater conditions via recharge that mobilizes concentrations at shallow depths (McMahon et al, 2019). The land application of biosolids in agricultural settings also introduces unregulated manganese concentrations into the soil, as well as other heavy metals, at risk of mobilizing during precipitation events (Margui et al, 2016). The combination of high precipitation, shallow well depths, and nitrogen fertilizer and biosolid application in the region make the Carolina Coastal Plain susceptible to conditions which mobilize manganese and can result in high concentrations in groundwater. Private well users could be at greater risk of manganese exposure as private wells have shallower depths compared to public water supplies (Ramachandran et al, 2021).

With most of the North Carolina hired agricultural worker population located in the Coastal Plain, this worker group could be at risk for excessive manganese exposure from groundwater wells. Higher proportions of county agricultural activity are focused on cropland in the eastern portion of the state as opposed to forested regions in the west (WFMY, 2014) resulting in workers located in the east have greater likelihood of exposure from biosolid application and a variety of mobilization factors. Migrant workers and their families are especially vulnerable as they work and reside in the same region, which can present additional opportunities for exposure (Arcury and Quandt, 2011). A study conducted in eastern North Carolina found elevated urine levels for metals in the migrant worker population. Elevated arsenic was detected in wells in the study area as well as in the urine analysis (Quandt et al, 2010). Arsenic and other pollutants are permitted up to a ceiling concentration in sewage sludge for land application (EPA, 2022), so a possible exposure route for metal contamination in agricultural workers is via biosolid content and resulting runoff infiltrating groundwater drinking sources. Occupational exposure to groundwater manganese in North Carolina has yet to be investigated and migrant workers and their families may face a greater burden of disease from exposure.

Hafeman found that manganese exposure to infants in Bangladesh at levels exceeding the 400ug/L WHO limit have greater risk of mortality (Hafeman et al, 2022). Reid conducted a statewide analysis of manganese concentrations in North Carolina using the National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance data collected from 1973 to 1979 (Reid, 1993) and this data was used to inform the study by Spangler and Spangler investigating the association between county level infant mortality and groundwater manganese in North Carolina. A limitation of their study includes the time at which samples were taken. The manganese concentration data was obtained from 1973 to 1979 and the infant mortality records were combined from 1997-2001 and averaged for each county (Spangler and Spangler, 2009). Previous studies fail to account for temporal changes in manganese and infant mortality rates in North Carolina. Localized factors may influence changing concentrations and disease rates overlooked in other studies. Additionally, infant mortality rates can be affected by noise and statistical estimation methods may be employed to reduce this. A current infant mortality rate attributable to manganese in North Carolina is needed to identify and reduce risk for vulnerable populations by considering spatiotemporal changes.

CHAPTER 2: MATERIALS AND METHODS

2.1 Manganese

Data Acquisition

Manganese data was obtained from the USGS National Water Information System water quality portal for the years 2000 through 2019, consisting of 450 groundwater monitoring well stations located throughout the state (USGS Water-Quality Data for North Carolina, 2023). See appendix for more details. Results were filtered by parameters including date range, characteristic group (inorganic minor metals), site ID, site type (well and groundwater), and location. Manganese concentrations varied throughout North Carolina with a minimum concentration of 0.07ug/L and a maximum of 11600 ug/L (11.6mg/L) with most monitoring stations located in the eastern half of the state. Manganese data was time-averaged using a daily aggregation for each well, with 405 monitoring events. Monthly and yearly aggregations were also explored in the dataset, but resulted in less autocorrelation and created the potential to overlook finer scale influential factors such as precipitation or seasonality. Previous state-wide manganese studies aggregated values yearly (Spangler and Spangler, 2009) and did not account for changes on a daily scale. See appendix for more details on previous mapping studies.

BME Estimation Framework

The Bayesian Maximum Entropy method for spatiotemporal geostatistics was used for the space/time estimation of manganese (Serre and Christakos, 1999; Christakos and Serre 2000; Christakos et al, 2002; Serre et al, 2003). BME is ideally suited because it is a knowledge processing space/time geostatistical estimation framework that can process a wide range of general and site-specific knowledge bases, including hard and soft data (Sanders et al, 2011; Messier et al, 2014). Here we treat all manganese observation as hard data, in which case BME reduces to the linear kriging estimator (Messier et al, 2015; Gomez et al, 2021).

2.2 Infant Mortality

Data Acquisition

Infant Mortality data was obtained from the North Carolina Department of Health and Human Services NC State Center for Health Statistics for the years 2000 through 2019 (North Carolina Center for Health Statistics, 2023). Values for number of live births, number of infant deaths, and infant mortality rates were listed for each county for a given year. If infant mortality rates were not listed for a county for a given year, the rates were calculated by dividing the number of infant deaths by the number of live births and multiplying by the disease rate factor of 1000. The county centroid longitude and latitude values were assigned to each county in North Carolina and joined with infant mortality values.

Estimation Methods

Hard Kriging, BME interval, and Poisson methods were evaluated for infant mortality data. Counties with small populations and high counts of infant mortality can inflate the resulting infant mortality rate. Likewise, small changes in the number of infant deaths will have a large impact on the resulting infant mortality rate. Counties with small populations will have a larger impact on the statewide infant mortality rates. Hard kriging estimates will not reduce the error resulting from the variability in population size and number of cases and can result in an inaccurate disease rate distribution. The hard kriging method can over or underestimate the infant mortality in counties with a small numbers problem. To smooth out the noise due to this small numbers problem, BME interval or Poisson methods can be employed. (Hampton et al. 2011; Fox et al. 2015). The NC State Center for Health Statistics states that infant death rates based on fewer than ten deaths are to be considered unreliable (State Center for Health Statistics, 2011). The interval method is preferred for infant mortality estimation, as indicated by Hampton et al, and allows for a changeable parameter for uncertainty in infant death counts, compared to Poisson kriging. The interval of 10 will be used in modeling infant mortality across the state to reduce the error associated with the small numbers problem.

CHAPTER 3: RESULTS AND DISCUSSION

Space Time Mapping of Manganese

Manganese concentrations varied throughout North Carolina with a minimum concentration of 0.07ug/L and a maximum of 11600 ug/L (11.6mg/L). The manganese data is skewed to the right and the data was log-transformed to normalize the distribution (appendix). Manganese concentrations had a mean of 111.5ug/L (4.7 log ug/L) and median of 35.2ug/L (3.6 log ug/L). Three hundred thirty-nine samples exceeded the EPA secondary contaminant level for manganese and 45 samples exceeded the EPA lifetime health advisory of 300ug/L (5.7 log ug/L). 39 samples exceeded the WHO adverse effect limit of 400ug/L (6.0 log ug/L). Manganese is dispersed throughout the state and higher concentrations are observed in the Piedmont and coastal regions. The time trend of manganese shows concentrations fluctuating, indicating additional localized factors may influence changes in concentrations at sampling sites. See appendix for more details.

The covariance for manganese is modeled by the equation $cX(r,\tau)=c01\ exp(-3r/a_{r1})\ exp(-3\tau/a_{t1}) + c02\ exp(-3r/a_{r2})\ exp(-3\tau/a_{t2})$ with the sill (variance) c_{01} = 0.70, the spatial range a_{r1} =0.15 degrees, the temporal range a_{t1} =1200 days, the sill c_{02} = 0.30, the spatial range a_{r2} =1.25 degrees, and the temporal range a_{t2} =6000 days. See appendix for more details on the covariance parameters.

To evaluate how the BME estimate for manganese is changing over space at a specific time, mean log-manganese concentrations were mapped in Figure 1. Manganese concentrations are the lowest in the western portion of the state and higher concentrations of manganese (exceeding the EPA secondary limit) are detected in the Piedmont and Coastal Plain regions of the state for all years.

