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Are Harmful Algal Blooms Increasing in the Great Lakes?

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Abstract: This study used satellite remote sensing to investigate trends in harmful algal blooms (HABs) over the last 21 years, focusing on four regions within the Laurentian Great Lakes: western Lake Erie, Green Bay, Saginaw Bay, and western Lake Superior. HABs in the water column were identified from remote sensing-derived chlorophyll concentrations, and surface HAB scums were classified based on the Normalized Difference Vegetation Index (NDVI) band ratio index. Using imagery from the Moderate Resolution Imaging Spectroradiometer sensor on the Aqua satellite (MODIS-Aqua) from 2002 to 2022, we generated daily estimates of the HAB and surface scum extents for each region, which were then averaged to generate mean annual extents. We observed a significant decline in the Saginaw Bay mean annual HAB extents over the 21-year study period. Otherwise, no significant changes were observed over this period in any region for either the HAB or surface scum mean annual extents, thus suggesting that HABs are not increasing in the Great Lakes. Despite the lack of increasing trends, the blooms are still recurring annually and causing a negative impact on the nearby communities; thus, we believe that it is crucial to continue studying Great Lakes HABs to monitor the impact of current and future abatement strategies.

Keywords: remote sensing; HABs; cyanobacteria; Great Lakes; Lake Erie; Saginaw Bay; Green Bay; Lake Superior

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Citation: Bosse, K.R.; Fahnenstiel, G.L.; Buelo, C.D.; Pawlowski, M.B.; Scofield, A.E.; Hinchey, E.K.; Sayers, M.J. Are Harmful Algal Blooms Increasing in the Great Lakes? *Water* **2024**, *16*, 1944. https://doi.org/10.3390/w16141944

Received: 4 June 2024
Revised: 2 July 2024
Accepted: 3 July 2024
Published: 10 July 2024

1. Introduction

Harmful algal blooms (HABs) have been a recurring problem in the Laurentian Great Lakes for over 50 years, with levels rising and falling in response to anthropogenic actions and other drivers. Historical inputs of phosphorus from industry, municipalities, and non-point sources drove the proliferation of algal blooms in many areas, including western Lake Erie (WLE), Green Bay, and Saginaw Bay [1–3]. Public attention in response to these blooms and other environmental issues facing the Great Lakes led to the signing of the Canada–United States Great Lakes Water Quality Agreement (GLWQA) in 1972. Subsequent decreases in nutrient inputs in the late 1970s and 1980s, especially from municipal wastewater and residential fertilizer, led to improvements in water quality and a decline in HABs over the same time period [4].

More recently, a number of changes have again created conditions favorable for excess algal growth. Phosphorus loading to Lake Erie increased in the 2010s from the lows in the 1990s, especially the highly bioavailable dissolved reactive form [5]. The invasion and establishment of dreissenid mussels has drastically altered Great Lakes food webs in ways that could favor cyanobacteria growth, with mussel filter feeding increasing light availability, selective filtration favoring cyanobacteria, and the nearshore shunt hypothesis suggesting increased nutrient retention in nearshore areas, particularly of the dissolved form [6–8], though recent data have shown that populations have declined in western Lake

Erie and Saginaw Bay since their initial invasion [9,10]. There is also growing concern that climate change may increase the potential for HABs via rising temperatures [11], increased nutrient loading associated with precipitation changes [12], and altered in-lake conditions, such as stronger water column stratification that can favor cyanobacteria [13]. Climate change-driven increases in temperature and storm events have recently been linked to the observation of cyanobacteria blooms in regions historically believed to be unimpacted, including western Lake Superior [14,15].

HAB monitoring programs have been established in several impacted regions to track the occurrence and intensity of blooms. The most comprehensive programs, including those in WLE and Saginaw Bay, consist of routine ship-based sampling supplemented by long-term buoy deployments [16]. Other regions, including Lake Superior, have limited HAB monitoring programs and rely more on the public to report blooms [17]. However, there are inherent limitations to monitoring programs built around public reporting or in situ monitoring. Cost and time restraints limit the spatial spread and temporal frequency of sampling events. Additionally, perceived or documented bloom increases based on either public reporting or in situ monitoring (e.g., [14,18,19]) can result from increases in public awareness or sampling effort. For example, while a recent increase in the number of blooms reported per year in Lake Superior seems to indicate a rise in bloom frequency, this increase may also be "due to increased public awareness and management agency attention" [20]. In response to these limitations, satellite remote sensing has become a valuable component of HAB monitoring programs [21]. The greater spatial and temporal coverage offered by remote sensing approaches is better able to capture the variability of blooms without the time and cost constraints of in situ sampling. Remote sensing also allows for retrospective analyses of bloom occurrences, which is particularly useful for areas like Lake Superior without historic in situ monitoring programs.

