Harmful Algae 150 (2025) 102999

Contents lists available at ScienceDirect

Harmful Algae

journal homepage: www.elsevier.com/locate/hal

Exposure to harmful algal blooms and socio-demographic patterns: Evidence from six decades of analysis in Florida, USA

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ARTICLE INFO

Keywords:
Harmful algal blooms
Red tide
Karenia brevis
Socio-demographics
Inequality

ABSTRACT

Harmful algal blooms (HABs) have emerged as a critical environmental hazard in U.S. coastal waters, posing substantial risks to human health. This study examines six decades of HAB events (1960–2019) across 34 coastal counties in Florida, USA, to evaluate the relationship between HAB exposure and socio-demographic patterns. We further use the Gini coefficient to measure spatial disparities in exposure, with a particular focus on children and seniors, two groups especially vulnerable to environmental hazards. Our analysis reveals that HAB exposure is significantly linked to population decline and a reduced proportion of children in affected counties. In contrast, areas with greater HAB exposure tend to have a higher share of senior residents. Notably, spatial inequality is evident: counties with fewer children generally experience greater exposure, while those with more seniors face disproportionately higher exposure. These findings underscore the importance of addressing environmental justice in policy responses to HABs.

1. Introduction

Harmful algal blooms (HABs) have become a pressing environmental issue in U.S. coastal waters, driven by a variety of species and occurring across diverse habitats (Anderson et al., 2021). These blooms are often exacerbated by nutrient pollution and climate change, leading to the release of potent toxins that contaminate drinking water, pose serious health risks to humans and animals, and severely impact fisheries and recreational industries (Anderson et al., 2002). Among the most harmful bloom-forming species in the U.S. is Karenia brevis, commonly known as the red tide. This dinoflagellate produces neurotoxic compounds that affect a wide range of marine and estuarine organisms (Anderson et al., 2021). Notably, fish kills linked to Karenia brevis have been long documented in the Gulf of Mexico since 1844 and continue to occur almost annually, with blooms often persisting for several months (Steidinger, 2009).

HABs impose significant economic burdens across multiple sectors in the U.S. According to Hoagland et al. (2002), the annual costs associated with HABs can exceed $100 million, driven by impacts on public health, commercial fisheries, tourism, and water treatment. These events often necessitate increased municipal spending on water treatment infrastructure and emergency response, particularly during large-scale blooms that compromise drinking water supplies. A notable example is the 2014 Microcystis bloom in Lake Erie, which led to a multi-day shutdown of Toledo's water system (Steffen et al., 2017). Importantly, the economic consequences of HABs are not evenly distributed. Small-scale fishers, low-income populations, and Indigenous communities frequently bear a disproportionate share of the burden, who may lack the resources needed for rapid recovery (Moore et al., 2020; Weir et al., 2022).

Despite a well-established understanding of the ecological and economic impacts of HABs, empirical research remains limited on how exposure to HABs over time intersects with socio-demographic patterns. Prior studies have demonstrated that HABs disrupt critical sectors such as fisheries, tourism, and waterfront recreation (Alvarez et al., 2024; Jayasekera et al., 2024), with cascading effects that may reduce employment opportunities and household income. Health risks associated with HABs are also significant, particularly for households with a higher proportion of older adults, who are more vulnerable to environmental hazards (Hoagland et al., 2014). Moreover, HABs can degrade the overall quality of life by curtailing recreational access and imposing fiscal burdens on local governments, as increased spending on water treatment and healthcare may crowd out other essential services. Through these interconnected pathways, HABs have the potential to

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https://doi.org/10.1016/j.hal.2025.102999
Received 11 June 2025; Received in revised form 13 September 2025; Accepted 7 October 2025
Available online 10 October 2025

influence demographic outcomes in ways that extend beyond their immediate ecological and economic consequences.

In this study, we analyze six decades of HAB events from 1960 to 2019 across 34 coastal counties in Florida, U.S., to quantify the relationship between HAB exposure and socio-demographic patterns. We focus on three distinct measures of HAB exposure: the total number of events, cumulative algal cell concentration, and average algal cell concentration. This multidimensional approach provides a more comprehensive understanding of HAB impacts. Additionally, we use the Gini coefficient to assess spatial disparities in exposure, with particular attention to children and seniors, who are especially vulnerable to environmental hazards. This paper makes two key contributions. First, while prior research has primarily focused on the ecological, health, and economic consequences of HABs, we present one of the first long-term analyses of their relationship with socio-demographic patterns by linking sixty years of exposure data to county-level population trends. Second, by employing analytical tools such as the Lorenz curve and Gini coefficient, we reveal spatial disparities in HAB exposure and examine their implications for vulnerable demographic groups. Together, these contributions deepen our understanding of how environmental hazards intersect with demographic processes and offer insights for designing more equitable and effective environmental policies.

2. Literature review

Harmful algal blooms (HABs) pose a significant threat to human health due to their release of potent toxins such as microcystins and domoic acid (Fleming et al., 2011). These toxins can lead to a range of adverse health outcomes, including respiratory distress and gastrointestinal disorders (Grattan et al., 2016). In the U.S. alone, approximately 20 % of all foodborne disease outbreaks are linked to seafood consumption, with half of these cases attributed to algal toxins. Globally, such toxins are responsible for an estimated 60,000 poisoning incidents annually, with a mortality rate of 1.5 % (Van Dolah, 2000).

The public health burden of HABs is particularly acute in communities that depend on coastal or freshwater ecosystems. Medical expenditures have risen in response to these health impacts. For instance, Bechard and Lang (2024) report that in Florida, HABs have led to an average increase of 23.67 healthcare admissions per zip code per month, translating to an estimated $250,000 in additional healthcare costs across affected areas. Beyond physical health, HABs also induce psychological and socio-economic pressures. Communities frequently exposed to blooms report heightened stress and anxiety, largely due to disruptions in local economies and livelihoods. Individuals in the fishing industry are especially vulnerable, often experiencing declines in emotional well-being because of financial losses and the challenges of economic recovery (Moore, 2020). Furthermore, the interruption of commercial and social activities can erode community identity, diminish place attachment, and weaken the sense of distinctiveness (Willis, 2018).