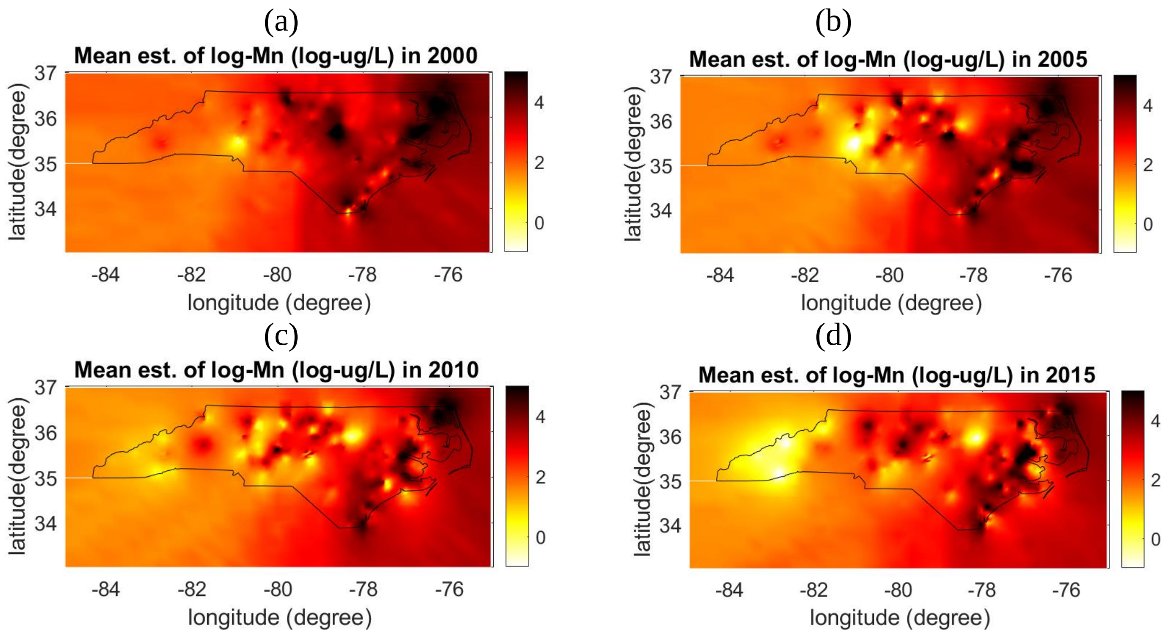


Figure 1: Mean estimates for manganese throughout North Carolina for years (a) 2000, (b) 2005, (c) 2010 and (d) 2015. Values greater than 4 log-ug/L (dark red to black) exceed the EPA secondary standard for manganese.

The geology and mobilization factors present in both the Piedmont and Coastal Plain support the changing concentrations seen in the manganese data. As this dataset shows variability in manganese concentrations, and variability is often seen in private wells compared to public water supplies, the data shown here can represent what we would see in private wells in the state.

Space Time Mapping of Infant Mortality

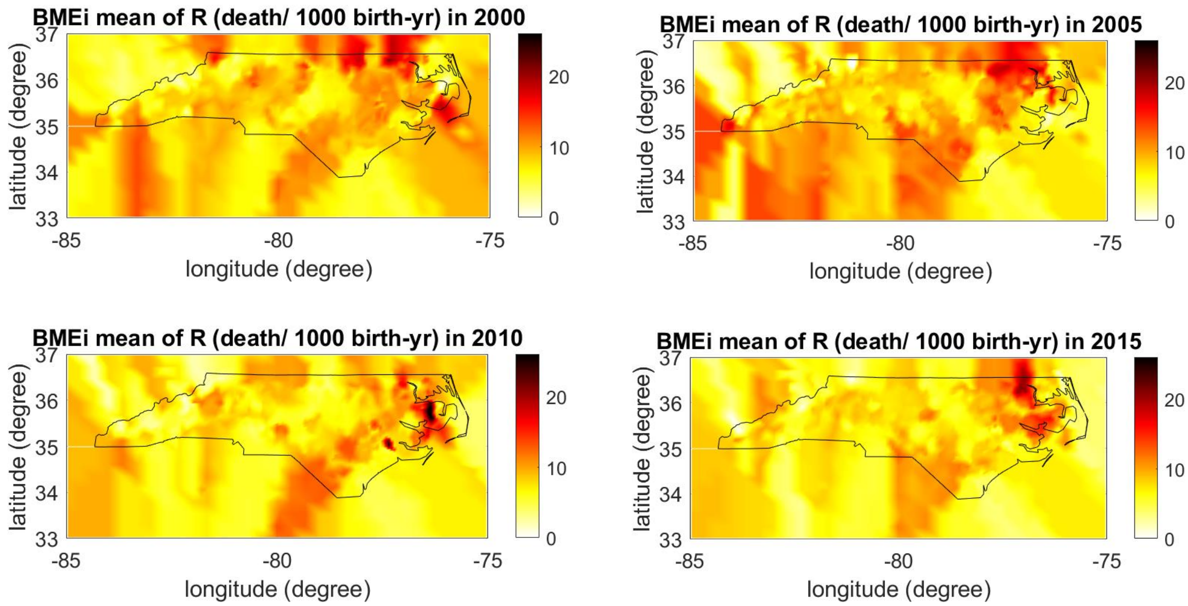
Infant Mortality rates in North Carolina have a bimodal distribution with a maximum of approximately 58 deaths/thousand live births and minimum of 0 deaths/thousand live births. See appendix for more details. One mode corresponds to counties with zero counts of infant deaths, where a small numbers problem exists. Counties that have a low number of live births can cause the infant mortality rate to be inflated or appear lower than the actual mortality count when given as a ratio. The mean for the infant mortality data set is approximately 8 deaths/thousand live births. The counties with higher infant mortality rates, such as Halifax, Caswell, and Robeson, do not have the highest corresponding population density per county in North Carolina. This indicates that a large population per county does not necessarily correlate to a higher infant mortality rate and influences such as manganese exposure may be contributing to the burden of disease. See appendix for color plots of infant mortality for select years.

The infant mortality covariance is modeled by the equation $cX(r,\tau)=c01\ exp(-3r/a_{r1})\ exp(-3\tau/a_{t1}) + c02\ exp(-3r/a_{r2})\ exp(-3\tau/a_{t2})$ and is represented by two exponential covariance structures with the sill (variance) c_{01} = 0.3, the spatial range, a_{r1} =0.2 degrees, the temporal range a_{t1} =5 years, the sill c_{02} = 0.1, the spatial range a_{r2} =1 degree, and the temporal range a_{t2} =10 years. See appendix for the covariance plot.

Three estimation methods were evaluated for modeling infant mortality data: hard kriging, BME interval, and Poisson. Kriging estimates revealed areas of North Carolina with high infant mortality rates, but due to the small numbers problem, the results did not provide a stable estimate. A county with a smaller population (number of live births per county per year) inflated the infant mortality rate, thus interval or Poisson methods are preferred. The three estimation methods were mapped for 4 select years and while the kriging method showed higher mortality rates, the interval and Poisson maps were more reliable and had greater smoothing. See appendix for plots of each estimation method for a given time period.

The cross-validation analysis revealed that both the interval method and Poisson methods had a reduced error compared to kriging. The BME alpha value was optimized to improve the cross-validation results by basing the estimation on an interval of 10. The North Carolina vital records state that county infant death values of less than 10 are to be considered unreliable and the interval method uses this value to smooth results and eliminate inflated mortality rates (North Carolina Center for Health Statistics, 2011). The interval method had the least error associated with the estimation method for the majority of the time period compared to kriging and Poisson methods, so for these reasons the interval method was ideal for infant mortality estimation. Cross validation results for the three estimation methods can be found in the appendix. The BME interval estimation plots are shown in Figure 2 for select years. Overall, high and low infant mortality rates are experienced throughout the state, but certain regions have repeatedly higher rates, such as in the Coastal Plain of North Carolina.

(a) (b)



(c) (d)

Figure 2: Mean estimates for infant mortality throughout North Carolina for years 2000 (a), 2005 (b), 2010 (c) and 2015 (d). The BME interval method is used for a fixed smoothing factor of 10 to reduce uncertainty due to the small numbers problem.

Infant Mortality Attributable to Manganese

We assume that the relationship between infant mortality Y and manganese concentration X is exponential, $Y=a \exp(bX)$, where a and b are parameters. Cherry et al reports that the odds ratio of infant mortality is 1.11 for an increase of 400 ug/L in manganese (Cherry et al, 2010). Since infant mortality is small, we also assume that the relative risk (RR) of infant mortality is also approximately equal to 1.11 for an increase of 400 ug/L in manganese, from which we calculate b = log(1.11)/400 ug/L = 0.000261 per ug/L. The attributable fraction (AF) corresponds to the fraction of incidence rate Y that is attributable to exposure X above background X_0. We use a background concentration of 0.002ug/L, and we obtain AF using AF=1-exp -bDX, where DX =X-X_0. The AF is multiplied by the infant mortality (Y) to yield the infant mortality that is attributable to manganese, $DY = Y(1\text{-}\exp -bDX)$, or, put simply, $DY = Y\,AF$. Maps of *AF* and infant mortality attributable to manganese are shown in Figure 3. Since *X*, *b* and *Y* are random variables, we map their median estimates, and we then map the median estimates of *AF* and *DY*. The median estimates for AF and delta Y above the adequate intake level of 3ug/L are shown in Figure 3.

