# Characterizing the climate risks, social vulnerability, and neonatal transport burden on neonatal intensive care units in the United States under 2°C and 50cm sea level rise

Mathida Ngamsiripol

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Committee:
Joan A. Casey
Joel D. Kaufman
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## ABSTRACT

# Characterizing the climate risks, social vulnerability, and neonatal transport burden on neonatal intensive care units in the United States under 2°C and 50cm sea level rise

Mathida Ngamsiripol

Chair of the supervisory committee:
Joan A. Casey
Department of Environmental and Occupational Health Sciences, Department of Epidemiology

### Introduction

The impacts of climate change are becoming more significant, leading to more extreme weather events across the United States, including extreme temperatures, flooding, and wildfires. Climate disasters can threaten healthcare access and induce hospital shut-downs, forcing relocation of patients, with the potential for serious health consequences for vulnerable populations like neonates in neonatal intensive care units (NICUs). Socially vulnerable populations also face a disproportionate burden of climate disasters and more limited healthcare access. Understanding which NICUs face risks from climate hazards and transport distances to other NICUs could enhance preparedness and response. This research aims to characterize the spatial distribution of climate risk, the relationship between social vulnerability and climate risk, and areas with a dual high transport burden per neonate and high climate risk.

### Methods

Four publicly available datasets were used to conduct descriptive analyses identifying NICUs located in census tracts experiencing climate risks. 2023 NICU locations came from the Neonatology Solutions Directory. Climate risks under 2°C warming and 50cm sea level rise (SLR) from the US Environmental

Protection Agency (EPA) were z-transformed and summed to create a total climate risk variable, and a linear regression assessed the association between Centers for Disease Control and Prevention's (CDC) Social Vulnerability Index (SVI) and total climate risk, controlling for non-time-varying relationships. Such non-time-varying relationships include the state and geographic jurisdictional state. To model the scenario of a climate hazard resulting in a full NICU shutdown, Euclidean transport distances were calculated from longitude and latitude coordinates between NICUs of the same level or higher. Average transport distances per neonate were calculated for three bed capacity scenarios: 100% capacity at the sending NICU and 25, 50, and 75% capacity at the receiving NICU. A simulation was applied to reallocate neonates starting with the closest NICU available that was the same level or higher. Unadjusted linear regression was conducted between climate risk and average transport distance per neonate to identify NICUs with high climate risk and long transport distances. All analyses were conducted in R v2024.12.1+563.

## Results

The analysis included 1,392 NICUs operating in 2023. The US South is projected to have the highest total climate risk; 12 NICUs are projected to have elevated climate risk as a result of risk for property inundation from coastal flooding. The 12 NICUs located in states with elevated climate risk include Texas, Florida, Maine, Louisiana, California, Virginia, North Carolina, South Carolina, and Georgia. There was no association between SVI and total climate risk. There were associations between total climate risk and average transport distance per neonate. For example, using the 25% capacity scenario a 1-unit increase in total climate risk was associated with 1.88 additional miles (95%: 0.36, 3.39) of transport distance, with the relationship strengthening with higher receiving NICU bed capacity scenarios (50%, and 75%). The top 10 NICUs with metrics in the top quartile for total climate risk and transport distances were identified, with 8 NICUs requiring neonates be transported >300 miles, on average.

## Conclusion

Careful planning and tailored disaster mitigation for NICUs are critical, especially for NICUs with high climate risk and transport burden.

## Introduction

The impacts of climate change are becoming more significant, leading to more extreme weather events across the majority of the United States.[1] Extreme temperatures, flooding, and wildfires are the primary climate risks to population health in the U.S.[2] Climate disasters in the past have led to major health system disruptions, like power outages, damaged infrastructure, disruption of transportation routes, evacuation of hospitals, and relocation of existing patients. Such disruption is especially problematic for critical care settings, like neonatal intensive care units (NICUs), which serve premature and sick neonates.[3] In 2012, Hurricane Sandy caused New York City Bellevue Hospital to shut down and move all patients elsewhere, disrupting 500,000 prospective patients that year and forcing them to travel further to access critical care.[3] Among those in need of relocation at New York City Bellevue Hospital during Hurricane Sandy were 21 neonates in the NICU.[4]

NICUs are divisions within a hospital that provide specialized intensive care for infants born preterm, critically ill, or who have complications during birth.[5] NICUs are categorized into four levels (I-IV), where Level I NICUs provide care for stable, healthy infants, and Level II NICUs specialize in the care of sick or premature newborns.[5] Level III NICUs care for more critically ill infants, and Level IV NICUs offer advanced care for newborns requiring major surgery.[5] NICUs are highly technology-dependent environments that provide critical care for sick or premature infants. This reliance on advanced medical technologies means they are particularly vulnerable to disruptions caused by climate-related disasters, which can severely compromise their ability to function and endanger neonatal health outcomes.[6] Past climate disasters have also led to an increased number of admissions due to extreme temperatures.[7] Therefore, it is critical that NICUs are identified according to climate risk so that stakeholders can prepare and respond to impacts from climate hazards.

Disparities also persist in NICU access.[6] Patients coming from higher SVI are more likely to self-identify as Black.[8] Those requiring NICU admission live in areas with lower per capita income and a higher number of mobile homes; while moderate SVI is also associated with increased neonatal morbidity.[9] Many NICUs are concentrated in urban centers, creating access barriers for rural populations who must travel long distances for care.[10] These existing challenges are likely to be exacerbated by climate change, which may further disrupt transportation and healthcare infrastructure.[11] As climate disasters occur more frequently, NICUs can be temporarily closed or relocated, requiring transportation of neonates to the next nearest facility.[11] In September 2020, wildfires came very close to a hospital containing a NICU, forcing a specialized evacuation of critically ill neonates.[10] Further, in 2022, Hurricane Ian in the West Coast of Florida forced the evacuation of neonates from the third floor of Golisano Children's Hospital in Fort Myers.[12] While there were generators to compensate for the power outage, they lacked access to water.

Despite such documented events, there is minimal literature identifying the NICUs located in high climate risk regions and describing their neonatal transport burden. When a NICU shuts down, a large proportion of neonates will require transport to an equivalent level NICU. Understanding the landscape of climate risks at US NICUs and transport distances to the closest NICUs is critical for planning and response purposes. In addition, using this evidence can project potential health issues among maternal and neonatal populations, relocation burden during a shutdown, and have long-term systemic implications in advancing climate resilience planning. This research aims to characterize future climate risks at present-day US NICUs, characterize their accompanying social vulnerability, and identify transport distances between NICUs in the event of a climate-induced NICU closure.

## Methods

Study design and Setting: This study included a characterization of NICUs in high climate risk areas, and an analysis on: 1) social vulnerability and climate risk and, 2) climate risk and average transport distance required per neonate. The data comes from four publicly available sources in the United States.

NICU locations and characteristics: The 2023 Neonatology Solutions NICU Directory included data on 1,399 NICUs, including geocoded addresses, number of beds, and level (level II, III, and IV) in the US (excluding Puerto Rico and US Virgin Islands).[13] Additional details included practice type, job openings, community characteristics, key physician, neonatal nurse practitioners, and nursing leaders, but are not included in this analysis. The directory information was gathered from publicly accessible hospital and NICU websites, direct referrals from medical directors, recruitment firms specializing in neonatal care, and community contributions for real-time updates.[13]

Climate Risk: The US Environmental Protection Agency (EPA) Social Vulnerability Report: *Climate Change and Social Vulnerability in the United States* includes projected climate risks under 2°C and 50cm SLR at the census tract and block group level in four domains—extreme temperatures, coastal flooding, inland flooding, and air quality.[14] Data excludes Hawaii, Alaska, Puerto Rico, and the U.S. Virgin Islands. The five indicators used in this study address health, labor, and property risks linked to census tracts (non-flood data) and block groups (flood data) based on US census 2010 data (**Table 1**).

The analysis does not directly measure risk of NICU closures. Instead, it relies on human impacts, such as labor hours lost and traffic delays due to extreme temperatures, which does not fully capture the complexity of NICU disruptions, but serves as proxies for NICU-related climate disasters.

**Table 1.** US Environmental Protection Agency Climate Scenarios. Models are projected under 2°C and 50cm SLR

| **Climate Scenario** | **Indicator** | **Spatial Level** |
|---|---|---|
| Extreme temperature | Labor hours lost | Census tract |
| Coastal flooding | Permanent inundation and exclusion from protection by insurance; | Census block group |
| | Precipitation induced traffic delays on roads | Census tract |

| | | |
|---|---|---|
| Inland flooding | Annual damage ratio (annual ratio of property damage to total property value in floodplain) | Census block group |
| Air quality | $PM_{2.5}$, Incidence of asthma in children 0-17 yrs | Census tract |

To estimate the impact of extreme temperatures on labor hours lost for climate-exposed workers at the census tract level, the report used Neidell et al.'s approach, estimating the change in the number of days with temperatures over 90℉ (degree-days) for each census tract, under a global warming increase of 2℃.[14,15] They used American Time Use Survey (ATUS) from 2003-2018 and historical weather data to apply a simulation to future impact on high-risk workers including sectors like agriculture, construction, and manufacturing.[14,15]

To estimate the impact of traffic delays due to high-tide flooding at the census tract level, the report followed the methods proposed by Fant et al., identifying coastal roads that are vulnerable to damage from high-tide flooding under 50cm SLR.[16]