In the Great Lakes, remote sensing has been used to investigate HAB trends in several regions. Many studies have reported recent increases in the WLE blooms. These include reports of significantly increasing annual HAB and surface scum extents from 2002 to 2013 [22] and 1997 to 2017 [23], and increased bloom intensity over similar time periods [24–26]. In using Landsat satellite imagery to extend the bloom record back to 1984, [27] the found WLE blooms were smallest in the early-to-mid 1990s, a period of low phosphorus loading to Lake Erie [28], but blooms had increased from the mid-2000s to 2015. Unlike in WLE, blooms in Green Bay and Saginaw Bay have been reported as being relatively stable from 2002 to 2013 [22] and 2000 to 2019 [29] (Saginaw Bay only). In addition to the study periods analyzed, there are many differences in approaches between these studies, including the type of detection algorithms (line height vs semi-analytical algorithms), satellite sensors used (with varying spatial, spectral, and temporal resolutions), primary metric (e.g., extent, intensity, duration), and method for calculating the annual metric [30,31].

The purpose of this study was to use satellite imagery to assess HAB trends over the past 21 years (2002–2022) for four regions of the Great Lakes: WLE, Saginaw Bay, Green Bay, and western Lake Superior. This work builds on the analysis of Sayers et al. [22,23], adding 5 years to the WLE data record and 9 years to those of Saginaw Bay and Green Bay, allowing us to assess whether those previously reported trends have persisted. In western Lake Superior, this analysis will provide greater historical context for the recently observed blooms, which are perceived to be a new phenomenon.

2. Materials and Methods

2.1. Study Area

The study area for this analysis consisted of four distinct regions within the Laurentian Great Lakes, each of which has a recorded history of cyanobacteria blooms and can be observed via satellite remote sensing. These study areas include WLE, Saginaw Bay in Lake Huron, Green Bay in Lake Michigan, and western Lake Superior (Figure 1). To best represent the nearshore Lake Superior region where the recent cyanobacteria blooms have most often been reported, while still accounting for the coarse spatial resolution of our satellite sensors, the Lake Superior study area included the waters extending from Duluth to the Apostle Islands, from shore to 10 km offshore (Figure 1 inset).

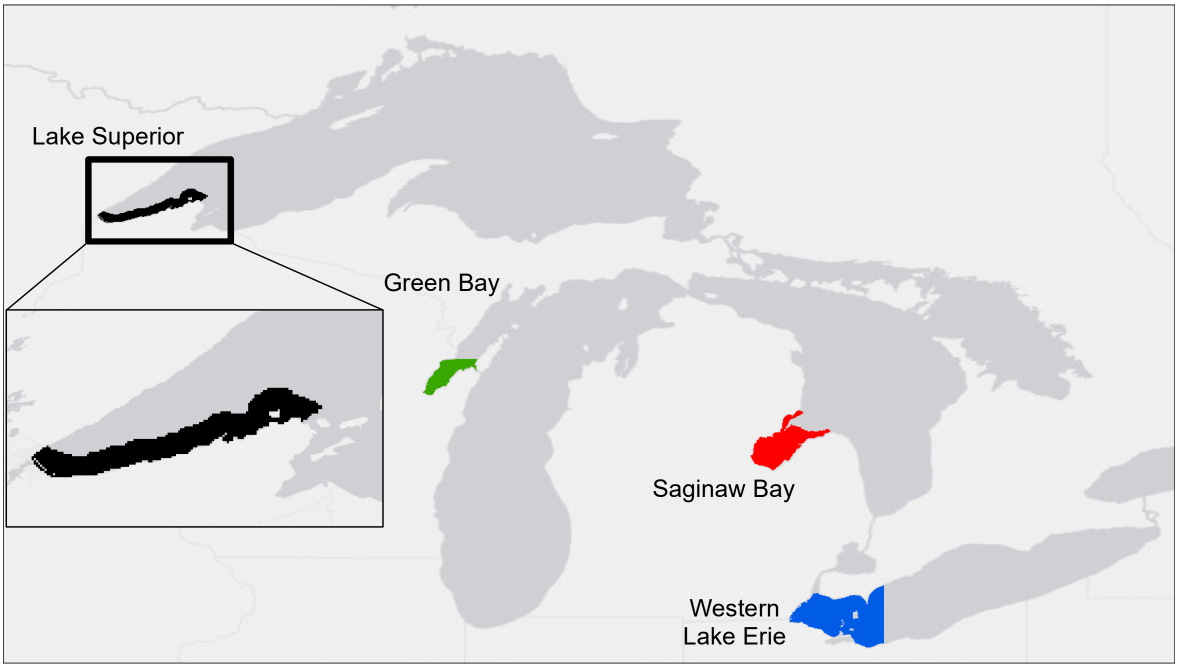

Figure 1. The regions studied for historical HAB extents include western Lake Erie (WLE), Saginaw Bay, Green Bay, and western Lake Superior.