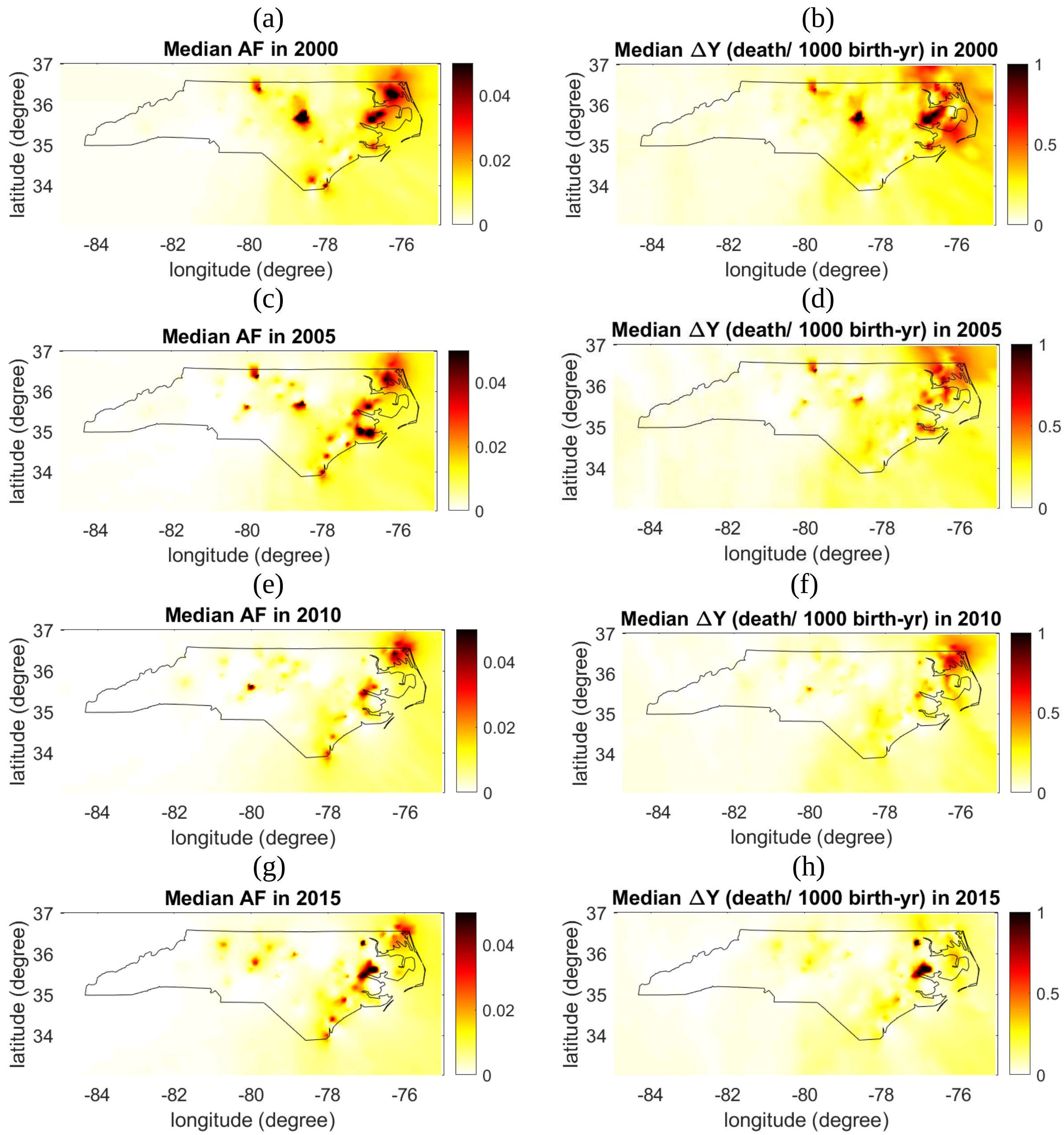


Figure 3: AF and Infant mortality attributable to manganese is shown above for years 2000 (a) and (b), 2005 (c) and (d), 2010 (e) and (f), and 2015 (g) and (h) respectively of the total 20-year sampling period. Both manganese concentrations and infant mortality rates are driving the overall number of deaths, with manganese impacting higher mortality in the northeastern coast.

Manganese concentrations are contributing to the overall number of infant deaths, with higher mortality rates in the northeastern coast near Herford, Washington and Beaufort counties.

The median AF and delta Y according to a background limit set to the limit of detection (0.002ug/L) is shown in the appendix. Not only does the Coastal Plain have higher manganese concentrations throughout, but the counties facing the largest impact of infant mortality are also those that have the highest minority population (Tippett, 2019).

Infant Population on Private Well

The number of live births per county were divided by the area of each county in square miles to obtain the infant population per square mile. The population on private well (according to the 1995 USGS report) was divided by the total population to obtain a ratio for each county's population on private well compared to the total population (Walters, 1997). The infant population per square mile was then multiplied by the proportion of people on private well to yield the number of infant live births per square mile on private well in NC. The histogram and plot are shown in Figure 4 for averaged numbers of live births on private well.

(a) (b)

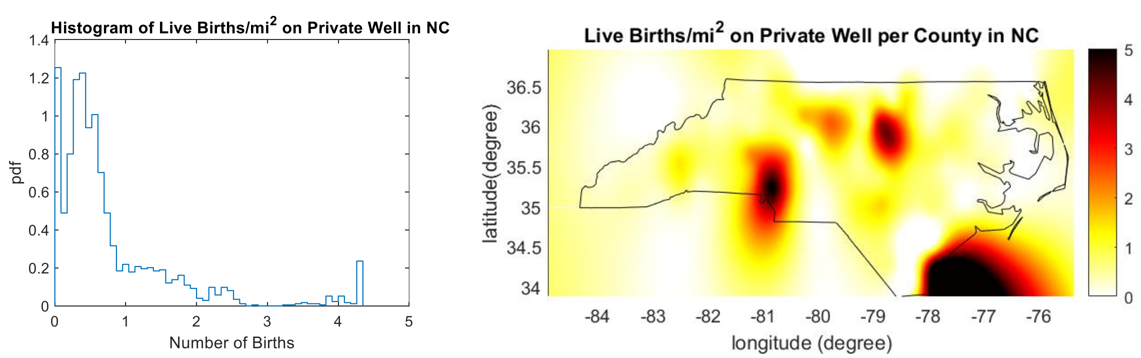
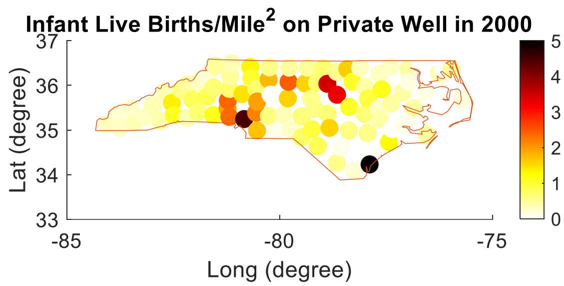


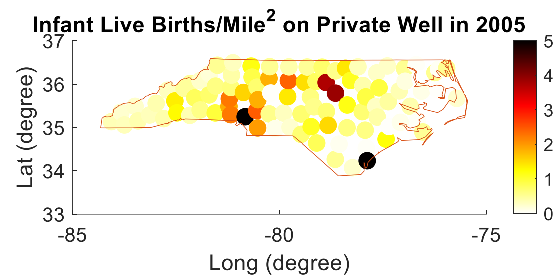
Figure 4: North Carolina Infant Births on Private Well (a) Histogram of live births per square mile on private well in NC. (b) Map of North Carolina infant births on private well

The above plots show the range of live births on private well, which vary across North Carolina. The highest number of live births per square mile on private well in NC is 6.6853, with the minimum being 0.0017. The infant population on private well is highest in the Piedmont and southeastern coast. The above plots show an average across the study period of live births from the years 2000 to 2019, with the proportion on private well factor obtained from the 1995 USGS report. Color plots for select years are shown in Figure 5.

