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ESTIMATING THE BENEFITS OF OCEAN COLOR DATA IN MITIGATING HAB EVENTS

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II. Executive Summary

Ocean color observations are rarely used directly by those whose decisions and actions are designed to reduce the effects of harmful algal blooms (HABs). Instead, they are a component in complex value chains. They are used to inform models whose outputs are disseminated to a diverse array of end users who also rely on a wide range of other information. Estimating the Benefits of Ocean Color Data in Mitigating HAB Events provides national-scale estimates of the costs of HABs in the United States and the potential benefits of the National Ocean and Atmospheric Administration's (NOAA) satellite-based ocean color observations as they contribute to reducing those costs.

National-scale estimates of the economic effects of HABs are one important product of this investigation. Another is a national-scale estimate of the potential benefits of ocean color observations as they are used in products that inform the management of HABs to reduce their impacts on society.

Perhaps more importantly, *this analysis provides a framework for refining these estimates in the future*. The research upon which this analysis is based has three important limitations.

- Studies tend to be focused on a few of the areas where HABs regularly occur.
- Existing literature focuses almost exclusively on larger, less frequent events and the few species that cause them. Estimating the full impacts of HABs will require analysts to account for all events, including the more frequent, less impactful events whose combined losses will represent a significant share of the total.
- We have a limited understanding of how ocean color data are used to mitigate the impact of HAB events.

Aggregating county-level HAB damage estimates derived from peer-reviewed literature across coastal counties in the continental U.S. (CONUS) gives a total expected annual HAB damages of $1.3 billion.

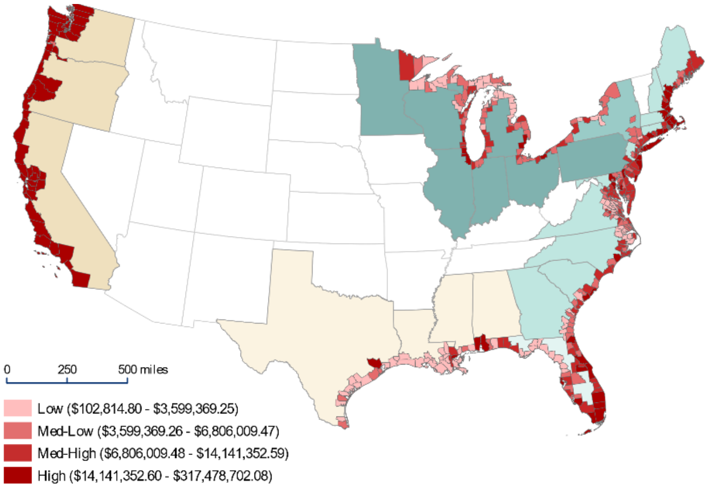

Figure 1. Estimated expected annual damages due to HAB events by county

OCEAN COLOR DATA

Currently, ocean color data for United States waters are provided by polar satellites, which have orbits that pass over the poles of the earth. These satellites can view the entire earth but can only take observations at a single point every 12 hours. This leads to several significant impacts when using these satellites for ocean color observations. The 12-hour orbit means there is only a possible maximum of two observations per day at any specific location. Clouds frequently obscure the ocean when satellites pass over, resulting in the loss of observations and creating data gaps. The frequency of observations and data gaps make accurate estimations of algae concentrations difficult because algae tend to move up and down in the water column based on environmental factors. The sunlight reflected out of the ocean measured by the satellites can only reach the upper limits of the water column, so if the satellite passes during a time the algae are lower in the water column, the concentration of algae will be underestimated. To remedy these problems, NOAA plans to add ocean color sensors to future geostationary satellites (e.g., GeoXO), whose orbits always place them above the same field of view. This would allow for observations every 1-2 hours, reducing data gaps caused by clouds and less frequent observations.

Ocean Color

"Ocean color" refers to the hue of water bodies, including the oceans and Great Lakes, which changes due to sunlight interacting with the water and its components. In the ocean, sunlight is either absorbed or scattered. Much of the scattering can be attributed to organisms in the water that contain pigments, such as chlorophyll-a. Satellite sensors collect ocean color data allowing for regular surveys of larger areas of water. After being calibrated for other water-based and atmospheric elements that can scatter light, ocean color satellite observations can be used to estimate the concentration of organisms in the water. This has practical applications for a variety of fields, such as the detection of harmful algal blooms, hypoxic zones, and pollution, as well as monitoring of fisheries, aquaculture, carbon observations, and marine ecosystems. Many different satellites and sensors provide ocean color observations.

ECONOMIC IMPACTS OF HABS

Harmful algal blooms (HABs) are caused by the excessive growth of some types of algae when exposed to the right environmental conditions, usually warm temperatures and excess nutrients. Although blooms of "nuisance" algae are widespread, what makes harmful algal blooms unique—and dangerous—is that they produce toxins that pose significant health risks to humans. HAB toxins can be transmitted through contaminated seafood, water, or air, depending on the type of toxin. These toxins cause a wide range of health problems, including gastrointestinal, respiratory, or neurological issues, and can cause death in some cases.

HABs pose a significant economic threat and are associated with many costs across a variety of economic sectors. For example, the direct health impacts of HABs include increased medical expenses, lost employment, and reduced quality of life from HAB-associated chronic illnesses.

Efforts to prevent health impacts usually focus on shutting down fisheries or beaches to prevent exposure to HAB toxins, but this leads to lost revenue and reductions in tourism. Aside from the health effects, algae blooms can be unpleasant to be around due to their appearance and smell, often leading to reductions in recreational fishing and tourism activities and property values.

Much of the existing research on the economic impacts of HABs can be broken down into the following major categories: public health, commercial fishing, recreational fishing, tourism, property values, water treatment, and monitoring and management (See Figure 2). HABs can cause other impacts, such as costs to clean up masses of algae that have washed ashore, and costs that are more difficult to quantify, such as fish kills. However, most research on HAB economic impacts can be grouped into one of these categories, and previous national HAB impact estimates have organized their findings similarly.

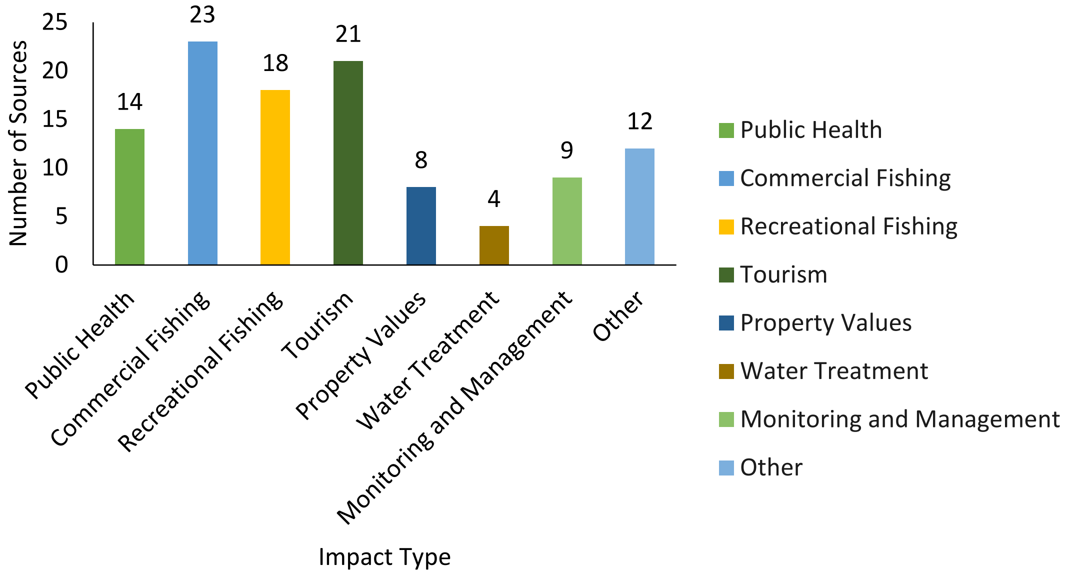

Figure 2. Number of Sources Reviewed by Economic Impact Type

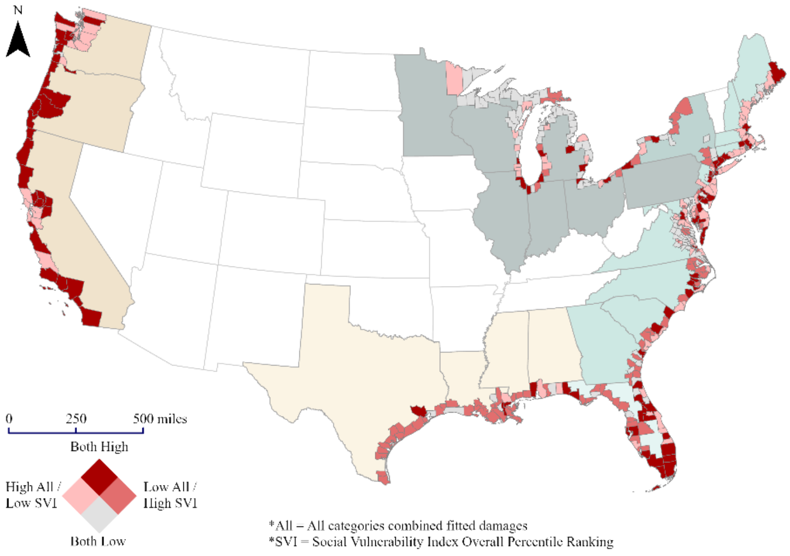

Figure 3. Estimated expected annual damages due to HAB events combined with the CDC's Social Vulnerability Index

Combining aggregated county-level damage estimates with geospatial analysis allows for a broad understanding of specific economic impacts of HABs in locations across the U.S. For instance, Figure 1 indicates that expected annual damages are likely to be high for nearly the entire West coast, parts of Florida, and southern and central New England. Another example combines HAB damage estimates with the CDC's Social Vulnerability Index demonstrating numerous instances of overlap between highly vulnerable communities and high HAB-related damages (See Figure 3).

ESTIMATING THE BENEFITS OF OCEAN COLOR DATA PRODUCTS

Ocean color data are being used to monitor HABs and create HAB forecasts. NOAA releases regular, regional bulletins with data about current and forecasted HABs. The bulletin for *Karenia brevis* (i.e., red tide) on the Gulf Coast of Florida has used satellite data for its predictions for 20 years. More recent efforts in Florida have used machine learning to analyze satellite imagery, resulting in HAB forecasts that are 91% accurate 8 days in advance, allowing for early closures of beaches before they can be contaminated with aerosolized HAB toxins. On the West Coast, satellite data are used for the California Harmful Algae Risk Mapping (C-HARM) system, with plans to incorporate that data into the NOAA West Coast HAB bulletin. Satellite imagery can be used to detect HABs (such as cyanobacteria (i.e., blue-green algae)) in inland waters with a resolution up to 300-meters. These data are publicly available through the CyAN mobile app, which can help everyday consumers such as recreational fishers and beachgoers know which waters to avoid.

Using the total expected damage estimates we can estimate the benefits of ocean color products in reducing HAB-related impacts. However, we need a better understanding of how ocean color products are used in managing and mitigating HAB events and their impacts to develop more accurate estimates. Previous studies on ocean color observations have assumed that "improved observations from GeoXO can reduce the effects of HABs on human health and the economy by 5 percent." NOAA's satellite and physical scientists have validated this initial assumption, noting that more concrete studies are being developed to refine it. If we also assume a flat 5% reduction in damages across all regions and damage categories, it would represent a **total expected annual benefit from Ocean Color products of $65.1 million.** Those benefits would be realized annually for the life of the sensor.

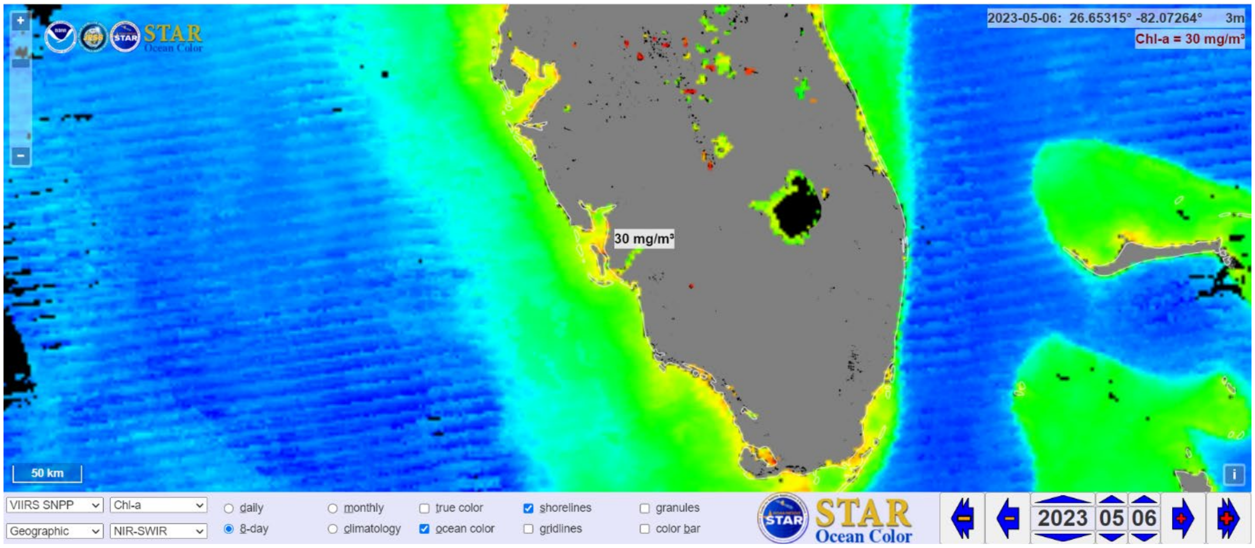

Figure 4. High chlorophyll concentrations near Sanibel, FL on May 6, 2023. Image courtesy of NOAA OCView.

This framework and assessment provide initial estimates of the economic effects of HAB events, the potential benefits of ocean color observations, and a methodology for future assessments. The analysis integrates findings from the current body of research into the framework, noting significant gaps and limitations. Addressing those gaps and limitations is a necessary first step in refining future estimates.

III. Introduction

BACKGROUND AND CONTEXT

“Ocean color” refers to the hue of water bodies, including the oceans and Great Lakes, which changes due to sunlight reflecting off components in the water, then scattering throughout the atmosphere.[1] In the open ocean and Great Lakes, variations in hue are mostly due to organisms in the water that contain photosynthetic pigments, such as chlorophyll-a. Ocean color data can be collected from sensors placed on satellites, which allows for larger areas of water to be regularly surveyed than is possible with in situ sensors. After being corrected for other water-based and atmospheric elements that can scatter light, ocean color satellite observations can be used to estimate the concentration of organisms in the water. This has practical applications for a variety of fields, such as the detection of harmful algal blooms, hypoxic zones, and pollution, as well as monitoring of fisheries, aquaculture, carbon observations, and marine ecosystems.

So far, ocean color observations have been provided by a variety of satellites and sensors, operated by different agencies.[2] In the United States, the current satellite sensors are the Visible Infrared Imaging Radiometer Suite (VIIRS) on the NOAA Joint Polar Satellite System and the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Aqua satellite. In the European Union, data are currently provided by the Ocean and Land Colour Instrument (OCLI) on the Sentinel-3 satellite, managed by the European Space Agency.

Currently, ocean color data for United States waters is provided by polar satellites, which have orbits that pass over the poles of the earth. These satellites can view the entire earth but can only take observations at a single point every 12 hours. This leads to several significant impacts when using these satellites for ocean color observations.[3] The 12-hour orbit means there are only a maximum of two observations per day at a specific point. Clouds frequently obscure the ocean when the satellite passes, resulting in the loss of observations and leaving large gaps in monitoring data. The minimal readings also make true estimations of algae concentrations

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[1] Groom, S., Sathyendranath, S., Ban, Y., Bernard, S., Brewin, R., Brotas, V., Brockmann, C., Chauhan, P., Choi, J., Chuprin, A., Ciavatta, S., Cipollini, P., Donlon, C., Franz, B., He, X., Hirata, T., Jackson, T., Kampel, M., Krasemann, H., & Lavender, S. (2019). Satellite Ocean Colour: Current Status and Future Perspective. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00485

[2] Groom et al., 2019

[3] Adkins, J. (2022). GeoXO benefit analysis. *Noaa.gov*. https://doi.org/10.25923/7tqj-r641

difficult because algae tend to float up and down water columns based on environmental factors. The sunlight measured by the satellites can only reach the upper limits of the water column, so if the satellite passes during a time the algae are lower in the water column, the concentration of algae and the spatial extent of blooms will be underestimated. To remedy these problems, NOAA plans to add ocean color sensors to future geostationary satellites, whose orbits place them above the same field of view at all times.[4] This will allow for observations every 1-2 hours, reducing the data gaps caused by clouds and allowing for monitoring of algae as they move throughout the water columns.

Harmful Algal Blooms

Harmful algal blooms (HABs) are caused by the excessive growth of some types of algae when exposed to the right environmental conditions, usually warm temperatures and increased nutrient availability. Although blooms of "nuisance" algae are widespread, what makes harmful algal blooms unique and dangerous is that they produce toxins that pose a significant risk to human health. HAB toxins can be transmitted through contaminated seafood, water, or air, depending on the type of toxin. When consumed, these toxins cause a wide range of health problems, including gastrointestinal, respiratory, or neurological issues, and can cause death in some cases.[5,6,7]

HABs pose a significant economic threat and are associated with many costs across a variety of economic sectors. For example, the direct health impacts of HABs cause medical expenses, lost employment, and reduced quality of life from HAB-associated chronic illnesses. Efforts to prevent health impacts usually focus on shutting down fisheries or beaches to prevent exposure to HAB toxins, but this leads to lost revenue and reductions in tourism. Aside from the health effects, algae blooms can be unpleasant to be around due to their appearance and smell, leading to further reductions in recreational fishing, tourism, and property values. The most recent estimate this study was able to find for the national economic impact of HABs suggest an

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[4] Adkins, 2022

[5] Hoagland P, Jin D, Polansky LY, Kirkpatrick B, Kirkpatrick G, Fleming LE, Reich A, Watkins SM, Ullmann SG, Backer LC. 2009. The costs of respiratory illnesses arising from Florida Gulf Coast Karenia brevis blooms. Environmental Health Perspectives 117:1239-1243. https://doi.org/10.1289/ehp.0900645

[6] Anderson DM, Hoagland P, Kaoru Y, White AW. 2000. Estimated annual economic impacts from harmful algal blooms (HABs) in the United States. WHOI-2000-11. Woods Hole, MA: Department of Biology, Woods Hole Oceanographic Institution.

[7] Hoagland P, Scatasta S. 2006. The economic effects of harmful algal blooms. In Granéli E, Turner JT, eds., Ecology of Harmful Algae. Ecological Studies, Vol. 189. Berlin: Springer-Verlag, Chap. 30, pp. 391-402. https://doi.org/10.1007/978-3-540-32210-8_30

annual impact of $129 million (in 2023 dollars),[8] but that study was working with incomplete data, that value was a conservative estimate, and that study was published in 2006 using data from 1987 to 2000.

Harmful algal blooms usually occur in a seasonal pattern, causing minor annual effects. Major economic consequences of HABs are usually due to outside factors such as unusual weather patterns or human interference that amplify blooms. One major factor affecting the severity of algae blooms is temperature. Warmer weather leads to more algae growth, in turn increasing toxin concentrations and the severity of HABs. For example, in 2015, a marine heatwave caused abnormally high temperatures in the Pacific Ocean, leading to a major HAB and widespread economic effects.[9] The association with temperature is also somewhat concerning given the global rise in sea temperatures due to climate change, which has the potential to increase the severity of blooms and allow existing types of algae to migrate to newly warmer waters.

Existing research on the economic impacts of HABs can be broken down into the following major categories:

1) public health,
2) commercial fishing,
3) recreational fishing,
4) tourism,
5) property values,
6) water treatment, and
7) monitoring and management.

The impacts of HABs on human health vary by toxin type, HAB type, and exposure method. There are over two dozen species of algae that produce harmful algal blooms,[10] but the majority of HAB research focuses on a few of the most common species and their associated toxins. This includes cyanobacteria, which is commonly referred to as blue-green algae and included in HAB research, despite the definition of algae typically not including prokaryotes such as bacteria. The following information about HAB types and their toxins was retrieved from a report on the proceedings of a 2020 workshop hosted by the Woods Hole

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[8] Hoagland, P., & Scatasta, S. (2006). The Economic Effects of Harmful Algal Blooms. *Ecological Studies*, 391–402. https://doi.org/10.1007/978-3-540-32210-8_30

[9] McCabe, R. M., Hickey, B. M., Kudela, R. M., Lefebvre, K. A., Adams, N. G., Bill, B. D., Gulland, F. M. D., Thomson, R. E., Cochlan, W. P., & Trainer, V. L. (2016). An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, *43*(19). https://doi.org/10.1002/2016gl070023

[10] U.S. National Office for Harmful Algal Blooms. (2019). *By Name – Harmful Algal Blooms*. Whoi.edu. https://hab.whoi.edu/species/species-by-name/

Oceanographic Institute (WHOI).[11] This is not an exhaustive list, and there are additional types of HABs, toxins, and species producing specific toxins that are not referenced here, usually because they are not the focus of current HAB literature.

Much of the economic literature on HABs focuses on five types of algae[12], each with their own toxin. Saxitoxin is primarily produced by the genus *Alexandrium*, commonly found on the Northeast Atlantic Coast and West Coast. Saxitoxin can bioaccumulate in shellfish, which is then consumed by humans. This can cause paralytic shellfish poisoning (PSP), resulting in gastrointestinal and neurological symptoms, as well as paralysis. Domoic acid is another HAB toxin, produced most often by the genus *Pseudo-nitzschia*, which is commonly found on the West Coast but is also present on the Northeast Atlantic Coast. Like saxitoxin, it spreads through bioaccumulation in shellfish. When consumed, domoic acid causes amnesic shellfish poisoning (ASP). Testing for domoic acid in potentially contaminated shellfish beds and waters has made ASP cases rare, but when they do occur, symptoms generally include gastrointestinal distress. Less common, but more serious neurological symptoms may also occur, including the namesake short-term memory loss, headaches, confusion, and dizziness. Another common toxin is brevetoxin, which is created by the HAB species *Karenia brevis*, primarily found in the Gulf of Mexico. Although it is possible for brevetoxin to bioaccumulate, causing neurotoxic shellfish poisoning (NSP), that is not the most common exposure route. Brevetoxins are usually aerosolized and inhaled, resulting in mostly respiratory symptoms. Ciguatoxin is created by the genus *Gambierdiscus*, usually found in more tropical waters. Ciguatoxin accumulates in fish, resulting in ciguatoxin fish poisoning (CFP) when consumed. Ciguatoxin is particularly difficult to control because CFP has been linked to over four hundred fish species, can be found even in inland areas due to the international transport of contaminated fish, and causes nearly two hundred symptoms.[13] Finally, freshwater cyanobacteria HABs produce many toxins, including microcystin. Unlike other HAB toxins, people are usually exposed to microcystin through contaminated drinking water or by swimming in water bodies with active algal blooms. Microcystin causes liver damage in addition to gastrointestinal, neurological, and respiratory symptoms. However, freshwater cyanobacteria are a diverse group of organisms and can produce toxins other than microcystin, including saxitoxin.