The occurrence of HABs also adversely affects recreational activities, particularly fishing. Jayasekera et al. (2024) demonstrate that advisories specifically related to HABs significantly influence both the demand for and the perceived value of fishing, with heterogeneous effects across different groups. The estimated welfare loss at reservoirs impacted by HABs is approximately $12 per trip, with disproportionately higher losses observed among gamefish-oriented and college-educated anglers. Similarly, Wolf et al. (2017) report that fishing license sales decline by 10 % to 13 % when algal concentrations exceed the World Health Organization's threshold for moderate health risk. In counties bordering Lake Erie, a large, summer-long algal bloom could lead to an estimated reduction of 3600 fishing licenses and a corresponding loss of $2.25 million to $5.58 million in fishing-related expenditures. Furthermore, Wolf et al. (2019) estimate that, should water quality deteriorate to the extent that the western basin of Lake Erie is closed, annual aggregate losses would amount to $7.7 million for beachgoers and $69.1 million for recreational anglers.

The tourism industry is also significantly affected by HABs. For instance, Alvarez et al. (2024) estimate that the 2018 Florida red tide bloom resulted in an estimated $2.7 billion loss to tourism-related businesses. However, they find that the relationship between HAB concentrations and tourism impacts exhibits an inverted-U pattern. This suggests that higher concentrations of HAB organisms do not necessarily correspond to greater economic losses. In the case of Long Beach, WA, Weir et al. (2022) estimate that a full-season closure could lead to substantial revenue losses across various sectors: $16,875 for gas stations, $117,600 for food stores, $217,800 for accommodations, and $491,400 for food service establishments, amounting to a total lower-bound economic impact of $843,675.

Finally, HABs exert a significant negative impact on the housing market. Using a detailed multi-lake hedonic analysis across six Ohio counties from 2009 to 2015, Wolf and Klaiber (2017) estimate capitalization losses for near-lake homes ranging from 11 % to 17 %, with losses exceeding 22 % for lake-adjacent properties. Bechard (2021) analyzes six counties in Southwestern Florida affected by four major algal blooms over the past two decades and finds that properties within one mile of the coast sold for up to 30 % less than comparable homes in unaffected counties during the same month. Similarly, Wolf et al. (2022) report that the effects of HABs on housing prices are spatially concentrated within 1.2 km of Lake Erie, where a 1 μg/L increase in algae concentration is associated with a 1.7 % ($2205) decline in property value for the average near-lake home. Zhang et al. (2022) highlight regional heterogeneity in the marginal cost of HABs, with a 10-percentage-point increase in annual occurrence reducing average near-shore home values by 3.5 % in the Upper Midwest, 3.8 % in the South, 3.3 % in the Southeast, and 4.3 % in the Northeast of the U.S.

3. Data and methods

3.1. Study region

Our study focuses on Florida's coastal counties along the Gulf of Mexico and the Atlantic Ocean, where recurrent HABs caused by Karenia brevis, commonly referred to as "Florida red tide," have been systematically recorded since the 1840s.[1] Counties along the Gulf Coast, particularly in the southwestern region (e.g., Pinellas, Hillsborough, Sarasota, and Lee), experience the most frequent and intense Karenia brevis blooms (see Fig. 1). This elevated exposure is largely attributed to their proximity to the West Florida Shelf, where subsurface nutrient dynamics and interactions with the Loop Current create favorable conditions for bloom initiation (Weisberg et al., 2019).

In contrast, counties along Florida's Atlantic Coast, such as Miami-Dade, Broward, and Palm Beach, experience fewer and less frequent HABs, yet face distinct exposure risks due to higher population densities and the concentration of beach tourism infrastructure. This dual-basin geography gives rise to divergent socio-ecological vulnerability profiles. Gulf Coast communities contend with chronic, high-intensity Karenia brevis blooms that significantly impact fisheries, respiratory health, and coastal livelihoods. Meanwhile, Atlantic Coast populations, though exposed to blooms less frequently, are vulnerable to acute economic disruptions when events do occur. For instance, during the prolonged red tide event of 2018, widespread respiratory distress and the displacement of recreational activities contributed to estimated tourism-related losses of approximately $2.7 billion (Alvarez et al., 2024).

3.2. Harmful algal blooms data

We obtained geo-referenced data on HAB events from the Florida Fish and Wildlife Conservation Commission, covering the period from