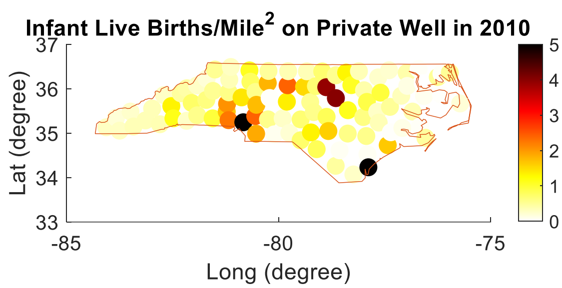
(a)



(b)



(c)



(d)

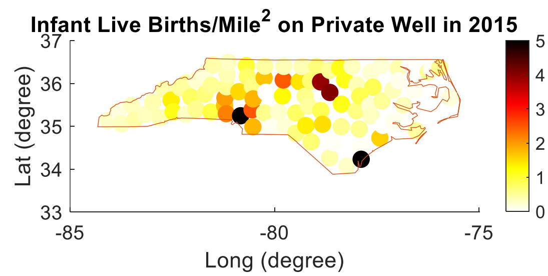
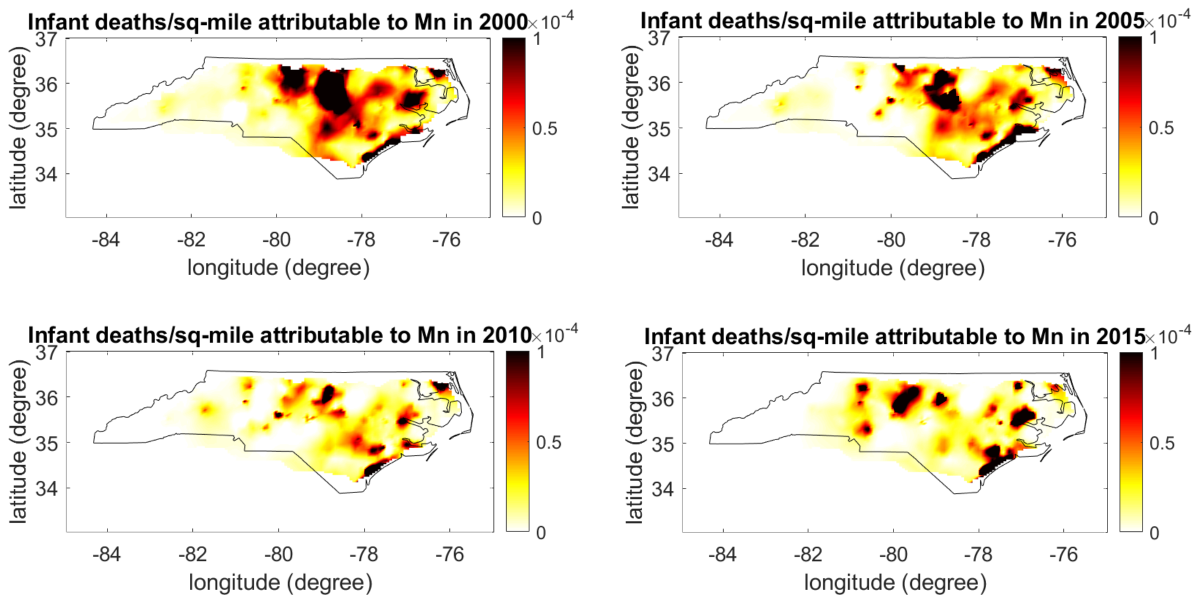


Figure 5. North Carolina statewide live births per square mile on private well for a) 2000, b) 2005, c) 2010, and d) 2015

Figure 5 depicts the distribution of live births on private well across North Carolina for given years. The number of infant births on private wells varies little between years, with consistently high births on private well for counties in the northeast and central portions of the state. The counties with high numbers of live births on private well are also areas that show high infant mortality rates. The high infant live births on private well in the northeast coincides with the area of high infant mortality attributable to manganese, supporting the findings that up to 1 infant death per thousand live births is attributable to groundwater manganese in the northeastern Coastal Plain. The number of infant deaths per square mile on private well was multiplied by the infant mortality attributable to manganese (ΔY) to determine the number of infant deaths per square mile on private well attributable to manganese, with plots shown in figure 6.

(a) (b)



(c) (d)

Figure 6. The number of infant deaths per square mile on private well attributable to manganese for a) 2000, b) 2005, c) 2010, and d) 2015

A greater number of infant deaths occurred in the northern Piedmont as well as the east coast and Carolina Coastal Plain. Approximately 1 in 10,000 infant deaths per square mile in NC is attributable to manganese for private well users, specifically in the Piedmont, eastern coastline and Carolina Coastal Plain and spanning majority of each region. Up to 3 in 10,000 infant deaths per square mile are attributable to manganese for private well users in the Piedmont and southeastern coast of North Carolina. This includes Pender, Onslow, Duplin, Beaufort, Hertford, Randolph, Guilford, Alamance, Orange, and Wake counties.

Disability-Adjusted Life-Years

Disability-adjusted life-years (DALYs) are used in assessing the burden of disease. DALYs are calculated by combining the years of life lost (YLL) with the years lived with the disability (YLD). *DALY= YLL + YLD*. YLL is calculated as the number of infant deaths multiplied by the life expectancy at the given year. YLD is calculated by multiplying the number of infant deaths (incident cases) by the disability weight and the average duration of illness (Gibson et al, 2013). A disability weight for manganese exposure is not present, however the disability weight for mild Parkinson's (which displays similar motor responses as excessive manganese exposure) is 0.01 and the disability weight for preterm birth (for which manganese exposure is a risk factor) is zero (Global Burden of Disease Collaborative Network, 2020). Considering similar conditions and their associated disability weight, an overall disability weight of zero was assigned to manganese exposure for calculating YLD. The YLD term is then equal to zero, resulting in DALY=YLL for manganese exposure. Table 1 shows the life expectancy, the total infant deaths, and the resulting DALY for each year in NC from 2000 through 2019. Life expectancy in North Carolina is lower compared to the national average for all years of the study period (Institute for Health Metrics and Evaluation, 2022). Approximately 1 to 2 infant deaths are attributable to manganese for private well users in North Carolina for each year, making a total of 26.15 infant deaths attributable to groundwater manganese from 2000 through 2019. The corresponding DALY total for the study period is 2013.1. A 2007 review found that the economic burden associated with preterm birth was $51,600 per birth (Beam et al, 2020). We can expect that the cost burden associated with infant mortality to be higher due to the greater number of years of life lost.

	Life Expectancy USA	Life Expectancy NC	Total Infant Deaths	DALY
2000	76.8	75.5	2.06	155.5
2001	76.9	75.9	2.42	183.5
2002	76.9	76.0	1.65	125.7
2003	77.1	76.1	1.72	130.6
2004	77.5	76.5	1.51	115.5
2005	77.5	76.5	1.35	103.2
2006	77.8	76.7	1.81	139.2
2007	78.1	76.9	1.24	95.3
2008	78.2	77.1	1.11	85.7
2009	78.6	77.5	0.96	74.1
2010	78.7	77.8	0.79	61.4
2011	78.8	77.9	0.91	70.7
2012	78.9	77.9	0.95	74.3
2013	78.9	78.1	1.00	77.8
2014	79.0	78.1	1.11	86.7
2015	78.8	77.9	1.06	82.3
2016	78.8	77.9	1.22	94.9
2017	78.7	77.8	1.22	95.0
2018	78.9	78.1	1.09	85.4
2019	79.1	78.2	0.98	76.5

Table 1: Life expectancy (USA and NC), total infant deaths, and resulting DALY for each year in NC. The DALY for each year is a product of the life expectancy in NC and total infant deaths.

The average dollar value per DALY averted is approximately $100,000 (Weaver et al, 2022). This makes the cost associated with infant mortality due to manganese for private well users approximately $6,100,000 to $18,300,000 in North Carolina for the year with the least DALY (2010) and the year with the most DALY (2001) respectively. The cost associated with the DALY total from 2000 to 2019 is $201,310,000.

Agricultural Worker Exposure to Groundwater Manganese

In the wastewater treatment process, manganese and other metals are filtered out and separated from liquid waste and constitute the portion of the waste that is biosolids, or sludge. The sludge is nutrient-dense and is required to meet certain federal requirements to be repurposed. Class A requirements call for the elimination of pathogens present in the sludge, but class B biosolids are not required to meet those same standards prior to disposal. Biosolids can be disposed of in landfills, incinerators, or via surface application. Land application is the most common disposal method for biosolids in North Carolina and agricultural sites require a permit prior to application. Biosolids can be beneficial to agriculture by reducing the need for additional fertilizer and improving soil structure (US EPA, 2016; Lovingood et al, 2018).

In 1982, NC had 192 permitted septage (solid waste material) land application sites. By the end of 2009, 260 permitted facilities could apply biosolids to 107,200 acres in North Carolina (Wagner et al, 2015). By mid-2015, biosolids could be applied to 4,146 permitted fields across 78,669 acres in North Carolina, with most permitted sites located in the eastern half of the state (Chiosso and Perkins, 2015). Differences in the number of permitted sites could be due to how the sites are categorized (class A or B), with the 2015 count showing all non-discharge permitted sites.