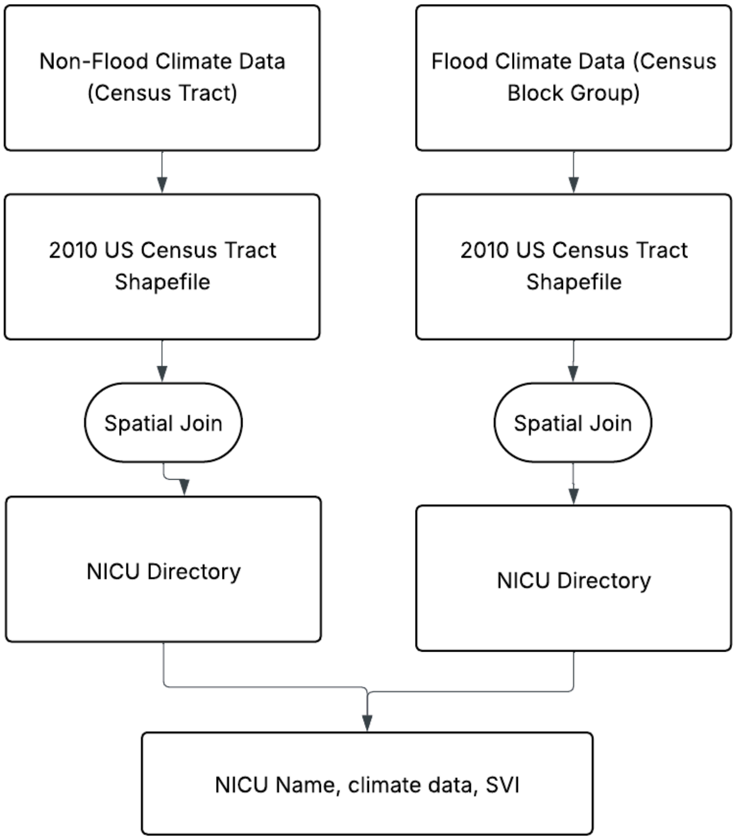
To estimate the impact of coastal flooding on permanent inundation on properties that are excluded from insurance protection at the census block group level, they used the National Coastal Property Model (NCPM) to identify coastal areas that are projected to be at risk of permanent inundation from SLR.[14]

To estimate the impact of inland flooding on annual damage of property to total property value in the floodplain at the block group level, the report projected changes in the frequency of flooding events with an average return period of two to 500 years associated with global warming.[14] They used First Street Foundation's flooding risk data to estimate baseline average flooding damages at the building level. These projections were scaled by building baseline damages according to the projected change in frequency of flooding events at the block group level.[14]

To estimate the impact of air quality $PM_{2.5}$ on incidence of asthma in children 0-17 years old at the tract level, the report followed Fann et al.'s estimations to project changes in $PM_{2.5}$ concentrations under 2 and 4℃ of warming.[17] Fann et al. used two global climate models, Community Earth System Model (CESM) and Coupled Model version 3 (CM3) to simulate conditions from 2025-2100 under a high-warming scenario. They combined these models with the Community Multiscale Air Quality (CMAQ) model to estimate $PM_{2.5}$ and $O_3$ concentrations. The projected changes in these concentrations were then used to estimate human health impacts. These five indicators were z-transformed and summed for a cumulative climate risk at the national level and at the NICU level. The climate risks proxy the overall risk of climate hazards affecting the NICUs located in these census tracts of block groups.

Parallel geographic joins were conducted at census tract and block group levels to create two separate datasets, each merged with SVI overall composite scores and NICUs separately. Then, the two datasets were merged by hospital name and address of the NICU into one final data set. The map creation and spatial calculations were conducted using the EPSG:5070 projected coordinate system (**Figure 1**).

**Figure 1.** Data Linkage Diagram for Multilevel Spatial Integration



85.93% of census tracts (n = 72,539) were potentially at risk of extreme temperatures and air pollution. All were included in analyses. There were 15,936 out of 239,780 (6.65%) block groups potentially at risk of coastal flooding in the United States because coastal flooding impacts measure only coastal areas. There were 147,398 (61.47%) block groups potentially at risk of inland flooding. The missingness is due to significant gaps in rural and less developed regions to obtain information from Federal Emergency Management Agency's (FEMA) Flood Insurance Rate Maps for inland flooding data.[14] As a result, data were filtered to only those block groups with >0 coastal and inland flooding impacts. The top tertile of flood risk was calculated based on these filtered data. Census tracts were derived from block group identifiers by truncating the final digit, as each block group is nested within a single census tract. Climate indicators were z-transformed and summed for each census tract or block group to create a total risk category, indicating total climate risk for each tract.

## 2010 US Census Data

US polygon shapefiles from 2010 census data were used to map NICU point coordinates to census tracts.

## Social Vulnerability Index

Overall composite scores from the 2010 social vulnerability data come from the Social Vulnerability Index (SVI) from the Centers for Disease Control and Prevention (CDC).[18] These composite scores reflect vulnerability across 15 variables. For each variable, a percentile rank is calculated for each census tract and the variables are then grouped into four themes: socioeconomic status, household characteristics, racial and ethnic minority status, and housing type and transportation. For each theme, the percentile rankings are summed to give a score of the variables within that theme. An overall SVI composite score is calculated by summing all 15 variable percentiles. This total is then ranked on a percentile scale from 0 to 1 across all census tracts. The overall SVI composite score was used in this analysis. The association between the SVI overall composite score and the z-transformed total climate risk scores were estimated using regression models with state fixed effects.

## Geospatial analysis

To compute average distances transported per neonate, all sending NICUs were assumed to be at full capacity. Receiving NICUs were assumed at 25%, 50%, and 75% capacity in three scenarios. Transport distances were weighted by capacities of the receiving NICU and calculated Euclidean distances in the following manner:

- A list of all potential transport distances were computed from each sending hospital to all eligible receiving hospitals with an equivalent or higher care level
- These transport distances were sorted by ascending distance

- A process was simulated so that neonates were first transferred to receiving NICUs down the sorted list (transferred to closest NICU first), until all the neonates of the affected NICU were reallocated to receiving NICUs. This step was repeated for receiving NICUs at 25%, 50%, and 75% capacity.
- A running total of distance transported (beds * distance) and total neonates (beds) reallocated were tracked to calculate the weighted average distance per neonate for each capacity scenario.

The association between z-transformed total climate risk score and average transport distance per neonate was estimated using an unadjusted linear regression model. Alaska and Hawaii were excluded in the regression analysis between climate risk and average transport distance per neonate because there was no climate data available; however, NICUs in those states were included in other analyses unrelated to climate risk.

All analyses were conducted in R version 2024.21.1+563. IRB approval was not required as the research involved analysis of publicly available datasets without personally identifiable information.

## Results

In 2023, there were 1,399 NICUs in the US, 7 of which were in Hawaii or Alaska. The median (IQR) number of NICUs of any level per state was 19 (22). Among 1,399 NICUs, the median number of beds available was 16. There were 559 (40.2%) Level II NICUs, 697 (49.8%) Level III NICUs , and 140 (10.0%) Level IV NICUs (**Table 2**). 140 (10.0%) NICUs were Level IV (highest acuity). The median number of beds among Level IV NICUs was 57. The Level IV NICUs with at least 50 beds were concentrated in urban areas, and Oregon, Idaho, Wyoming, Montana, and North and South Dakota had either one or none. In the Mountain, Northern Plain, and Central Plain states, there were either zero or one level IV NICUs available to the whole state. Nevada, Utah, Kansas, Nebraska, and South Dakota had Level III NICUs that are located on the border of the state. The highest level of NICU available in Alaska and Hawaii were Level III. There are no level II NICUs in Oregon or North and South Dakota.

**Table 2.** Summary statistics (Median (IQR: Q1-Q3)) for 1,399 NICU locations, stratified by level of care, including climate indicators from the EPA Social Vulnerability Report under 2°C and 50cm SLR, and overall composite score from the 2010 Social Vulnerability Index (SVI).[1]

| | **Overall** | **Level II** | **Level III** | **Level IV** |
|---|---|---|---|---|
| **NICU Characteristics** | | | | |
| Bed count | 16 (9-32) | 8 (6-12) | 24 (16-36) | 57 (42-75) |
| Level, n (%) | | 559 (40.2%) | 697 (49.8%) | 140 (10.0%) |
| **transport distance per neonate (miles)** | | | | |
| 25% | 12 (5-34) | 12 (6-27) | 10 (4-28) | 53 (13-131) |
| 50% | 14 (6-41) | 13 (6-30) | 12 (5-34) | 81 (21-156) |
| 75% | 20 (9-63) | 16 (9-38) | 19 (8-56) | 126 (67-202) |
| **Climate Indicator Characteristics** | | | | |
| Labor hours lost (Hours/person) | 14.50 (7.7-21.9) | 15.0 (7.65-22.3) | 14.4 (7.9-21.5) | 14.2 (7.4-20.1) |
| Asthma incidence among 0-17 yrs | 0.32 (-0.02-0.08) | 0.03 (-0.04-0.07) | 0.04 (-0.02-0.09) | 0.03 (0.00-0.09) |

| | | | | |
|---|---|---|---|---|
| (impacts/10,000 people) | | | | |
| Traffic delays from damage to roads (additional hours/ person) | 0.80 (0-1) | 0 (0-1.00) | 0 (0-0.72) | 0 (0-0.14) |
| Proportion of property at risk of permanent inundation from coastal flooding | 0.0006 (0-0) | 0 (0-0) | 0 (0-0) | 0 (0-0) |
| Annual property damage ratio from inland flooding | 0.008 (0.00-0.001) | 0 (0-0) | 0 (0-0.001) | 0 (0-0.001) |
| **Cumulative climate risk (z-transformed)** | | | | |
| Cumulative | 1.35 (0.60-2.27) | 1.32 (0.55-2.21) | 1.37 (0.63-2.29) | 1.43 (0.46-2.43) |
| **Social Vulnerability** | | | | |

| | | | | |
|---|---|---|---|---|
| Overall composite score | 0.57 (0.32-0.79) | 0.53 (0.29-0.76) | 0.58 (0.34-0.80) | 0.59 (0.38-0.84) |