2.2. Satellite Data Acquisition and Processing

The satellite imagery used in this analysis was collected by the Moderate Resolution Imaging Spectroradiometer sensor on the Aqua satellite (MODIS-Aqua). This sensor has a daily revisit rate, approximately 1 km spatial resolution, and a continuous data record extending from 2002 to the present. MODIS-Aqua was selected over other sensors with a higher spatial resolution (e.g., Landsat, MSI, OLCI, VIIRS) due to its combination of daily revisit time and extended data record (see Table 1 in [30]). Daily revisits are necessary due to the frequent cloud cover in the region and dynamic nature of the blooms [30,32].

Imagery acquisition and processing methods varied slightly between study regions, with one approach for the more eutrophic regions (WLE, Saginaw Bay, and Green Bay) and another for the more oligotrophic waters in Lake Superior. For the eutrophic regions, a fixed model pair atmospheric correction approach was utilized to be consistent with prior analyses [22,23]. This model was originally selected based on a qualitative analysis of the available models that did not assume negligible reflectance in the near-infrared (i.e., the black pixel assumption), in which it most consistently generated reflectance spectra that matched up well with in situ radiometry across a range of mild to severe bloom conditions (M. Sayers, pers. comm.). All images intersecting each region collected between June and October (the months when conditions are suitable for HABs in these regions) from 2002 to 2022 were identified and downloaded at Level 1A from the NASA OceanColor data portal (https://oceancolor.gsfc.nasa.gov/, accessed on 6 September 2022). Each Level 1A image was run through the MODIS GEO script, MODIS L1B processor, and *l2gen* function in the SeaDAS software package (v8.2) to generate georeferenced and atmospherically corrected Level 2 data files. In addition to the fixed model pair aerosol correction, a modified wavelength for cloud detection was used in the *l2gen* processing to ensure that high near-infrared reflectance values caused by surface scums were not interpreted as cloud contamination [22,23].

The standard NASA Ocean Biology Processing Group (OBPG) atmospheric correction [33] was used for the Lake Superior region. Despite being designed for oceanic applications, this correction approach has been shown to work well across several Great Lakes applications, including in nearshore oligotrophic waters and Lake Superior [34–37]. In contrast, using the fixed model pair atmospheric correction in Lake Superior resulted in unrealistically high reflectance values. All images intersecting this region between July and September (the months when most blooms have been observed [20]) were downloaded at Level 2, indicating that georeferencing and atmospheric correction have already been completed, from the NASA OceanColor data portal.

Once all images were acquired and processed to Level 2, they were each processed with the Color Producing Agents Algorithm (CPA-A) [36]. This semi-analytical inversion algorithm simultaneously estimates the levels of chlorophyll, suspended minerals, and CDOM in the water from the satellite reflectance and has been validated throughout the Great Lakes [36,38]. The CPA-A processing results in a chlorophyll concentration map for each image. Several NASA-provided quality flags were utilized to filter out lower quality data from the chlorophyll retrievals, including the flags for land, cloud/ice, and high sensor zenith angle (LAND, CLDICE, and HISATZEN, respectively). Since the polar-orbiting MODIS-Aqua sensor can sometimes generate multiple valid images of the same location in a given day, the mean of all same-day image retrievals was taken in order to generate daily chlorophyll concentration maps. Additionally, chlorophyll retrievals were excluded from analysis when the CPA-A derived suspended minerals concentration retrieval exceeded 5 mg/L, as an increased sediment signal has been shown to result in poor chlorophyll retrievals [39].

2.3. Bloom Classification

The daily chlorophyll maps were used to classify pixels as HAB or non-HAB, with a positive HAB classification indicating a likely presence of cyanobacteria. In WLE, Saginaw Bay, and Green Bay, a pixel was classified as a HAB if the chlorophyll concentration exceeded 18 mg/m^3. While the chlorophyll retrieval is not a direct indicator of cyanobacteria, a prior analysis between in situ chlorophyll and phycocyanin concentrations revealed that during the bloom growing period, chlorophyll concentrations above 18 mg/m^3 were significantly correlated with concentrations of phycocyanin, a pigment unique to cyanobacteria, and little phycocyanin was observed when chlorophyll concentrations fell below that threshold [22]. This HAB classification approach has been previously validated for these three regions, with an overall classification accuracy of 87% [22]. The continued validity of this threshold was confirmed based on an updated analysis using the routine HAB monitoring data collected in Lake Erie and Saginaw Bay by NOAA GLERL and CIGLR [16]. These monitoring datasets also confirmed that while the blooms tend to peak from July through September, measurable levels of phycocyanin are routinely observed along with high chlorophyll concentrations in June and October sampling. These data also highlight the differences in bloom intensity between regions: in WLE, a chlorophyll concentration of 18 mg/m^3 would represent a relatively typical observation (just above the median of all June–October non-scum surface measurements), while the same concentration in Saginaw Bay would be more extreme (approximately 75th percentile). Green Bay has been reported to have more of a mixed phytoplankton community than WLE and Saginaw Bay [40,41], but recent research has shown that cyanobacteria are nearly always present in significant quantities when chlorophyll concentrations are elevated (as indicated by a positive cyanobacteria index value) [41]. Therefore, a chlorophyll threshold approach should still be useful for identifying cyanobacteria presence, but using chlorophyll concentrations as an indicator of HAB intensity is more likely to result in over-estimates in Green Bay. To test the sensitivity of our bloom extent results to the chosen threshold, we repeated the analysis with a lower chlorophyll threshold (10 mg/m^3) and found that while observed bloom extents increased, the trends stayed the same. Example HAB classifications for each region can be viewed in the Electronic Supplementary Materials (Figures S1–S3).