The NC Division of Water Quality in the North Carolina Department of Environmental and Natural Resources (DENR) issues and conducts reviews of permits for biosolid application. However, permit holders are responsible for submitting an annual report detailing adherence to nutrient management requirements and self-reporting violations. Monitoring rarely occurs, except as a result of filed complaints or when contamination in areas surrounding the application site is evident. (Wagner et al, 2015).

Sludge application permits are non-discharge and biosolids cannot be applied within 100 feet from wells and 50 feet from property lines (NC Department of Health and Human Services, 2005). Additional factors to mitigate contamination include requiring buffer zones to prevent runoff and avoiding application during rain events. However, violations are self-reported and biosolid application has previously coincided with months of higher precipitation even though application is to be withheld during precipitation. A study conducted in North Carolina and surrounding states surveyed community members living near land application sites that witnessed application violations (Lowman, 2013), showing that workers and the surrounding community are at risk for adverse effects of improperly applied biosolids.

Both workers and persons residing near biosolid application sites are at risk for exposure and may experience effects such as neurotoxicity, respiratory distress, skin and eye irritation, and gastrointestinal effects. Due to the adverse effects experienced from exposure, the public is restricted from accessing biosolid application sites for one year following biosolid application. However, this does not apply to workers. Agricultural workers are at higher risk of exposure to manganese from ingestion of contaminated groundwater due to biosolid application (NC Department of Health and Human Services, 2005). Migrant workers and their families are especially vulnerable to exposure as they live and work in the same conditions yet experience fewer worker protections (Porru and Baldo, 2022). The histograms and maps of total hired farm workers and migrant agricultural worker population in North Carolina in 2017 are shown in Figure 7 with data obtained from the 2017 agricultural census (USDA, 2017). Total farm worker population per county is high in the Coastal Plain, northwest, and southwest portions of the state. Higher populations of migrant workers were hired for agricultural labor in the Coastal Plain region of North Carolina. The presence of high geogenic manganese in groundwater in this region may result in higher overall exposure for agricultural workers, their families, and nearby residents who are also exposed to manganese and other contaminants entering groundwater supplies via biosolid runoff and infiltration.

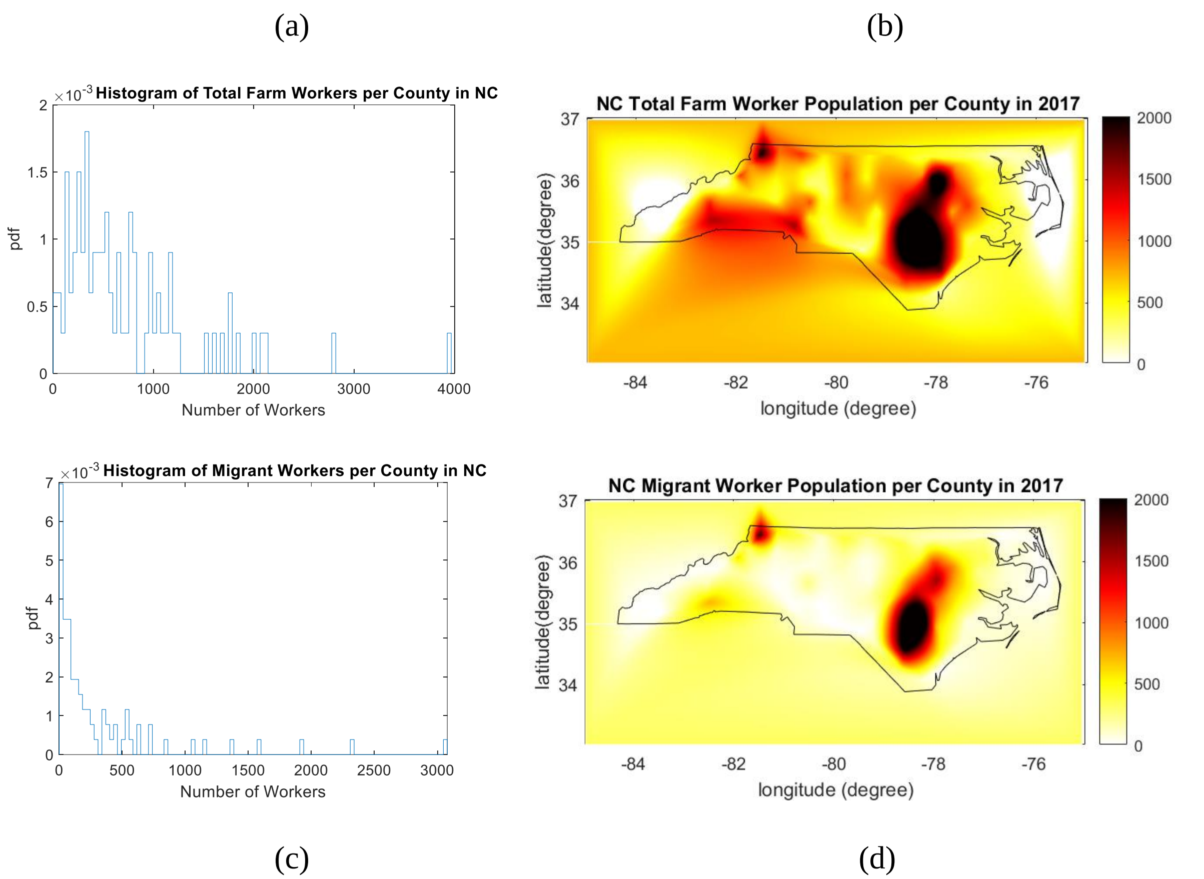


Figure 7: North Carolina agricultural worker population in 2017. (a) Histogram of total hired farm workers per county population in 2017. A total of 4571 farm laborers were hired in NC in 2017. (b) Map of total farm worker population per county in 2017 (c) Histogram of migrant workers per county population in 2017. (d) Map of migrant worker population per county in 2017. Counts range from 0 to 3466 workers, with some counties not disclosing and most migrant worker populations concentrated in the Coastal Plain.

CHAPTER 4: RECOMMENDATIONS AND LIMITATIONS

Manganese is present throughout North Carolina and high concentrations can be responsible for to up to 1 infant death per ten thousand live births for private well users per square mile. While the manganese data utilized from USGS is for monitoring wells, we can infer that private wells will yield similar results, as supported by the variability in manganese concentrations seen in the dataset. Private well users, particularly those with infants less than a year of age, need to take precautions to ensure that they are not exceeding advisory levels for manganese. Due to manganese absorption from dietary intake, any manganese ingested via drinking water is unnecessary and may be detrimental depending on concentration. Wells with fewer than 25 households utilizing it are unregulated (CDC, 2014) and point-of-use or point-of-entry filtration methods can be used to remove manganese at the household level. Manganese removal systems can range in price from a few hundred dollars to over a thousand, with cost varying by the size of the system and the number and concentration of contaminants removed. A low-entry household filtration system for iron and manganese can cost just under $500 initially, but upkeep will include replacement filters for added cost over time (Fitzgerald, 2023).

The cost of having a well tested for manganese and other contaminants can be a barrier for many individuals and the overall cost of well testing varies on a county basis. Wake County offers and recommends a First Timer's Package, which includes a full panel of testing for coliform bacteria, full inorganic panel, volatile organic compounds, and pesticides for a rate of $175 (plus trip fee). Repeat testing is recommended every five years, though additional testing is advised if a high concentration of a contaminant is present. A Single Inorganic Analyte can be tested for $20 (plus a possible added trip fee of an unlisted cost). Wake County does offer financial assistance for well testing based on income, and will test for common contaminants in private wells for $73 for families at or below the poverty line. Wake County charges $182.50 for testing of common contaminants for households at 2.5 times the federal poverty level (Wake County, 2023). As manganese is often omitted from the general panel testing, the additional single analyte fee may be incurred for specific manganese testing in certain counties. Not all counties offer financial assistance for private well testing and combined analyte testing packages can vary by what is included. The income-based financial assistance for well testing in Wake County is a model that can be used as a primary prevention method to incentivize testing and reduce the associated cost burden. Socioeconomic status and ethnicity are risk factors for infant mortality (Spangler and Spangler, 2009), and while these confounders were not investigated here, they can be considered in intervention methods employed. Additional intervention strategies to reduce manganese exposure can be through providing subsidies on water treatment for eligible households with test results showing high concentrations of manganese. As high manganese concentrations most affect infants in the form of acute toxicity, a preventative measure could be offering free point-of-use test kits at pregnancy care centers in counties with high infant mortality rates and agricultural worker populations while advising guardians to avoid using infant formulas that contain manganese.