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[11] U.S. National Office for Harmful Algal Blooms. (2021). *Workshop on the Socio-Economic Effects of Marine and Fresh Water Harmful Algal Blooms in the United States*. https://hab.whoi.edu/wp-content/uploads/2021/04/HAB-Socioeconomics-Workshop-Proceedings_14.pdf

[12] The literature commonly groups three algae genera (*Alexandrium*, *Pseudo-nitzschia*, and *Gambierdiscus*), an algae species *Karenia brevis*, and freshwater cyanobacteria under the broad umbrella of HABs.

[13] Food and Agriculture Organization of the United Nation, & World Health Organization. (2023). Report of the Expert Meeting on Ciguatera Poisoning. In *FAODocuments*. https://www.fao.org/documents/card/en/c/ca8817en

Attempts to limit the health impacts of HABs usually focus on frequent testing for HAB toxins in water or seafood that is likely to be contaminated. If toxins are found to be in excess of safe levels, commercial fisheries are shut down by state or local governments to prevent the collection and subsequent sale of contaminated shellfish. In states where fisheries operate on a seasonal schedule, the opening of the fishery can also be delayed until the toxins dissipate. Unfortunately, this can lead to additional economic impacts. Commercial fishery delays or closures result in lost revenue for the fishery business and lost wages for the employees. This in turn can have indirect effects on local economies, due to the reduction in spending by the fishery and its employees.

Recreational fishing, tourism, and local property values can also be affected by HABs. The same regular testing for contaminated shellfish can be used to shut down recreational fishing sites, and testing for toxins in the water can shut down beaches where HABs occur. Additionally, algal blooms often have an unpleasant sight or smell, making people avoid areas with ongoing blooms. This further reduces visits to recreational fishing sites, boating, beachgoing, and other recreational activities, and lowers the value of properties near water with frequent or ongoing HABs.

Efforts to manage harmful algal blooms or their effects generally fall into three broad categories: prevention, control, and mitigation.[14] Prevention programs seek to block the creation or expansion of HABs by reducing nutrient levels, such as nitrogen and phosphorus. These efforts show promise where algae growth is directly correlated with nutrient levels and agricultural runoff is a main source of these nutrients, and programs that reduce runoff have significantly reduced HAB severity. However, prevention programs may not be effective in some marine HABs that occur in natural cycles with no strong link to anthropogenic causes.

Control programs focus on removing or destroying HAB cells or their toxins to limit the effects of a bloom. These methods can be useful for smaller blooms, but enacting environmentally safe plans on large blooms is usually too costly or resource intensive to be feasible.

Mitigation measures attempt to reduce the negative effects of existing HABs. This is done in a variety of ways, including monitoring blooms, testing seafood or water for toxins, communicating with the public about the dangers of HABs, and forecasting the presence and severity of current or future blooms. The more accurate the forecast or monitoring, the more efforts can be taken to mitigate the bloom, protecting people from health risks and businesses

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[14] Anderson, D. M. (2009). Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean & Coastal Management*, *52*(7), 342–347. https://doi.org/10.1016/j.ocecoaman.2009.04.006

from economic consequences. Increased forecast accuracy also allows mitigation measures to focus more precisely on at-risk areas, reducing the cost of those measures. These methods depend on an accurate assessment of the size, location, and severity of the bloom, usually by testing the water directly for HAB cell counts or toxin concentrations. However, these monitoring strategies can be expensive or infeasible for HAB events that cover larger areas, such as a wide patch of ocean. Contrarily, they are also not effective for monitoring small or remote water bodies far away from authorities capable of administering tests, such as inland lakes. Using a testing method that can monitor a large or remote area without direct human involvement or contact can save money and organizational resources.

Ocean color satellites measure the scattering of light primarily caused by chlorophyll-a in algae. These measurements can be used to estimate algae concentrations, allowing for effective and reliable monitoring of HAB presence and severity over large and/or remote areas using minimal resources. This method requires an initial experimentation phase to correlate tested cell concentrations with satellite measurements, adjusting for other factors that can scatter the light and the level of chlorophyll in the algae. After this experimentation, the satellites can be used to determine HAB severity without further water testing. Since chlorophyll levels vary based on algae species and the algae species present vary based on the location, these experiments must be done for each coastal region. This approach has been used on West coast of Florida,[15] the Oregon coast,[16] and the Great Lakes.[17]

Ocean color data are now actively being used to monitor HABs and create HAB forecasts. The National Oceanic and Atmospheric Administration releases annual bulletins with data about current and forecasted HABs. The bulletin for *Karenia brevis* on the Gulf Coast of Florida has used satellite data for its predictions for the past 20 years.[18] More recent efforts in Florida have used machine learning to analyze satellite imagery, resulting in HAB forecasts that are 91%

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[15] Stumpf, R. P., Tomlinson, M. C., Calkins, J. A., Kirkpatrick, B., Fisher, K., Nierenberg, K., Currier, R., & Wynne, T. T. (2009). Skill assessment for an operational algal bloom forecast system. *Journal of Marine Systems*, *76*(1-2), 151–161. https://doi.org/10.1016/j.jmarsys.2008.05.016

[16] Mckibben, S. M., Strutton, P. G., Peterson, T. D., & Foley, D. G. (2012). Satellite-based detection and monitoring of phytoplankton blooms along the Oregon coast. *ResearchGate*, *117*. https://www.researchgate.net/publication/282819329_Satellite-based_detection_and_monitoring_of_phytoplankton_blooms_along_the_Oregon_coast

[17] Wynne, T., Stumpf, R. P., Tomlinson, M. C., Warner, R., Tester, P. A., Dyble, J., & Fahnenstiel, G. L. (2008). Relating spectral shape to cyanobacterial bloom in the Laurentian Great Lakes. *ResearchGate*, *29*. https://www.researchgate.net/publication/248977952_Relating_spectral_shape_to_cyanobacterial_bloom_in_the_Laurentian_Great_Lakes

[18] Stumpf, R. P., Culver, M. E., Tester, P. A., Tomlinson, M., Kirkpatrick, G. J., Pederson, B. A., Truby, E., Ransibrahmanakul, V., & Soracco, M. (2003). Monitoring Karenia brevis blooms in the Gulf of Mexico using satellite ocean color imagery and other data. *Harmful Algae*, *2*(2), 147–160. https://doi.org/10.1016/s1568-9883(02)00083-5

accurate 8 days in advance, allowing for early closures of beaches before they can be contaminated with aerosolized HAB toxins.[19] On the West Coast, satellite data are used for the California Harmful Algae Risk Mapping (C-HARM) system, with plans to incorporate that data into the NOAA West Coast HAB bulletin.[20] For freshwater cyanobacteria blooms, satellite imagery can be used to detect HABs in inland waters with a resolution up to 300m.[21] These data are publicly available through the CyAN mobile app,[22] which can help everyday consumers such as recreational fishers and beachgoers know which waters to avoid.[23]

Economic Costs of HABs

Identifying cost-effective strategies for mitigating the harmful effects of HABs requires an analysis of the cost of the mitigation measures and the degree to which those measures can be expected to reduce the societal effects of HABs. The societal costs of HABs are significant, negatively affecting both human health and the economy. However, measures that are implemented to reduce the costs of HABs are also costly. For example, closing fisheries can reduce the negative health effects that result from consuming contaminated seafood but such closures result in lost income for fishermen and other negative impacts to households and the local and national economies. More research is needed to improve the cost-effectiveness of HAB mitigation measures, including research on the cost of HABs, the cost of mitigation measures, and the degree to which these measures can reduce the cost of HABs.

Understanding HABs and their associated effects is an important first step in reducing those effects, but additional work in other fields is required to fully manage the problem. HABs are influenced by climate change, nutrient pollution, and other environmental and anthropogenic factors. Attempting to minimize the economic effects of HABs without considering these other factors is ineffective, because it fails to truly solve the root cause of the problem. Coordination in research and policy is essential to reduce the economic effects of HABs and to gain a better understanding of these related issues.

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[19] Hill, P. R., Kumar, A., Temimi, M., & Bull, D. R. (2020). HABNet: Machine Learning, Remote Sensing-Based Detection of Harmful Algal Blooms. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 3229–3239. https://doi.org/10.1109/jstars.2020.3001445

[20] Anderson, C. R., Kudela, R. M., Kahru, M., Chao, Y., Rosenfeld, L. K., Bahr, F. L., Anderson, D. M., & Norris, T. A. (2016). Initial skill assessment of the California Harmful Algae Risk Mapping (C-HARM) system. *Harmful Algae*, *59*, 1–18. https://doi.org/10.1016/j.hal.2016.08.006

[21] Schaeffer, B. A., Bailey, S. W., Conmy, R. N., Galvin, M., Ignatius, A. R., Johnston, J. M., Keith, D. J., Lunetta, R. S., Parmar, R., Stumpf, R. P., Urquhart, E. A., Werdell, P. J., & Wolfe, K. (2018). Mobile device application for monitoring cyanobacteria harmful algal blooms using Sentinel-3 satellite Ocean and Land Colour Instruments. *Environmental Modelling & Software*, *109*, 93–103. https://doi.org/10.1016/j.envsoft.2018.08.015

[22] https://www.epa.gov/water-research/cyanobacteria-assessment-network-application-cyan-app

[23] Schaeffer et al., 2018

There is mixed evidence on whether and the degree to which HAB frequency has increased over time.[24,25] Although the connection between HABs and climate change suggests there could be an increase, there has also been increased awareness, monitoring, and research of HABs in recent years, leading to more events being reported. While there is some evidence of regional or species-specific increases, there are too many confounding factors to determine if there has been a national increase in frequency. However, there have been several notable cases of increased HAB severity within the last decade. Since HAB severity is linked with environmental factors, changes to these factors due to climate change or human intervention can result in events with extreme impacts. For freshwater HABs, evidence suggests bloom intensity is directly correlated with nutrient availability, which is often caused by agricultural runoff.[26] This has led to frequent blooms in the Western Basin of Lake Erie, where runoff from the Maumee River feeds cyanobacteria. In 2014, this resulted in a bloom that received major media attention. Cyanobacteria toxins entered the water supply for the city of Toledo, Ohio, resulting in a three-day shutdown of the municipal water supply.[27]

HABs are also influenced by temperature and weather patterns, meaning that extreme weather can result in major HAB events. This occurred in 2015, when a bloom of *Pseudo-nitzschia* on the West Coast shut down fisheries in California, Oregon, and Washington for several months.[28] This bloom caused major economic impacts, especially due to the closure of the Dungeness Crab fisheries. The bloom was linked to unusually warm ocean temperatures at a key stage of the algae life cycle, followed by the movement of algae up the coast due to strong storms.[29] This also occurred in 2017-2019 in Florida with a major bloom of *Karenia brevis*. A 2019 study suggested this prolonged and widespread bloom was due to extreme weather conditions distributing the algae cells.[30] This resulted in simultaneous blooms on Florida's east, west, and

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[24] Anderson, D. M., Fensin, E., Gobler, C. J., Hoeglund, A. E., Hubbard, K. A., Kulis, D. M., Landsberg, J. H., Lefebvre, K. A., Provoost, P., Richlen, M. L., Smith, J. L., Solow, A. R., & Trainer, V. L. (2021). Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae*, *102*, 101975. https://doi.org/10.1016/j.hal.2021.101975

[25] Hallegraeff, G. M., Anderson, D. M., Belin, C., Bottein, M.-Y. D., Bresnan, E., Chinain, M., Enevoldsen, H., Iwataki, M., Karlson, B., McKenzie, C. H., Sunesen, I., Pitcher, G. C., Provoost, P., Richardson, A., Schweibold, L., Tester, P. A., Trainer, V. L., Yñiguez, A. T., & Zingone, A. (2021). Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. *Communications Earth & Environment*, *2*(1). https://doi.org/10.1038/s43247-021-00178-8

[26] Stumpf et al., 2012

[27] Bingham, M., Sinha, S., & Lupi, F. (2015). *Economic Benefits of Reducing Harmful Algal Blooms in Lake Erie*. https://legacyfiles.ijc.org/tinymce/uploaded/Publications/Economic-Benefits-Due-to-Reduction-in-HABs-October-2015.pdf

[28] McCabe et al., 2016

[29] McCabe et al., 2016

[30] Weisberg, R. H., Liu, Y., Lembke, C., Hu, C., Hubbard, K., & Garrett, M. (2019). The Coastal Ocean Circulation Influence on the 2018 West Florida Shelf *K. brevis* Red Tide Bloom. *Journal of Geophysical Research: Oceans*, *124*(4), 2501–2512. https://doi.org/10.1029/2018jc014887

panhandle coasts, resulting in major economic damage. In both cases, HAB events were amplified by extreme weather patterns. Global warming can lead to more extreme temperatures and stronger storms, resulting in unusually impactful HABs becoming more common over time.

These examples illustrate the importance of research and action in climate change, nutrient pollution, and other fields related to HAB causes. With the severity and frequency of HABs increasing, it is essential to understand and address the factors causing HABs to reduce economic impacts. Minimizing (or at least forecasting) climate change will allow for the reduction and prediction of extreme weather events that can influence HABs, expanding the time window for warnings to be released and HAB control measures to be deployed. Understanding the link between HABs and nutrient pollution is similarly essential, so that nutrient loads can be used to forecast the severity of HAB blooms and allow for control measures. There are additional benefits to understanding this link, especially for political applications. Nutrient runoff is a complicated problem to address, and HABs are a tangible example of what occurs if that problem is not addressed.

There is a large body of economic literature centered on the valuation of HAB impacts, mostly describing case studies regarding individual blooms or models of the effects of future blooms. However, there are significant limitations to available data due to the way current valuation studies are being performed. Research is usually opportunistic and reactive, attempting to calculate economic losses without a baseline of normal economic activity when there is no HAB present. A lack of coordination between researchers and institutions results in some specific HAB events being studied extensively, while others are largely ignored. Much of the literature focuses on a few specific HAB species and locations, making it difficult to estimate the full scope of HABs due to gaps in the data. Studies use a variety of research methods, resulting in conflicting or incomplete estimates for specific HAB events, as well as questions about the validity of some studies. Finally, these problems combined make it challenging to calculate large-scale economic impacts by using data from individual events, meaning any attempt at doing so usually uses incomplete data and results in a conservative estimate.

Most literature on HABs examines individual events or models of future individual events. Due to the focus on single blooms instead of the threat of HABs as a whole, it is difficult to generate an accurate estimate for the overall economic impact of HABs nationwide. WHOI attempted to estimate the nationwide impact of HABs in 2000, using HABs that occurred in 1987 through 1992.[31] All other national, multi-species, multi-impact estimates found by the literature review

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[31] Anderson et al., 2000

for this report were either updates or follow-up studies to this original paper. However, the original paper openly acknowledges that the estimate is likely an underestimate and is based on incomplete data. HAB valuation studies were uncommon at the time, records of HABs were incomplete, and some impacts had no accurate estimates available for some species or coastal areas. Updates and follow-up studies to this original report have included additional data but suffer from the same overall data limitations and resulting underestimates. Additionally, the most recent updates found only cover HABs that occurred through 2000, meaning they do not reflect the improved monitoring efforts of this century.

HAB research that does focus on individual events is usually not representative of harmful algal blooms as a whole. Disproportionate focus appears to be placed on events that are large, costly, or otherwise have significant major effects. Less focus is given to smaller or less severe events, even though these are likely to occur more frequently and still cause economic impacts. There also tends to be a bias towards certain types of algae. Much of the research focuses on cyanobacteria, *Alexandrium*, *Pseudo-nitzschia*, *Karenia brevis*, or *Gambierdiscus*, even though there are many other species that cause HABs. Even within species, there is a focus on specific locations or major blooms. Cyanobacteria blooms occur throughout the United States, but much of the research on them is based on blooms from the western basin of Lake Erie. *Alexandrium* and *Pseudo-nitzschia* both occur on the West Coast and Northeast Coast, but data from the Gulf of Maine in the northeast is scarce. Most data from the west coast are based on recreational clamming surveys in Washington state and on a particularly large 2015 bloom along the whole coast. Finally, there tends to be a bias towards more recent events. HAB research usually occurs after a bloom, and an increase in awareness and funding has led to more research done on recent HABs than on blooms from decades ago. However, most national estimates use older data, which does not reflect more recent research efforts.

There are also some methodological issues in how HAB impacts are measured. To accurately measure the economic effects of a HAB, it is necessary to establish a baseline of normal economic activity. This is especially important for fishery and tourism data, where it is essential to see what normal catch rates or tourism visitation rates were before the HAB occurred. Unfortunately, as is common with economic assessments, much of the research on the costs of HAB events is reactive, starting during or after a bloom and establishing a baseline using limited existing data. This makes it difficult to calculate the true impact of a bloom or differentiate from other confounding factors that may have impacted the fishing or tourism industries.

Individual HAB studies also have issues identifying, measuring, and extrapolating HAB effects from available data. HABs have impacts on many sectors, so the definition of what is classified as an impact is broad. Most studies focus on only a single easily measured impact, such as hospitalization rates of HAB-related conditions, catch rates from fisheries, or tax data from tourism-associated businesses. Focusing on a single impact means the true cost of a HAB is often not fully understood unless there are multiple studies done on different industries, but lack of coordination within the research field can prevent this from occurring. Although there are common ways of measuring HAB impacts, there are no standardized practices for a specific type of cost. Different studies can generate varied estimates for the same type of impact, even for the same HAB event, because they are calculating that impact with different methodologies. Some researchers also base their work on limited data sets, then extrapolate impacts based on what information is available. This often fails to account for extraneous factors affecting that sector, and the estimates created based on this extrapolation may not be accurate or generalizable for other HABs. Many studies also choose to use multipliers to address the indirect or induced impacts on the economy. Using these multipliers requires a better understanding of how the local economy operates than researchers generally have, and the inconsistency of some papers using multipliers while others don't creates large variation in the estimates of impacts that are generated.

This study estimates the national annual economic impacts of harmful algal blooms. In doing so, it addresses some of the problems with methodologies traditionally used to measure the costs of HABs, and notes the lack of a coordinated research approach. Several recent studies have conducted literature reviews of HAB impacts, but no recent meta-analysis generating a national impact estimate exists. Prior studies that have estimated national impacts have done so using limited sample sizes and older data. This study uses a large body of research, much of which has been published since the previous national estimates, to create a more accurate estimate.

In addition, the lack of a coordinated research approach on the economic damages caused by HAB events has resulted in a variety of estimates using similar data, and bias in terms of which HAB events, impacts, and geographic locations are studied. This report hopes to draw attention to underrepresented areas in HAB research so that a more comprehensive approach can be taken to understanding a fuller cost of HAB impacts across the U.S.

Finally, this study demonstrates the value of using new technology, specifically ocean color satellite sensors, to monitor and manage HABs. Satellite data allows for accurate forecasting of major HAB events, increasing the warning time needed to inform the public of dangerous locations, allowing fisheries to be notified before their catch becomes contaminated, and ultimately allowing a more comprehensive and precise emergency response to a HAB event. Satellite data also can help to establish a baseline of economic activity, and baseline algae concentrations, which can improve cost estimates for HAB events.

IV. Methods

DATA COLLECTION

Literature review and development of attributes table

The project team began the literature review with a report summarizing a 2020 workshop held by the WHOI that examined the socioeconomic effects of HABs.[32] The workshop provided a broad overview of HABs in the United States and how research was done on HABs, and then listed several case studies focusing on specific types of HABs in specific regions. The project team examined all sources cited in the WHOI report, summarizing data and information about the economic impacts of HABs. The team also analyzed all the citations included in the report, summarizing information from those cited sources. This process was repeated if the new source cited further potentially useful sources. The list of sources collected from this method includes several recent literature reviews on HAB economic impacts, though none of those sources included a meta-analysis of impacts to create a national-scale estimate.

After this initial search, the project team expanded the selection of sources through key word searches. Although there was no standardized search procedure to collect every possible paper on HAB economic effects, there was a method to identify and correct potential gaps in the data. The WHOI workshop grouped sources into five broad categories based on HAB type: cyanobacteria, Alexandrium, Karenia brevis, Pseudo-nitzschia, and Gambierdiscus, though previous estimates of national-scale HAB impacts have grouped papers by impact type. After refining those national-scale impact types to be more specific and adjusting for trends in the papers from the WHOI workshop, the project team grouped impacts into seven categories: **public health, commercial fishing, recreational fishing, tourism,** property values, water treatment, and monitoring and management. Limitations in the existing research resulted in this report only generating economic estimates for the first four categories (**in bold**). Based on the five algae categories and the seven impact categories, the project team was able to identify areas that did not yet have enough cited papers to draw conclusions, then conduct key word searches to find studies that examined that type of impact for that type of HAB.

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[32] U.S. National Office for Harmful Algal Blooms. (2021). Workshop on the Socio-Economic Effects of Marine and Fresh Water Harmful Algal Blooms in the United States. https://hab.whoi.edu/wp-content/uploads/2021/04/HAB-Socioeconomics-Workshop-Proceedings_14.pdf

Throughout the literature review process, the project team developed a “HAB Literature Attributes Table” (found with Supporting Documents within the NOAA Institutional Repository) a summary and key data from all the studies reviewed. Key data refers to all data parameters needed to undertake a regression analysis on the economic costs of HABs in the U.S. The attributes table also includes a citation for each paper reviewed, a brief summary of that paper, the type of HAB, the year the HAB occurred, the location of the bloom, the states affected, any known causes of the bloom, and what information the paper include (a specific bloom, multiple case studies, national estimates, non-economic info, etc.). In terms of economic information, the table includes costs calculated by the study, which impact categories the study focused on, and a brief explanation of the economic and statistical methods used to calculate that cost as available. The table also contains information on when data was collected for the study—restricted to papers published after 1998.[33] Economic impacts were adjusted to account for inflation. The attributes table contains data gaps due to limitations in information provided by the research, and because less effort was spent reviewing papers without economic information.