Without a similar in situ dataset for Lake Superior, we were unable to empirically relate chlorophyll concentrations to cyanobacteria. However, we can use our remote sensing dataset to evaluate if algal blooms, defined here as elevated concentrations of phytoplankton biomass, are becoming more frequent in this typically oligotrophic region. For this analysis, we used a threshold of 10 mg/m^3 to indicate a bloom. It is important to note that changing this algal bloom threshold from 10 mg/m^3 to 5, 18, or 20 mg/m^3 would not change the reported trends for Lake Superior. The coarseness of the MODIS-Aqua pixels may add some uncertainty to the nearshore Lake Superior results, potentially biasing our chlorophyll retrievals. However, we expect that the effect will be consistent over time and not impact our assessment of long-term trends. An example Lake Superior algal bloom classification from August 2020 is included in the Electronic Supplementary Materials (Figure S4).

2.4. Surface HAB Scum Classification

Under calm conditions, dense HABs can accumulate at the surface and produce surface HAB scums. These scums are associated with high concentrations of algae and elevated toxin levels [21]. To monitor these extreme events, the surface HAB scum presence was evaluated based on the Normalized Difference Vegetation Index (NDVI), a band ratio index calculated from the reflectance in a visible and near-infrared band (VIS and NIR, respectively; Equation (1)):

$$NDVI = (NIR - VIS)/(NIR + VIS) \tag{1}$$

where NIR is the reflectance at 859 nm, and VIS is the reflectance at 645 nm. The NDVI is a commonly used index for monitoring terrestrial ecosystems because green vegetation strongly absorbs light in the visible parts of the electromagnetic spectrum and scatters light in the NIR. Because NIR radiation is strongly absorbed by water, the reflectance at the NIR band is a useful indicator of whether the HAB has accumulated at or near the water's surface to form a scum [22,23]. Preliminary analyses of NDVI and toxin concentrations from the Lake Erie in situ HAB monitoring program suggest a strong correlation between variables (M. Sayers, pers. comm.).

The NDVI was calculated for each valid image, and data were filtered using the same flags as described above for chlorophyll. Daily NDVI maps were created from the individual image retrievals, and pixels with a positive NDVI were classified as a surface HAB scum [22]). To help rule out false-positive scum classifications due to sediment plumes, imperfect cloud masking, low water reflectance signals, and atmospheric correction errors, we also required scum pixels to have CPA-A-derived chlorophyll concentrations exceeding the aforementioned 18 mg/m^3 threshold. This approach has been shown to classify surface scums with an overall accuracy of 93% [22]. In summary, for WLE, Green Bay, and Saginaw Bay, all pixels where the chlorophyll concentration exceeded the 18 mg/m^3 threshold were labeled a HAB, and the HAB pixels where a positive NDVI was observed were classified as a surface HAB scum. In Lake Superior, any pixel where the chlorophyll concentration exceeded 10 mg/m^3 was labeled an algal bloom, and no surface HAB scums were identified.

2.5. Mean Annual Extent Calculation

For each region, the daily extents for each metric were calculated as the sum of pixels with a positive classification within the study area, with the pixel count then converted to area (km^2). The mean annual extents were calculated as the mean of the daily extents across the bloom season, representing the average extent of the bloom across any given day during the season. To avoid having the annual average biased low due to the inclusion of daily imagery where much of the region is missing data due to cloud obstruction or other quality flagging, daily images were only included when at least 50% of the region's pixels were observed. The number of daily images included in the analysis varied by year and by region. On average, WLE had the most days included with a mean of 51 (ranging from 33 to 68), followed by Saginaw Bay (mean of 49 days, ranging from 40 to 65), Green Bay (mean of 35 days, ranging from 26 to 47), and Lake Superior (mean of 35 days, ranging from 22 to 50 days).

To examine bias that may be introduced due to the number of clear images available in a given year or the distribution of images within the season (characterized by the average Julian date of all included images within each year), we investigated relationships between these metrics and our observed bloom extents. No significant correlation was found between either extent metric (HAB or surface scum) and the number of days included in a year or the average Julian date of images in a year. The distribution of included image days across regions and years can be found in the Electronic Supplementary Materials (Figures S5–S8). For readability, all future references to extents will indicate the mean annual extent.