APPENDIX 1: MANGANESE DATA ACQUISITION

Manganese data was obtained via the USGS water quality data portal. USGS monitoring wells are located across the United States. Monitoring wells vary in depth and location in North Carolina. Field sampling monitoring data results were filtered by parameters including date range, characteristic group (inorganic minor metals), site ID, site type (well and groundwater), and location (USGS Water-Quality Data for North Carolina, 2023).

APPENDIX 2: PREVIOUS MANGANESE STUDIES IN NORTH CAROLINA

Figure A2 shows previous manganese maps for studies of North Carolina. The Reid study of statewide concentrations of manganese (Reid, 1993) was used in future manganese studies in North Carolina like the Spangler and Spangler study of manganese and infant mortality (Spangler and Spangler, 2009) and a study by Polizzotto where manganese concentrations were mapped over the soil structure in NC (Polizzotto et al., 2015) shown in Figure A2a. The Reid study is not as relevant due to the time passed since sampling events occurred. The study was also conducted in respect to uranium and the assessment parameters for uranium may not align with that needed for manganese groundwater monitoring. The soil structure overlay in Figure A2a shows that high concentrations of manganese were previously found in the Carolina Slate Belt in the Piedmont and in the Coastal Plain in the eastern portion of the state (Polizzotto et al., 2015). This indicates that soil structure and geology may play a role in mobilization and high concentrations of manganese. A study by Johnson used kriging to map manganese concentrations in Buncombe County, NC shown in Figure A2b (Johnson et al, 2018) but a statewide geostatistical assessment of manganese had not been conducted.

(a) (b)

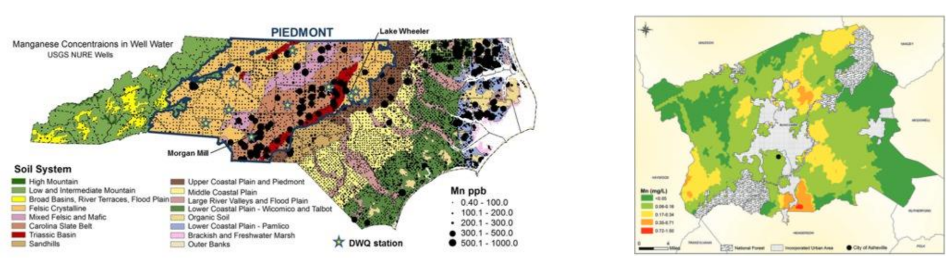


Figure A2. a) Map of historical manganese data with soil structure b) Map of manganese using kriging for Buncombe County, NC.

APPENDIX 3: MANGANESE EXPLORATORY DATA ANALYSIS

Figure A3 shows histogram plots for raw (A3a) and log (A3b) manganese over the 20-year study period. Manganese data is log-transformed for a normal distribution with vertical lines indicating the EPA secondary standard for manganese (yellow line), EPA adverse effect limit (magenta line), and WHO limit (red line). Some concentrations exceed all three limits, with most concentrations centered around the EPA secondary standard.

(a) (b)

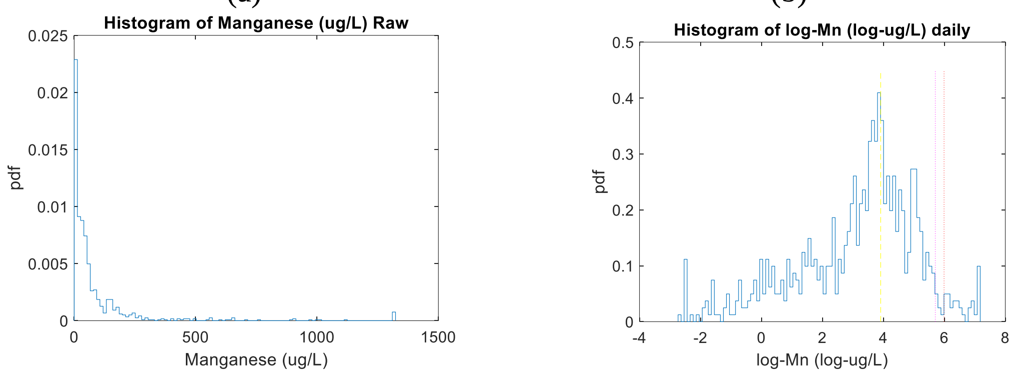


Figure A3. Histogram for manganese. a) Raw manganese data is skewed to the right, with concentrations exceeding 1000ug/L. b) Manganese data is log-transformed to normalize the distribution and concentrations were aggregated daily.

APPENDIX 4: TIME TRENDS AND SERIES FOR MANGANESE DATA

Manganese monitoring sites are located throughout the state, though repeat sampling did not occur at each station. The daily time trend in Figure A4a and associated mean and standard deviations in A4b show that concentrations fluctuate and may experience localized variability. Time series were created for six randomly selected stations (Figure A4c). Station 434 had the greatest number of sampling events, with most sampling occurring around the year 2016. Color plots for manganese for years 2000, 2005, and 2010 are shown in Figure A4d, A4e, and A4f respectively. Higher concentrations appear to occur near the east coast on the Coastal Plain (orange to red) with lower concentrations occurring further west (blue).

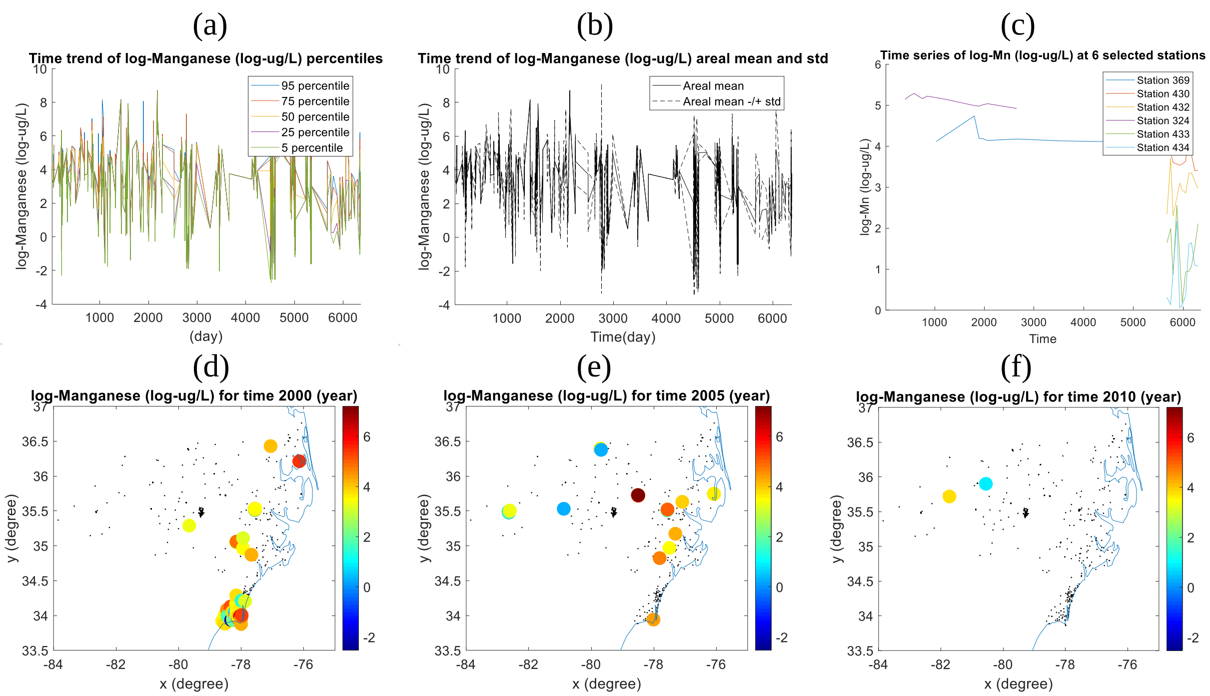


Figure A4. a) Time trend of manganese percentiles b) Areal mean and standard deviation and c) Time series at 6 selected stations based on a daily time aggregation for concentration. Color plots of manganese concentrations aggregated yearly for year d) 2000, e) 2005, and f) 2010 with values in the Coastal Plain exceeding the EPA secondary standard and the health advisory level.