Climate Risk of NICUs

NICUs are not accruing climate risks; rather, they are located within the census tracts for which the EPA data are projected. These data are used as a proxy for climate hazards hitting the NICU property. In the US under 2°C of warming, each climate-exposed worker is projected to lose a median of 12.70 hours of work per year (**Figure 2**). Taking into consideration the climate risks in the census tracts where the 1,392 NICUs were located in 2023, each climate-exposed worker is projected to lose a median of 14.50 hours of work per year under 2°C of warming. In the US, people 0-17 years are projected to experience a median of 0.27 new asthma cases per 10,000 people. Among 1,392 NICUs and their climate risks, people 0-17 years are projected to experience a median of 0.32 new asthma cases per 10,000 people (**Figure 3**). In the US under 2°C of warming, people are projected to experience an additional 0.00 hours on the roads due to traffic delays. Among 1,392 NICUs, people are projected to experience an additional 0.80 hours on the roads (**Figure 4**). In the US under 50cm SLR, there is expected to be a median annual damage ratio of property to total property value in floodplain of 0.00031 (**Figure 5**). Among 1,392 NICUs, there is expected to be a median annual damage ratio of property damage to total property value in floodplain of 0.008. In the US under 50cm SLR, there is expected to be a median permanent inundation risk from coastal flooding 0.00. Among 1,392 NICUs, there is expected to be a median risk of 0.0006 from coastal flooding (**Figure 6**).

When these climate risks are z-transformed and summed for all census tracts and block groups in the US, the median cumulative climate risk score was 2.06, ranging from -0.08 to 12.09. In census tracts containing 1,392 NICUs, the median cumulative climate risk score was 1.35, ranging from -6.04 to 18.10. In 2010, the median overall composite score from the 2010 Social Vulnerability Index (SVI) was 0.50 in the United States. In census tracts containing 1,392 NICUs, the median score was 0.57 (**Table 2**).

At a national scale, z-transformed climate indicators under 2°C of warming and 50cm SLR are projected to impact the US South most significantly (**Figure 7**). Extreme heat is projected to impact the US South (**Figure 2**). Asthma impacts are more widespread nation-wide, but also with higher impacts in the South (**Figure 3**). However, traffic delays do not have higher impacts in the South. There are hot spots of additional hours spent on the road due to extreme precipitation in most urban areas (**Figure 4**). Inland flooding impacts show overlap with traffic delays due to extreme precipitation (**Figure 5**). Coastal flooding impacts are concentrated on the coastlines, but areas of higher impact include the coast of southern California and the coast of North Carolina (**Figure 6**).

### Neonate transfer distances under varying capacities

Under the assumption that sending NICUs were operating at 100% capacity and receiving NICUs were operating at 25% capacity, the median number of neonates to transfer was 16. This number increased from 8 to 54 for Level II and Level IV NICUs, respectively. The median transport distance was also higher under higher capacity scenarios. Under 25% capacity at the receiving NICU, neonates were estimated to require a median transport distance of 12 miles to be transported to an equivalent or higher level of care. Under 50% and 75% capacity, neonates were estimated to require median transport of 14 and 20 miles, respectively (**Table 2)**.

Under 2°C warming and 50cm SLR, 364 (26.15%) of NICUs fell into the top tertile of exactly two climate risks (**Table 3**). Of these 365 NICUs, the most were in Texas (14 [13.19%]), California (41 [11.26%]), and Florida (23 [6.32%]) (**Figure 7**). 34 (9.34%) were Level IV NICUs, 160 (43.96%), 170 (46.70%) Level III, and Level II, respectively. There are 120 (8.62%) NICUs projected to fall into the top tertile of three climate risks. Of these 120 NICUs, most were in California (14 [16.67%]), Georgia (12 [14.29%]), and Alabama (11 [13.10%]). 13 (10.83%) were Level IV, 42 (35.0%) Level III, and 65 (54.17%) Level II NICUs. Lastly, 21 (1.50%) NICUs were in the top tertile of four climate risks. Of these 21 NICUs, most were in California (6 [28.57%]), Tennessee (5 [23.80%]), and Georgia (4 [19.05%]). 2 (9.52%) were Level IV, 10 (47.62%) were Level III, and 9 (42.86%) were Level II NICUs.

12 NICUs (0.91%) were in a census block group with some proportion of property at risk for permanent inundation due to coastal flooding, while 265 (20.23%) NICUs were in a census block group with some risk of annual damage ratio from inland flooding (**Figure 6**). The 12 NICUs projected to be impacted by coastal flooding under 50cm SLR are in Texas, Florida, Maine, Louisiana, California, Virginia, North Carolina, South Carolina, and Georgia. Three of these hospitals are level IV NICUs (**Figure 1**).

**Table 3: NICUs Projected (to be affected) by 1, 2, 3, 4 Climate Indicators under 2°C of warming and 50cm SLR[1]**

| | Top Tertile Cut-off | Number of NICUs in Top Tertile of Climate Risk (n=1392) |
|---|---|---|
| **Climate Indicator** | | |
| Labor hours lost (hours/person) | 18.6 | 511 (36.53%) |
| Asthma incidence among 0-18 yrs (impacts/1000 people) | 0.061 | 497 (35.53%) |
| Traffic delays from damage to roads (additional hours/person) | 1 | 204 (14.58%) |
| | | **Number of NICUs with Non-Zero Risk** |
| Proportion of property at risk of permanent inundation from coastal flooding | > 0 | 12 (0.91%) |
| Annual damage ratio from inland flooding | > 0 | 265 (20.23%) |
| **Elevated climate risk[2]** | | |
| 2 | | 364 (26.15%) |
| 3 | | 120 (8.62%) |

| | | | |
|---|---|---|---|
| | 4 | | 21 (1.51%) |

[1] Under projections of 2°C of warming or 50cm SLR

[2] Elevated climate risk: NICUs are classified in the top category (tertile or non-zero risk) in 2 or more climate indicators

**Figure 2.** Temperature-related labor hours lost in the United States by census tract with NICUs overlaid, by US Top-tertile. Dots represent NICU locations for those at high risk, defined by US top tertile thresholds, greater than 18.5 hours (white), and low risk, less than or equal to 18.5 hours. Fill colors represent the z-transformed total climate risk, with 0 representing no risk and 40 being the highest risk. NICU locations in 2023 come from Neonatology Solutions and climate risk from EPA Social Vulnerability Report: *Climate Change and Social Vulnerability in the United States*.

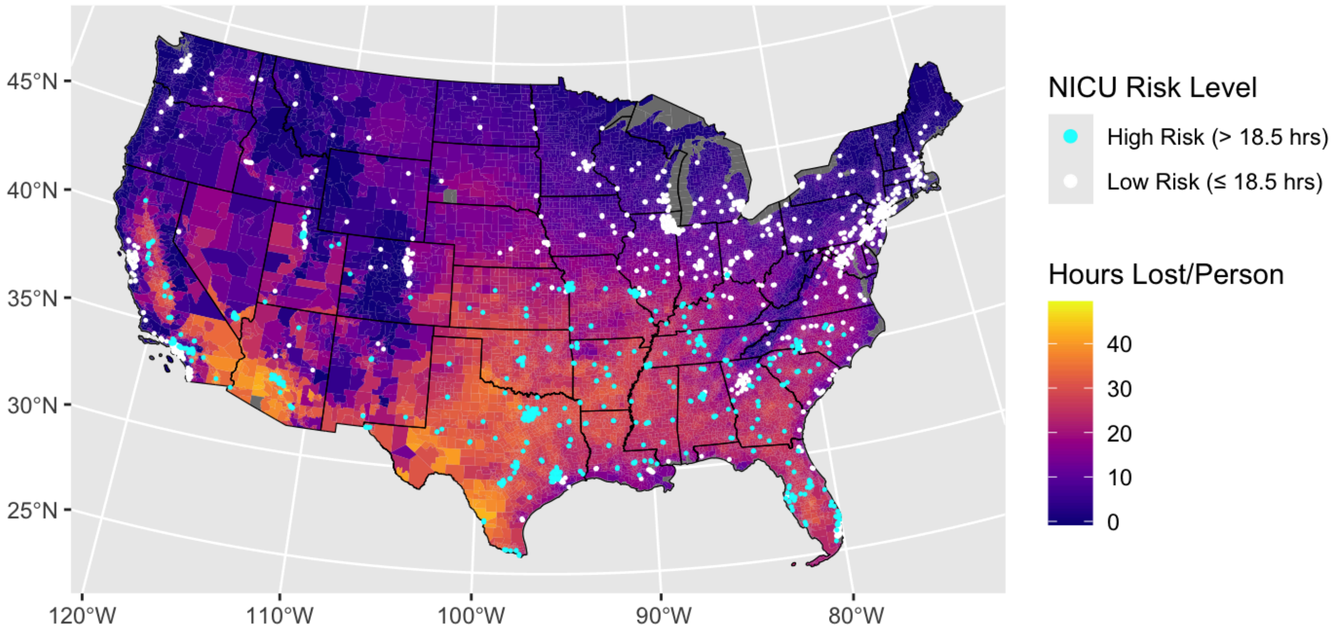


**Figure 3.** Asthma impacts among people 0-17yrs in the United States by census tract with NICUs overlaid by US Top-Tertile. Dots represent NICU locations for those at high risk, defined by US top tertile thresholds, greater than 0.000061 impacts (white), and low risk, less than or equal to 0.000061 impacts. Fill colors represent the z-transformed total climate risk, with negative to 0 representing no risk and 0.000061 being the highest risk. NICU locations in 2023 come from Neonatology Solutions and climate risk from EPA Social Vulnerability Report: *Climate Change and Social Vulnerability in the United States*.