2.6. Statistical Analyses

Bloom extent trends were evaluated using a regression approach that accounts for the possibility of temporal autocorrelation, as described in [42]. In using this approach, the annual extent time series is first assessed for autocorrelation. If found to be statistically significant, the autocorrelation component of the data is removed using the Cochrane–Orcutt procedure [43], iterating as necessary until the autocorrelation is no longer significant. The corrected time series data are then run through a regression in MATLAB. The signal-to-noise ratio (SNR), representing the strength of the trend, is calculated as the derived slope divided by the square root of the model uncertainty. A trend is considered statistically significant if the SNR exceeds 2, roughly equal to the 95% confidence level [42]. Pearson correlation coefficients were also calculated between HAB extents and surface HAB scum extents within each region, and across regions for both of the indices.

3. Results

The mean annual extents of HABs and surface HAB scum were calculated for each year from 2002 to 2022 for WLE, Saginaw Bay, and Green Bay, and mean annual algal bloom extents were calculated for the Lake Superior region. Table 1 contains the minimum, maximum, mean, and standard error of the mean (SEM) for WLE, Saginaw Bay, and Green Bay HAB extents and Lake Superior algal bloom extents, along with the slope and strength of the trend. Table 2 contains the same metrics for surface HAB scum extents.

Table 1. Summary statistics (minimum, maximum, mean, and standard error of the mean) for the mean annual HAB extents in WLE, Saginaw Bay, and Green Bay and algal bloom extents in Lake Superior. Note that Lake Superior algal blooms have a lower chlorophyll classification threshold. The last column contains the slope of the regression and the SNR (with SNR > 2 indicating significance).

Region	Min (km^2)	Max (km^2)	Mean (km^2)	SEM (km^2)	Slope/SNR
WLE	147.5 (2009)	1045.9 (2015)	369.2	39.6	5.1/0.8
Saginaw Bay	7.0 (2017)	91.7 (2006)	27.4	4.3	**−2.1/3.9**
Green Bay	2.8 (2009)	31.5 (2018)	10.3	1.7	0.1/0.5
Lake Superior	1.2 (2007)	61.7 (2014)	27.5	3.3	0.7/1.2

Table 2. Summary statistics (minimum, maximum, mean, and standard error of the mean) for the mean annual surface HAB scum extents in WLE, Saginaw Bay, and Green Bay. No surface HAB scums were observed in the Lake Superior region. The last column contains the slope of the regression and the SNR (with SNR > 2 indicating significance).

Region	Min (km^2)	Max (km^2)	Mean (km^2)	SEM (km^2)	Slope/SNR
WLE	0.87 (2005)	77.9 (2011)	9.9	3.8	0.25/0.4
Saginaw Bay	0.03 (2012)	0.39 (2016)	0.18	0.02	0.004/1.0
Green Bay	0.37 (2012)	6.0 (2018)	1.1	0.3	0.06/1.4

The highest mean annual extents for both HAB and surface HAB scums were observed in WLE. Saginaw Bay had the next highest mean HAB extents (though still less than 10% the size observed in WLE) but experienced low surface HAB scum extents. Conversely, Green Bay had the second highest observed surface HAB scum extents but lower HAB extents than the other eutrophic regions.

No significant trend was observed in the WLE HAB extents over the 21-year study period (Figure 2A). The largest blooms were observed in the middle years of the data record, particularly the peak years of 2015 and 2013, with mean bloom extents of 1046 km^2 and 586 km^2, respectively. Likewise, no significant trend was observed for the surface HAB scum extents (Figure 3A). WLE surface HAB scums peaked a few years prior to the HAB blooms with the 2011 scum extent registering at nearly 8 times the study period average. Other large surface HAB scum extents occurred in 2013, 2015, and 2017. A non-significant correlation was observed between annual HABs and surface HAB scum extents (r = 0.35, p = 0.12, Figure 4A),with 2011 registering as a major outlier due to its average HAB extent but high surface HAB scum extent.

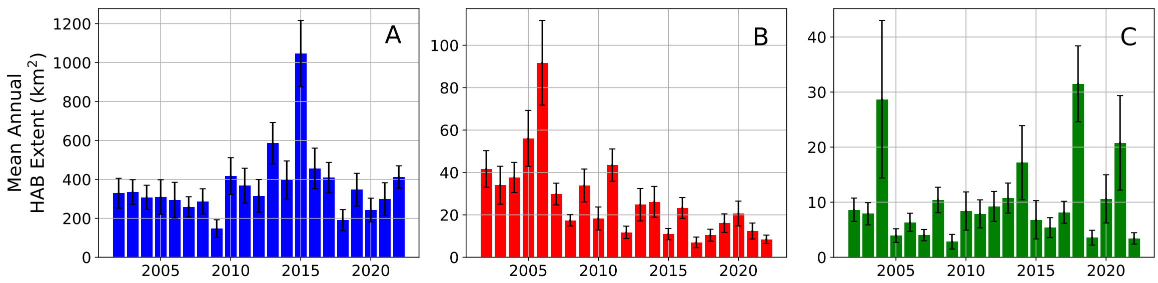

Figure 2. Mean annual HAB extents for WLE (panel (**A**)), Saginaw Bay (panel (**B**)), and Green Bay (panel (**C**)). Error bars represent the standard error of the mean. Only Saginaw Bay had a significant trend over the data record (slope = −2.1 km^2/yr; $p < 0.05$).