Stakeholder interviews/outreach

In addition to the quantitative aspects of this study, the team sought an initial understanding of: 1) how ocean color data are being used to inform decision making about and research on HABs by a variety of audiences and 2) how ocean color data and products could be tailored to be more useful for HAB-related and other efforts. While this outreach was intended to be aimed at end-users of ocean color products and tools, the short timeframe of the study precluded access to actual end-users. Instead, the project team modified the approach and engaged informally with six people from NOAA and NOAA Sea Grant (See Table 1) identified by our project partners and NOAA staff to help identify potential end-users for future research.

Although these conversations were largely open-ended (i.e., not structured), two guiding questions included:

- How do federal state and local managers use ocean color data to manage and mitigate HABs?
- Beyond HABs, what are other potential (or current) uses of ocean color observations (via platforms like NOAA CoastWatch and the STAR Ocean Color Viewer)?

Through this outreach, we learned that there is a network of several dozen NOAA staff and contractors working on different aspects of incorporating ocean color data into HAB-related information and tools (e.g., HAB bulletins / forecasts, interactive web maps). There is not one

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[33] 1988 was the year that the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) first established a NOAA mandate on HABs

central NOAA office or position that oversees all these efforts, but members of this network conveyed that they somewhat regularly interact with other network members.

Table 1. NOAA and Sea Grant staff engaged

NAME	TITLE	AFFILIATION	CONVERSATION DATE
Rachael Franks Taylor	Senior Coastal Management Specialist	NOAA's Office for Coastal Management	3.28.23
Lou Nadeau	Vice President	Eastern Research Group, under contract to NOAA	4.7.23
Nicole Bartlett	NOAA Regional Coordinator, North Atlantic	NOAA	4.11.23
Betty Staugler	NOAA HAB Liaison	Florida Sea Grant / University of Florida	4.12.23
Chiara Zuccarino-Crowe	Great Lakes outreach specialist; Sea Grant Liaison to NOAA	Michigan Sea Grant	4.13.23
Andrea VanderWoude	Research Physical Scientist - Remote Sensing Researcher Great Lakes CoastWatch Node Manager	NOAA, Great Lakes Environmental Research Laboratory	4.27.23

As noted above, we had originally intended to conduct conversations with end users outside of the sphere of NOAA, for example, with city water managers, public health agencies, and people affiliated with tourism and fisheries. These types of positions and others play key roles in communicating information about HABs to the public, businesses, and other decision makers. However, given the time allotted to complete this study and the inability to conduct a more comprehensive examination using tools such as focus groups, the team was not able to conduct additional conversations with other NOAA staff and affiliates that are working on HABs nor end users outside of NOAA.

REGRESSION ANALYSIS

This project proposes an approach to estimating a model of HAB damages across the country based on extrapolating from a limited number of existing valuation projects. This approach approximates a benefit transfer meta-analysis. Benefit transfer is the use of existing economic estimates of benefit or cost values outside of their original study context. For instance, suppose a study estimates the impact of a particular HAB event on tourism to be $25 per visitor to a particular beach. If a later analysis uses that $25 value reported in the original study to estimate the costs of a different HAB event at a different beach, this would be an application of benefit transfer. Researchers refer to the original beach as the "study site" and the new beach as the "policy site." For the direct transfer of a value like this example, there are three validity criteria defined by Boyle and Bergstrom (1992)[34]:

1. The thing being valued at the study site and policy site are identical;
2. The populations affected at the study and policy sites have identical characteristics;
3. The same value measure must be appropriate for both sites.[35]

The existing HAB literature examines several different types of values associated with HABs, including both market and non-market values. Market values would include directly measured market outcomes including the loss of income of commercial fishing operations or restaurants and hotels during HAB events, the healthcare costs related to treating medical conditions caused by HABs, or the cleanup and water treatment costs borne by utilities or municipalities. Non-market values cannot be directly measured from economic data. These represent the lost "welfare" of people affected by the HAB like coastal residents, recreational anglers, or tourists. Researchers use other methods like travel costs studies, hedonic property value models, or stated preference surveys to estimate non-market values. The existing HAB literature is not nearly rich enough to offer transferable values for all types of HAB-related costs in all types of communities across the United States. In simple cases, an average of values from studies estimating values for similar circumstances may be appropriate. In this case, however, given the variation in regions and types of damages associated with HABs, a "point transfer" based on a single estimated value is insufficient. A "function transfer" approach, which constructs a general value function based on a meta-analysis regression, may be more appropriate.[36]

A meta-analysis is any study which synthesize the findings of several independent studies to draw some overall conclusion. Meta-analysis grew out of clinical research, where the data from several similarly designed experiments could be pooled to search for treatment effects that were not statistically detectible in the individual studies, or so that treatment effects could be compared across different populations.

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[34] Boyle, K. J., & Bergstrom, J. C. (1992). Benefit transfer studies: myths, pragmatism, and idealism. Water resources research, 28(3), 657-663.

[35] For example, if a study estimates values for fishing based on the price of transferable permits in an area where there is a market for such permits, it would not be appropriate to use that value as a direct estimate of willingness-to-pay in an area where a similar market did not exist.

[36] Bergstrom, J. C., & Taylor, L. O. (2006). Using meta-analysis for benefits transfer: Theory and practice. Ecological economics, 60(2), 351-360.

There are two basic approaches to meta-analysis. Individual participant data (IPD) studies pool the data of the selected studies into a single set and estimate statistics on the pooled data. When individual participant data are not available, or there is sufficient dissimilarity in the research designs to allow participant level comparisons, aggregate data (AD) use the statistics reported in the selected studies as data for further statistical analysis. Given the variation in research designs across the HAB data used in this study, an aggregate data approach is appropriate.

For both benefit transfer and meta-analysis, the selection of studies used in the analysis is a key decision. *The incorporation criteria for this study included the date and location of the study, the types of values included, and the estimation approach for the values reported.*

As described in the section above, we limited the search of papers to HABs that occurred in the US. The currency of the papers used to construct the data set is important because of (a) potential changes in HAB patterns and values over time and (b) significant improvements in economic valuation techniques over the past several decades. This analysis focuses on papers published after 1998, the year that the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA)[37] first established a NOAA mandate on HABs.

The project team assigned damages to four categories: Commercial Fishing, Recreational Fishing, Tourism, and Health. This is not exhaustive of the full range of effects of HABs, but these categories align well with NOAA's mission and have adequate valuation numbers to model. There are a number of other categories of damages and costs with significant damage values. These include effects on property value and the welfare of coastal residents, water treatment costs, monitoring and cleanup costs, and impacts on ecosystems and wildlife. However, for some categories, there are too few papers with well-documented economic impacts. Other complications led to the exclusion of additional categories; for example, water treatment costs are often non-recurring equipment upgrades so do not fit well within this analytic framework.

The meta-analysis only includes papers where the original estimates were based on a recognized valuation methodology. It excludes papers in the data set that estimated economic values based on simulations using documented assumptions, but with an inadequate empirical basis or those that relied on values published in earlier studies.

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[37] Harmful Algal Bloom and Hypoxia Research and Control Act of 1998, Pub. L. 105–383, title VI, §601 (1998). https://uscode.house.gov/view.xhtml?path=/prelim@title33/chapter53&edition=prelim

Of the 170 papers, reports, and resources described in the attribute table, 58 had a clearly expressed measurement of economic damages. From those, there were *37 peer review papers that presented new estimates, produced by well-documented methodologies, for at least one of the four damage categories.* This is a relatively small sample for the purposes of a benefit transfer meta-analysis on this scale; however, some of these papers presented multiple estimates that are attributable to different damage categories or areas. This provides multiple observations per paper, which increases the statistical utility of the dataset.

The analysis is performed at the county level. Geographically speaking, HABs can range in extent from a sub-county scale bay or pond to a regional event affecting multiple states. Many of the studies that reported reasonable economic damage estimates examined the effect over one or multiple counties, so this is a reasonable scale. Of the papers that reported on events that spanned multiple counties, some reported separate estimates for different counties while others reported aggregate damages for a larger, multi-county region. For papers that just reported aggregate total regional damages, we apportioned these damages to counties based on the proportion of population exposed.

The HAB cost data are on a dollars per year basis meaning that the dollar values for each county include a year's worth of HAB events, on average. Ideally, a longitudinal set of county level HAB event observations over several years could produce more precise model estimates. If there were annual damage estimates on a standard geographical basis, this could produce estimates that are more precise for a geographic unit. Annual damage estimates would also help to control for unobserved, confounding factors that vary across time and geography—such as local ecological or economic conditions. The currently available HAB damage estimates are too sparse to allow for that level of analysis. All values used in the analysis were adjusted to reflect price levels in 2023.

The distribution of HAB damages skews to the right and has a long tail, meaning that a large number of values exceed the mean, some of them greatly; there is no similar pattern for values that fall below the mean. This is true for both absolute and per capita values (See Figure 5 and Figure 6). This is also true (and typically the case) of population and other economic variables like sector income, so the model is specified as a log-log, or constant elasticity model.

A log-log model specification transforms the variables using a natural logarithm. This implies multiplicative instead of additive effects, and is appropriate when considering changes in terms of percentages instead of units. For example, what a $10,000 increase in damages *implies* in the context of a HAB event that only has a few thousand dollars in impacts is different from what it *implies* to a multi-state, multimillion-dollar event. It is more appropriate to think of the impact in terms of a percent increase in damages rather than an absolute amount.

An advantage of using the log-log model specification is that the model estimates for the continuous variables can be interpreted as the percent by which the dependent variable changes with respect to the percent change in an independent variable. For instance, if we

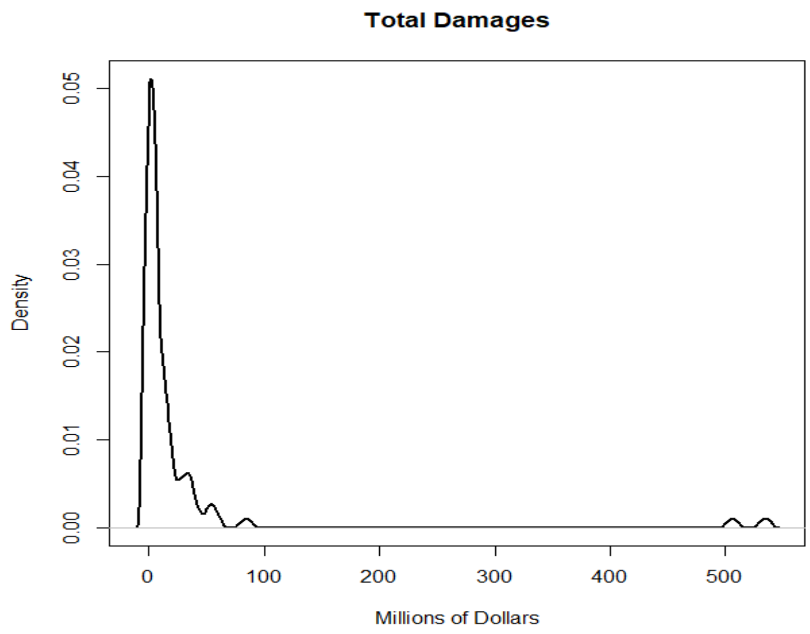

Figure 5. Distribution of HAB Damages, Total Damages

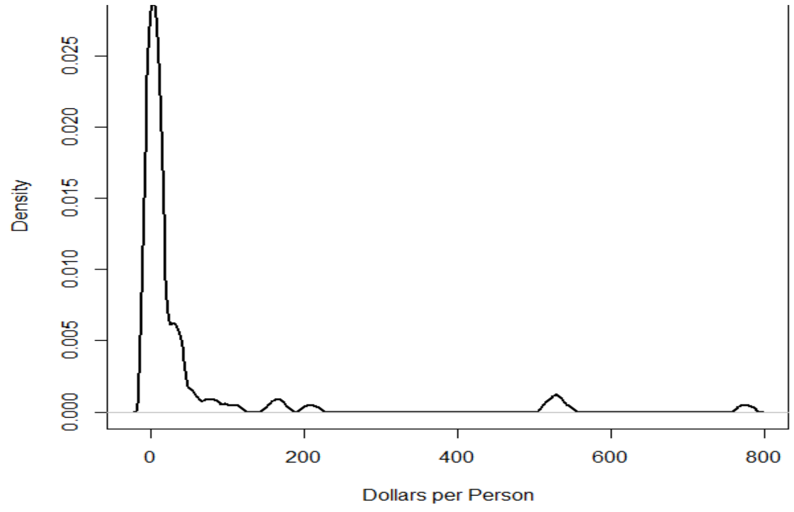

Figure 6.Distribution of HAB Damages, Per Capita

model damage as a function of the size of the commercial fishing industry, and estimate an effect of 0.5, that means that a 1% increase in the size of the commercial fishing industry, in a given area, would be associated with a 0.5% increase in damages from HAB events.

The estimated model relates damages to both the population in the area where the HAB occurred as well as potential economic activity subject to disruption by the HAB event. A general statement of this relationship would be:

$$\begin{aligned}\ln(Damage_i) = {} & \beta_0 + \beta_1 * Year_i + \beta_2 * \ln(Population_i) \\ & + \beta_3 * \ln(Economic\ Exposure_i) + \mu_i\end{aligned} \quad (1)$$

where damage, population, and economic exposure are measured for the year in which a HAB event affects county i. The β's represent estimated parameters, and the μ_i is an error term with an assumed distribution dependent on the estimation approach.

A key question is how the parameters from this model vary across regions and cost types. One extreme would assume that the parameters in the model are the same across all regions and damage types. For example, this would imply that the marginal effect of an increase in "exposure" on damages is the same for an *Alexandrium catenella* event in the Gulf of Maine that shuts down commercial shellfish operations is the same as for a *Karenia brevis* event in Florida that causes respiratory impacts. This is likely not the case. The existing valuation literature is not rich enough to support estimates for different species of bacteria, and an understanding of the ecology of certain types of HABs events continues to evolve. To capture some of this variation, we separate the damage by region and damage type.

This analysis uses regions based on NOAA ocean regions with some modifications. Alaska and Hawaii are not included. Alaska does experience HABs but we were not able to locate any studies that estimated economic effects in the region. In addition, geostationary satellites may not provide as complete coverage of Alaska as existing polar orbiting satellites, depending on operational choices regarding the areas that are observed ("field of view"). We were not able to find any documentation of HABs occurring in Hawaii, with or without assessments of economic impacts. In addition, we combine the North Atlantic and Southeast and Caribbean regions into a single East region because there are only three papers with usable economic estimates specifically focused on areas in the Southeast and Caribbean region (See Figure 7).

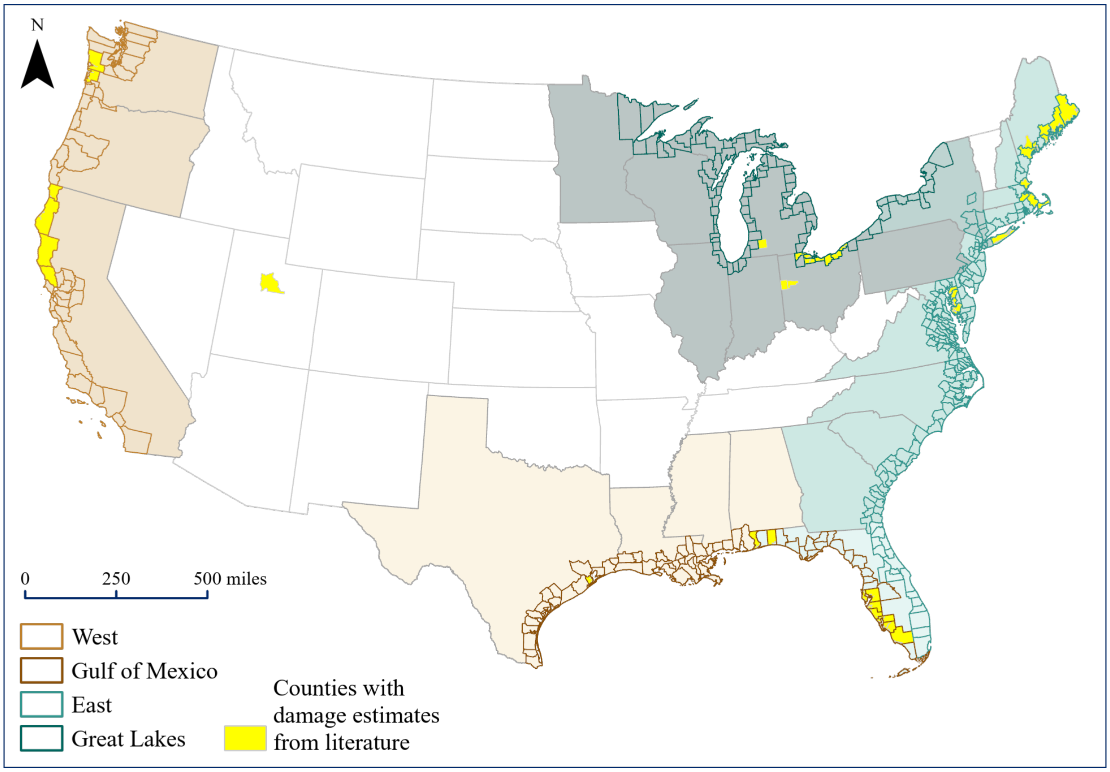

Figure 7. U.S. coastal and Great Lakes counties used in analysis, by region, including Counties with economic damage estimates from HAB literature.

Data for the values expressed in equation (1), "population" and "economic exposure," were obtained from statistics published by the US Census Bureau and the Bureau of Economic Analysis. The model is estimated using data from the year of the HAB event, but then fitted using the most recent available data. If, for example, a study estimates impacts occurring in the year 2015, the model was estimated using population and economic exposure data for 2015; results were then adjusted to reflect conditions in 2019, the most recent year for which representative data are available[38].

To capture economics exposure, we include total county GDP from the Bureau of Economic analysis.[39] We also include income associated with the commercial fishing, recreational fishing, and tourism industries. Since commercial fishing, in particular, tends to be self-employed or catch-sharing arrangements, income estimates were based off both the Census Bureau's Non-Employer Statistics (NES)[40] and County Business Patterns (CBP)[41] data sets.

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[38] The disruption from COVID means that some data are not yet available for the most recent years (for instance, the Census Bureau's Non-Employer Statistics) or the available data are atypical of historic patterns (like tourism income for 2020 and 2021), so the most current, representative values available are 2019.

[39] https://www.bea.gov/data/gdp/gdp-county-metro-and-other-areas

[40] https://www.census.gov/data/datasets/2019/econ/nonemployer-statistics/2019-ns.html

[41] https://www.census.gov/data/datasets/2019/econ/cbp/2019-cbp.html

NES and CBP report income data at the NAICS industry level. We selected industries or industry groups that would be most directly affected by damages from the four damage categories. Commercial Fishing income includes receipts and payments associated with NAICS series 11411x (Fishing). Tourism includes all 72xxx (Travel and Accommodations) as well as 713990 (Other Recreation Services). Income associated with Recreational fishing includes 4872xxx (Recreational Water Transportation and Charters) and 532284 (Retail Recreation Equipment Rentals). Table 2 summarizes these assignments.

Table 2. Economic Exposure Industry Assignments

Damage Category	**NAICS Industries**
Commercial Fishing	11411x (Fishing)
Recreational Fishing	4872xxx (Recreational Water Transportation and Charters), 532284 (Retail Recreation Equipment Rentals)
Tourism	72xxx (Travel and Accommodations), 713990 (Other Recreation Services)

Recreational fishing is difficult to quantify since most of the value is non-market. Other available use data sets like the Marine Recreational Information Program data does not report at the county level. Reporting of other metrics of recreational use like licenses and landings are inconsistent across states. Even if income associated with charters and rentals doesn't fully capture the value of recreational fishing, is can still serve as a proxy to capture variation in the demand for recreational fishing across counties.

The four regions and four damage categories could be estimated as sixteen separate linear models. However, that would assume that these processes are completely independent. There is likely correlation between the error terms if the models were estimated this way, and lower variance estimates could be produced by incorporating this correlation. A more efficient approach, referred to as Seemingly Unrelated Regions (SUR), estimates this as a single system with a more complex error stricter than the traditional independent, identically distributed assumption. Researchers often use SURs when estimating similar processes that occur over time; however, they apply to any that have the same outcome variable and potentially cross-correlated errors. They may have the same regressors in each component model (symmetric) or the regressors may vary across component models (asymmetric). For example, researchers often use SURs estimate demand for related goods like energy from different sources or tourism travel to similar regions.[42,43,44,45]

One way of specifying the SUR model is by using dummy variables for the regions and damage categories and using a full set of interactions between the two groups of dummy variables and all the continuous variables. Using this approach, we perform several restriction tests to evaluate, and where appropriate simplify the full specification detailed in Appendix A. It is notable that in most cases, the tests reject restriction across regions but fail to reject restriction across damages. Based on the results of these restriction tests, we estimate a final specification as:

$$ln\left(Damage_{i,r,s}\right) = \beta_0 + \sum_{r\,\in Regions}\left(\sum_{s\,\in Damage\ Catagories}\left(\begin{array}{c}\gamma_r + \delta_s + \rho_{r,s} + \theta_1 * Year_{i,r,s} \\ + \theta_2^r * ln(Population_{i,r,s}) + \theta_3^r * ln\left(GDP_{i,r,s}\right) \\ +\theta_4^r\, ln\left(Commercial\ Fishing\ Income_{i,r,s}\right) \\ + \theta_5^r * ln\left(Recreational\ Fishing\ Income_{i,r,s}\right) \\ +\theta_6^r * ln\left(Tourinsm\ Income_{i,r,s}\right)\end{array}\right)\right) + \mu_i. \ (2)$$

The estimated parameters for this model are reported in Table 3. Note that the public health effect is omitted as the base case (i.e., **represented by the constant, $\boldsymbol{\beta_0}$**). Public health was chosen as the base because it does not have additional exposure income variables, so it simplified some of the associated restriction tests. The other damage effects, δ_s are relative to public health effects. The estimates for these (Commercial Fishing, Recreation Fishing, and Tourism in Table N+1) are in log-dollars, and best interpreted just in terms of statistical significance and relative size. The estimates for the θ_k^rparameters reported in that table (the ln() values) are in constant elasticity form. So, for instance, in the Gulf region, a 1% increase in commercial fishing corresponds with a 0.46% increase in expected annual HAB damages in a county, all else remaining equal. *These estimates are informative in terms of their significance, direction, and relative size; however, these parameters are primarily used at the basis of the damage estimates constructed in the next section.*

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[42] Beierlein, J. G., Dunn, J. W., & McConnon, J. C. (1981). The demand for electricity and natural gas in the northeastern United States. The Review of Economics and Statistics, 403-408.

[43] Saboori, B., Gholipour, H. F., Rasoulinezhad, E., & Ranjbar, O. (2022). Renewable energy sources and unemployment rate: Evidence from the US states. Energy Policy, 168, 113155.