[1] See the source: https://myfwc.com/research/redtide/faq/

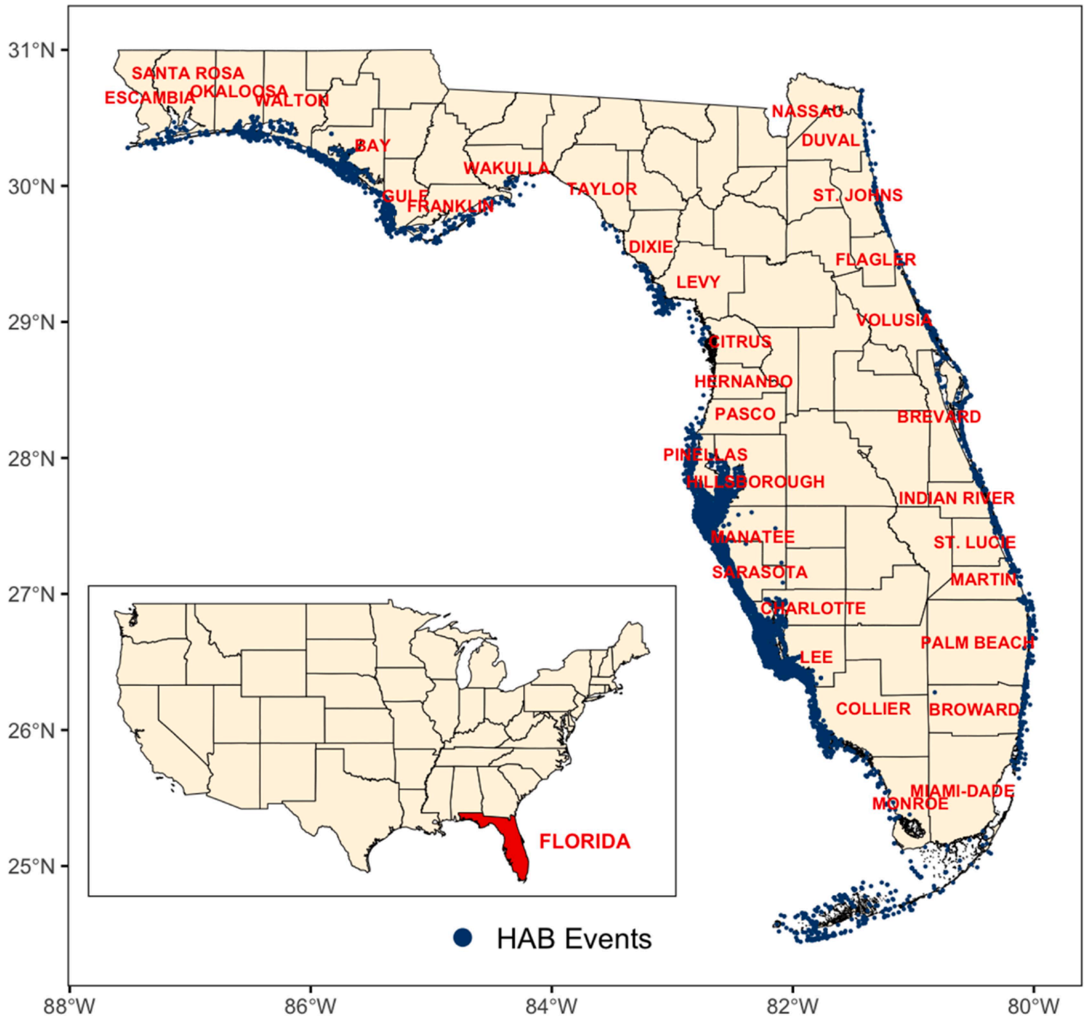

Fig. 1. Study region.
Notes: This figure shows our study region, 34 coastal counties in Florida, U.S. The blue dots denote all geo-referenced harmful algal bloom events from 1960 to 2019 along the coastline.

1960 to 2019.[2] Each record includes the sampling date, geographic coordinates (latitude and longitude), and the concentration of Karenia brevis (the toxic algae responsible for red tides) measured in cells per liter. Our data processing involved several steps. First, we excluded records with zero algal cell concentration. Second, we spatially matched each sampling location to a specific Florida county using a county-level shapefile with coastal boundaries, as most sampling sites are located in nearshore waters. This process yielded 28,197 valid HAB events. The spatial matching revealed that between 1960 and 2019, HABs were recorded in 34 coastal counties, including Bay, Brevard, Broward, Charlotte, Citrus, Collier, Dixie, Duval, Escambia, Flagler, Franklin, Gulf, Hernando, Hillsborough, Indian River, Lee, Levy, Manatee, Martin, Miami-Dade, Monroe, Nassau, Okaloosa, Palm Beach, Pasco, Pinellas, Santa Rosa, Sarasota, St. Johns, St. Lucie, Taylor, Volusia, Wakulla, and Walton. Third, we divided the study period into six decades: the 1960s (1960–1969) through the 2010s (2010–2019). For each of the 34 counties and each decade, we calculated the total number of HAB events, the cumulative algal cell concentration (per liter), and the average algal cell concentration (per liter).

3.3. Census variables

County-level socio-demographic data were sourced from the U.S. decennial census via the National Historical GIS (NHGIS) provided by IPUMS.[3] To align census data with HAB events, we assigned each decennial census to the preceding decade (e.g., the 1970 census represents socio-demographic conditions for 1960–1969). Due to the unavailability of 2020 decennial census data, we used the 2022 American Community Survey 5-year estimates as a substitute. This approach allowed us to construct a panel dataset at the county-decade level across six decades. From the census records, we extracted a list of key socio-demographic variables for this study's analysis, including total population, age distribution, racial composition, educational attainment, and income levels.

3.4. Empirical model

To empirically investigate the relationship between HAB exposure and socio-demographic changes, we estimate the following two-way fixed effects model:

[2] See data source and description: https://geodata.myfwc.com/datasets/myfwc::recent-harmful-algal-bloom-hab-events/about

[3] See data source and description: https://www.nhgis.org

$$y_{it} = \beta_1 HAB_{it} + f_i + f_t + \varepsilon_{it} \quad (1)$$

where HAB_{it} denotes the three distinct measures of HAB exposure, including total HAB events, cumulative algal cell concentration, and average algal cell concentration for county i in decade t. Since the values of these three variables are large in magnitude and contain many zeros, we applied the inverse-hyperbolic-sine transformation to normalize them, as commonly done in the literature (see Bellemare and Wichman, 2020 for a discussion). Let y_{it} denote a list of socio-demographic variables for county i in decade t, including the total population (Total population), the percentage of the population aged under 18 (% Children), the percentage of the population aged 65 and older (% Senior), the percentage of Black or African American residents (% Black), the percentage of residents holding a college degree (% College), and the percentage of household income below $25,000 (% Low income).

To account for any unobserved factors that may confound the relationship, we include county fixed effects f_i and decade fixed effects f_t. Specifically, the county fixed effects control for any time-invariant factors specific to each county, while the decade fixed effects capture temporal shocks common across all counties. Standard errors are clustered at the county level to account for within-county correlation over time.

3.5. Spatial inequality analysis

To quantitatively assess the extent of spatial inequality in exposure to HABs and its evolution over time, we map the Lorenz curve and calculate the Gini coefficient accordingly across a six-decade span, from the 1960s through the 2010s. We focus on the proportions of children and seniors in each county as proxies for population vulnerability. For a comprehensive analysis, we analyze three measures of exposure: the total HAB events, the cumulative algal cell concentration, and the average algal cell concentration.

To illustrate our methodology for calculating the Gini coefficient, Fig. 2 provides an example using the total HAB events and proportion of seniors from the 2010s. Figure 2(a) ranks Florida's 34 coastal counties in ascending order by the proportion of senior residents. This ranking forms the basis of the x-axis in the Lorenz curve presented in Figure 2(c). Figure 2(b) shows the corresponding number of total HAB events for each county, aligned with the order in Figure 2(a). Figure 2(c) then displays the Lorenz curve, where the x-axis represents the cumulative share of counties (ordered by% Senior), and the y-axis represents the cumulative share of total HAB events. The 45-degree dashed line indicates perfect equality. The area between the Lorenz curve and the equality line (A), relative to the total area under the line ($A + B$), defines the Gini coefficient, where $Gini = \frac{A}{A+B}$. In practice, we applied a trapezoidal approximation to compute the Gini coefficient using the following formula:

$$Gini = 1 - \sum_{i=1}^{34} (Y_i + Y_{i-1}) \times (X_i - X_{i-1}) \quad (2)$$

where X_i denotes the cumulative share of counties, and Y_i denotes the cumulative share of HAB exposure. By definition, a Gini coefficient ranges from 0 to 1, where a Gini coefficient approaching 1 indicates that HAB exposure is highly concentrated in a small number of counties, reflecting a high level of spatial inequality. In contrast, a Gini coefficient approaching 0 suggests that exposure is more evenly distributed across regions.