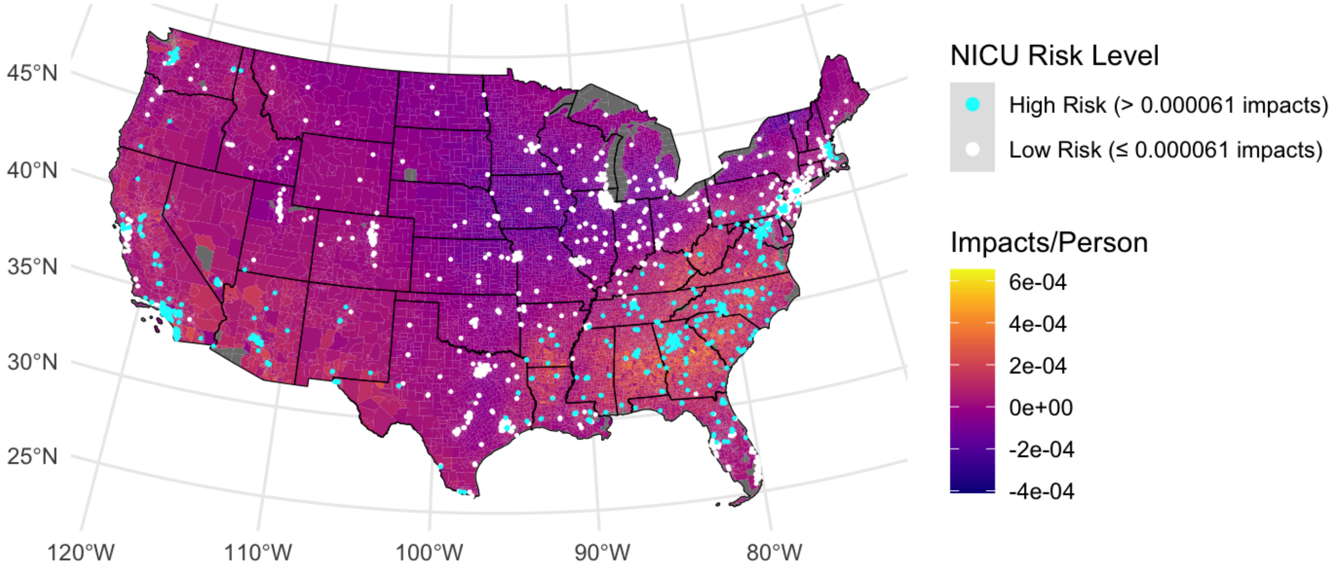


**Figure 4.** Additional hours per person spent on roads due to precipitation related traffic delays in the United States with NICUs overlaid by census tract level. Dots represent NICU locations for those at high risk, defined by US top tertile thresholds, greater than 1 hour (white), and low risk, less than or equal to 1 hour. Fill colors represent the z-transformed total climate risk, with 0 representing no risk and 100 being the highest risk. NICU locations in 2023 come from Neonatology Solutions and climate risk from EPA Social Vulnerability Report: *Climate Change and Social Vulnerability in the United States*.

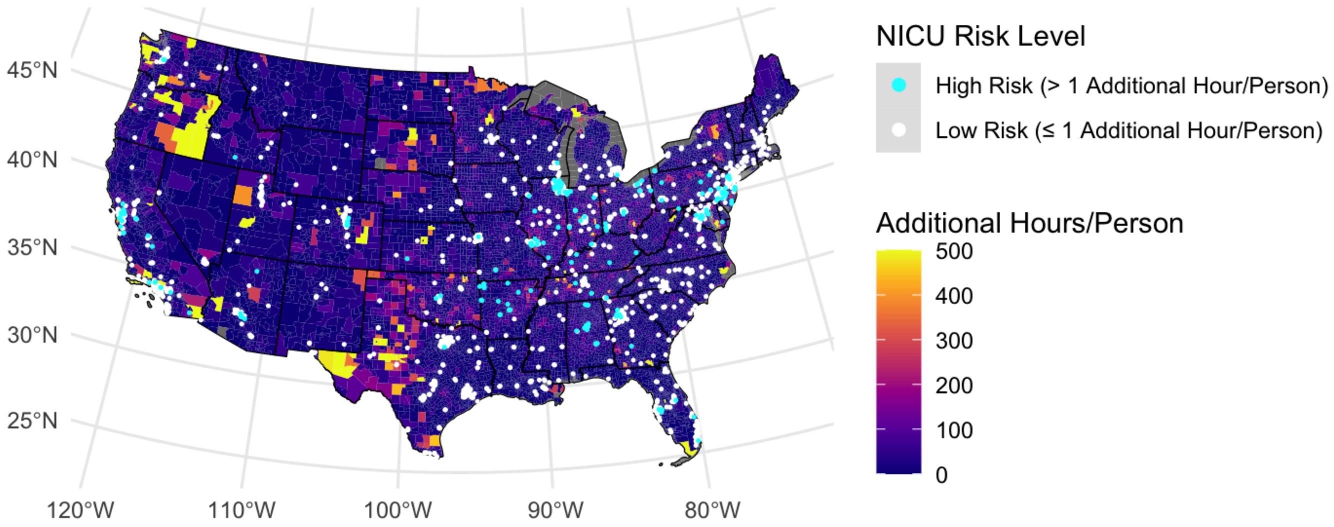


**Figure 5.** Annual property damage ratio to total property value in floodplain in the United States with NICUs overlaid by census block group. Dots represent NICU locations for those at high risk, defined by US top tertile thresholds, greater than 0 annual property damage ratio. All NICUs plotted have greater than 0.00 risk. Fill colors represent the z-transformed total climate risk, with 0.00 representing no risk and 0.04 being the highest risk. White fill colors represent missing data. NICU locations in 2023 come from Neonatology Solutions and climate risk from EPA Social Vulnerability Report: *Climate Change and Social Vulnerability in the United States*.