[44] O'Hagan, J. W., & Harrison, M. J. (1984). Market shares of US tourist expenditure in Europe: an econometric analysis. Applied economics, 16(6), 919-931.

[45] Sheng, M., & Sharp, B. (2019). Aggregate road passenger travel demand in New Zealand: A seemingly unrelated regression approach. Transportation research part A: policy and practice, 124, 55-68.

Table 3. Final Combined Model Estimates for HAB damages.

	West			East			Gulf of Mexico			Great Lakes		
	B	p-value		B	p-value		B	p-value		B	p-value	
β_0	45.57	0.39		37.68	0.68		37.45	0.69		**11.83**	**0.09**	*
Commercial Fishing	16.81	0.56		1.68	0.28		14.94	0.27		16.95	0.84	
Recreational Fishing	-40.12	0.45		**-75.51**	**0.00**	***	**34.19**	**0.00**	***	10.10	0.53	
Tourism	4.02	0.86		**-20.97**	**0.09**	*	18.59	0.17		9.05	0.64	
Year	-0.02	0.46		-0.02	0.46		-0.02	0.46		0.46	0.46	
ln(Population)	3.47	0.67		0.87	0.78		-3.50	0.24		1.57	0.26	
ln(County GDP)	-2.36	0.73		-0.03	0.94		2.20	0.45		1.05	0.33	
ln(Com Fishing Income)	-1.50	0.30		0.08	0.55		**0.46**	**0.00**	***	**-3.63**	**0.03**	**
ln(Rec Fishing Income)	**-1.20**	**0.00**	***	**-1.61**	**0.00**	***	**-1.20**	**0.00**	***	**-1.20**	**0.00**	***
ln(Tourism Income)	-0.32	0.84		-0.40	0.98		**1.41**	**0.00**	***	-0.32	0.84	
N	21			43			37			22		
Adjusted R^2	0.72											

*, **, *** indicate statistical significance at the 10%, 5%, and 1% level, respectively, significant values are in **Bold**.

DEVELOPING NATIONAL SCALE ESTIMATES OF THE ANNUAL ECONOMIC IMPACTS OF HABS

This framework proposes to offer a methodology for estimating the benefit of the reduction in HAB damages due to improved sensing equipment at the national level. This requires national damage estimates. The model described in Table 3 allows for the estimation of damages across counties on an annual basis. Fitting this model for all coastal counties gives county level potential damage estimates for each county: $\widehat{PotentialDamage}_i$.

We cannot simply sum up these estimates for an estimate of national total damage though. The scale of damages attributed to HABs in the economic literature vary across events, and may not be representative of a typical HAB event. They also only represent years in which a HAB occurred in a particular area, and many counties do not experience HAB of that scale every year. The estimates in Table 3 represent the expected damage for each category during a year where the county experiences a HAB that is of average scale for events studied in the economic literature included in the meta-analysis. Some counties do experience regularly recurring HABs, but these vary in intensity from year to year. There are other areas where HABs occurrences are rare. Therefore, a simple total of county fitted damage estimates would tend to overestimate total national damages. We need to adjust these county estimates to account for the frequency of HAB events.

The best annual systematic national level reporting of HABs that we were able to locate is the Hazardous Algae Events Database (HAEDat) compiled by UNESCO’s International Council for Exploration of the Seas.[46] HAEDat is an international database of reports measurements and attributes of HAB events. State and regional monitoring organizations gather individual HAB observations and report them to HAEDat, which aggregates them into defined ocean regions. Differences in monitoring intensity and procedures between states and regions mean that differences in events might be more related to differences in monitoring than to actual differences in HAB frequency. Within the United States at least, monitoring efforts have trended towards increasing regularity across states. Prior to 1990, the vast majority of HABs reported in the US were limited to California, Massachusetts, and Maine. Through the 1990s and 2000s, however, the frequency of reporting from other states increased, with most coastal states reporting with at least some regularity. Therefore, we focus on the rate of events reported in the 11 years from 2012 to 2022 (See Figure 8).

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[46] United Nations Educational, Scientific and Cultural Organization (UNESCO), Intergovernmental Oceanographic Commission(IOC) (2023). The Harmful Algal Event Database. Accessed April 1, 2023 online at http://haedat.iode.org.

Figure 8. HAB events reported by HAEDat Regions.

As part of the data preparation, slightly over half the events reported on in the economic data were associated with HABs in HAEDat. We were able to link 21 papers, or about 56% of the usable set to HABs events in HAEDat. The remaining papers reported on HABs that did not appear to be listed in HAEDat. Many of these were from the Great Lakes (which does not have a formal HAEDat region associated with it, although there are a handful of Lake Erie HABs listed in it), although there were a few in the Gulf of Mexico and the East Coast. *The overall distribution of economic papers vs. HAEDat entries suggests that either there is an over-focus in the economic literature, or under reporting in HAEDat for HABs in the Gulf Coast, and an under-focus in economic literature or a higher HAEDat reporting frequency for the East and West Coasts.* HAEDat does not formally identify the Great Lakes as a region, and there is no identified economic literature focused on Alaska.

Using the frequencies of HAEDat data, we can construct event frequency estimates across regions. We assign the Great Lakes region the same frequency as the Gulf region since HAEDat has very limited data on the Great Lakes, and they have a similar rate of representation in the economic literature. The scale of HABs damages described in the economic literature spans an average of 3.1 counties. Based on the 20 years of HAEDat data, the average frequency in each region is:

$$HABRate_r = (TotalHABEvents_r * 3.1)/(20 * NumberOfCounties_r).$$

This will estimate the expected number of events per year. Alternately, dividing 20 by this rate gives the average frequency of HABs for a county in that region in years. Alternately, taking the inverse of that gives the expected interval between HAB events. Results are presented in the Analysis section.

GIS ANALYSIS

For this study, the research team conducted geospatial analyses to broadly understand location-specific economic impacts of HABs across the U.S. Because most HAB-related data used for this study occurred in coastal and Great Lakes waters, the team used coastal counties and counties adjacent to the Great Lakes as the unit of analysis. Although the spatial extent of any HAB, and its corresponding effects on fisheries, tourism, and public health, varies from hyper-local to multi-state, there were several reasons why we elected to use counties as the unit of analysis, including the availability of county-level demographic and socioeconomic data and the high likelihood that the size of the effects of HABs are likely greatest in the places adjacent to where the HABs occur.

We used coastal and Great Lakes counties as defined by NOAA’s Economics: National Ocean Watch (ENOW), which contains 17 counties that "are not shore-adjacent but do have significant levels of ocean- and Great Lakes-dependent economic activity."[47]

To analyze county-level effects of HABs on commercial and recreational fisheries, tourism, and public health, we used 2019 U.S. Census County Business Patterns (CBP) estimates of the ocean economy and 2019 Census Nonemployer Statistics (NES).[48,49] We joined these data to the coastal and Great Lakes counties layer by county FIPS code.

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[47] NOAA Office for Coastal Management (Nov. 2017). Counties List: Economics - National Ocean Watch (ENOW). Accessed April 1, 2023 at https://coast.noaa.gov/data/digitalcoast/pdf/enow-counties-list.pdf.

[48] U.S. Census (March 3, 2023). 2020 CBP Ocean Economy Table. Accessed April 1, 2023 at https://www.census.gov/data/tables/2020/econ/cbp/2020-ocean-economy.html

[49] U.S. Census (June 30, 2022). 2019 Nonemployer Statistics. Accessed April 1, 2023 at https://www.census.gov/programs-surveys/nonemployer-statistics/data/tables.html

To analyze county-level effects of HABs on fisheries, tourism, and public health as they relate to metrics of diversity, equity, inclusion, and justice (DEIJ), we used the Overall Percentile Ranking (RPL_THEMES) from the 2020 Centers for Disease Control and Prevention's (CDCP) Agency for Toxic Substances and Disease Registry (ATSDR) Social Vulnerability Index (SVI).[50] SVI data were classed into four quantiles for the purposes of display and analysis.

We joined all the CBP, NES, SVI data, and this study's estimated damages to coastal and Great Lakes counties using county Federal Information Processing System (FIPS) codes.

From the HAB Literature Attributes Table, we identified 87 events that could be linked to individual counties; four of these events occurred in freshwater systems not part of the coastal and Great Lakes counties. We associated these data manually with the Coastal and Great Lakes counties and joined them to the CBP, NES, SVI, and this study's estimated damages. The specific HAB event data are limited to the continental U.S. for reasons described previously.

Using the geodatabase consisting of CBP, NES, SVI, and this study's this study's estimated damages by county, we mapped and analyzed:
- HAB-related costs from the HAB Literature Attributes Table;
- Final combined model estimates for HAB damages; and,
- Estimated HAB-related fitted damages overlaid with the CDC's Social Vulnerability Index.

HAB-related costs from the HAB Literature Attributes Table and Final combined model estimates for HAB damages were classed into four quantiles (which distribute observations equally across classes) for the purposes of display and analysis. Estimated HAB-related fitted damages overlaid with SVI data were classed using a bivariate choropleth approach. This spatial/statistical method generates a single map colored based on the values of two variables, allowing viewers to see how the variables are related to each other in a particular geographic area. The result is a visually comprehensible classification of the relative (i.e., low vs. high) HAB-related damages and relative social vulnerability of counties.

A subset of maps is provided in Section V, and additional maps are available in Appendix B: Additional Maps. An interactive ArcGIS Online Web App for viewing all spatial data derived for this study, "The Estimates of the Benefits of Ocean Color Data in Mitigating HAB Events Web Map," is viewable at

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[50] Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry/Geospatial Research, Analysis, and Services Program (2020). CDC/ATSDR Social Vulnerability Index Database (U.S.). Accessed on April 1, 2023 at https://www.atsdr.cdc.gov/placeandhealth/svi/data_documentation_download.html.

https://www.arcgis.com/apps/instant/basic/index.html?appid=466a593394664325b405229fbb643162. Table 8 in Appendix B describes the layers and sources included in the Web App.

A compressed geodatabase containing all combined input and model-derived output data is available upon request.

V. Analysis

LITERATURE REVIEW

The project team examined 170 total sources in the literature review. A breakdown of the sources is as follows: 101 of these sources were from the 2020 WHOI workshop on HAB socioeconomic effects; 1 was the workshop report itself; and the other 68 sources were referenced in sources that had already been examined or were found through key word searches. Most sources were scientific articles in peer-reviewed journals, but the literature review also included textbook chapters, reports from workshops or conferences, documents from organizations that manage HABs, websites detailing HABs and their effects, and other similar sources. Of the 170 total sources, 58 included economic estimates of HAB impacts in the United States. That only includes sources that provided a dollar value for impacts and does not include sources that did not have monetary values attached, such as fish kills.

In the literature review, the project team grouped sources based on the type of HAB that was being studied: cyanobacteria, *Alexandrium*, *Karenia brevis*, *Pseudo-nitzschia*, *Gambierdiscus*, or other types. Most of the sources containing data on U.S. economic impacts focused on at least one of the five major types of HABs (55 of 58), though there was one source each for effects from *Aureococcus anophagefferens*, *Pfiesteria piscicida*, and *Prymnesium parvum*. Some sources did not specifically name a HAB species, but the project team was able to assume the type of HAB based on what HABs were normally present in that location (See Figure 9). The sum of the number of sources for each type of HAB exceeds 58 because there were 11 papers that examined more than one HAB.

The categorization of HABs into one of five types may be due to bias from the source selection method. The project team based this report on the 2020 WHOI workshop report, which included case studies and separate reference lists for each of the five major HAB types. Due to the strong influence of this report on how the project team selected sources, it is possible that other species that cause HABs are underrepresented in this analysis. Notably, this report does not include any sources on *Dinophysis*, which causes diarrhetic shellfish poisoning.

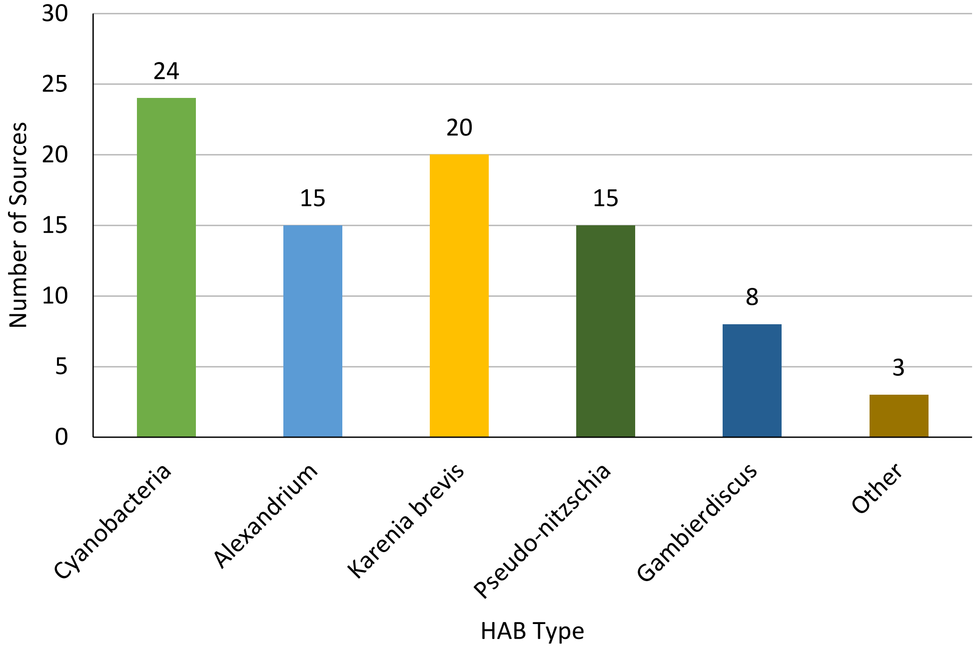

Figure 9. Number of Sources Reviewed for Each HAB Type

The project team also grouped sources by the type of HAB impact they described. This grouping was based on the cost categories laid out in previous national-scale estimates of HAB economic impacts. A 2000 WHOI estimate grouped HAB impacts into public health, commercial fisheries, recreation/tourism, and monitoring/management, and updates to that report have kept those cost categories. This analysis breaks HAB impacts into 8 cost categories: public health, commercial fishing, recreational fishing, tourism, property values, water treatment, monitoring and management, and a catch-all other category for any impacts that don't clearly fit any other category (See Figure 10). Some sources measured the impacts of more than one category.

Public health costs focus on the total cost of healthcare associated with HAB-related illnesses. This includes seafood poisoning, inhalation of aerosolized brevetoxins (from *Karenia brevis* HABs), and illness from touching or drinking contaminated water (from cyanobacteria HABs).

Commercial fishing costs refer to the lost income by fisheries, which occurs when fisheries are delayed or closed due to the presence of HAB toxins. Some studies also use multipliers to account for indirect effects, as reduced income by the fishery results in less pay for their employees, which in turn results in less spending in the local economy. This type of cost can occur with any type of HAB, but much of the data comes from losses to shell fishing in New England and Washington state, as well as delay to the Pacific Dungeness Crab fishery in 2015.

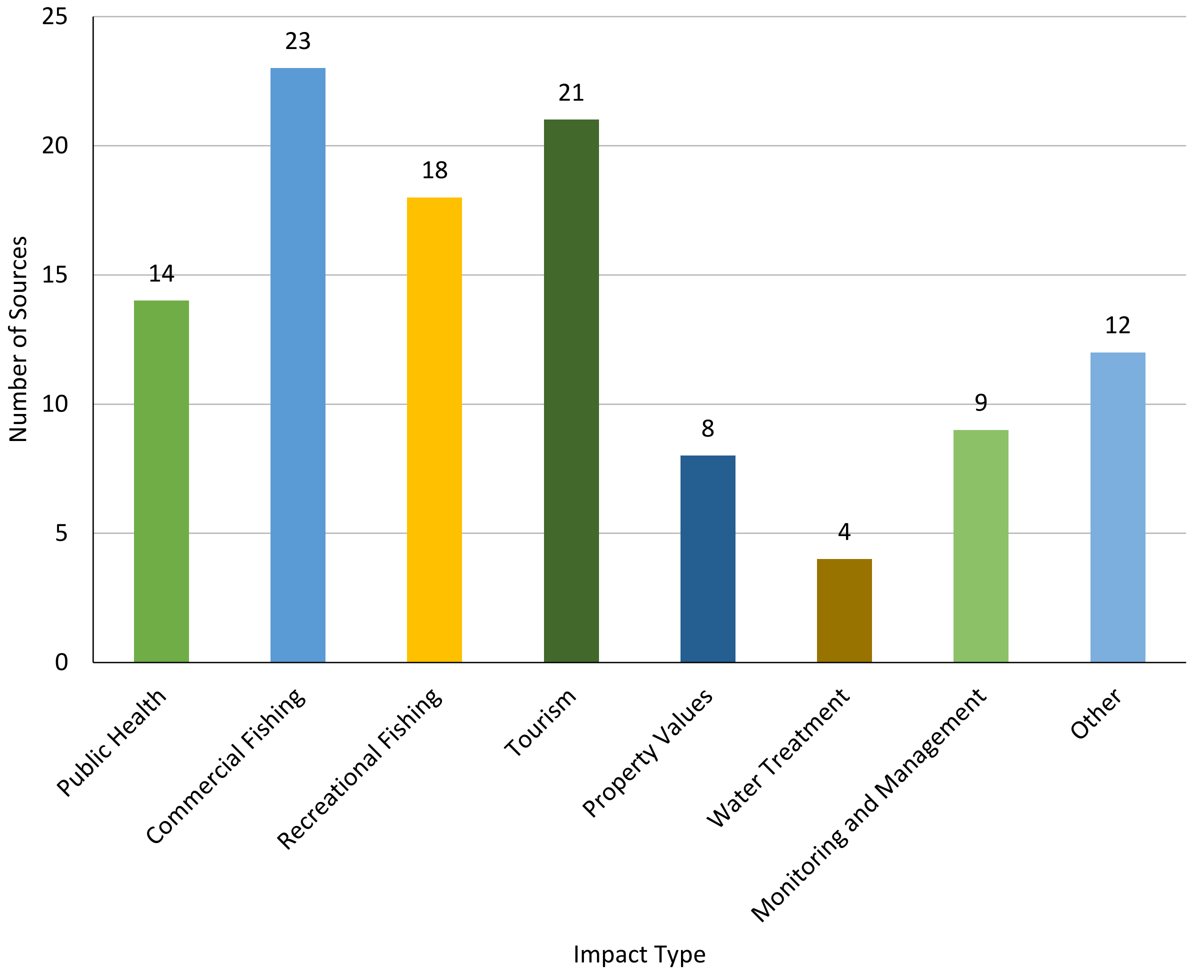

Figure 10. Number of Sources Reviewed by Economic Impact Type

Recreational fishing costs occur when closures to beaches, lakes, or other fishing spots prevent recreational fishers from fishing. This is usually measured by reduction in visitation costs in terms of impacts on the local economy, including decreased spending at restaurants, hotels, fishing supply stores, etc. Recreational fishing impacts most commonly occurred due to freshwater cyanobacteria blooms and blooms affecting recreational clamming beaches in Washington state. Tourism impacts refer to a variety of costs that originate due to a reduction in tourism from a HAB. This is commonly measured by examining the effect on businesses that cater to tourists, such as hotels, restaurants, and transportation, though this category is broad enough to also include other effects. Research on recreational fishing and tourism costs sometimes uses economic multipliers, similar to commercial fishing, as reduction in profits from fishing- and tourism-related businesses can impact the employees of those business and how they interact with other aspects of the local economy.

Property value costs refer to a decrease in the value of a property due to a HAB. This occurs due to the unpleasant sight and odor of the HAB and only affects properties near the shore, with waterfront locations being the most impacted.

Water treatment costs occur when drinking water systems have to be improved to filter out HAB toxins. This only occurs for cyanobacteria HABs, as other HABs occur in marine water, which is not used as a drinking water source.

Monitoring and management costs describe the money used by organizations to prevent, control, or mitigate HABs.

Finally, there are some costs that do not fall into any of these categories, so they were broadly categorized as “other”. This includes lost wages due to HAB-related business shutdowns or missed work from HAB-related illnesses, boat sales, marine mammal strandings, cleanup of HAB debris from beaches, decreased seafood sales, money spent attempting to avoid biodiversity losses due to HABs, changes in bottled water sales due to contaminated drinking water, lost welfare due to boat ramp closures, and a reduction in quality of life due to HAB-related illnesses.

There are some trends in the number of sources collected for each impact type based on the type of HAB or changes made to which papers were analyzed in the literature review. *Gambierdiscus* does not typically form visible blooms and does not result in fishery closures, meaning it does not have any other measurable impacts besides public health. Water treatment costs only occur if the HAB is located in a drinking water source, meaning this impact does not occur with marine HABs, though it does occur due to freshwater cyanobacteria HABs. Public health impacts associated with *Pseudo-nitzschia* are not common enough to be easily measurable, as regular water and shellfish testing has made amnesic shellfish poisoning cases rare. The project team was also not able to find any impacts on property values related to *Alexandrium* or *Pseudo-nitzschia*. The reason behind this lack of data is unknown, but one hypothesis is that these blooms are not visible enough from shore to have a measurable impact on property values. Finally, there are fewer sources for water treatment and monitoring and management impacts because water treatment costs are often one-time costs incurred when upgrading a treatment system, making it difficult to translate them into an annual estimate, and monitoring and management costs are focused on a response to HABs rather than impacts to the economy.

The literature reviewed by the project team included HABs from across the Continental United States. Some regions are overrepresented in the literature, whether this is due to the number of HABs occurring in those locations, our methodology, or other factors is beyond the scope of this analysis (See Figure 11). Many studies focused on the Gulf of Mexico, due to the frequent *Karenia brevis* blooms on the West Coast of Florida. Cyanobacteria studies came from a variety of locations, but one-third of them focused specifically on Lake Erie, due to frequent HABs that result from excess agricultural runoff bringing nutrients to the Western Basin of the lake. There were several Pacific Ocean studies, many focusing either on a 2015 bloom that affected Dungeness Crab fishing, or frequent blooms affecting clamming beaches in Washington state. Studies in the North Atlantic mostly focused on the Gulf of Maine, though there were also studies from Maryland rivers and New York. There were only two studies in the Southeast and Caribbean region, with one focusing on North Carolina and the other on Puerto Rico. There was one study in the Central region, focusing on lakes in Kansas. Finally, there were 10 studies examining HAB effects on the national scale.