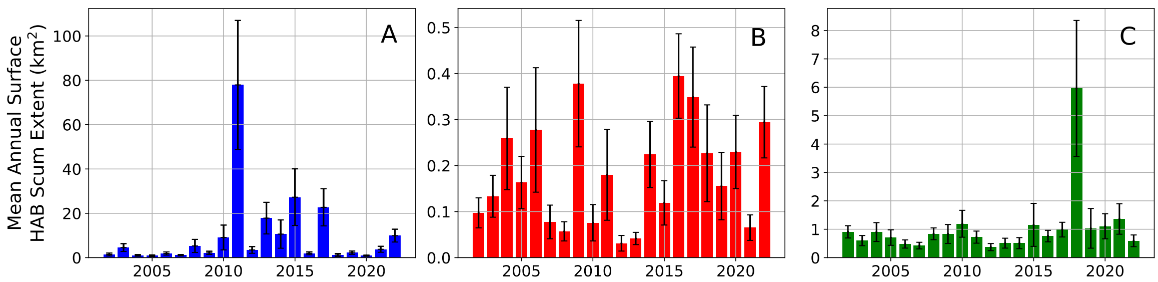

Figure 3. Mean annual surface HAB scum extents for WLE (panel (**A**)), Saginaw Bay (panel (**B**)), and Green Bay (panel (**C**)). Error bars represent the standard error of the mean.

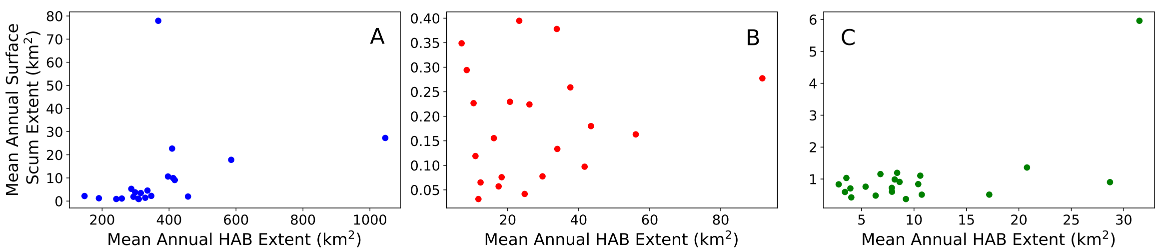

Figure 4. Mean annual HAB extent plotted against mean annual surface HAB scum extent for WLE (panel (**A**)), Saginaw Bay (panel (**B**)), and Green Bay (panel (**C**)). Only Green Bay showed a significant correlation between these indices (p < 0.01).

A significant decrease was observed in the mean annual Saginaw Bay HAB extents over the 2002–2022 data period (Figure 2B, $p < 0.05$), with the peak bloom occurring in

2006. No significant trend was observed in the Saginaw Bay surface HAB scum mean annual extents (Figure 3B), and no correlation was observed between the annual HAB and surface HAB scum extents in Saginaw Bay (r = 0.14, p = 0.54, Figure 4B).

Green Bay also experienced no significant trends in HAB or surface HAB scum extents over the study period (Figures 2C and 3C). Both indices experienced peak extents in 2018, while 2004 experienced a large HAB extent but typical surface HAB scum extents. As observed in Saginaw Bay, these peaks were much lower in magnitude than even the average year in WLE. Unlike the other regions, a significant correlation was observed between the HAB and surface HAB scum extent in Green Bay (r = 0.64, $p < 0.01$; Figure 4C), though this is largely influenced by the 2018 observations.

No significant trend was observed in mean annual algal bloom extent for the Lake Superior region. As with WLE, the peak bloom years occurred near the middle of the study period, from 2011 to 2018 (Figure 5). No surface HAB scums were identified in Lake Superior.

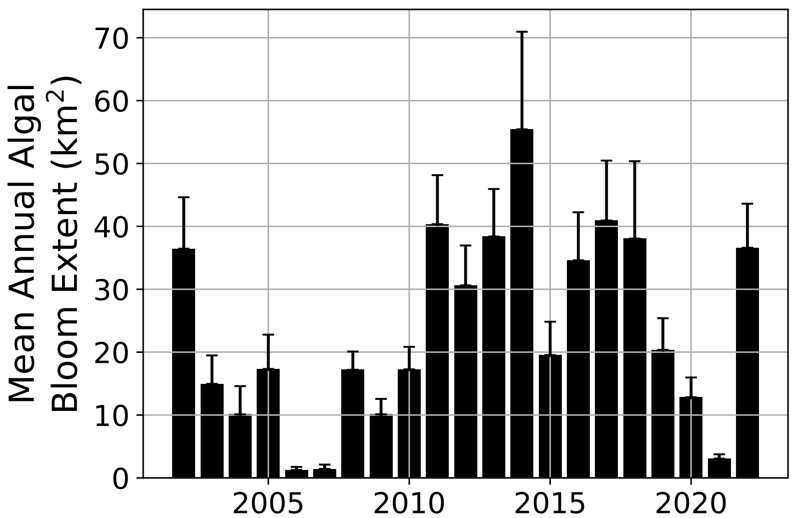

Figure 5. Mean annual algal bloom extent for Lake Superior. Error bars represent the standard error of the mean.