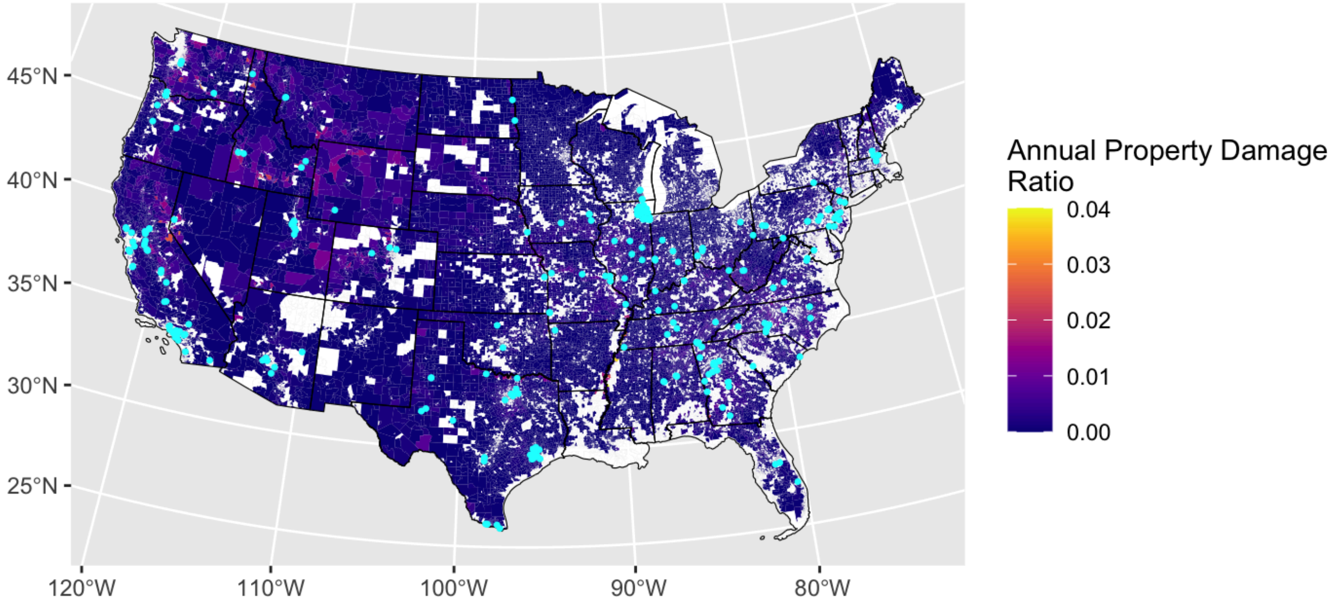
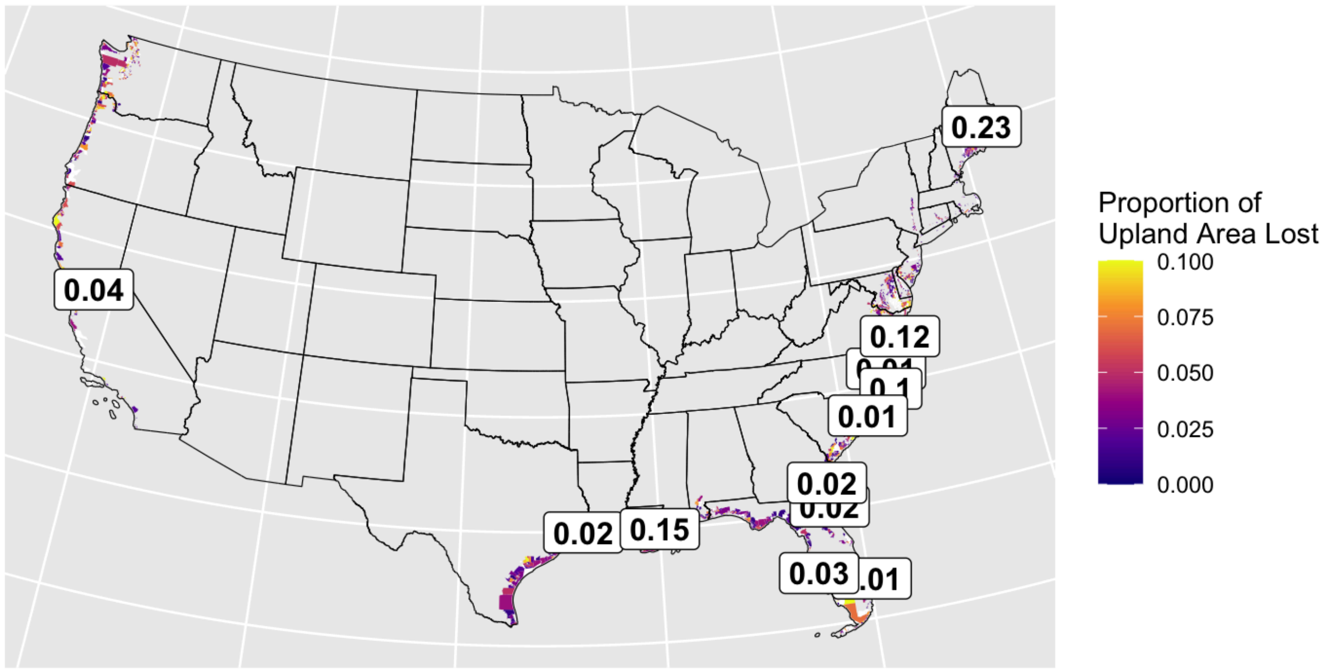
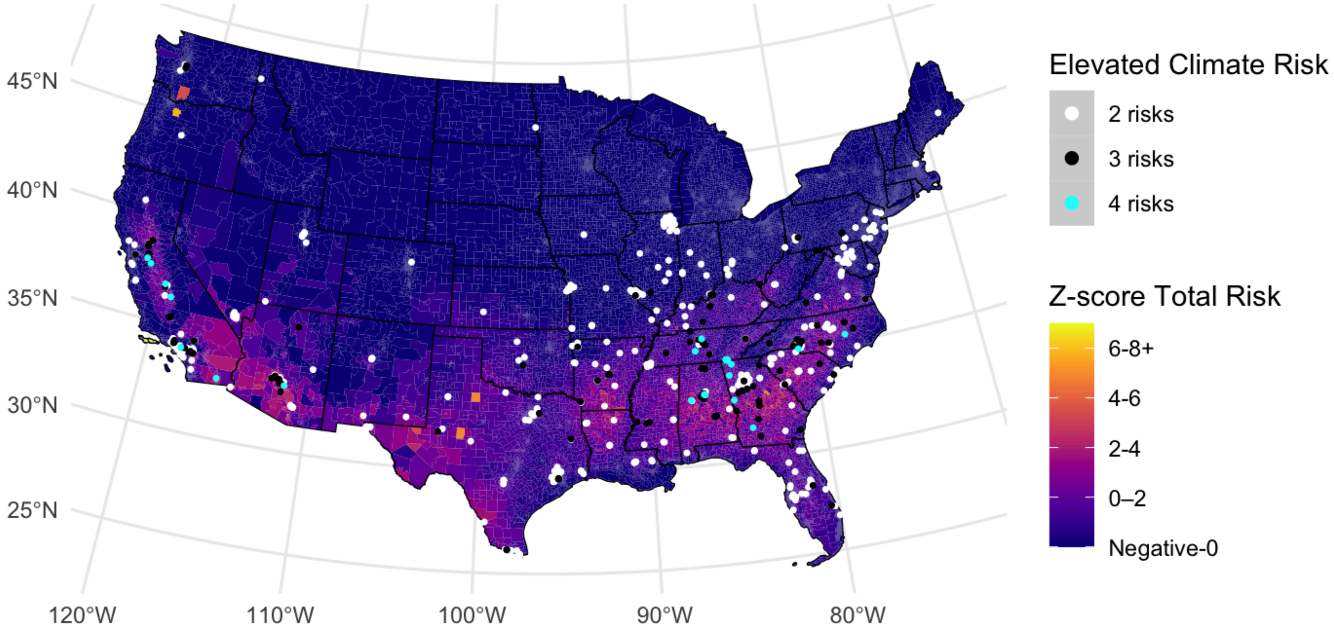


**Figure 6.** Risk of permanent inundation from coastal flooding in the United States with NICUs overlaid by census block group. Dots represent NICU locations for those at high risk, defined by US top tertile thresholds, greater than 0. All NICUs plotted have greater than 0.00 risk. Fill colors represent the z-transformed total climate risk, with 0.00 representing no risk and 0.1+ being the highest risk. Transparent areas represent no risk. Each of the 12 NICUs that are plotted also have their own respective quantitative coastal flooding risk. NICU locations in 2023 come from Neonatology Solutions and climate risk from EPA Social Vulnerability Report: *Climate Change and Social Vulnerability in the United States*.



[1] Proportion of Upland Area lost is filtered by risks > 0

**Figure 7.** Z-score of five total climate risks in the United States under 2°C warming and 50cm SLR by census tract overlaid with the locations of NICUs in census tracts projected to be in the top tertile of 2, 3, and 4 climate indicators. Dots represent NICU locations for those at risk of 2 (white), 3 (black), and 4 (turquoise) climate hazards. Fill colors represent the z-transformed total climate risk, with 0 representing no risk and 6-8+ being the highest risk. NICU locations in 2023 come from Neonatology Solutions and climate risk from EPA Social Vulnerability Report: *Climate Change and Social Vulnerability in the United States*.



Social Vulnerability and Climate Risk

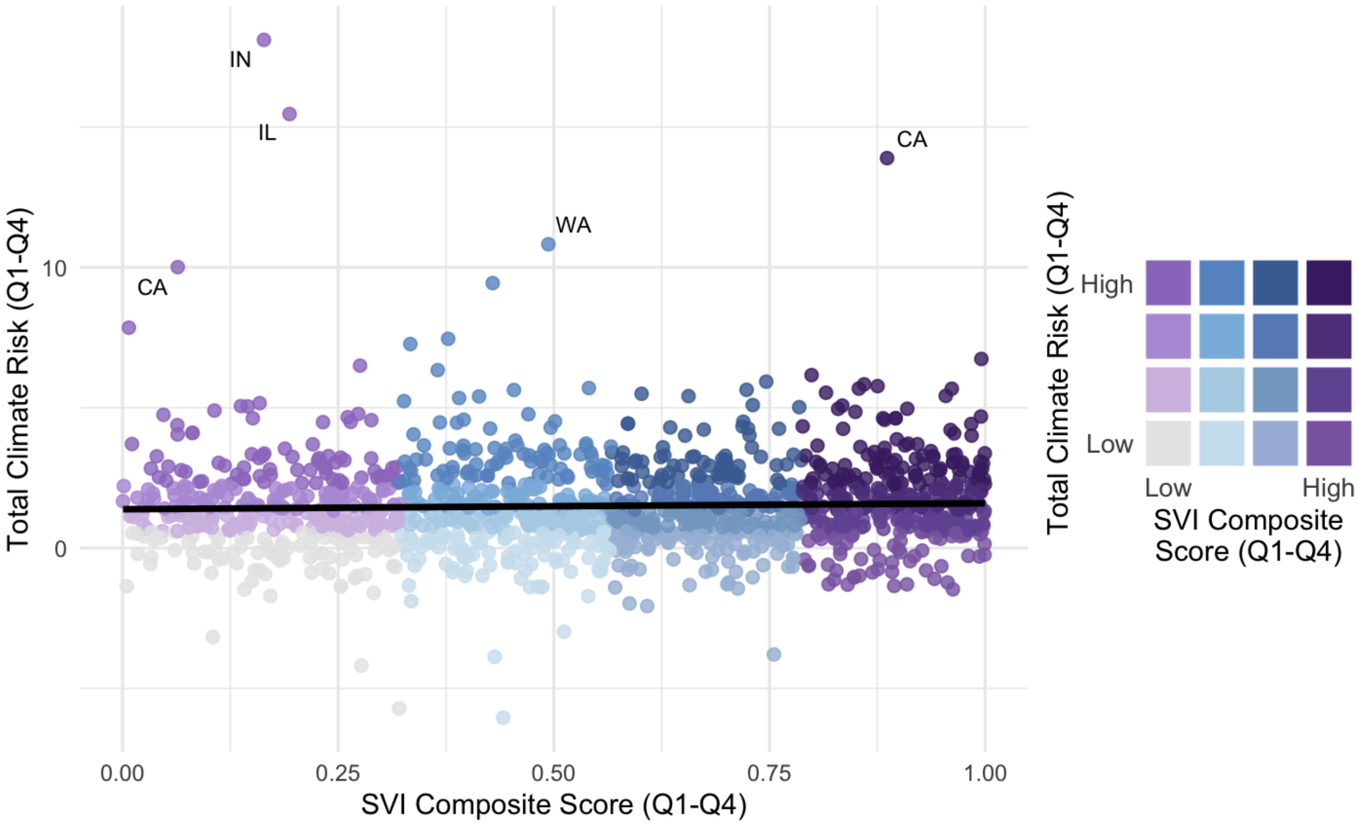
After linking SVI data to NICU and climate risk data by census tract, linear regression controlling for state-fixed effects results showed that there was no association between social vulnerability and total climate risk (β = -0.12, 95% CI: -0.37, 0.13) (**Table 4**).