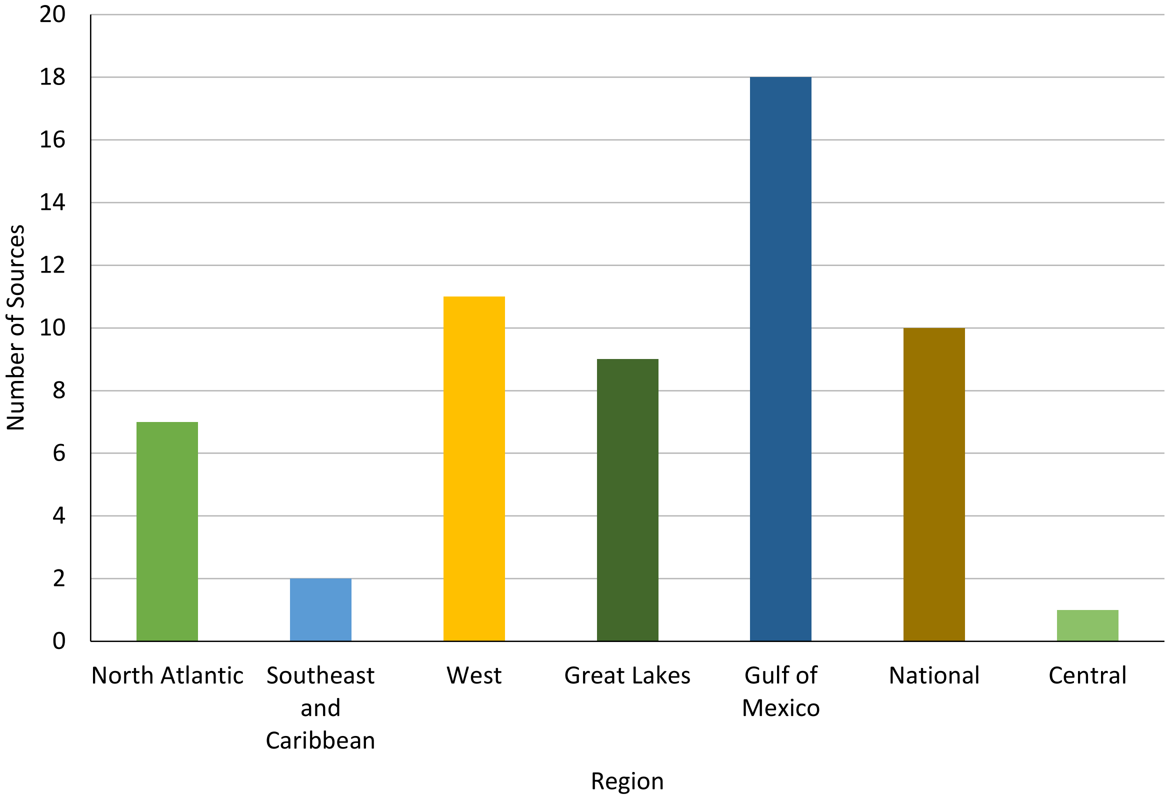

Figure 11. Number of Sources Reviewed by Region

One key takeaway from this literature review is that there may be bias in HAB research towards examining high-impact events, which may cause an underestimation of the impacts from minor, but more frequent blooms. Much of the literature reviewed either focused on unusually severe HABs (Lake Erie 2014, West Coast 2015, Gulf of Mexico 2019, etc.) or on HABs that occurred on a seasonal basis but had significant effects in a particular year (clamming beach closures in

Washington, decreased tourism and respiratory illnesses in Florida, etc.). Less of the research examined smaller blooms, even though many HABs occur in annual cycles and cyanobacteria blooms can occur in virtually any freshwater in the country. For instance, there is a lack of studies for the Southeast Atlantic Coast and Chesapeake Bay, few studies in the Northeast Atlantic, and few studies on the California Coast in years other than 2015. There also appears to be limited economic studies on HABs such as *Pfiesteria*, *Dinophysis*, and *Sargassum* in the U.S. The unequal distribution of HAB research towards a few species and locations makes it difficult to calculate national-scale estimates of HABs. The project team found 10 sources that contained national-scale estimates for HAB economic effects. Two of these were not specific to HABs but calculated national healthcare costs for a variety of toxins and poisoning syndromes, including some caused by HAB toxins. Two others only examined the effects of Cyanobacteria and did not include impacts from other types of HABs. One was not a true national-scale estimate, but focused on Maryland and North Carolina, however, it was counted as national because it covered multiple NOAA regions. The other five papers were based on one study, done by WHOI in 2000 using data from 1987 to 1992, which was updated four times. The most recent update was published in 2006, and to our knowledge, there has not been a national, multi-species, multi-impact study published since then.

REGRESSION ANALYSIS/NATIONAL SCALE ESTIMATES OF THE ANNUAL ECONOMIC IMPACTS OF HABS

Regression Model

Table 3 reports the results of the regression model. Despite a limited dataset of economic damages reported in the literature, the model has a reasonably strong fit (Adjusted R2 = 0.72) and several individually significant coefficients. The variation in the effects of damage categories across regions is substantial. For instance, estimated health impacts in the Great Lakes are significantly higher than in other regions. There is also significant and substantial variation in the recreational fishing across regions.

The effects of income in the industries associated with the damage categories are especially interesting. We generally would expect that as the income of the industry increases, the potential damage would also increase. We initially described these variables as representing the “economic exposure.” However, this is not always the case. Recreational fishing, in particular, is consistently significant and negative, suggesting that as the size of industries supporting recreational fishing increases, we should expect the damage from HABs to *decrease*. We discussed some of the problems with quantifying recreational fishing above, and it could be that some of the other activates included in NAICS category 532284 benefit from a decrease in water related activities. A more effective metric of the impact on recreational fishing may give different results. The commercial fishing income is also interesting in that it goes in different direction in different regions. It could be that this represents differences in commercial fishing industries between the Gulf and Great Lakes regions.

One should be cautious of reading too much into these estimates though, as they are based on a small number of noisy underlying data. This combined with the fact that there are some cases where we use multiple county level estimates from the same paper gives an opportunity for high value outliers to be particularly influential. A multilevel mixed effects model could help control for this, but it would require substantially more data to estimate.

National Scale Estimates

Generally, the meta-regional benefit transfer methodology is able to produce reasonable national level estimates of total annual damage from HABs and potential values for the benefits provided by ocean color-based products. The relative thinness of published HAB valuation research and limited understanding of the potential damage reduction offered by ocean color products limits the flexibility and reliability of these estimates. Further development of both of these inputs to the model would go a long way in increasing its utility.

Table 4 reports the value for each region.

Table 4. Frequency of HAB Events Across Regions

Region	Rate (per year)	Interval (years)
North Atlantic	0.16	6.3
Southeast and Caribbean	0.04	22.7
Gulf of Mexico	0.08	13.2
West	0.37	2.7
Great Lakes	0.11	9.1

These county level frequency estimates can scale the county level potential annual damage estimates to calculate expected annual damage for county i in region r:

$$National\ Expected\ Annual\ Damamge = \sum_{i \in Counties} \widehat{PotentialDamage}_{\imath} * \ HABRate_{r,i}$$

This is a high level of aggregation. The North Atlantic region has 131 counties, so in any given year we would expect that about 21 counties will experience a HAB event. This approach assumes that any county in a region is equally likely to have a HAB in a year. That tends not to be the case. HABs frequently occur in the same places year after year. A county level longitudinal count of annual HAB events would allow more understanding of the autocorrelation in HAB events, which would allow for more nuanced estimates.

Table 5 presents the results by region and by impact type. ***The total expected annual HAB damages for the CONUS is $1.3 billion.*** This is consistent with multiple relatively localized events in the $10's to $100s of million in annual costs reported in the literature.

Table 5. Total Expected Annual Damages ($Thousands)

	Commercial Fishing	Recreational Fishing	Tourism	Public Health	Total
North Atlantic	29,660	0	47,057	12	76,729
Southeast & Caribbean	22,558	0	36,780	10	59,348
Gulf of Mexico	5,741	13,238	2,748	211	21,938
West	259,075	120	822,815	302	1,082,311
Great Lakes	3,071	16,256	42,255	471	62,053
Total	320,104	29,613	951,655	1,005	1,302,378

Using total expected damage estimates, we can estimate damage reductions due to ocean color sensing products. A good estimate of this reduction requires a deeper understanding of the potential damage reductions of ocean color production across damage categories than we have been able to develop so far. Previous studies on Ocean Color observations have assumed that "improved observations from GeoXO can reduce the effects of HABs on human health and the economy by 5 percent."[51] NOAA's satellite and physical scientists have validated this initial assumption, noting that more concrete studies are being developed to refine it. If we also assume a flat 5% reduction in damages across all regions and damage categories, it would represent a **total expected annual benefit from Ocean Color products of $65.1 million.** Those benefits would be realized annually for the life of the sensor. Table 6 displays the distribution of these benefits across regions and damage categories.

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[51] Adkins, J. 2022. GEO/XO Benefit Analysis, page 113.

Table 6. Total Expected Annual Benefit of Ocean Color Products ($Thousands)

	Commercial Fishing	Recreational Fishing	Tourism	Public Health	Total
North Atlantic	1,483	0	2,353	1	3,836
Southeast & Caribbean	1,128	0	1,839	0	2,967
Gulf of Mexico	287	662	137	11	1,097
West	12,954	6	41,141	15	54,116
Great Lakes	154	813	2,113	24	3,103
Total	16,005	1,481	47,583	50	65,119

The heterogeneity for the damage estimates in Table 6 may also be rooted in a small number of noisy underlying data. The Recreational Fishing damages in the eastern region (North Atlantic and Southeast and Caribbean) are less than $1,000, largely because there are few recreational estimated in these areas, and those that have been done are quite small relative to other areas. Likewise, both commercial fishing and tourism damages are relatively large in the west coast. This is likely due to two specific commercial fishing papers and one tourism paper that reported particularly large values relative to research done elsewhere in the country. The high values in the western region are also heavily influenced by the high frequency of events as reported in Table 4. Whether this is an accurate depiction of the true frequency of HAB events or is a result of increased monitoring in that region is unclear. HAEDat entries also support the idea that there is an unequal distribution of economic literature as compared to reported HAB events. Table 7 lists the locations and frequencies of HAB events reported by HAEDat. It might be worth revising these papers in more detail to see if there is a way to improve consistency. Additional quality studies would also help improve the mismatch. And it may be that this is also, to some extent, reasonably representative of the variation in HAB damages

While we were able to use these damage estimates to calculate potential value of ocean water products, better estimates of the effectiveness of the product in reducing damages would allow for substantiate more meaningful value estimates. It is likely that the effectiveness, or potential for damage reduction, varies across different damage categories. An advantage of differentiating damages by category is that we can consider how interventions based on ocean color products can differ across different categories. For example, the actions taken in response to a HAB for a commercial fishery are different than would be taken to prevent health effects. For example, if we knew that ocean color-based products could prevent 5% of impacts to fisheries by improved targeting of closures, but prevent 40% of public health effects by earlier beach closures, this would represent a better estimate than simple flat percentage estimates. Additionally, the dynamics of HABs in different regions could make them more or less amenable to management with ocean color-based products. We had hoped to be able to make some informed assumptions on the differentiation of effectiveness of ocean color products across different categories base on literature and outreach efforts, but so far, we have not been able to find detailed enough information to justify differentiation assumptions.

Table 7. HAEDat Events, 2012-2022

HAEDAT Regions	NOAA Region	Number of Counties	Events in HAEDat		Papers Linked to HAEDAT Events		Papers Not Linked to HAEDat Events		Total Papers	
01-10	North Atlantic	131	134	43%	8	38%	2	13%	10	27%
11-15, 29	Southeast & Caribbean	56	16	5%	1	5%	2	13%	3	8%
16-18	Gulf of Mexico	63	31	10%	5	24%	4	27%	9	24%
19-24	West	47	112	36%	6	29%	0	0%	6	16%
25-27	Alaska	24	17	5%	0	0%	0	0%	0	0%
NA	Great Lakes	75	0	0%	1	5%	7	47%	9	24%
Total			310	100%	21	100%	15	100%	37	

GIS ANALYSIS

As noted above, there is limited information available from the literature on spatially explicit estimates of the costs of HABs. This study mapped and analyzed data available from the literature in the HAB Literature Attributes Table and study-generated model outputs.

Estimates derived from sources in the HAB Literature Attributes Table suggest that the per capita economic effects of HABs across all categories are highest in portions of Washington State, California, and the southwest Gulf coast of Florida (See Figure 12).

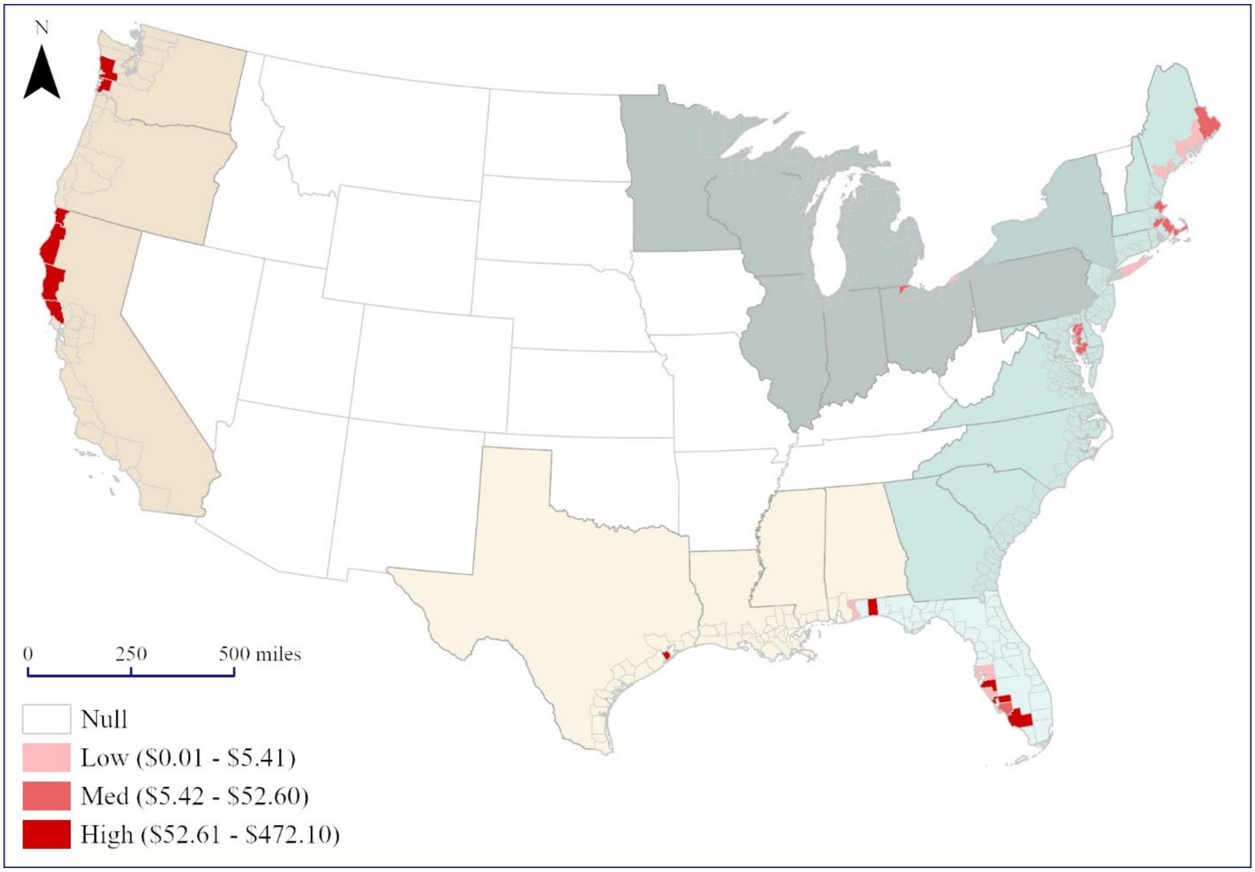

Figure 12. HAB-related costs to all categories combined in 2022 real dollars per capita by county

Model-derived final estimates for HAB damages across categories is notably high for nearly the entire West coast, parts of Florida, and southern and central New England (See Figure 13).

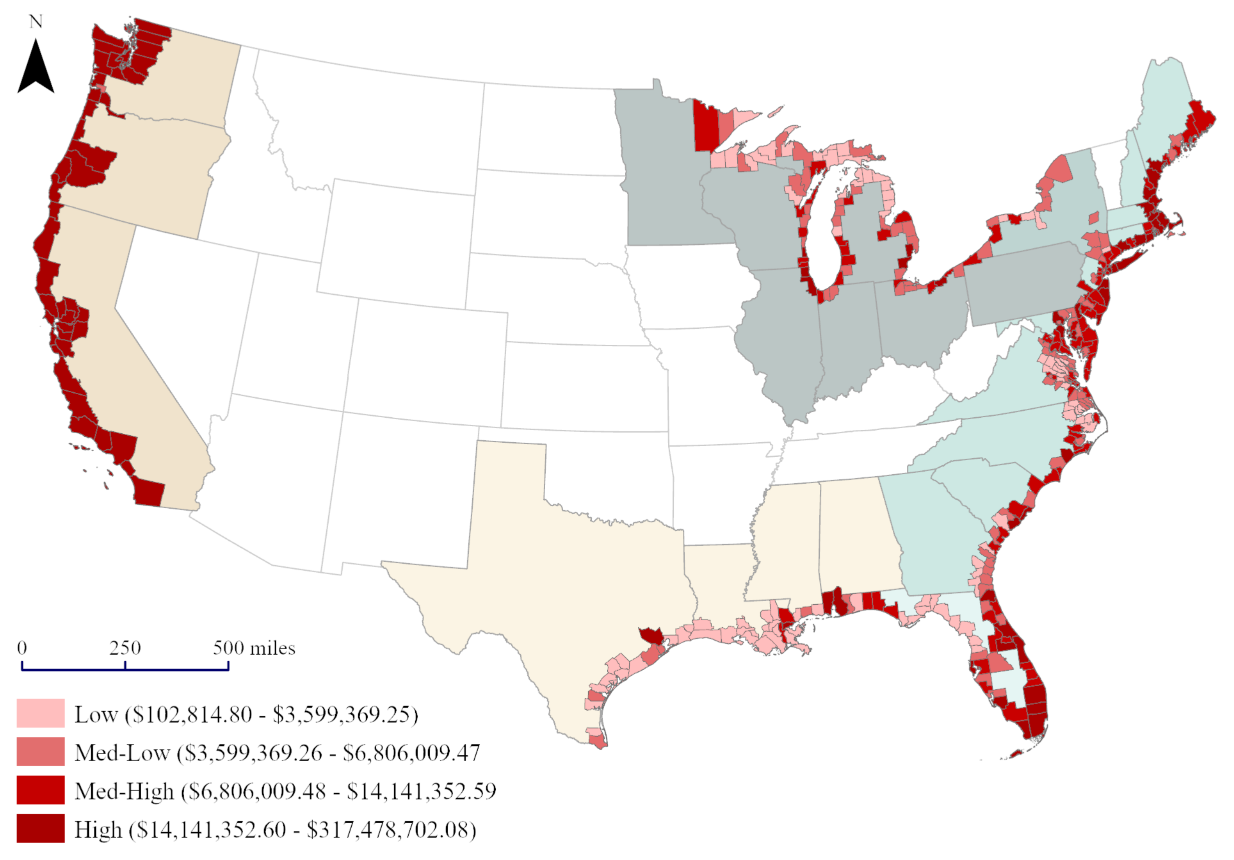

Figure 13. Final combined model estimates for HAB damages to all categories combined by county

Combining model-derived estimates of HAB-related damages with the CDC's Social Vulnerability Index demonstrate that there are numerous instances of overlap between highly vulnerable communities and high HAB-related damages (See Figure 14).

Additional maps, detailing each of the impact categories, can be viewed in "Appendix B Additional Maps" and viewed online in an interactive ArcGIS Online Web App, "The Estimates of the Benefits of Ocean Color Data in Mitigating HAB Events Web Map," viewable at **https://www.arcgis.com/apps/instant/basic/index.html?appid=466a593394664325b405229fbb643162**.

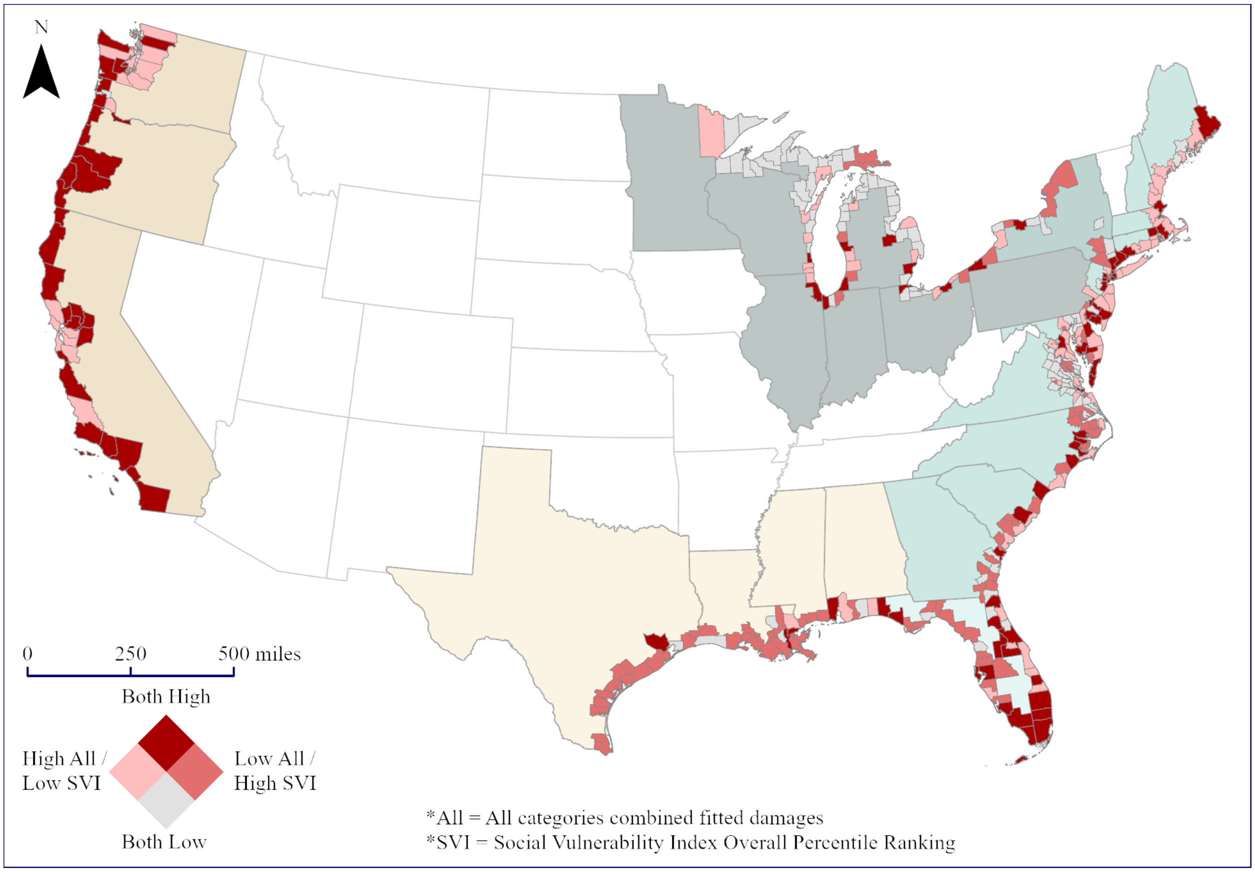

Figure 14. Estimated HAB-related fitted damages to all categories combined and CDC's Social Vulnerability Index (SVI) overall percentile ranking by county

STAKEHOLDER INTERVIEWS/OUTREACH

Based on conversations with individuals listed in Table 1 and using past reports and presentations that they provided, the research team was able to get a general sense of how ocean color data are being used on work related to HABs across several geographies (Gulf of Mexico, Great Lakes, and Northeast) and user groups, and a limited sense of its value to those users. Findings are summarized below.