3.6. Summary statistics

Table 1 presents the summary statistics for HAB variables and socio-demographic characteristics used in this study. The dataset comprises 28,197 geo-referenced HAB records from 1960 to 2019, spanning 34 coastal counties in Florida. Aggregated at the county-by-decade level, the final panel includes 204 observations. On average, each county experienced 138 HAB events per decade, with a cumulative total of approximately 81 million Karenia brevis cells per liter. The average algal concentration per event is 0.164 million cells per liter. Regarding socio-demographic characteristics, the average county population is 0.3 million. Children (under 18) and seniors (65 and older) account for 23.0 % and 19.4 % of the population, respectively. The average proportion of Black or African American residents is 11.5 %. Regarding educational

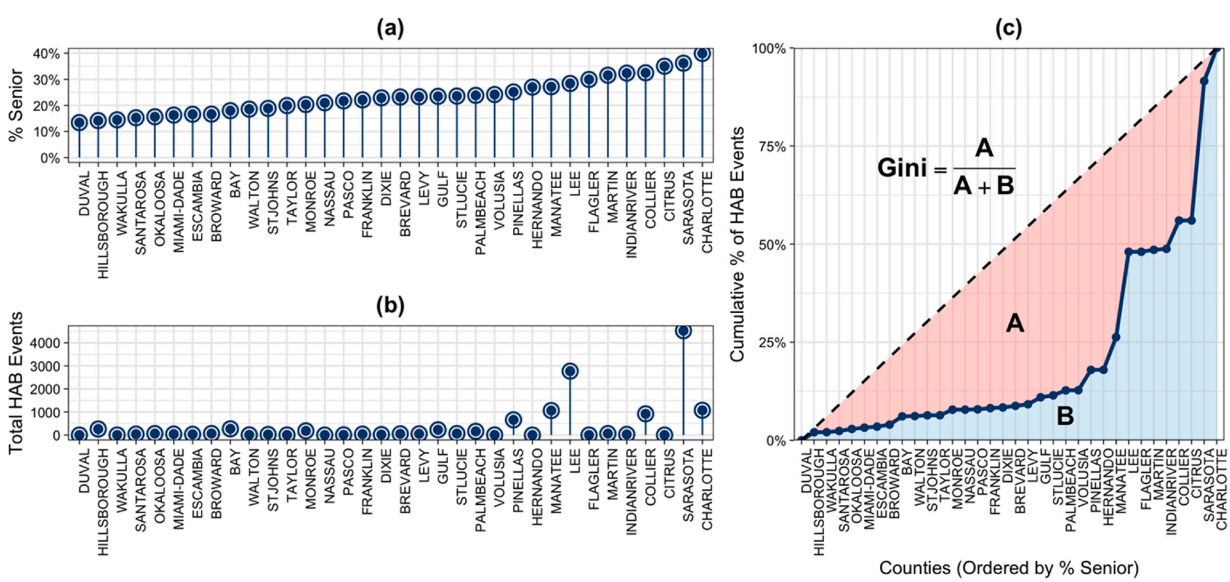

Fig. 2. Illustration of constructing the lorenz curve and gini coefficient.
Notes: This figure illustrates the methodology for calculating the Gini coefficient using the total HAB events and proportion of seniors from the 2010s as an example. Figure 2(a) ranks Florida's 34 coastal counties in ascending order by the proportion of senior residents, which forms the basis of the x-axis in the Lorenz curve presented in Figure 2(c). Figure 2(b) shows the corresponding number of total HAB events for each county, aligned with the order in Figure 2(a). Figure 2(c) then displays the Lorenz curve, where the x-axis represents the cumulative share of counties (ordered by% Senior), and the y-axis represents the cumulative share of total HAB events. The 45-degree dashed line indicates perfect equality. The area between the Lorenz curve and the equality line (A), relative to the total area under the line (A + B), defines the Gini coefficient, where Gini=A/(A + B).

Table 1
Summary statistics.

Variable	Mean	S.D.	Min.	Max.
Panel A: Harmful algal bloom				
Total events	138.2	451.2	0	4528
Cumulative cell concentration (million per liter)	81.37	377.4	0	3215
Average cell concentration (million per liter)	0.164	0.299	0	1.752
Panel B: Socio-demographic characteristics				
Total population (in 1000,000)	0.322	0.472	0.004	2.702
% Children	0.230	0.059	0.120	0.402
% Senior	0.194	0.076	0.034	0.399
% Black	0.115	0.066	0.019	0.309
% College	0.179	0.084	0.018	0.445
% Low income	0.503	0.295	0.111	0.994

Notes: This table summarizes the county-by-decade level harmful algal bloom variables and socio-demographic characteristics for a balanced panel of 204 observations spanning 34 coastal counties in Florida and 6 decades.

attainment, 17.9 % of residents hold a college degree. Additionally, 50.3 % of households report annual incomes below $25,000, which are considered low-income.

4. Results

4.1. Trends in harmful algal blooms during 1960–2019

Fig. 3 presents the temporal trends in HAB exposure along Florida's coastal regions from the 1960s through the 2010s. During this period, the frequency of HAB events rose substantially, with a pronounced surge beginning in the 1980s. While such events were nearly nonexistent in the 1960s, their annual occurrence escalated to approximately 1274 events by the 2010s—a seventeen-fold increase. Concurrently, cumulative algal cell concentrations experienced a dramatic rise, increasing from 25 million cells per liter in the 1960s to roughly 724 million cells per liter in the 2010s. This indicates significant growth in both event frequency and total biomass. Notably, there has been a marked expansion of HAB events since the 1990s, together with an increase in cumulative cell concentration. However, the average cell concentration per event peaked in the 1990s at around 0.7 million cells per liter, followed by a gradual decline. By the 2010s, average bloom intensity ranged from 0.005 to 1.25 million cells per liter per event, suggesting that although HABs have become more frequent, their per-event intensity has slightly diminished.