**Table 4**. Estimated effects of linear regression between overall composite scores and z-transformed climate risk, adjusted for state-fixed effects

| **Variables** | **Coefficient (β)** | **95% CI** |
|---|---|---|
| Intercept | 3.86 | 3.28, 4.43 |
| Overall composite SVI score | -0.12 | -0.37, 0.13 |

To further evaluate the relationship between SVI climate risk and SVI,  the two variables were categorized into quartiles, and their combinations were assigned to a bivariate classification system, resulting in 16 distinct categories ranging from 1-1 to 4-4. A single level IV NICU was located in a tract in the top quartile of climate risk and social vulnerability. It was in California, with an overall composite score of 0.89 and total z-transformed climate risk of 13.89 (**Figure 8)**. There were 9 additional NICUs in the highest quartile of climate risk and SVI, and they were located in Alabama, Arizona, Arkansas, Georgia, Mississippi, and Texas. 2 (20%) were level II, 7 (70%) were level III, and one Level IV.

**Figure 8.** Bivariate scatterplot of association between SVI composite score and climate risk. The five climate risk scores were z-transformed and summed to create the total climate risk score plotted. Colors depict quartiles of the social vulnerability and climate risk scores, with dark purple indicating NICUs located in tracts with the highest social vulnerability scores and highest climate risk. The thick black line is a fitted linear regression. The outliers are labelled with the state that the NICU is located in.



Average transport Distance Per Neonate in High Climate Risk Census Tracts

NICUs located in census tracts in the highest quartile of total climate risk with the top twelve farthest average transport distance per neonate were located in Alabama, Alaska, Arizona, Arkansas, Florida, Hawaii, Louisiana, Maine, Mississippi, Nevada, New Mexico, Texas (**Table 5**).

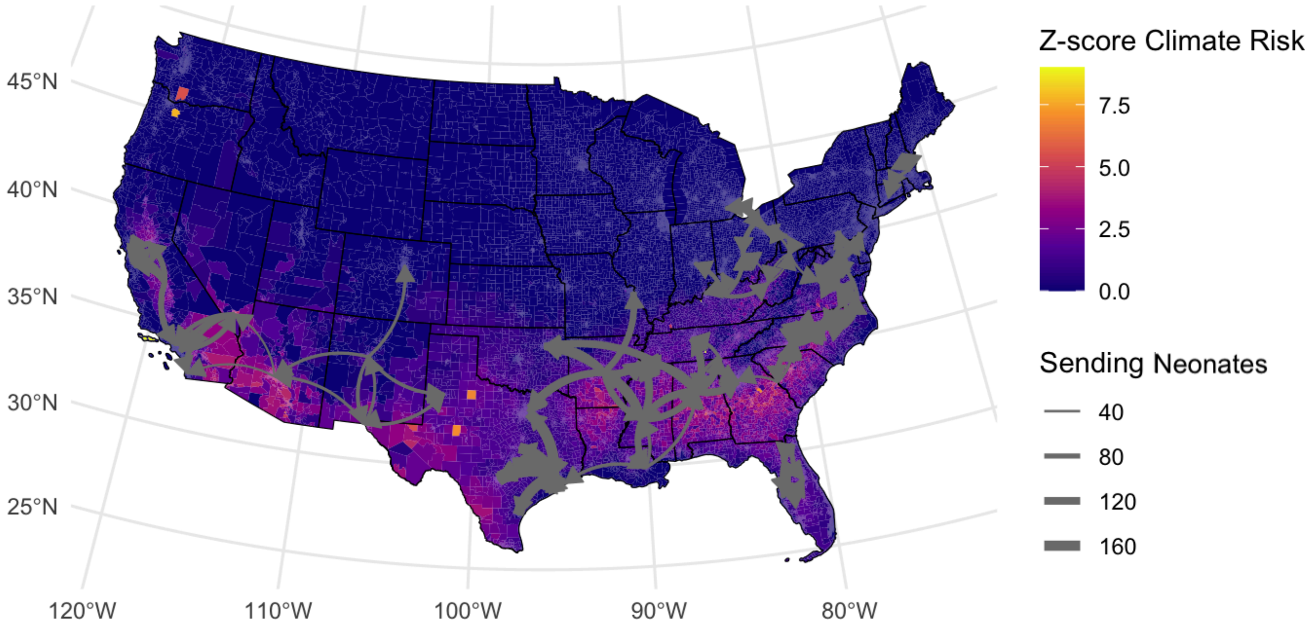
**Table 5.** Among NICUs in the highest quartile of climate risk, the table shows the 10 with the greatest average transport distances under a scenario of 100% capacity at sending NICUs and 75% capacity at receiving NICUs, including sites in Hawaii and Alaska. All listed NICUs are Level IV, except those in Hawaii, Alaska, and Maine, which are Level III.[1]

| NICU | State | Beds | Average Distance per Neonate (mi) | Climate Risk |
|---|---|---|---|---|
| Kapi'olani Medical Center | Hawaii | 70 | 2,019 | NA |
| Providence Alaska Medical Center | Alaska | 66 | 1,460 | NA |
| University of New Mexico Children's Hospital | New Mexico | 35 | 388 | 2.47 |
| Arkansas Children's Hospital | Arkansas | 104 | 362 | 3.65 |
| Phoenix Children's Hospital | Arizona | 33 | 359 | 3.06 |
| El Paso Children's Hospital | Texas | 50 | 342 | 2.28 |
| Ochsner Hospital for Children | Louisiana | 54 | 341 | 5.77 |
| Children's of Mississippi | Mississippi | 102 | 333 | 3.09 |

| | | | | |
|---|---|---|---|---|
| University of Alabama Hospital | Alabama | 120 | 279 | 4.63 |
| Sunrise Children’s Hospital | Nevada | 72 | 271 | 2.96 |
| Eastern Maine Medical Center[2] | Maine | 29 | 249 | 7.27 |
| Baptist Medical Center Jacksonville | Florida | 75 | 239 | 2.78 |

[1] Climate risk data for Hawaii and Alaska are missing because there were no climate projections for those states.

**Figure 9.** Direction of transport flow to receiving NICUs, from the sending NICUs (n=33) in census tracts with the highest quartile of climate risk and highest quartile of average transport distance under a 100% capacity at sending NICUs and 75% capacity at receiving NICUs scenario. Fill colors represent the z-transformed total climate risk, with 0.00 representing no risk and 7.5 being the highest z-transformed climate risk. The number of neonates that need to be sent from each hospital are depicted with thickness levels.



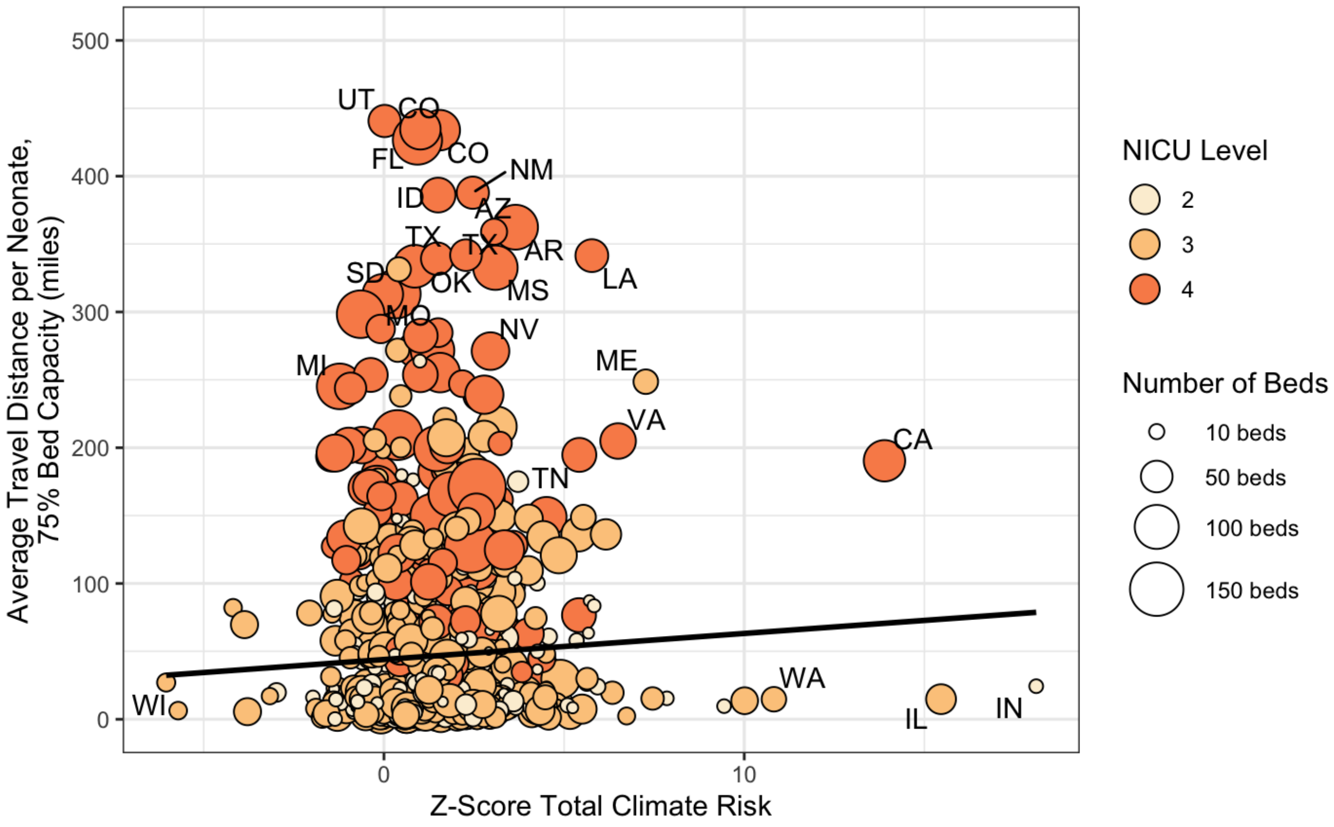
Unadjusted linear regression showed associations between total climate risk and transport distance in all three capacity scenarios. When comparing groups that differed by a 1 standard deviation higher climate risk, the NICUs with the higher climate risk had to transport neonates, on average, 2.07 miles (95% CI: 0.04, 4.09) farther under a 100% sending and 75% receiving bed capacity scenario (**Table 6**). Under a 100% sending and 25% receiving bed capacity scenario, on average, a neonate had to be transported 1.88 miles farther (95% CI: 0.36, 3.39) when comparing groups that differ by 1 standard deviation increase in climate risk. Under 50% scenarios, neonates are estimated to transport 1.87 miles (95% CI: 0.22, 3.52) more when compared with a group that has 1 standard deviation higher climate risk score.