Our initial findings indicate that there are likely additional opportunities to use ocean color data in HAB monitoring, forecasting, damage assessments, and communications. Conversations revealed that there are different levels of benefits of using ocean color data for HAB-related work based on location, waterbody type, end user group, and project purpose. More than one conversation revealed that there is both the need and opportunity to extend ocean color and other satellite imagery data to new communities and users. Smaller and less-well-resourced communities, for example, should have better access to the data and training on how to use it effectively.

Multiple conversations revealed that for ocean color data to be more effective as a component of decision making and research for end users, it must be provided at greater resolution and frequency than what is currently available. At a resolution of 300 meters, Sentinel-3 ocean color data provided through tools such as the Cyanobacteria Assessment Network Application (CyAN app)[52] is considered useful to inform decisions about HABs in larger inland lakes and reservoirs. However, as one participant shared, ocean color satellite data in its current formats may not be as useful for smaller inland water bodies like those on Cape Cod, Massachusetts. A team of researchers there attempted to use ocean color data to classify the water quality status of about 900 freshwater ponds.[53] The resolution of ocean color imagery from daily-derived sources like VIIRS, however, was insufficient at a maximum of 250-meters to adequately resolve these small coastal ponds. In contrast, 10-meter Sentinel data provides much more appropriate resolution for these purposes, but only in seven-to-ten-day intervals. The respondent shared that it might be possible to accurately resolve and classify about 400 ponds on Cape Cod at a resolution of 30 meters.

In all conversations, participants shared that in-situ, lab experiments, and other forms of remote sensing are all key to their work on HABs. In some instances, these data are used along with ocean color data. Several conversations revealed that it is important to be clear about distinguishing among which types of HAB-related products provide value to end users. The range of types of products relevant to this study include, at least, different ocean color data formats, other satellite data, in-situ monitoring data, and derived products like forecasts, bulletins, and other tools. Parsing out the value, specifically, of ocean color data that are incorporated into derived products is likely to be challenging.

Our conversations revealed that there have been an increasing number of stakeholder surveys in recent years to understand the usefulness of HAB-related information (including satellite data, HAB bulletins, and web tools) as well as the effectiveness of communications about these products.[54] A January 2023 Chesapeake Bay pre-workshop survey for a workshop titled

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[52] U.S. EPA (n.d.). Cyanobacteria Assessment Network Application (CyAN app). Accessed online April 1, 2023 at https://www.epa.gov/water-research/cyanobacteria-assessment-network-application-cyan-app.

[53] Nicole Bartlett, pers. comm. April 11, 2023

[54] See, for example: 1) Staugler, E.A., Simoniello, C., & P. Monaghan (August 2021). Insights from Natural Resources and Public Health Professionals on Key Elements of Red Tide Messaging and Modes of Communication. SGR-144.; 2) Krimsky, L.S. (August 2021). Usability Analysis of the Florida Department o Environmental Protection's Algal Bloom Sampling Status Dashboard. SGR-142.; 3) Krimsky, L.S. (August 2021). Usability Analysis of the Florida Fish and Wildlife Conservation Commission's Florida Wildlife Research Institute Red Tide Website.; 4) Krimsky, L.S.

"Identifying HAB Assessment and Forecasting Needs" that had 22 agency participants and 27 industry participants revealed that a majority of surveyed agency personnel and members of industry are not using satellite imagery to detect or respond to HABs.[55] Their chief limitations included not knowing where to find the imagery, not knowing how to process it, and spatial constraints. Respondents indicated that real-time satellite-based bloom information would be the most useful product for their work. The workshop itself revealed that many people in the Chesapeake Bay region are interested in using satellite imagery in part due to the stated high number of HABs in the Bay.

On behalf of NOAA National Ocean Service, the Eastern Research Group (ERG) conducted a survey in 2020 that examined how HAB bulletins are used by stakeholders in the Lake Erie and Gulf of Mexico regions.[56] Over 60% of respondents in both regions reported that they were "very satisfied" with the HAB bulletins and that the bulletins were used frequently in their work. ERG developed a limited set of benefit transfer estimates regarding HAB bulletins. Values ranged from $2.72 million annually to Ohio beachgoers to $16.8 million annually to Florida beachgoers.

In the same study, ERG evaluated *how* HAB bulletins are used by specific stakeholder groups including drinking water facilities, commercial fishing, resource managers, public officials, and academics. These interviews revealed that stakeholders use HAB bulletins and forecasts differently; commercial fishers in Lake Erie, for example, are largely not using these products because commercial fisheries are not greatly impacted by HABs there, while public health agencies do use these products and are primarily interested in the severity of the blooms. In this study, ERG did not specifically evaluate the extent to which ocean color data are used by stakeholders in these two regions, although end users indicated that real-time satellite imagery is an important contributor to decision making. 75% of Lake Erie survey respondents indicated that satellite imagery is "very useful," and shared further that the addition of more satellite imagery to the bulletins would be "useful" or "very useful."

Several participants revealed that there is an opportunity for ocean color data products to be made more user-friendly. They shared that ocean color data (and satellite data in general) and

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(August 2021). An Annotated Bibliography of *Karenia brevis* Red Tide Communications Literature. SGR-140.; 5) Florida Survey Research Center (2021). HABScope Red Tide Respiratory Forecast Website Survey Results. Completed on behalf of Florida Sea Grant and the University of Florida.; 6) [NEED CORRECT NAME OF THIS FROM CHIARA: effort underway here to assess user needs related to the GL CoastWatch node website overall.

[55] NOAA, Sea Grant, & MARACOOS (January 2023). Identifying HAB Assessment and Forecasting Needs: Pre-Workshop Survey Summary PowerPoint.

[56] Eastern Research Group (May 14, 2021). Use and Economic Value of NOAA Harmful Algal Bloom Forecasting Products: Final Report. Written under contract for NOAA National Ocean Service; 30pp.

the corresponding products that may use ocean color data (e.g., HAB bulletins) are being developed and targeted primarily for technical audiences. Those participants also shared that satellite data are being accessed for HAB-related purposes, but that those data are occasionally being misinterpreted. One person commented that misinterpretation of ocean color data is not likely as significant as it may be for other types of satellite data.

A few region-specific takeaways from our conversations revealed that:

- Ocean color is not used extensively for HAB-related efforts on the west coast of Florida because the HAB bulletins and forecasts that are developed by the National Centers for Coastal Ocean Science (NCCOS) for that area do not use ocean color. Instead, they use wind speed and direction data provided by the National Weather Service and in-situ observations.
- Particularly in places like Florida, where *Karenia brevis* red tides that produce brevetoxin that can be aerosolized can occur, several conversations highlighted that there is substantial opportunity to conduct more research into the effects of HABs on public health, especially as it relates to respiratory illnesses.
- In the Great Lakes region, remotely sensed data other than ocean color is used to develop HAB bulletins. The primary users of CoastWatch, which serves ocean color data, in the Great Lakes region are scientists, including those who work for NOAA and its cooperative institutes.

VI. Summary/Discussion

This analysis provides estimates of the costs of HABs in the United States and the potential benefits of satellite-based ocean color observations as they are used to reduce those costs. Ocean color observations are rarely if ever used *directly* by those whose decisions and actions are designed to reduce the harmful effects of algal blooms. Instead, they are a component in a complex value chain within which data and information inform models whose outputs are disseminated to a diverse array of end users who also rely on a wide range of other information. National scale estimates of the economic effects of HABs are one important product of this investigation. Another is a national scale estimate of the potential benefits of ocean color observations as they are used in products that inform the management of HABs to reduce their impacts on society.

The total expected annual HAB damages across the CONUS is $1.3 billion. This is consistent with multiple relatively localized events in the $10's to $100s of million in annual costs reported in the literature. Assuming the flat 5% reduction in damages from the use of ocean color observations (validated by NOAA's physical and satellite scientists) to mitigate the impacts of HAB events—across all regions and damage categories—it would represent a **total expected annual benefit from Ocean Color products of $65.1 million.** Those benefits would be realized annually for the life of the sensor.

Perhaps more importantly, this analysis provides a framework for refining these estimates in the future. The research upon which this analysis is based has three important limitations. First, studies tend to be focused on a few of the areas where HABs regularly occur. Figure 7 illustrates the sparse coverage of damage estimates from HAB events in the scientific literature. As discussed previously, the expected annual damage estimates modeled in this analysis are driven by economic cost estimates from the literature. Figure 15 exemplifies how this bias can affect the results, with 83% of the total expected annual damages from our model occurring on the West Coast derived from four counties in Northern California and two in the state of Washington. West Coast damage estimates tend to focus on infrequent high-cost events and extrapolating those high costs down the entire coast can drive artificially inflated cost estimates. There are great stretches of coastline where economic damage estimates simply don't exist (See Figure 12) and yet we know that HAB events have been reported there (See Figure 8). These include the Mid-Atlantic coast (the Chesapeake Bay excepted), the Southeast Atlantic coast, much of Texas and Louisiana, Southern California, and Oregon.

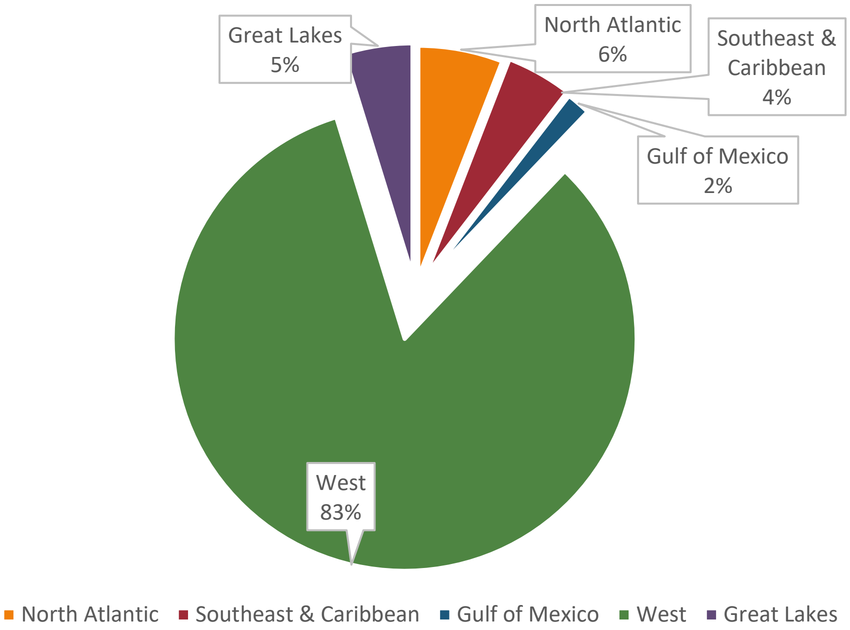

Figure 15. Total Expected Annual Damages by Region ($Thousands)

Second, the literature focuses almost exclusively on larger, less frequent events. Estimating the impacts of HABs at a national scale requires researchers to account for the full range of events, including the more frequent and less impactful events whose losses will represent a significant share of the total. This large-event bias is exemplified in Figure 16 which shows the total expected annual damages by impact type. Impacts to tourism and commercial fisheries dwarf the impacts to recreational fishing and public health. Tourism impacts comprise 73%, and commercial fishing 25% of the total expected annual impacts. Recreational fishing and public health impacts comprise 2% and less than 1% respectively. This can likely be attributed to the more diffuse nature of recreational and public health impacts, i.e., many more smaller events that aren't the focus of research efforts. That bias is likely exacerbated by the high proportion of tourism, and to a lesser extent, commercial fisheries, in the total economic activity in coastal areas.

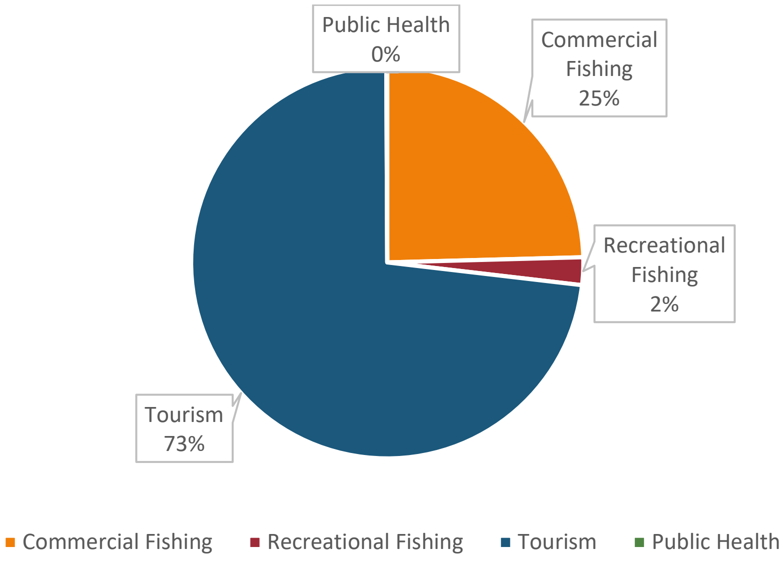

Figure 16. Total Expected Annual Damages by Impact Category ($Thousands)

Third is an understanding of how local officials, emergency managers, natural resource managers and other users *use* ocean color products to mitigate the impacts of HAB events, and the extent to which the impacts can be mitigated. This issue is common to efforts aimed at valuing information, such as data and observations provided by satellites. Satellite observations often have long and complex value chains,[57] and the use of ocean color data to reduce the damages caused by HAB events is only one of many potential end uses. Nevertheless, *the value of data are defined by their use*, and a thorough understanding of how these products are used is a key piece in determining value. For this study, we were able to conduct only a limited numbers of conversations with NOAA staff and contractors who are using ocean color satellite data. However, desktop research and conversations revealed that there are varying degrees of usage of ocean color observations and data products and that there remains opportunity to disseminate such information more broadly and to better educate end users in how to use these products, thereby increasing their value.

There are three fundamental components to this framework approach that can be used together in future assessments to revise and refine estimates of the economic effects of HAB events and the value of ocean color observations and data: 1) a spatially explicit distribution of losses due to HAB events, 2) the probability of a HAB event happening at a county scale, and 3)

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[57] See, for example, Adkins, GeoXO benefit analysis.

what proportion of the damages caused by HAB events can be mitigated by the use of ocean color data.

The first component is represented by the regression analysis which presents curves that estimate the distribution of losses. These are the curves with the long tails to the right. We need data points all along the curve, but, research tends to focus only on the extreme events (the far-right end of the long curve). The use of a log distribution helps to estimate the full curve, based on the assumption that most HAB events are low to medium impact. However, what is missing is valuation/cost data on low to medium impact events.

Using the HAEDat data to measure where HAB events are taking place (regardless of whether they are being valued or not) leads us to the second component; probability. As noted in the report, there is a mismatch between economic valuation literature and reported HAB events in HAEDat. This is not surprising, as big events get more attention than smaller events. However, it complicates the valuation process. HAEDat is also an international source of data; lack of consistent and comprehensive monitoring in the U.S. hampers our understanding of the probability of a HAB event happening.

Perhaps the biggest gap is in our understanding of how important ocean color observations and data are to our user base, or how ocean color is used to mitigate HAB events. The distribution of losses and probability of events are fairly straightforward questions, with noted information gaps. However, understanding how end-users use ocean color information to mitigate the potential impacts of each event is likely to be the greatest source of uncertainty in the current assessment.

This analysis integrates findings from the current body of research into the framework, noting significant gaps and limitations. Addressing those gaps and limitations is a necessary first step in moving forward.

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VIII. Appendix A: Detailed Methodology

One way of specifying the SUR model is by using dummy variables for the regions and damage categories and using a full set of interactions between the two groups of dummy variables and all of the continuous variables. This is expressed as:

$$
\begin{aligned}
&\ln\left(Damage_{i,r,s}\right) \\
&= \beta_0 + \sum_{r\,\in Regions}\left(\sum_{s\,\in Damage\ Catagories}\left(\begin{gathered}\gamma_r + \delta_s + \rho_{r,s} + \theta_1^{r,s} * Year_{i,r,s} \\ + \theta_2^{r,s} * \ln\left(Population_{i,r,s}\right) + \theta_3^{r,s} * \ln\left(GDP_{i,r,s}\right) \\ +\theta_4^{r,s} \ln\left(Commercial\ Fishing\ Income_{i,r,s}\right) \\ + \theta_5^{r,s} * \ln\left(Recreational\ Fishing\ Income_{i,r,s}\right) \\ +\theta_6^{r,s} * \ln\left(Tourinsm\ Income_{i,r,s}\right)\end{gathered}\right)\right) \\
&+ \mu_i.
\end{aligned}
$$

(3)

In this specification, γ_r represents a set of four region specific effects, δ_s represents a set of four damage category specific effects, and $\rho_{r,s}$ represents a set of sixteen region-damage category interaction effects. Each $\theta_j^{r,s}$ is a set of sixteen parameters associated with the regressors. The single grouped error term, μ_i distinguishes SUR from sixteen separately estimated equations which would each have independently distributed error terms, $\mu_{i,r,s}$. We estimate this model using the two-stage Feasible Generalized Least Squares approach.[58]

Note that this specification explicitly does not restrict the exposure variables to the matching categories of damage. For instance, it allows commercial fishing damages to be a function of not only commercial fishing income, but also recreational and tourism income. This allows for a more flexible specification. There may be overlap between the effect of some of these industries, both because of the relation of the industries (e.g., popular tourism destinations may see a related increase in recreational fishing because more people are consuming leisure activities at that destination) and because of overlap between industrial classification in some of these categories. Additionally, sub-models that contain the same set of regressors are symmetric, which allows us to test linear restriction on the specification (or, equivalently, the

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[58] Zellner, A. (1963). Estimators for seemingly unrelated regression equations: Some exact finite sample results. Journal of the American Statistical Association, 58(304), 977-992.

joint significance of a set of variables).[59] This is preferable to the standard Wald test, which can be biased towards failing to reject for GLS estimates. We test this assumption as part of the specification tests in the Analysis section.

We perform a number of restriction tests to evaluate, and where appropriate simplify the full specification detailed in (2). Table N documents the statistics for these tests. The null hypothesis for this test favors the unrestricted model, while rejection of the null favors the restricted model. For example, we test the restriction that $\forall\theta_1^{r,s} = \theta_1^r$, or that the effect of time varies across region, but not damage type. The calculated value for this test is F=1.36 with df=(4,9), which has a p-value of 0.31. Since the null is not rejected, we can restrict the effect of time to be the same across regions. We also fail to reject $\forall\theta_1^{r,s} = \theta_1^s$ (p=0.16). We finally test $\forall\theta_1^{r,s} = \theta_1$, or that the effect of year is equal across all regions and damage types, and also fail to reject (p=0.12). Therefore, we can estimate a single parameter for time instead of 16 separate parameters. When restricting population across regions, however, $\forall\theta_2^{r,s} = \theta_2^r$, we reject the null (p=0.01), so have to estimate separate population effects for each region. We fail to reject differentiation of the effect of population across damage types (p=0.73), and since we have already rejected the restriction across region, we do not test restriction across both region and damage type. The final three tests test whether the three income variables should be restricted just to their corresponding damage equations. The test rejects all three of those restrictions.

Table N: Restriction Tests

Restriction	F-Stat	df	p-value
$\gamma_r = 0$	9.9	(4,9)	0.000
$\delta_s = 0$	13.6	(4,9)	0.000
$\rho_{r,s} = 0$	19.3	(16,5)	0.002
$\forall\theta_1^{r,s} = \theta_1^r$	1.4	(4,9)	0.310
$\forall\theta_1^{r,s} = \theta_1^s$	1.8	(4,9)	0.161
$\forall\theta_1^{r,s} = \theta_1$	2.9	(16,5)	0.120
$\forall\theta_2^{r,s} = \theta_2^r$	6.2	(4,9)	0.011
$\forall\theta_2^{r,s} = \theta_2^s$	0.5	(4,9)	0.730
$\forall\theta_3^{r,s} = \theta_2^r$	5.2	(4,9)	0.019
$\forall\theta_3^{r,s} = \theta_2^s$	0.8	(4,9)	0.550
$\forall\theta_4^{r,s} = \theta_2^r$	14.8	(4,9)	0.001
$\forall\theta_4^{r,s} = \theta_2^s$	1.2	(4,9)	0.371
$\forall\theta_5^{r,s} = \theta_2^r$	12.9	(4,9)	0.001
$\forall\theta_5^{r,s} = \theta_2^s$	1.1	(4,9)	0.421

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[59] Hashimoto, N., & Ohtani, K. (1990). An exact test for linear restrictions in seemingly unrelated regressions with the same regressors. Economics Letters, 32(3), 243-246.

$\forall\theta_6^{r,s} = \theta_2^r$	22.2	(4,9)	0.000
$\forall\theta_6^{r,s} = \theta_2^s$	6.7	(4,9)	0.009
$\forall\theta_4^{r,s} = 0, s \neq CF$	8.7	(8, 7)	0.005
$\forall\theta_5^{r,s} = 0, s \neq RF$	18.2	(8, 7)	0.001
$\forall\theta_6^{r,s} = 0, s \neq T$	9.4	(8, 7)	0.004

IX. Appendix B: Additional Maps

Maps presented below represent three categories of outputs from this study:

- HAB-related costs from the HAB Literature Attributes Table by county;
- Final combined model estimates for HAB damages by county; and,
- Estimated HAB-related fitted damages overlaid with the CDC's Social Vulnerability Index (SVI) by county.

Summary maps that combine the four categories are included in the GIS Analysis subsection.