Fig. 4 illustrates the spatial distribution of county-level HAB events across Florida from the 1960s through the 2010s. In the early decades (1960s–1980s), HAB occurrences were primarily concentrated in the nearshore waters of southwest Florida, particularly in counties such as Pinellas, Sarasota, Lee, and Collier. During this period, the geographic spread of events remained relatively limited. However, beginning in the 1990s, the spatial footprint of HABs expanded markedly, extending northwest toward Escambia County and southward to the Florida Keys, eventually covering nearly the entire western coastline. This geographic expansion was accompanied by a sharp rise in event frequency across several counties. For example, the number of HAB events in Lee County increased from approximately 300 in the 1960s to nearly 2800 in the 2010s. Similarly, Collier County saw a rise from around 50 to 920 events over the same period.

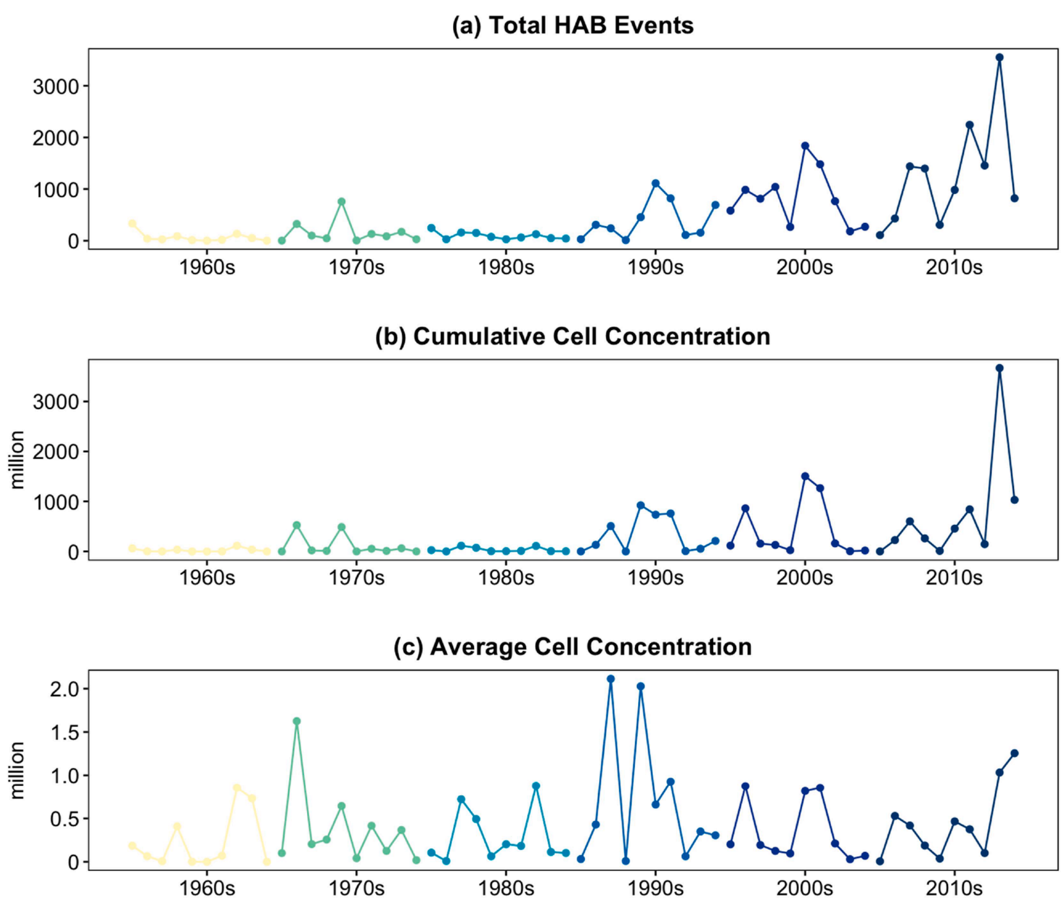

Fig. 3. Trends in harmful algal blooms between the 1960s and 2010s.
Notes: This figure plots the yearly total number of harmful algal bloom events, the cumulative algal cell concentration, and the average algal cell concentration along the 34 counties in Florida during 1960–2019.

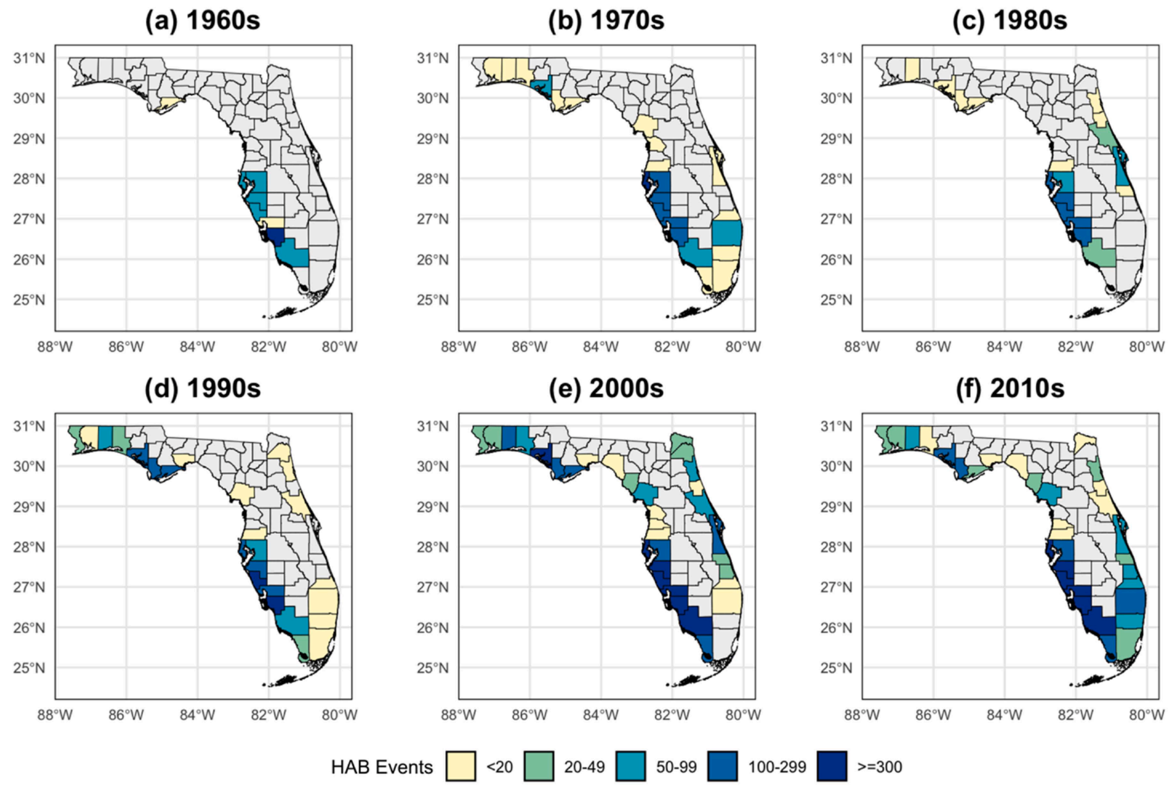

Fig. 4. Spatial distribution of county-level harmful algal bloom events by decade.
Notes: This figure presents the spatial distribution of the total harmful algal bloom events along the 34 counties in Florida from the 1960s to the 2010s.