With higher bed occupancy scenarios, neonates are burdened with higher average transport distances (**Figure 10)**.

**Table 6.** The result of unadjusted linear regression between total climate risk and average transport distance per neonate, under each capacity availability scenario

| Bed Capacity Available Scenario | Climate Risk Coefficient (z-score) | 95% CI |
|---|---|---|
| 25% | 1.88 | 0.36, 3.39 |
| 50% | 1.87 | 0.22, 3.52 |
| 75% | 2.07 | 0.04, 4.09 |

**Figure 10.** Scatterplot fitted with linear regression line on the association between total climate risk and average transport distance per neonate for sending NICUs operating at 100% capacity and receiving NICUs operating at 75% bed capacity[1]



[1]This figure excludes Hawaii and Alaska because there was no climate data for those states.

## Discussion

### Significant Findings

Aim 1: Southern states are projected to be most burdened by climate impacts. Specifically, 12 NICUs are projected to be impacted by coastal flooding, and those NICUs were located in Texas, Florida, Maine, Louisiana, California, Virginia, North Carolina, South Carolina, and Georgia. Coastal flooding impacts increased climate risk in the states listed above, raising the number of climate indicators in the U.S. top tertile from two to three. The addition of the third climate risk in the US top tertile was driven by coastal-related factors, and these were all Level III NICUs.

Aim 2: There was no association between overall composite SVI scores and climate risk after adjusting for state-fixed effects. Within a state, census tracts with higher social vulnerability are not projected to experience higher climate risk. While adjusting for state-fixed effects accounts for all the unobserved, state-level characteristics that are constant across tracts within a state, there could be more heterogeneity within a state. Additionally, there could be high climate risk due to coastal flooding in less socially vulnerable areas, and among more socially vulnerable areas, climate risk could be lower due to low inland flooding risk. This suggests that social vulnerability, as measured by overall composite scores, are not the lone predictor of climate risk for tracts within a state. While this adjustment removes state-level differences, it could still mask policy-relevance between states. SVI alone does not predict climate risk but places with higher SVI will have less access to resources to recover from a climate disaster. Social vulnerability may also operate at finer spatial scales. This necessitates further research that better quantifies between state variations at a national level.

Aim 3: Under 100% capacity at sending NICUs and 25%, 50%, and 75% capacity at receiving NICUs, neonates require longer transport distances, on average, when bed capacity scenarios increase to higher occupancies. The most realistic scenario for higher level NICUs would be that they are always operating anywhere from 75 to 100% capacity.[19–21] These findings suggest, under 75% receiving bed capacity, Level IV NICUs would be burdened with the highest transport distances per neonate in the event of a climate disaster. NICUs that are more isolated tend to have higher average distances. Alaska and Hawaii both have substantially higher relocation burdens under 75% capacity scenarios, compared to the rest of the NICUs in the top quartile of both metrics. NICUs located in census tracts with the highest quartile of total climate risk and average transport distance per neonate were located predominantly in the US South, and these NICUs were all higher levels of care (Levels III and IV). 1.29% (n=18) of 1,399 NICUs had over 300 miles of transport distance per neonate, where three are Level III and 15 are Level IV NICUs. Two of these NICUs included Alaska and Hawaii. This underscores the distinct risks and operational challenges Level III and IV NICUs may face during disasters. The concentration in the US South also highlights several policy-relevant issues, including potential patterns of systematic underinvestment in healthcare infrastructure, regional disparities in climate resilience planning, and restricted access to reproductive healthcare services, including abortion.

## Connection to existing literature

There is an array of literature that highlights the spectrum of challenges associated with NICU evacuation during disasters. The Oregon wildfires during the summer of 2020 showed that it is critical that NICUs have disaster plans in place to evacuate their neonates.[10] Similarly, Hurricane Sandy hit New York University (NYU) Langone Medical Center, leading to a successful evacuation of 21 neonates within 4.5 hours following electrical power loss. This outcome underscores the hospital's access to preparedness resources and its urban location may have facilitated a more rapid evacuation. In addition, NYU Langone Medical Center is a Level IV NICU in close proximity to other Level IV NICUs. If this situation occurred in another location where there were no other hospitals in close proximity, the evacuation might have been much harder.

The conversation around NICU levels of care is also linked to the unique and heightened vulnerabilities of premature and critically ill neonates, necessitating evacuation protocols distinct from those used for pediatric and adult patients. Neonates in NICUs face elevated baseline health risks, including thermoregulatory instability, underdeveloped respiratory and immune systems, and heightened sensitivity to environmental stressors such as noise, temperature fluctuations, and destabilizing movement.[22–24] Disruptions to this care during evacuation can result in clinical deterioration and long-term consequences, including neurodevelopmental and psychosocial impacts.[22–24] These factors underscore the need for highly specialized and coordinated evacuation plans tailored specifically to the needs of neonates. For example, neonates with Transient Tachypnea of the Newborn (TTN) and Very Low Birth Weight (VLBW) are more likely to experience clinical deterioration when transported over long distances.[25, 26] Additionally, neonates with higher Transport Risk Index of Physiologic Stability (TRIPS) scores, reflecting physiological instability during transport, have been associated with increased risks of mortality and adverse neurodevelopmental outcomes throughout the lifecourse.[27] Neonates who are transported intra-hospital have also been linked to significant physiological changes, including changes in blood glucose levels and body temperature.[28] Therefore, this existing literature can be supplemented with quantitative evidence around NICU transport distance burdens to tailor disaster planning efforts to specific neonatal vulnerabilities.

The impacts of climate disasters also do not impact communities equitably. Boudreaux et al. (2025) highlight that communities prone to wildfire smoke lack the geographic access to get timely care, specifically pregnant people and infants during the perinatal period.[29] The findings from this research, specifically more isolated NICUs in rural areas, can be integrated with retrospective cases to develop more tailored and context-specific disaster preparedness and response plans, ensuring that strategies are informed by both empirical evidence and real-world experiences.

There is also global literature on previous climate disasters impacting NICUs. Specifically, a cyclone impacted a NICU in Beira, Mozambique, underscoring the complex challenges of neonatal evacuation.[30] The facility experienced sequential system failures including: loss of electricity, water, communication services, followed by a generator failure and structural damage that led to flooding. These conditions necessitated the relocation of patients 100 meters away to a pediatric unit. Although this scenario occurred outside the United States, it illustrates the critical vulnerabilities and offers valuable insights for emergency preparedness and response planning in similar contexts.[30]

There remains a major gap in the literature concerning the intersection of NICUs and climate-related disasters, specific to the burden of relocation. Existing studies primarily focus on retrospective accounts of hospital responses to events such as wildfires and hurricanes, emphasizing lessons learned and recommendations for future preparedness. These accounts underscore persistent challenges, including inconsistent training, inefficient communication, and limitations in existing emergency plans.[30-32] Additional gaps in literature include the unknowns on the economic burden of a NICU shutdown and forced evacuation. Even historic NICU evacuations do not publicly represent the short and long-term costs induced on health systems. Furthermore, there are no examples to date of a neonate being adversely affected by transport during a climate disaster. This research aims to build on prior work by providing quantitative evidence to inform prioritization efforts and support the development of evidence-based response strategies for NICUs facing climate threats.