Table 8. Layers and sources included in GIS Analysis

LAYER NAME	SOURCE
Coastal and Great Lakes Counties (2022 & 2023)	NOAA; U.S. Census; U.S. National Ice Center
HABs documented in the HAB Literature Attributes Table by county	HAB Literature Attributes Table
HAB-related costs by category from the HAB Literature Attributes Table	
HAB-related costs to **commercial fishing** in 2022 real dollars per capita by county	U.S. Census CBP + NES, HAB Literature Attributes Table
HAB-related costs to **recreational fishing** in 2022 real dollars per capita by county	U.S. Census CBP + NES, HAB Literature Attributes Table
HAB-related costs to **tourism** in 2022 real dollars per capita by county	U.S. Census CBP + NES, HAB Literature Attributes Table
HAB-related costs to **public health** in 2022 real dollars per capita by county	U.S. Census CBP + NES, HAB Literature Attributes Table
HAB-related costs to **all categories combined** in 2022 real dollars per capita by county	U.S. Census CBP + NES, HAB Literature Attributes Table
Final combined model estimates for HAB damages by category	
Final combined model estimates for HAB damages to **commercial fishing** by quantile by county	Study-derived

Final combined model estimates for HAB damages to **recreational fishing** by quantile by county	Study-derived
Final combined model estimates for HAB damages to **tourism** by quantile by county	Study-derived
Final combined model estimates for HAB damages to **public health** by quantile by county	Study-derived
Estimated HAB-related fitted damages by category and SVI	
Estimated HAB-related fitted damages to **commercial fishing** and SVI overall percentile ranking by county	Study-derived & CDC/ATSDR SVI
Estimated HAB-related fitted damages to **recreational fishing** and SVI overall percentile ranking by county	Study-derived & CDC/ATSDR SVI
Estimated HAB-related fitted damages to **tourism** and SVI overall percentile ranking by county	Study-derived & CDC/ATSDR SVI
Estimated HAB-related fitted damages to **public health** and SVI overall percentile ranking by county	Study-derived & CDC/ATSDR SVI
Estimated HAB-related fitted damages to **all categories combined** and SVI overall percentile ranking by county	Study-derived & CDC/ATSDR SVI

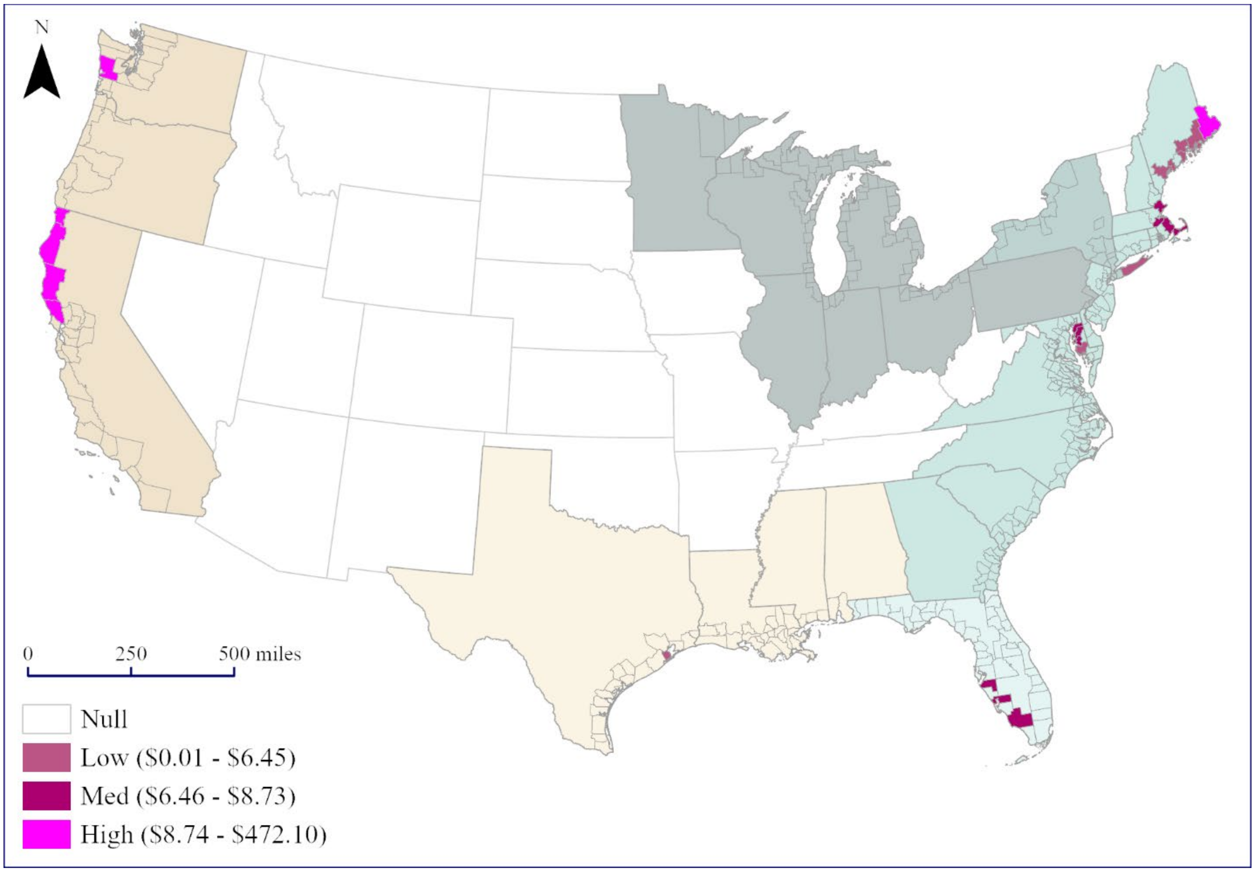

Figure 17. HAB-related costs to commercial fishing in 2022 real dollars per capita by county from the HAB Literature Attributes Table

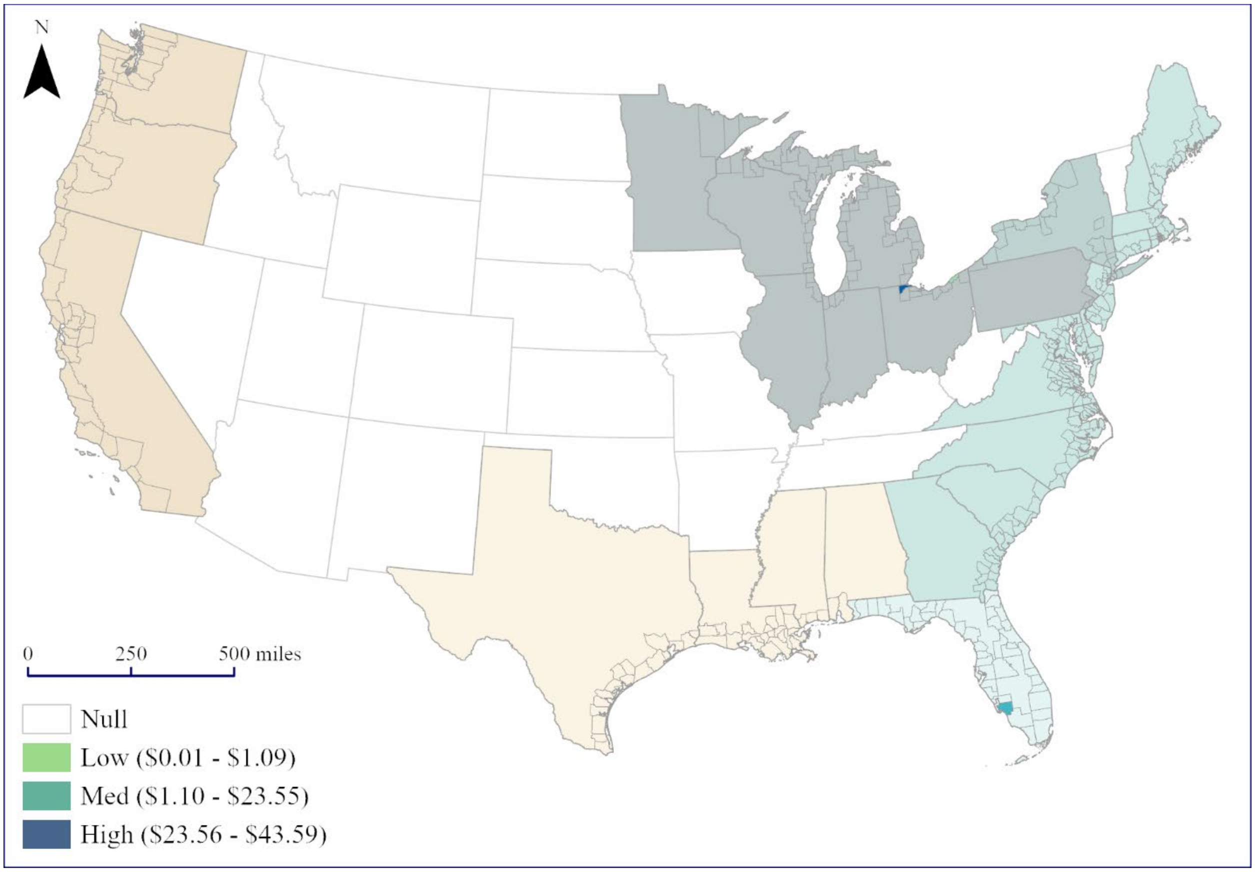

Figure 18. HAB-related costs to recreational fishing in 2022 real dollars per capita by county from the HAB Literature Attributes Table

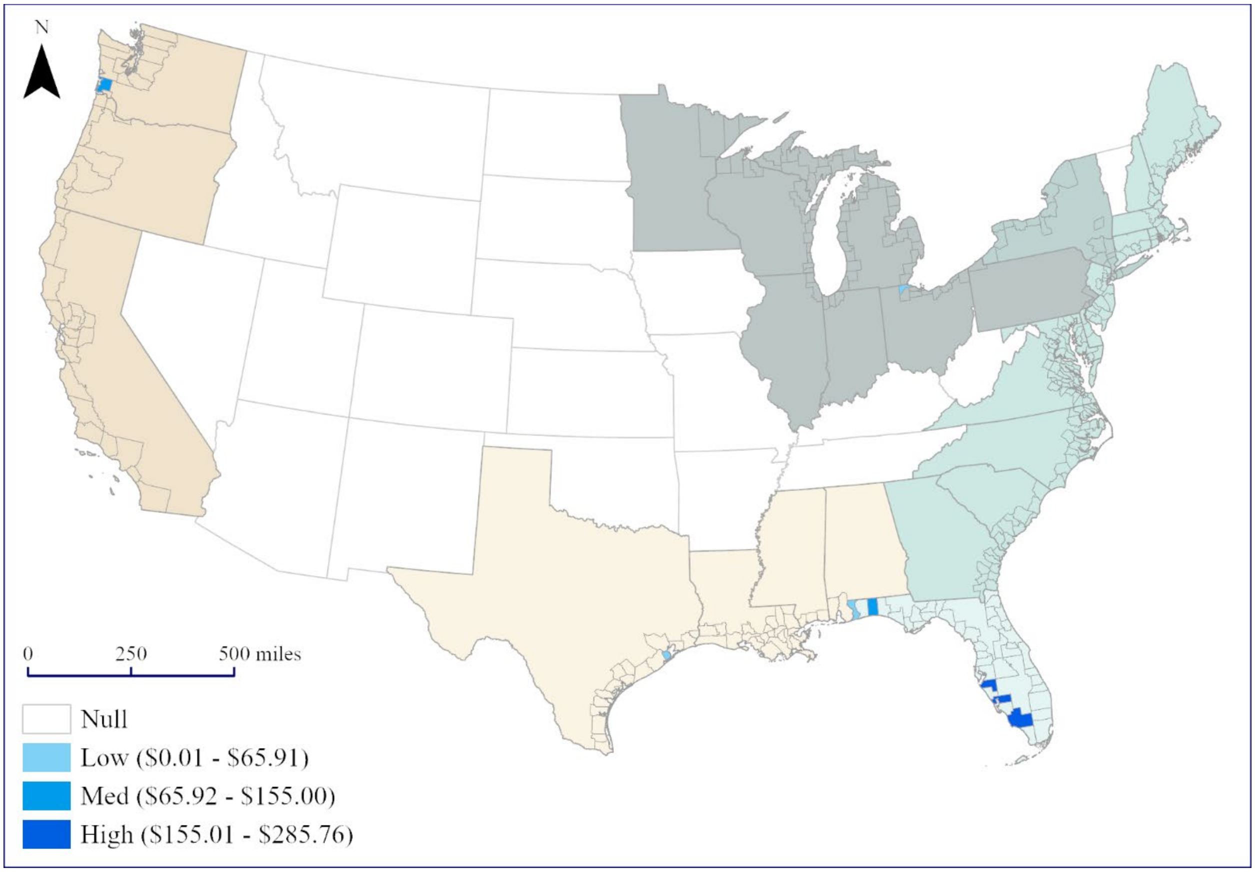

Figure 19. HAB-related costs to tourism in 2022 real dollars per capita by county from the HAB Literature Attributes Table

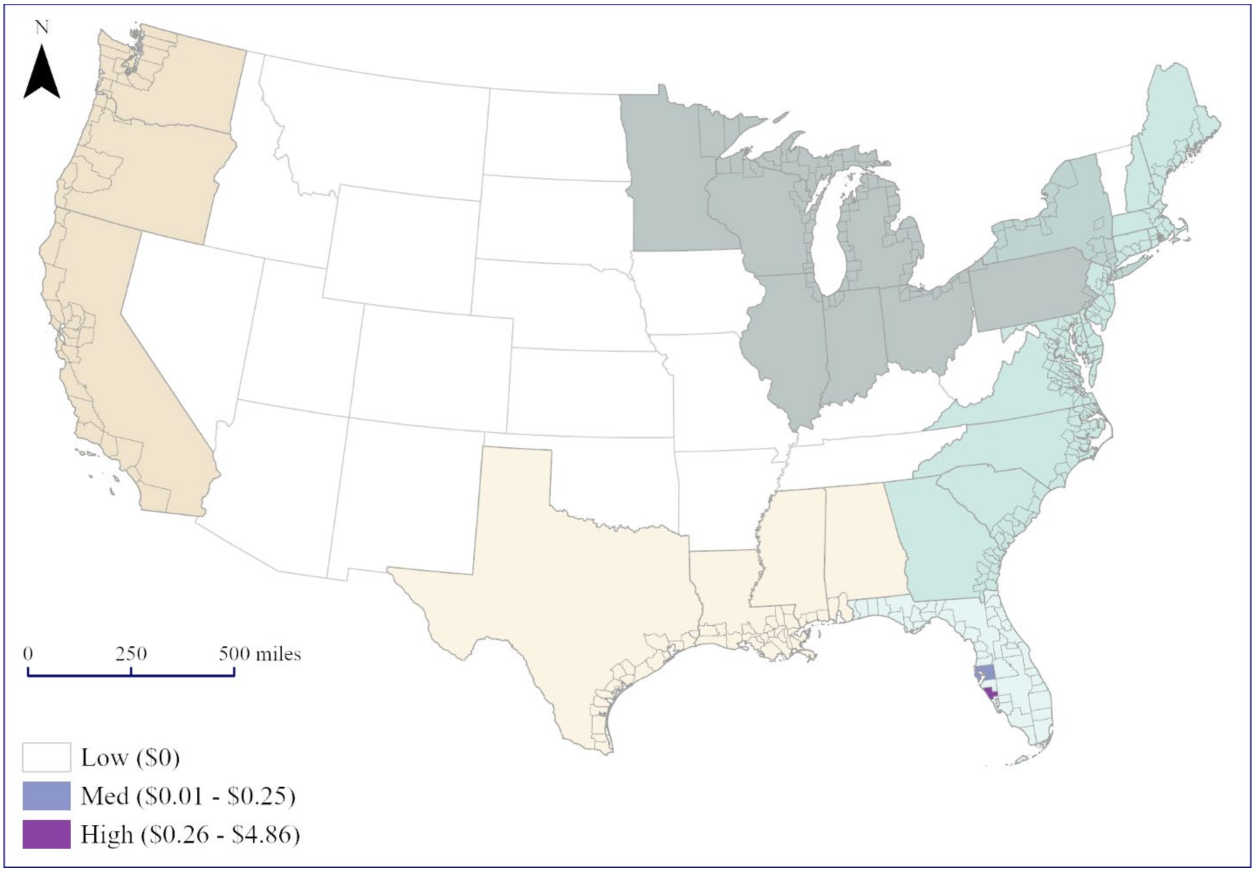

Figure 20. HAB-related costs to public health in 2022 real dollars per capita by county from the HAB Literature Attributes Table

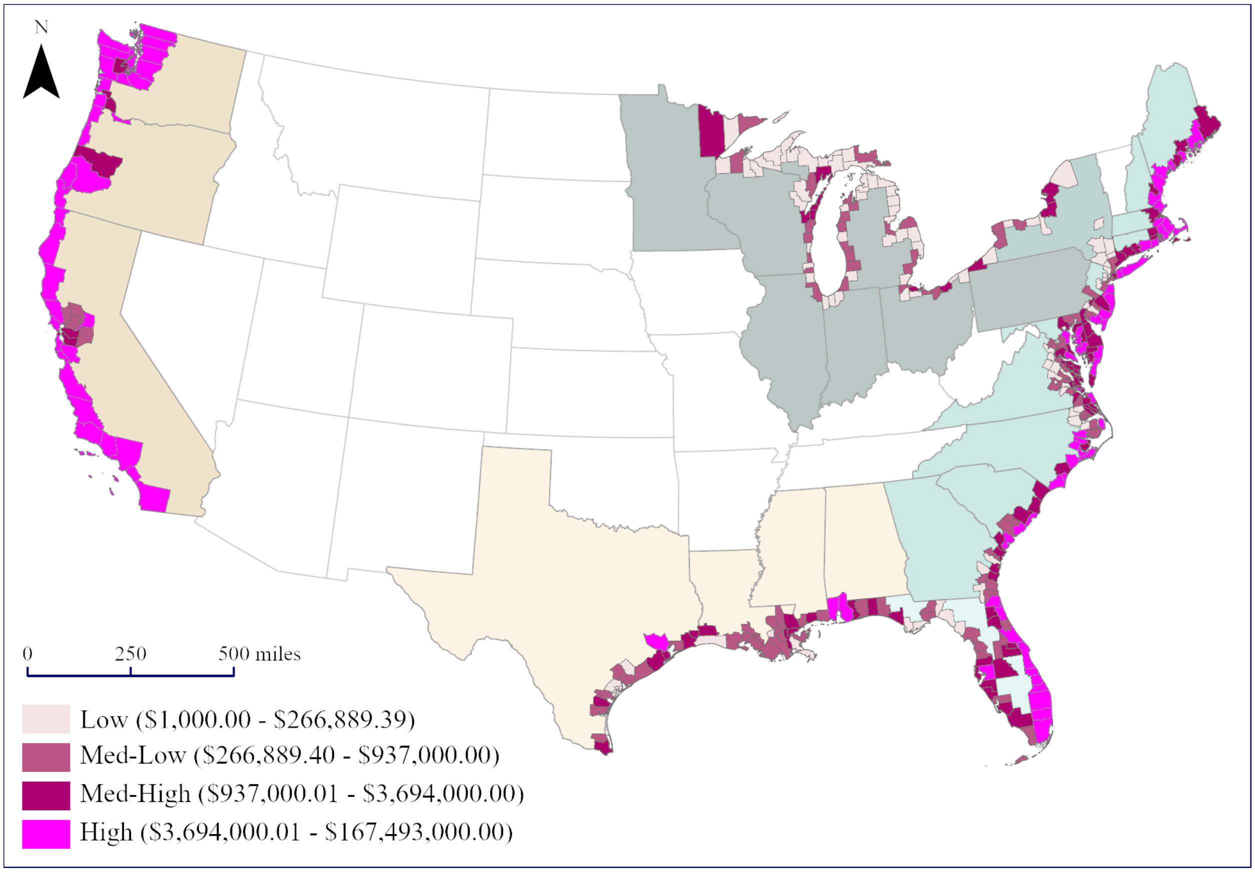

Figure 21. Final combined model estimates for HAB damages to commercial fishing by quantile by county

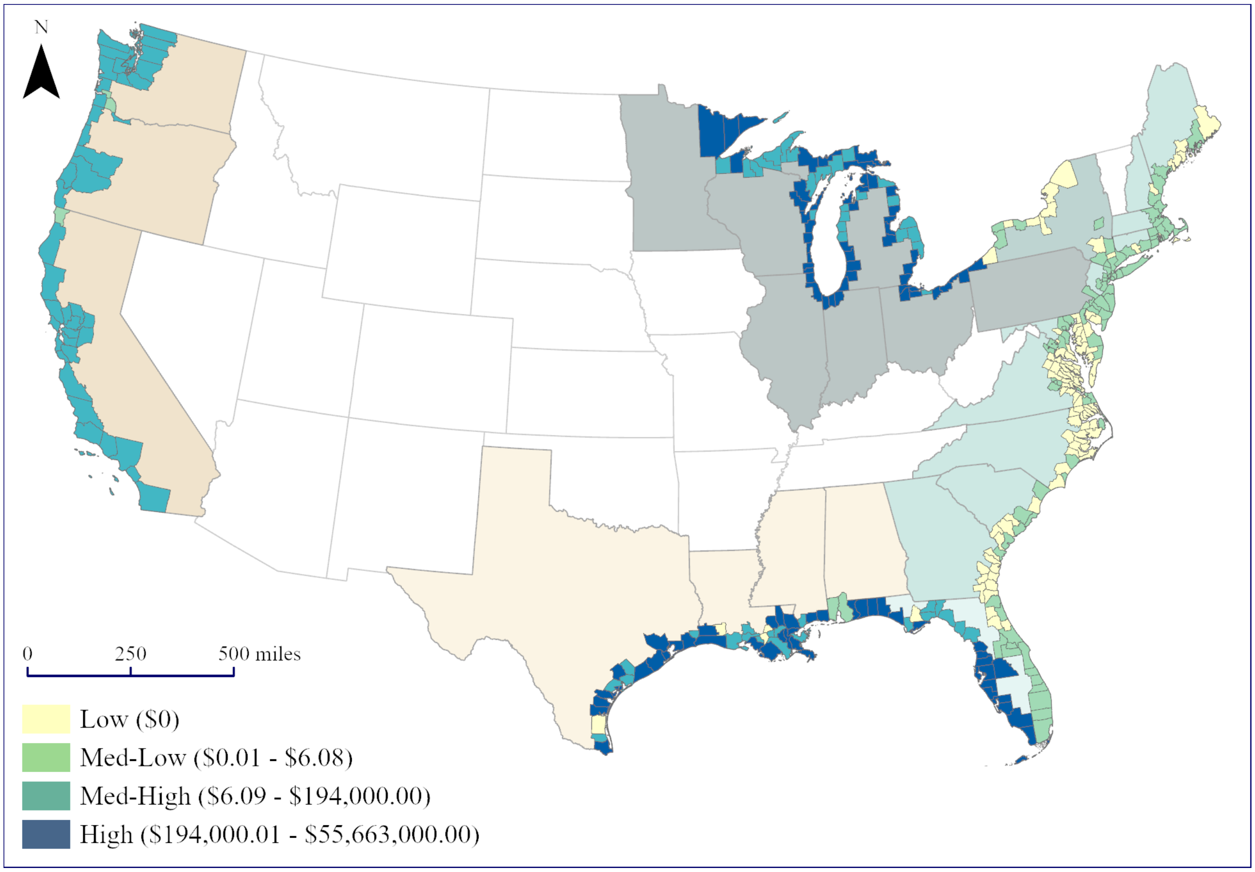

Figure 22. Final combined model estimates for HAB damages to recreational fishing by quantile by county