Temporal coherence between bloom extents across regions was limited (Table 3), with the majority of correlations being negative and no correlations having p-values below 0.15. No significant correlations of surface HAB scum extents were noted for any pair of regions (all $p > 0.5$).

Table 3. Pearson correlation coefficients and p-values for HAB/algal bloom extents between each pair of study regions.

	WLE	Saginaw Bay	Green Bay	Lake Superior
WLE	1	−0.24 (p = 0.3)	−0.18 (p = 0.42)	0.25 (p = 0.28)
Saginaw Bay		1	−0.18 (p = 0.44)	−0.28 (p = 0.22)
Green Bay			1	−0.05 (p = 0.84)
Lake Superior				1

4. Discussion

This analysis represents the most spatially (four Great Lakes regions) and temporally (2002–2022) comprehensive analysis of cyanobacteria algal blooms in the Laurentian Great Lakes to date. This work joins a growing list of publications over the last decade that have used remote sensing to study temporal trends in these blooms [22–27,29,41]. These publications, using a varied suite of indices and covering a range of time periods, have helped build an understanding of the algal bloom dynamics and drivers in the Great Lakes.

The results of this study clearly demonstrate that cyanobacteria algal bloom extents have not increased over the past 21 years in four major regions of the Great Lakes. Furthermore, while no region exhibited an increase in HAB extents over the years investigated, Saginaw Bay experienced a significant decline in HAB extent over this period. The cause of the decline in Saginaw Bay bloom extents is not entirely clear. The prior literature has indicated that *Microcystis* bloom biomass in Saginaw Bay is sensitive to the size of total phosphorus loadings [29,44], which have declined significantly since the late 1960s as a result of the GLWQA and Great Lakes Restoration Initiative (GLRI) [45–47]. After the initial GLWQA-related declines, the loadings were largely stable from the mid-1980s to 2011, with a peak in 2006 aligning with our peak bloom year [45,46], and flow-normalized phosphorus concentration estimates in the Saginaw River continued to decline from 2011 to 2020 [47]. However, we found no significant relationship between Saginaw River discharge (which is often used as a proxy for nutrient loading) and bloom extent between 2002 and 2022 ($p = 0.65$). This lack of relationship is consistent with our prior analysis [22], though this could be due to a shifting relationship between discharge and nutrient loading over time related to continued phosphorus abatement measures [29]. We also found no evidence that the significant decrease in algal blooms was due to climate changes (surface temperature, wind speed). The only significant relationship observed was with the mean June–October water level (calculated from the Army Corps of Engineers mean monthly water level data for Lake Huron), which had a moderate negative correlation with mean annual extent ($r = -0.47$, $p = 0.04$). It is possible that higher bloom extents are observed in low water level years due to impacts related to sediment/nutrient resuspension, water residence times (flushing), and the effectiveness of wetlands at retention and filtering nutrients.

Our results stand in contrast to other recent studies that reported increasing trends in the algal blooms in Lake Erie (e.g., [23,27,48]) and Lake Superior [14] and stable blooms in Saginaw Bay [22,29]. The most important factor responsible for the differences among these published studies is the observation period used for the analysis. As noted previously, the peak blooms in WLE were observed in the middle years of our analysis, with HAB extents peaking in 2013 and 2015 and surface HAB scum extents peaking in 2011 and 2015 (Figures 2 and 3). The studies that reported an increasing trend were published during this peak bloom period or shortly after. The significant increase from 2002 to 2015 is also observed in the results of this study ($p = 0.03$); however, the 7 years of results following the historically large bloom in 2015 show the annual bloom extents subsequently decreased to pre-peak levels. The differing trend in Saginaw Bay, as compared to [22], can also be explained by the longer time period of analysis in this study. Consistent with [22], no significant trend is observed when looking at our annual data from 2002 to 2013 ($p = 0.17$). The trend becomes significant after adding the latter years (2014–2022) in which we observed 9 of the 13 lowest annual extents in the 21-year dataset including the four lowest. Recently observed cyanobacteria blooms in Lake Superior have been met with great concern due to their apparent novelty for the region [14]. While these specific bloom events are difficult to study from satellite imagery due to their limited size and duration [14], satellite remote sensing allows us to investigate the frequency of algal bloom occurrences in the broader region going back to 2002. This dataset did reveal a slight peak in algal bloom extent from 2011 to 2018, but these blooms are neither a new phenomenon (with moderately sized blooms occurring in many years prior to 2011) nor do they appear to be increasing.