## Public Health Implications

The results from the research identify NICUs that should be particularly vigilant and allocate additional resources toward disaster preparedness. NICUs in Texas, Florida, Maine, Louisiana, California, Virginia, North Carolina and Georgia are projected to be impacted by elevated climate risks because of their risk of coastal flooding. These states should account for their unique geographical risks and establish disaster plans in coordination with similarly or more advanced NICUs in regions not projected to be impacted by a similar disaster. These findings suggest that NICUs burdened with high climate risk and high transport distances per neonate need to be prioritized in funding disaster protocols to prepare for climate disasters. Furthermore, neonates that are at Level IV NICUs in Utah, Colorado, and Florida would need to transport the furthest average distance, as defined by the top quartile of climate risk and transport distances. Neonates at Level IV facilities are already needing more critical attention and expertise, and in the event of a climate disaster, Utah, Colorado, and Florida are projected to have delays in transfer due to the longer average transport distances. This delay of transport may result in the risk of further complications to neonates already in critical states, suggesting a higher vulnerability among Level III and IV neonates that needs to be considered in resource prioritization or tailored disaster plans. Lessons learned from past climate disasters like Hurricane Sandy, wildfires in Oregon and California highlight the need to prepare before a disaster hits, prioritizing streamlined communication between hospitals.

While there were no significant findings for the relationship between overall SVI composite scores and total climate risk, there are also important implications for socially vulnerable populations during climate-related disasters. Socially vulnerable populations face economic disadvantages and systemic inequities that lead marginalized communities to struggle more in disaster preparation efforts and recovery. Infrastructure in lower-income regions lack resiliency, compounding risk of property inundation and health risks. In addition, occupational exposures of socially vulnerable populations also differ. Those in more socially vulnerable groups often work in outdoor jobs, including agricultural jobs, and are more susceptible to extreme temperatures which are related to a number of adverse health outcomes. Therefore, socially vulnerable populations face heightened risk both in the lead-up to a climate disaster and in its aftermath.

The average transport distance per neonate indicates the degree of isolation of a NICU and its respective relocation burden, regardless of a NICU's projected climate risk. Whichever NICUs are most isolated will also need an evacuation plan that anticipates transporting neonates over long distances, especially given the uncertainty around climate events or other major disasters like sweeping blackouts or cyberattacks. Meanwhile, NICUs at the highest climate-related risk will need to develop plans that are tailored to the disasters they might encounter. Any NICUs that are particularly high on both metrics should be prioritized for disaster readiness funding. Policies often prioritize wealthier areas, leaving vulnerable communities underprotected; so funding plans should address this inequity. Additionally, both neonates and their families must be considered. Drawing on lessons from past climate disasters, as noted by existing literature, and supplementing those experiences with quantitative evidence from this research is critical for identifying areas in need of improvement.

This evidence is really aimed at minimizing the operational stress of a climate-induced NICU shutdown, organizing surge capacity of receiving NICUs, and maximizing resource allocation so that quality of care is still maintained for neonatal care. In addition to understanding the hospital responses that are required, designing effective and timely disaster plans according to relocation burden would also save neonatal lives during critical and sensitive periods of development. Any stresses induced on neonates like a shutdown that requires relocation will also have neurodevelopmental and psychosocial impacts on the neonate.[22–24] At Level II NICUs, most neonates are born premature infants but do not require intensive care.[33] They may have respiratory distress syndrome, infections, hypoglycemia, or hyperbilirubinemia.[33] In a Level III NICU, neonates require more critical care as they have more severe and complex conditions that require specialty. These include need for advanced respiratory support, invasive monitoring, and subspecialty consultations (e.g., surgery, neurology, cardiology).[34] In Level IV NICUs, neonates often require surgical repair of complex congenital or acquired conditions such as congenital diaphragmatic hernia, complex congenital heart disease, and severe neurological disorders.[34] On top of the level-specific vulnerabilities of neonates, there are implications of transporting neonates during these critical periods. Any vibration, noise, and altitude changes can exacerbate infants' cardiorespiratory systems, especially preterm infants and those with congenital heart diseases.[35] Therefore, critical planning tailored to NICU level and relocation burden are essential to minimize the delay to treatment in an climate-induced shutdown, having long-term health impacts on neonatal populations.

The findings of this research have important implications for understanding the potential health impacts of climate change on maternal and neonatal populations. Although the climate projections utilized in this study are resolved at the census tract and block group levels, and NICUs are geographically situated within these spatial units, this analysis serves as a proxy to estimate potential exposures for not only climate disasters NICU properties face, but also NICU-admitted populations. While it cannot be definitively assumed that individuals residing within a given census tract or block group will seek care at the corresponding NICU, the spatial alignment provides a reasonable approximation for assessing climate-related health risks to these vulnerable populations. Understanding these direct health impacts is essential for planning future chronic disease and mental health interventions, particularly as neonates represent the next generation. Neonates face elevated baseline health risks; so this research aims to help NICUs prepare in advance to mitigate those risks during disasters and onwards.[22–24]

## Limitations

This analysis excluded seven NICUs from Alaska and Hawaii in the climate risk analysis, and Alaska and Hawaii may arguably have some of the higher climate risks, as evidenced by SLR and wildfires in the previous years. Hawaii experiences unique climate stressors due to its geographic location. Warming in the oceans and SLRs make Hawaii extra susceptible to flooding.[36] In addition, the 2023 Maui wildfires killed over 100 people, having immense social and health impacts.[37] Alaska also experiences unique climate stresses due to its geographic location, including warmer annual temperatures leading to less snow and rising levels of precipitation.[38] Both Hawaii and Alaska's unique climate stressors also have led to changes in ecosystem, wildlife, and animal migration patterns which all have an impact on the cultural diversity of Alaska Natives, Pacific Islanders, and Native Hawaiian populations. By excluding these states from the analysis, it also fails to capture the unique climate exposures and barriers to resilience among Alaska Native and Native Hawaiian populations. While the SVI attempts to capture the unique social vulnerabilities of marginalized populations in the United States, Native American communities in the United States are often underrepresented in census data. The data itself is a reflection of power structures; therefore, SVI may not capture the full complexity of cultural diversity, resilience, and generational trauma experienced by socially vulnerable populations.

Another key limitation of this analysis is the assumption that NICU locations and capacities from 2023 will remain constant in a future with 2℃ global warming and a 50cm SLR. This does not take into account potential changes in infrastructure, service availability, or capacity over time. The analysis does not directly measure risk of NICU closures, relying instead on human impacts as proxies, such as extreme temperature events and labor hours lost, and temperature-related mortality, which may not fully capture the complexity of NICU disruptions. These climate projections are also estimates, so there are varying models for climate projection data. The climate indicators were z-transformed and summed which led to individual NICU observations having individual negative or positive climate risks, which cancelled out each other in some instances. This could have minimized the climate risk of a specific area and led to attenuated effects. The data are also limited in capturing the policy variations in regards to neonatal access, environmental policy, access to reproductive health services, so the analysis cannot account for interstate heterogeneity in climate awareness and its consequent policy outcomes further than a state-fixed effects model.

Several assumptions were also made under the modeling scenario for average transport distances per neonate. First, assuming that the sending NICU would be at full capacity, they would need to fully relocate all neonates, as quantified by the number of beds at each NICU. Not all sending NICUs may be at full capacity and some neonates may be discharged rather than transported in the event of a climate hazard. The three bed capacity scenarios attempted to illustrate the varying availability of the receiving NICU, where the 75% bed capacity is likely the most realistic, but it is possible that some receiving NICUs will have no capacity to accept neonates. The simulation was created on the condition that sending NICUs would reallocate neonates to receiving NICUs that are the same or higher level of care. However, this might fail to take into account the varying levels of bed capacity when it comes to Level II vs Level IV NICUs, as higher level NICUs are usually at capacity. Some receiving hospitals also ended up being a sending hospital, which is why the analysis offers the average transport distance per neonate. In addition, the transport distances were calculated using Euclidean distances, which may be susceptible to measurement error, specifically, non-differential misclassification, as it affects all units of the analysis. This might lead to inaccurate estimations of true transport distance. Some relocation scenarios may not require helicopters; thus, Euclidean distances would not take into account road pathways and traffic delays. There is no strict time cutoff for inter-hospital neonatal transports; however, those that are critically ill or VLBW are prioritized to transfer within 60-90 minutes.[39] This analysis does not incorporate transport time as a variable; therefore, the weighted distance metric alone does not fully capture the urgency or clinical risk associated with neonatal evacuation. Travel time, which can vary significantly due to geography, infrastructure, and weather conditions, is a critical factor in assessing the feasibility and impact of transport for neonates in critical states.[40]

This study's climate data provides estimates for census tracts from 2010, failing to take into account changes in urban development, land use, and new zoning that might occur in the future. These projections also fail to consider how census tracts may evolve over time, particularly by the years when 2°C of warming and 50 cm of SLR are anticipated. In addition, the social vulnerability data come from SVI 2010, which does not consider future advancements in medical technology, changes in healthcare behavior, or changes to access to care for socially vulnerable populations, all of which could influence future NICU operations, health outcomes, gentrification, and immigration. While current census data projects the absolute number of people of childbearing age and number of children, these numbers are stable and go up. Therefore, census data takes into account these possible changes to the population like immigration over time. However, using SVI 2022 data might have been more reflective of current data projections, potentially impacting the applicability of results to future populations.

## Conclusion

NICUs in the US South are projected to have a dual burden of high climate risk and high average neonate transport. Any NICUs that are high on both metrics should be prioritized for disaster readiness funding. Higher-acuity NICUs (Level III and IV) are associated with longer transport distances per neonate, reflecting their limited availability and underscoring the need to consider neonatal vulnerabilities and specialized critical care requirements in disaster response planning. This research aims to supplement existing literature, which focuses heavily on retrospective accounts of NICU exposures to climate disasters, to provide an evidence base to alert stakeholders of where NICUs stand in terms of climate risk and relocation burden in the event of a climate-induced NICU shutdown. Next steps include involving Alaska and Hawaii in the climate risk and transport burden analysis so those NICUs can also have a quantitative evidence base to use in disaster planning and readiness.

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