Additionally, counties along Florida's eastern coastline, such as Martin, Palm Beach, and Broward, began experiencing a notable rise in HAB events after the 2000s, despite having recorded minimal activity in earlier decades. For instance, Palm Beach County reported over 150 HAB events during the 2010s alone. Throughout the study period, southwest Florida consistently emerged as the region most affected by HABs, serving as a persistent hotspot. However, this concentration has gradually expanded both northward and southward along the western coastline. By the 2010s, nearly all of Florida's coastal counties had reported HAB occurrences, highlighting the growing geographic spread and intensifying impact of these environmental hazards.

4.2. *Relationship between harmful algal blooms and socio-demographic changes*

Fig. 5 displays the estimated impacts of HABs on six socio-demographic variables, based on results from estimating Eq. (1). The analysis reveals that HABs are significantly associated with reductions in both total population and the proportion of children in affected counties. Specifically, a 1 % increase in total HAB events corresponds to an estimated decline of approximately 18,000 residents and a 0.4 percentage point decrease in the child population share. Similarly, a 1 % rise in cumulative or average algal cell concentration is linked to population decreases of roughly 5000 and 6000 individuals, respectively, along with 0.1 percentage point reductions in the share of children.

In contrast, HABs are positively associated with the proportion of seniors. A 1 % increase in total HAB events, cumulative cell concentration, or average cell concentration is estimated to raise the senior population share by 0.4, 0.1, and 0.1 percentage points, respectively. While the estimated effects on the proportions of Black residents, college-educated individuals, and low-income households are generally negative, these associations are not statistically significant. The only exception is the effect of average cell concentration on the proportion of Black residents, which is marginally significant at the 10 % level ($p < 0.10$).

4.3. *Spatial inequality in exposure to harmful algal blooms*

Fig. 6 presents Gini coefficients measuring spatial inequality in three measures (i.e., total HAB events, cumulative algal cell concentration, and average cell concentration) of HAB exposure across Florida counties, stratified by the proportions of children and senior populations. In Figure 6(a), Gini coefficients for both child- and senior-sorted counties generally range between 0.4 and 0.6, indicating a moderate level of spatial disparity. Notably, in the 2010s, the Gini coefficient for senior-sorted counties rises sharply, reaching approximately 0.612, signaling a marked increase in the spatial concentration of HAB exposure among counties with higher proportions of senior residents.

Figure 6(b) reveals the highest levels of spatial inequality in HAB exposure. During the 1990s, Gini coefficients for both child- and senior-sorted counties exceeded 0.75, indicating that HAB cell concentrations were heavily concentrated in a small number of counties. Although these values declined slightly in the following decades, the overall level of inequality remained elevated. In contrast, Figure 6(c) shows consistently lower Gini coefficients, with values dropping to around 0.1 in the 1980s. This suggests that average exposure levels were more evenly distributed across counties during that period. However, a modest uptick in the 2010s points to a mild resurgence in spatial inequality.

5. Discussion

The combined evidence from our regression analysis, Lorenz curves, and Gini coefficients reveals systematic associations between HAB exposure and demographic composition across Florida's coastal counties. The regression results indicate a significant negative relationship between HAB exposure and the proportion of children, aligning with Lorenz curves (Appendix Figures S1–S6) that predominantly lie above the line of equality, suggesting disproportionate exposure in