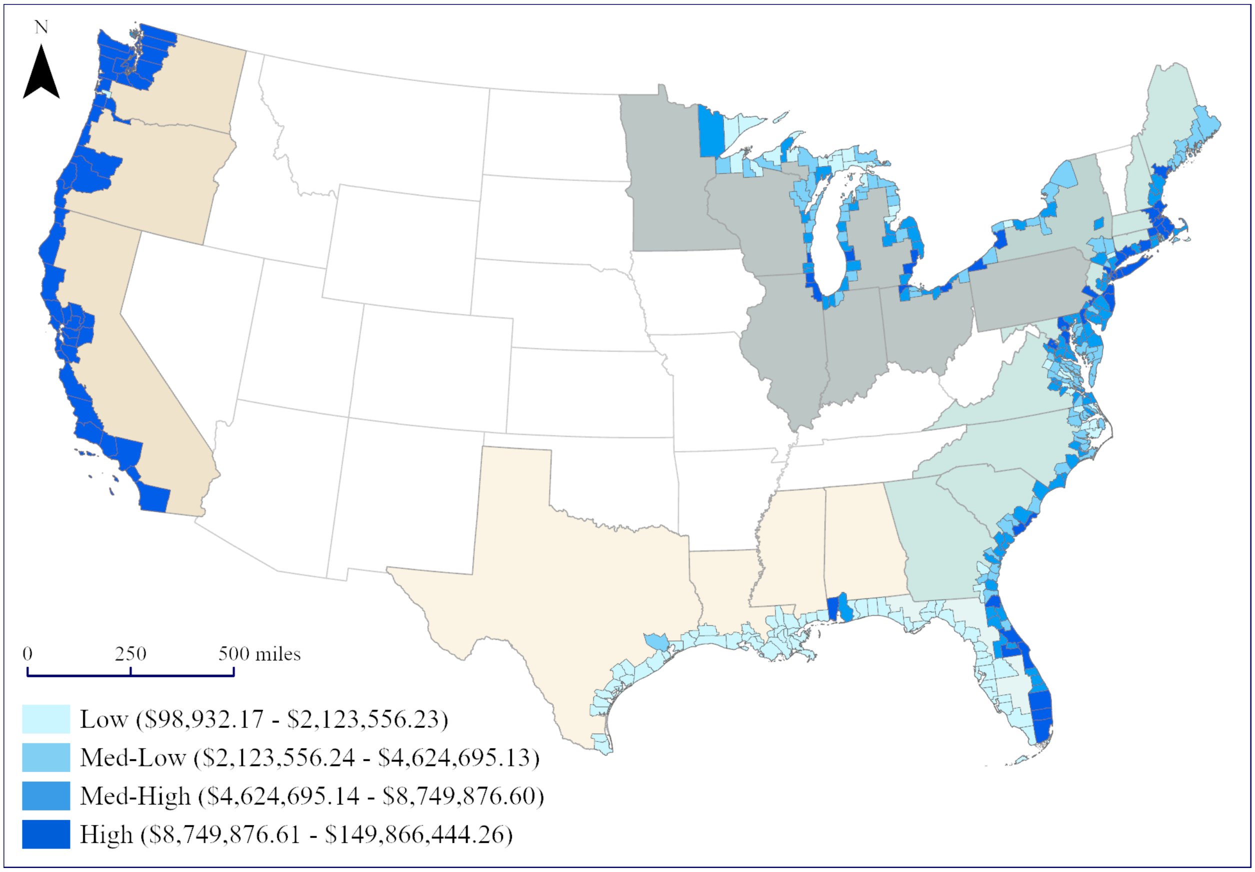

Figure 23. Final combined model estimates for HAB damages to tourism by quantile by county

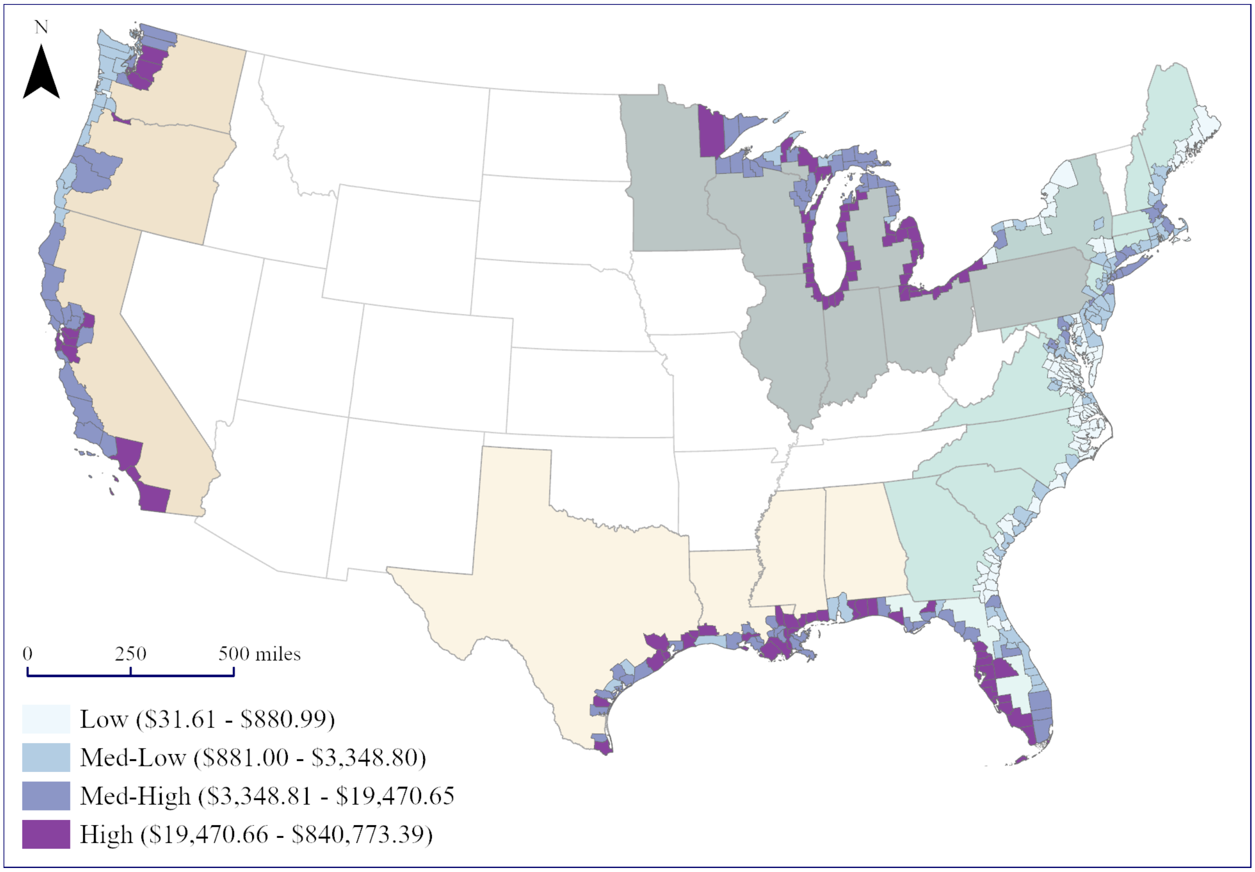

Figure 24. Final combined model estimates for HAB damages to public health by quantile by county

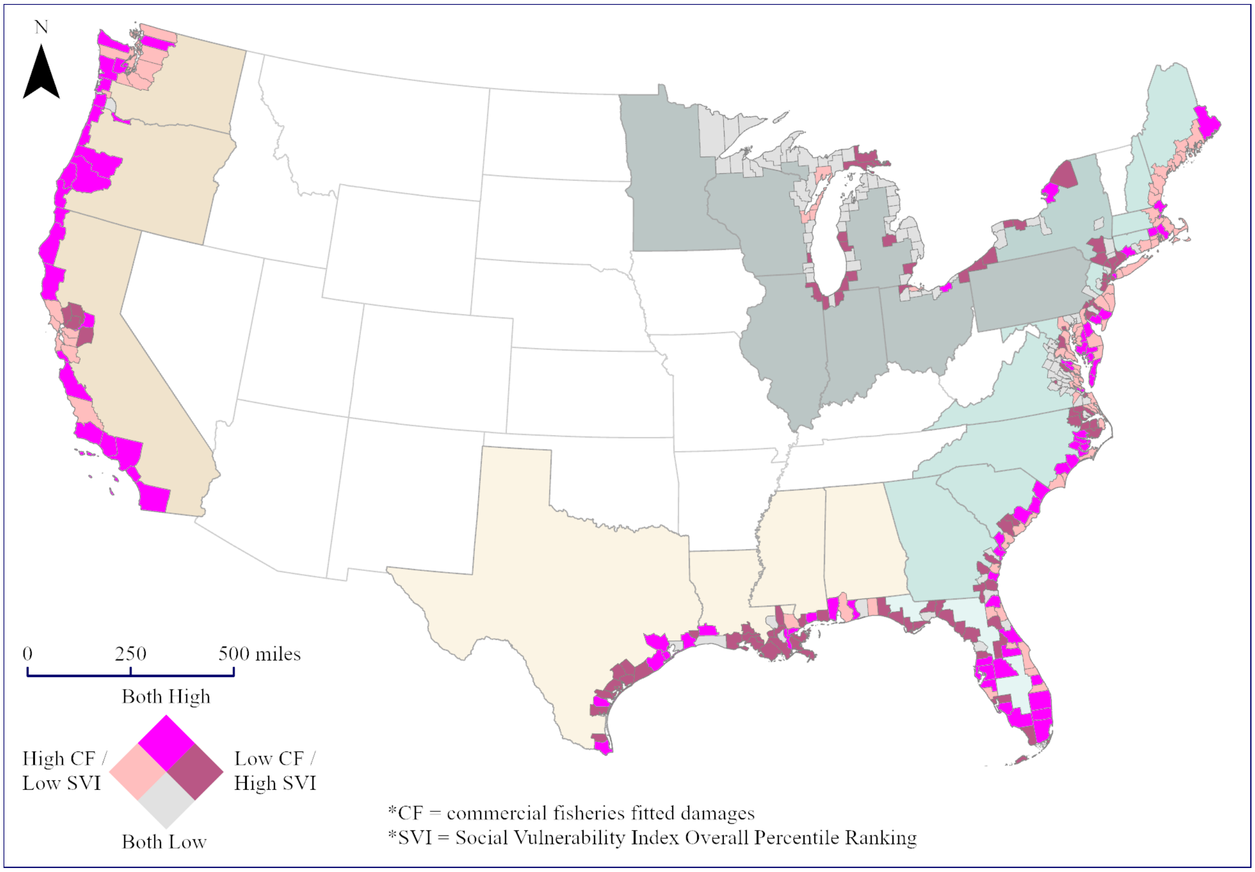

Figure 25. Estimated HAB-related fitted damages to commercial fishing and CDC's Social Vulnerability Index (SVI) overall percentile ranking by county

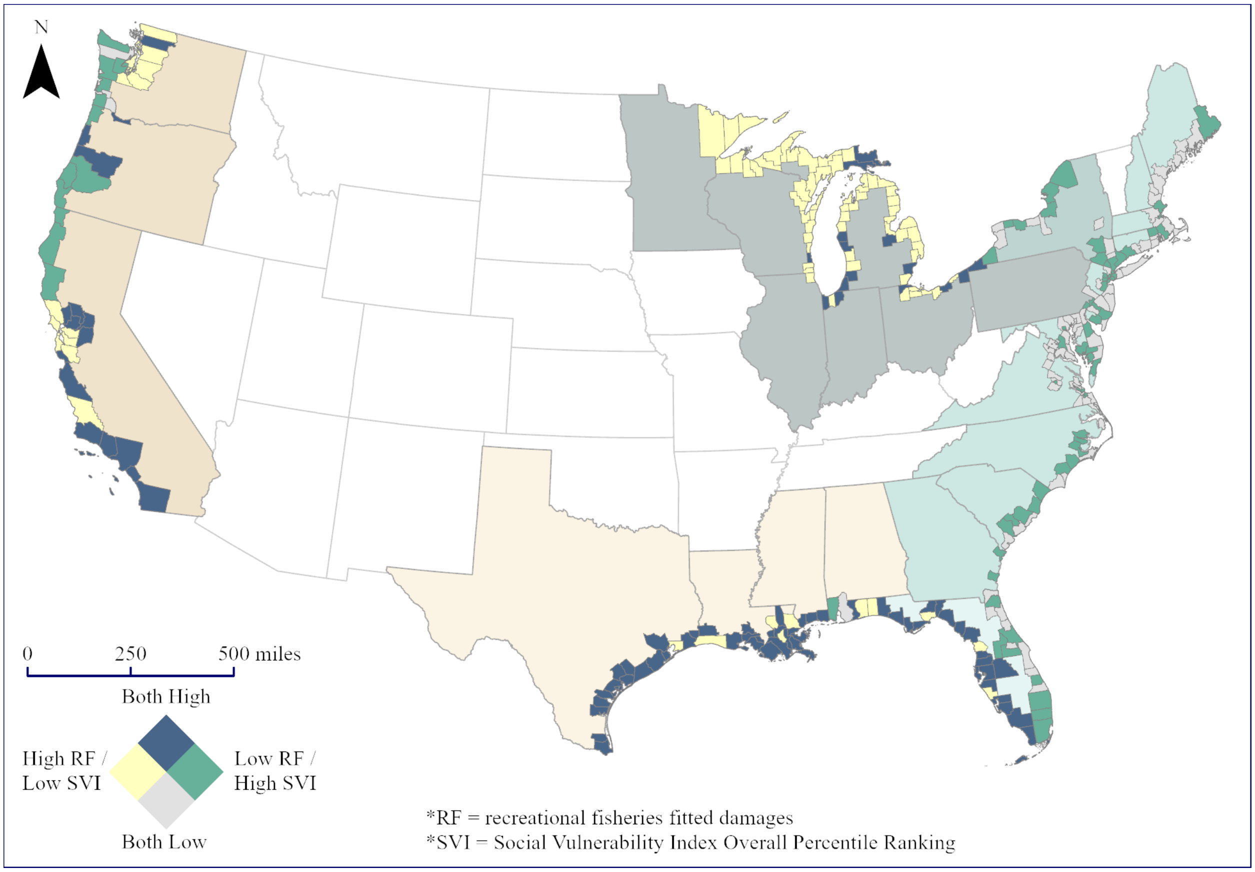

Figure 26. Estimated HAB-related fitted damages to recreational fishing and CDC's Social Vulnerability Index (SVI) overall percentile ranking by county

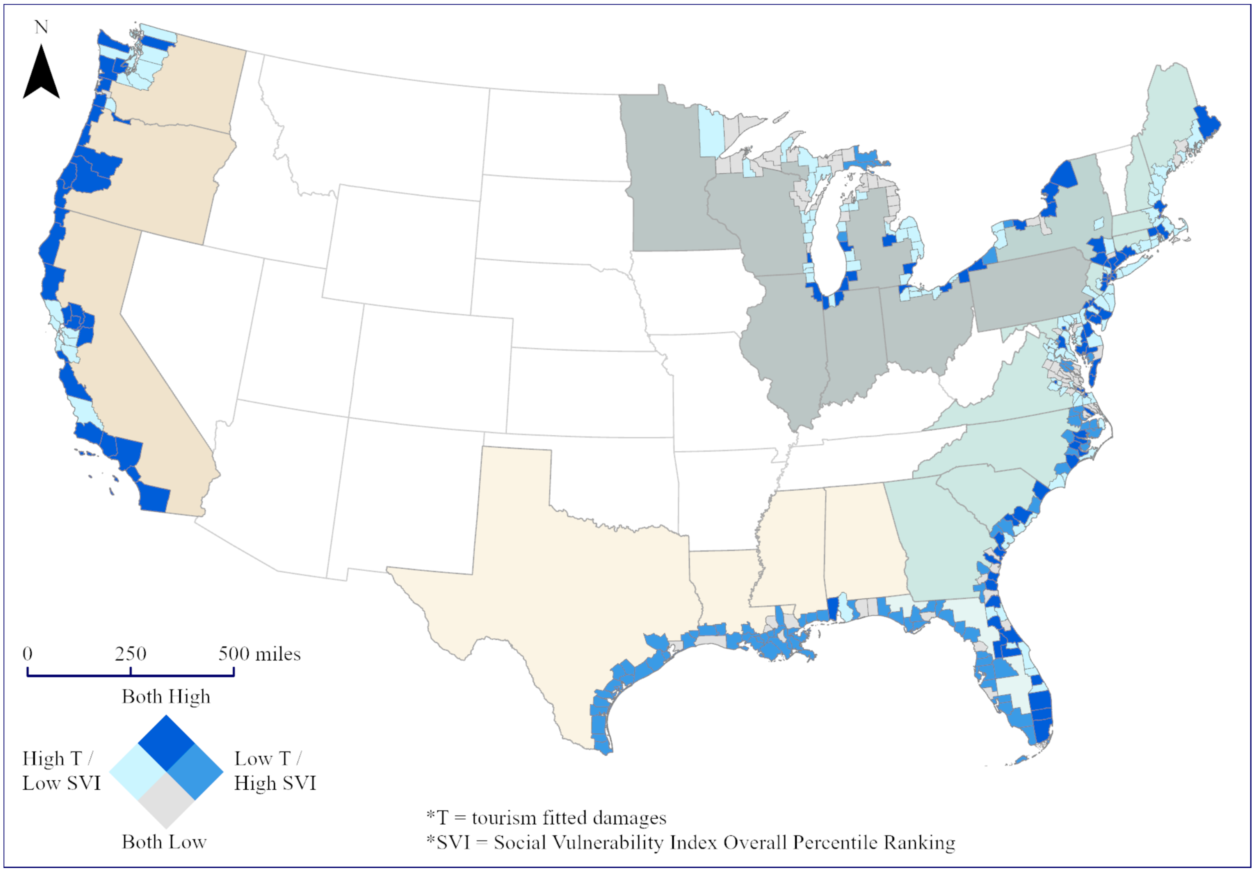

Figure 27. Estimated HAB-related fitted damages to tourism and CDC's Social Vulnerability Index (SVI) overall percentile ranking by county

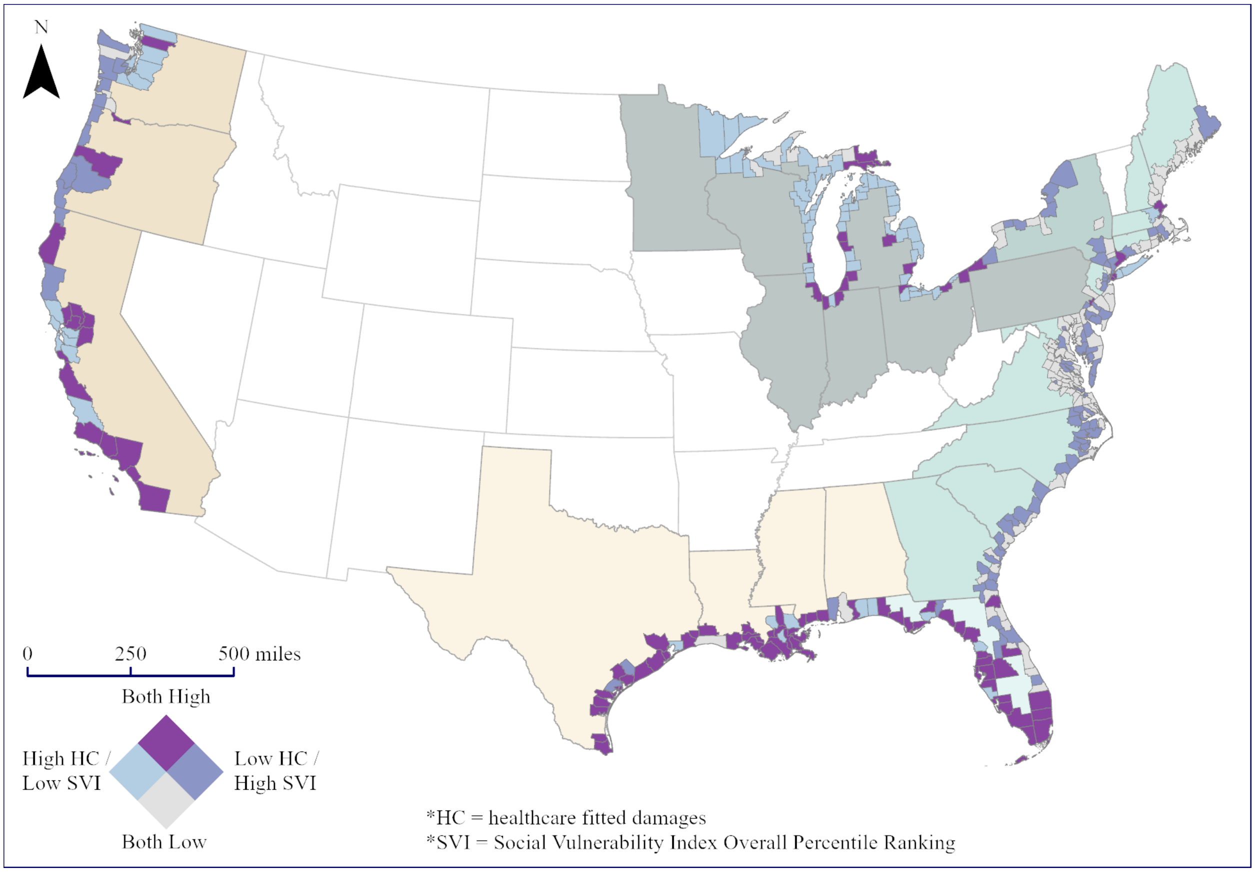

Figure 28. Estimated HAB-related fitted damages to public health and CDC's Social Vulnerability Index (SVI) overall percentile ranking by county