APPENDIX 5: MANGANESE COVARIANCE ANALYSIS

Two covariance structures were evaluated for manganese data, a long structure with the model fitting the experimental data points and a short structure that considers how experimental data noise impacts the model by including a nugget effect. The long covariance structure is represented by two exponential covariance structures with the sill (variance) $c_{01} = 0.25$ (log ug/L)^2, the spatial range, a_{r1} =0.50 degrees, the temporal range a_{t1} =6000 days, the sill $c_{02} = 0.30$, the spatial range a_{r2} =1.25 degrees, and the temporal range a_{t2} =6000 days (Figure A5a). The short covariance structure is represented by two exponential covariance structures with the sill (variance) $c_{01} = 0.70$, the spatial range, a_{r1} =0.15 degrees, the temporal range a_{t1} =1200 days, the sill $c_{02} = 0.30$, the spatial range a_{r2} =1.25 degrees, and the temporal range a_{t2} =6000 days (Figure A5b). The short covariance model structure fit the experimental covariance while extending the spatial range over which the data is autocorrelated, thus the short model was utilized in further analysis of the manganese data. Covariance was also modeled for manganese data with a daily, monthly, and yearly time aggregation. The daily aggregation revealed the most autocorrelation, so further analysis proceeded using the daily aggregated data.

(a) (b)

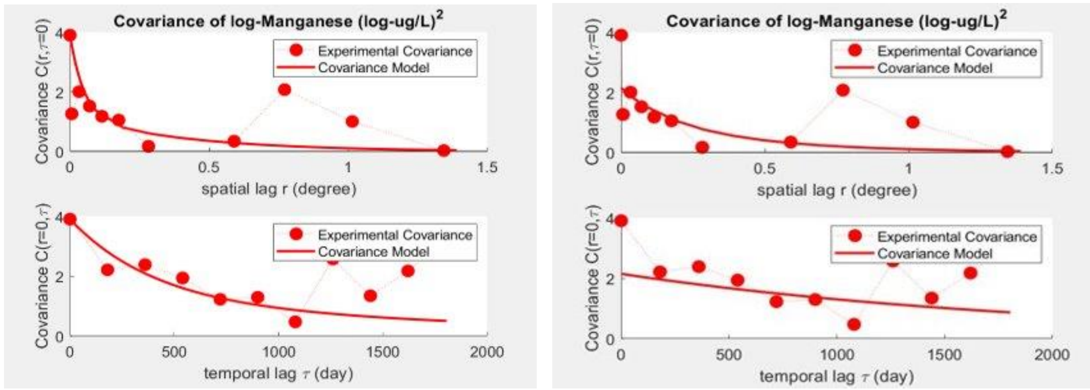


Figure A5. Covariance plots for manganese with a) long covariance structure and b) short covariance structure, with the short covariance structure autocorrelated over space and time.

APPENDIX 6: BME ESTIMATION FOR MANGANESE

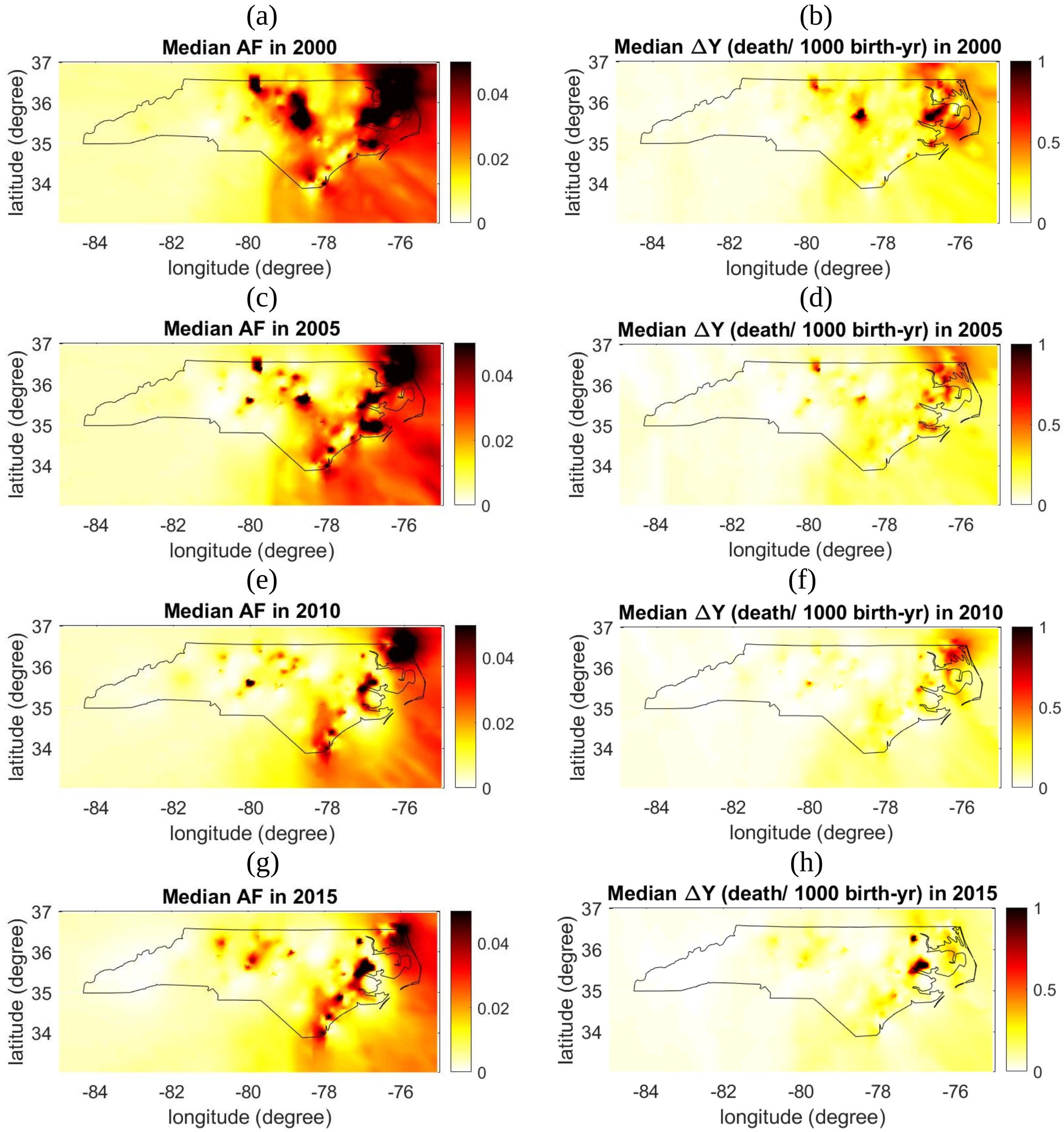


Figure A6: AF and Infant mortality attributable to manganese is shown above for years 2000 (a) and (b), 2005 (c) and (d), 2010 (e) and (f), and 2015 (g) and (h) respectively of the total 20-year sampling period. Both manganese concentrations and infant mortality rates are driving the overall number of deaths, with manganese impacting higher mortality in the northeastern coast.

APPENDIX 7: EXPLORATORY ANALYSIS FOR INFANT MORTALITY

Figure A7 shows histogram and time series plots for infant mortality over the 20-year study period. The data has a bimodal distribution. One mode corresponds to counties with zero counts of infant mortality, where a small number problem exists. The time series shows that variability exists between counties experiencing high infant mortality rates, with high rates not occurring at the same time for all counties.

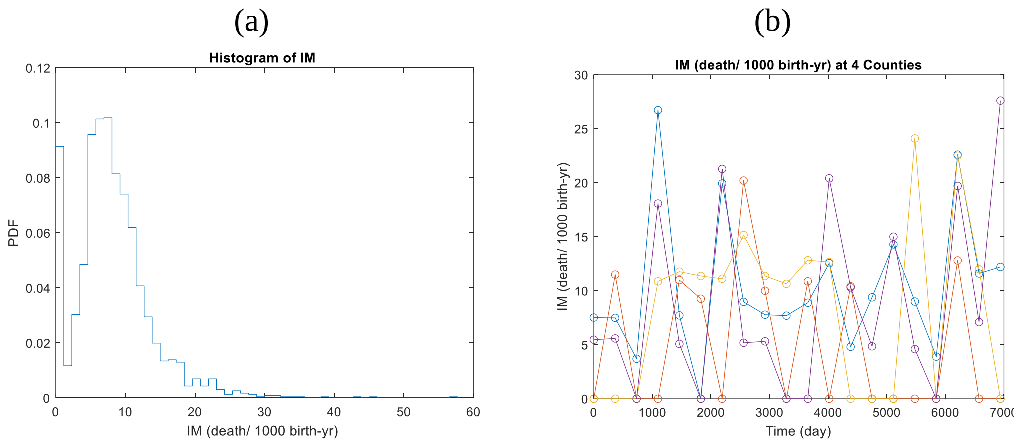


Figure A7. Infant Mortality a) Histogram b) Time Series. Infant mortality is measured yearly by county. The average number of infant deaths per thousand live births per county is 8, though counts less than 10 are to be considered unstable according to the NC state vital statistics records.