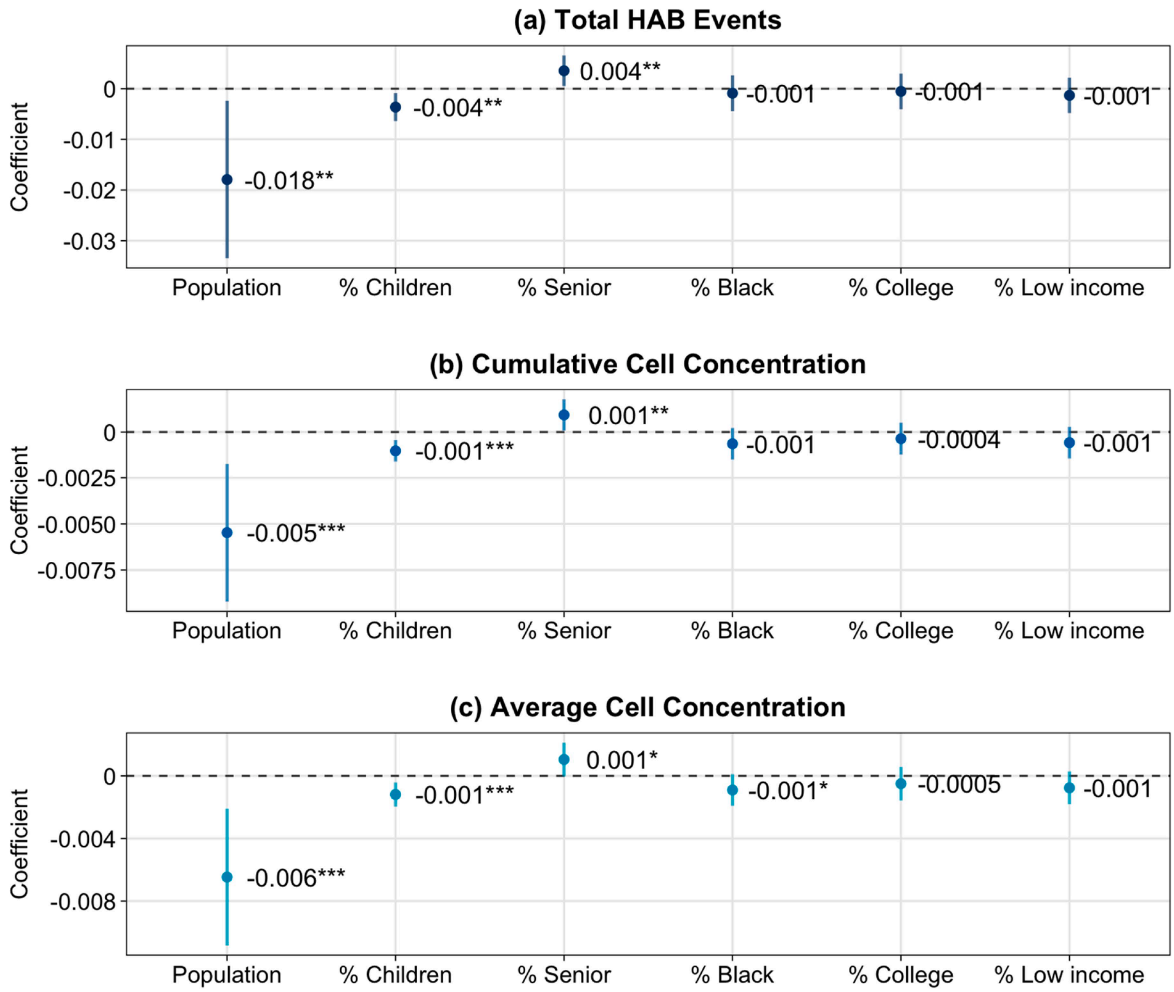

Fig. 5. Relationship between harmful algal blooms and socio-demographic patterns.
Notes: This figure plots the coefficient estimates from estimating the model specified in Eq. (1), with vertical lines denoting the 95 % confidence intervals. The model specification controls for county and decade fixed effects. Standard errors are clustered at the county level. *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

counties with fewer children. In contrast, positive regression coefficients for seniors, along with Lorenz curves falling below the equality line, point to a higher concentration of HAB exposure in counties with relatively larger elderly populations. This pattern may be influenced by factors such as Florida's warm climate, which attracts retirees (Howells, 2011), the historical development of retirement communities in areas like Sarasota and Charlotte (Sheskin, 2010), and favorable tax policies, including the absence of state income and estate taxes (Holcombe, 2015). The persistence of these associations over multiple decades underscores the intersection of HAB exposure and demographic structure in shaping spatial disparities in environmental inequality along Florida's coastline.

Building on these demographic patterns, the implications for environmental health equity are particularly critical for aging populations. Florida consistently ranks as the top destination for retirees (Howells, 2011), and our results indicate that seniors are disproportionately concentrated in HAB-affected counties. Given that older adults are especially susceptible to the adverse health effects of HABs, including respiratory distress, gastrointestinal illness, and the exacerbation of chronic conditions (Koszalinski et al., 2024), there is an urgent need for policy frameworks that incorporate age-sensitive risk mitigation. Public health strategies should prioritize targeted outreach, early warning systems, and adaptive infrastructure to protect vulnerable senior populations from the escalating impacts of HABs.

First, early warning systems must be designed with the specific needs of older adults. Our findings, which show a disproportionate concentration of seniors in counties with higher HAB risk, underscore the importance of ensuring that public health advisories are disseminated through senior-accessible communication channels such as community centers, senior housing facilities, caregiver networks, and local health departments. Tailoring both the format and delivery of these messages can significantly enhance their reach and effectiveness among aging populations. For example, providing information through platforms commonly used by older adults, such as printed materials or phone-based systems, may be more effective than relying solely on digital channels.

Additionally, Jacobi et al. (2024) highlight that awareness and concern about HABs vary across demographic groups. Notably, individuals who reported awareness of HAB-related health risks were more likely to be older and possess higher levels of income and education. However, concern about the impacts of HABs was lowest among males and individuals identifying as White and non-Hispanic. These findings suggest that public health practitioners can improve outreach by leveraging demographic insights to craft more resonant and inclusive messaging strategies. Specifically, in counties with higher HAB exposure and aging populations, outreach efforts should be tailored to address the unique concerns of older adults who may be more vulnerable to health impacts. By aligning communication efforts with the awareness profiles and concerns of different subpopulations, especially those at heightened risk, agencies can foster more equitable and effective public health

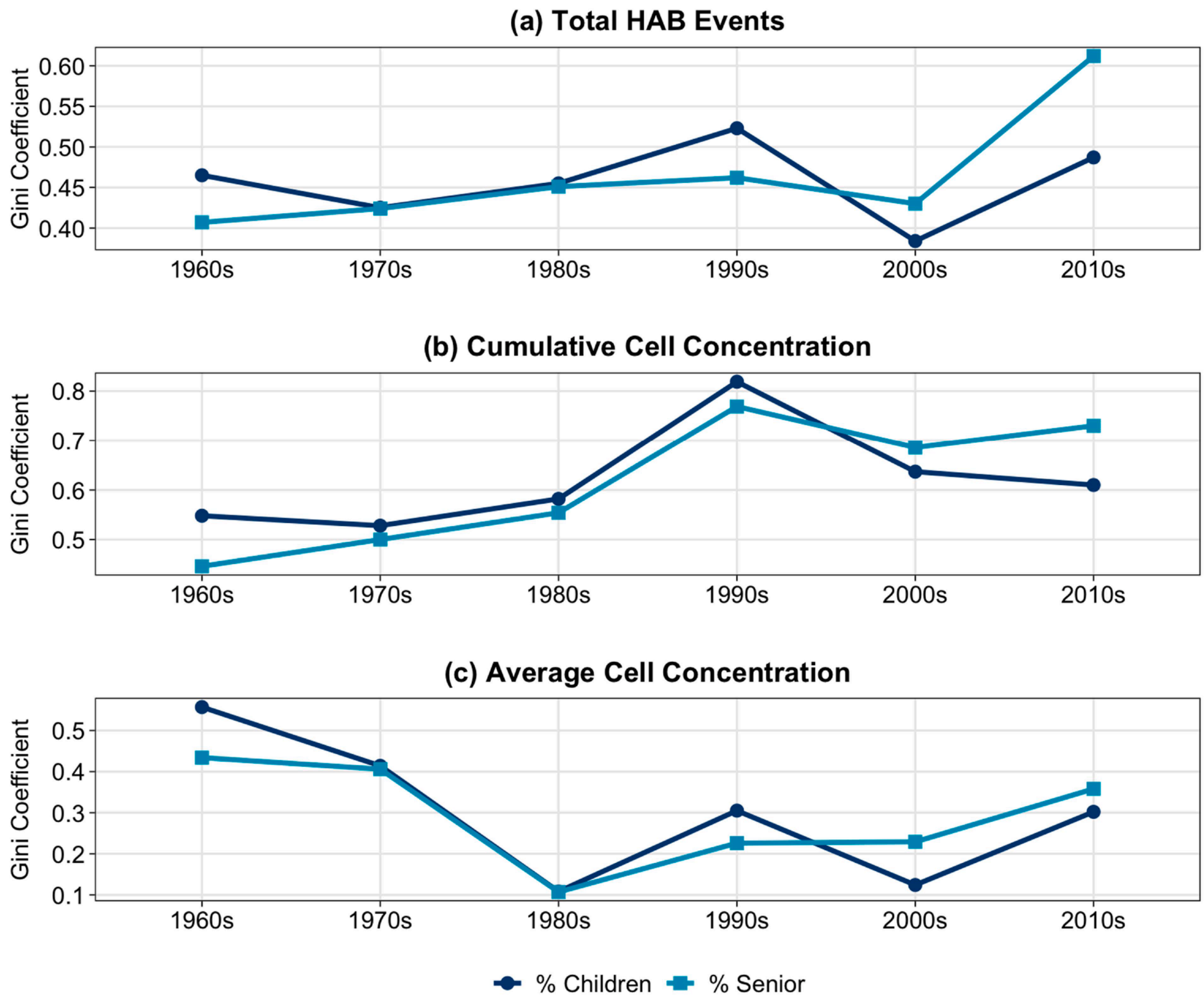

Fig. 6. Spatial inequality and gini coefficients.
Notes: This figure plots Gini coefficients measuring spatial inequality in three measures of harmful algal blooms exposure across Florida counties, stratified by the proportions of children and senior populations.

responses to HAB events.

Second, both the content and delivery of public health information must be strategically designed to address spatial and perceptual disparities in awareness of HABs. Research indicates that individuals' geographic location can significantly influence their perceptions and understanding of HAB risks. For example, Kuhar et al. (2009) find that many residents in Florida lacked timely and accurate information about red tide events due to inconsistent public outreach efforts. This information gap can hinder effective risk mitigation, particularly in high-exposure areas. Moreover, Smith et al. (2014) observe that while most survey participants had heard of algae, few could accurately define it or articulate its health implications. However, they also demonstrate that simple interventions, such as distributing educational brochures, can substantially improve public knowledge. These findings underscore the importance of not only disseminating information but also ensuring it is accessible, comprehensible, and relevant to diverse audiences. For example, in counties like Sarasota, where senior populations are large and HAB exposure is frequent, public health messaging should emphasize the specific health risks that seniors face, such as respiratory distress or exacerbation of chronic conditions, and provide information through senior-accessible formats like printed materials, phone notifications, or community events. To bridge these gaps, scientists and public health professionals must take a more proactive role in translating research findings into actionable public knowledge. This includes engaging directly with communities, leveraging local networks, and using culturally and demographically tailored messaging.

Third, adaptive infrastructure is critical to reducing the risks faced by senior populations in HAB-prone counties. Our findings show that areas with higher concentrations of seniors also experience more frequent HAB exposure, which increases vulnerability. Therefore, investments in infrastructure that specifically address the needs of older adults are crucial. This includes improving indoor air quality in senior housing facilities, enhancing access to healthcare services for conditions exacerbated by HABs (such as respiratory or gastrointestinal issues), and reinforcing coastal infrastructure to minimize the impact of HAB events on local communities. Additionally, adaptive infrastructure should focus on increasing mobility options for seniors in high-exposure areas, such as providing accessible transportation to evacuation centers or health facilities during HAB events. By aligning infrastructure development with the demographic needs of Florida's coastal communities, policymakers can help safeguard vulnerable senior populations from the compounded risks of HAB exposure and mobility limitations.

While this study provides new insights into how socio-demographic patterns have intersected with HAB exposure over the past six decades, several limitations exist. First, although we link nearshore HAB events to county-level exposure and correlate them with socio-demographic patterns, our approach does not account for intra-county migration. Exploring migration patterns within counties could offer a more nuanced understanding of how populations perceive and respond to environmental hazards. Second, our analysis focuses on correlation rather than causation. While we examine the relationship between HAB exposure and demographic variables, we do not account for other potential drivers of population change, such as major natural hazards. As Smith (2005) notes, population dynamics are shaped by a complex interplay of factors beyond environmental stressors like HABs. Moreover, although HABs may influence demographic patterns, their impacts are generally less severe than those of other natural disasters, such as tropical cyclones or coastal floods, in terms of frequency, fatalities, and economic losses (Hoagland et al., 2020).

6. Conclusions

In this study, we examine six decades of HAB events, spanning from 1960 to 2019, across 34 coastal counties in Florida, U.S., to quantify the relationship between three measures of HAB exposure and socio-demographic changes. We also use the Gini coefficient to assess spatial disparities in HAB exposure, focusing on children and seniors, the two groups who are especially vulnerable to environmental hazards. Our findings reveal that HAB exposure is significantly associated with declines in both the total population and the proportion of children in affected counties. Conversely, HAB exposure is positively correlated with a higher share of senior residents. Notably, spatial inequality in HAB exposure is evident: counties with lower proportions of children tend to experience more exposure, while those with higher concentrations of seniors face disproportionately greater exposure.

Our study provides new insights into how socio-demographic patterns have intersected with HAB exposure over the past six decades, and it highlights several directions for future research. First, future research could explore the causal mechanisms behind the observed correlations, particularly by examining intra-county migration patterns and considering other factors, such as larger natural disasters, that might also drive population dynamics. A more integrated approach would provide a deeper understanding of how multiple factors shape socio-demographic shifts in response to environmental risks like HABs. Second, research on adaptive capacity and community resilience in the context of HAB exposure remains underdeveloped. Future studies should explore how communities adapt to recurring HAB events, with particular attention to the roles of local organizations, healthcare access, transportation infrastructure, and social capital in shaping recovery trajectories. Third, integrated assessment models offer a promising framework for simulating how different demographic groups might respond to alternative HAB management strategies under various climate change scenarios. Bridging earth system dynamics with human responses can thus support the development of more equitable and effective environmental policies.

CRediT authorship contribution statement

Hao Chen: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Haoluan Wang:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hal.2025.102999.

Data availability

Data will be made available on request.

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