APPENDIX 8: COLOR PLOTS FOR INFANT MORTALITY

Infant mortality has generally decreased overall from 2000 to 2019 in North Carolina. The North Carolina statewide infant mortality rate in 2000 was 8.6 deaths/thousand live births, 8.8 deaths per thousand live births in 2005, 7.0 deaths per thousand live births in 2010, 7.3 deaths per thousand live births in 2015, and 6.8 deaths per thousand live births in 2019. Color plots of infant mortality rates are shown in Figure A8 for years 2000 (a), 2005 (b), 2010 (c), and 2015 (d).

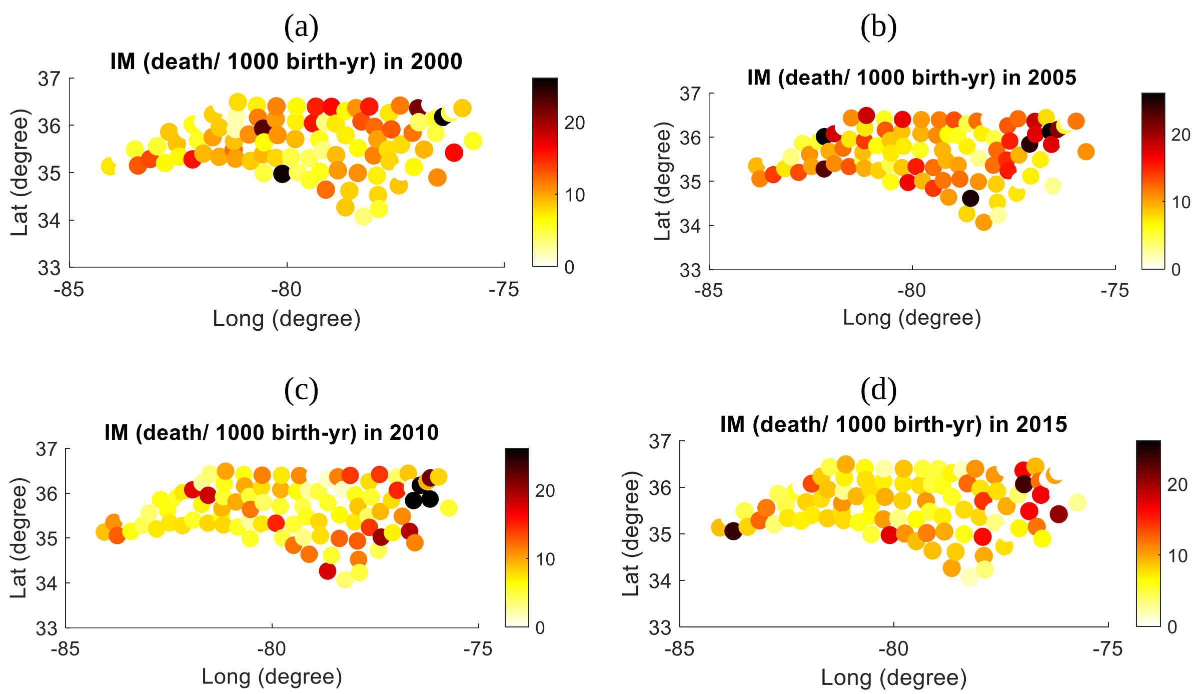


Figure A8. North Carolina statewide infant mortality rates for a) 2000, b) 2005, c) 2010, and d) 2015. Infant mortality rates are consistently highest in the northeast with rates above 20 infant deaths/thousand live births.

APPENDIX 9: COVARIANCE MODEL FOR INFANT MORTALITY

Infant mortality covariance is modeled using two exponential structures. The spatial and temporal components are shown in Figure A9 with the experimental covariance and modeled covariance.

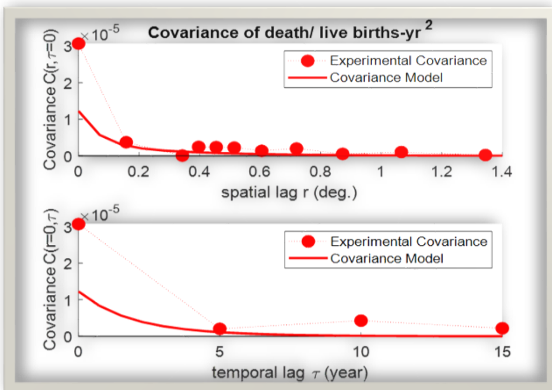


Figure A9. Spatial and temporal components of the covariance model with experimental covariance for infant mortality rates in North Carolina from 2000 to 2019.

APPENDIX 10: ESTIMATION METHODS AND CROSS VALIDATION RESULTS FOR INFANT MORTALITY

Hard kriging (A10a), BME interval (A10b), and Poisson (A10c) estimation methods are shown in Figure A10 for infant mortality rates in North Carolina in the year 2015. The kriging method shows greater areas of high infant mortality rates, but this is due to the small numbers problem and counties with small populations creating potentially inflated risk estimations. The cross-validation (Figure A10d and A10e) shows that Poisson and interval method produce similar results, which is also seen in the maps of mean estimates. Both Poisson and interval methods reduce the noise associated with the data and have advantages over the kriging method. The interval method is ideal for this study of infant mortality rates in North Carolina by providing an adjustable interval for data smoothing.

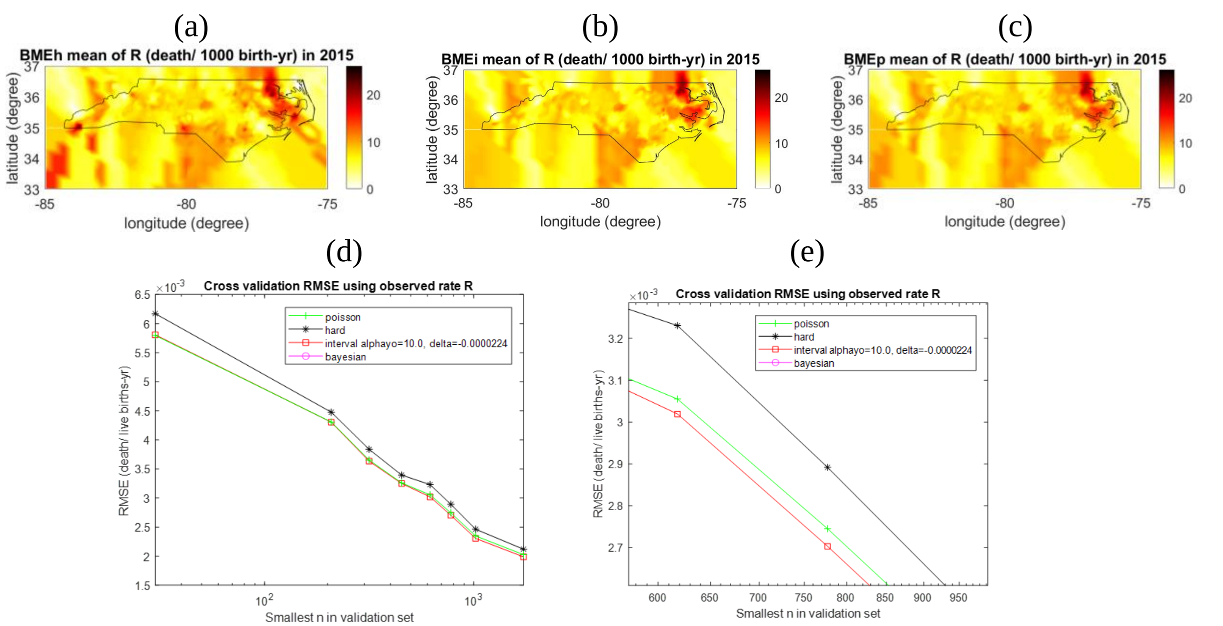


Figure A10: Mean estimates for infant mortality throughout North Carolina in 2015 using estimation method a) hard kriging b) BME interval c) Poisson. d) Cross validation results show that the BME interval method is furthest from the kriging estimation more often than the Poisson method. The distinction is visible in (e) the zoomed in cross validation results.

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