Methodological differences between studies are another possible explanation for differences in results, including the selected sensor and the specific index used to assess HAB trends. While we chose to use the MODIS-Aqua sensor for its long data record and daily revisit time, its coarse resolution cannot resolve the nearshore waters as well as other higher resolution sensors that have been used for HAB monitoring including MERIS, OLCI, and Landsat. While [29] also used the MODIS sensor, their Saginaw Bay analysis included portions of the bay that we had masked out. Specifically, the waters from Sebewaing, MI north to Wild Fowl Bay were excluded from our analysis due to persistent contamination from bottom reflectance and emergent vegetation.

There are also several differences between the index used in this analysis and those used in other studies. While this study focuses on average HAB and surface HAB scum extents across the growing season, other studies have investigated the peak bloom within the year or used a bloom severity index rather than the bloom extent (e.g., [24,26,29]). These differences could contribute to why our results reveal decreasing Saginaw Bay HAB extents while [29] reported that the blooms were stable over a similar time period (2000–2019), as our index is driven by both the magnitude and duration of the bloom but not the intensity while the peak biomass index considers intensity but not duration. While bloom intensity metrics are critical for monitoring public health, they do not tell the full story of the blooms, as bloom extent and duration are also important ecological indicators [49]. Bloom metrics targeting magnitude, severity, and duration have been shown to vary independently in other North American lakes, often with differences in trend significance between metrics in the same lake [50]. These differences highlight the importance of having multiple indices available to the management agencies that make decisions about bloom monitoring and remediation in order to produce a more complete understanding of the blooms, particularly in regions that experience high-intensity blooms [31].

To investigate how the differences between approaches may have impacted our results, we compared our WLE HAB extent results to a measure of peak bloom biomass from 2002 to 2015 (CI-Max) [26]. There was a significant correlation between these metrics ($r = 0.69$, $p < 0.01$), indicating that the use of different indices is likely not driving differences in observed trends for this region. Interestingly, the 2011 bloom stands out as an outlier between the indices. This year represented the most severe bloom year across multiple HAB metrics [26,51] due to the combination of extreme levels of spring discharge, long water residence times, and calm lake conditions allowing the blooms to stay near the surface [48]. However, 2011 represented only the eighth largest HAB extent observed in our data even though it was also the year with the highest observed surface HAB scum extent. This discrepancy is partly due to our method of calculating the annual bloom extent as the average extent across all clear images as opposed to using temporal windows [26] or moving averages [51]. Due to extensive haze and cloud cover, our approach only included four images in September 2011. Since this is typically the time period when the WLE bloom peaks [23], our 2011 estimate may be an underestimate of the true bloom size. The 2011 surface scum extent is also impacted by the lack of September data, but that year still resulted in the largest scum extents due to several large October blooms. While the 2011 result does not impact our conclusions regarding WLE HAB trends due to its location near the middle of the time series, this discrepancy does further emphasize the value of incorporating a suite of indices to assess HABs in any environment.

Our finding that bloom extents are not increasing in these four areas of the Great Lakes is consistent with the most comprehensive analyses of HABs across North American lakes. Ref. [50] found little long-term evidence of widespread HAB intensification across more than 300 inland lakes studied, with nearly 90% of lakes experiencing either no trend or a significant decline. Ref. [52] studied changes in HAB magnitude in nearly 2000 lakes in the contiguous United States and observed an increase in only 4% of lakes, while 25% experienced a decline. As noted above, studies that have reported HAB increases in certain areas of the Great Lakes were more limited in temporal and spatial scale than this study or did not include more recent years after several lakes reached their peaks.

An important factor contributing to the lack of significant trends in Great Lakes HAB and surface scum extents over the last 21 years is the high degree of interannual variability observed in our data. With coefficients of variation for each region exceeding 49% as well as a few large surface scum outlier years (2011 in WLE, 2018 in Green Bay), subtle trends may be masked such that only large shifts would be resolvable. The interannual variability is largely due to the episodic nature of blooms and the role of many factors contributing to their formation. There have been many explanations suggested for what is controlling HAB growth in the Great Lakes, including meteorological forcing, nutrient inputs, seed population, ecological timing, and even climate change [14,22–24,26,48,53]. Multiple publications have noted the importance of springtime Maumee River discharge, which is correlated with nutrient input to the western basin, as a strong predictor of the annual Lake Erie bloom intensity [22–24,26,53] as well as scum extents [22,23]. There is also evidence that internal loading is a significant source of nutrients to WLE [54–56]. In addition to depositing nutrients, discharge from the Maumee and Detroit Rivers have been reported as a source of cyanobacteria seed stock into the region [57,58]. Meteorological conditions during the growing season have also been shown to impact the development of the blooms: elevated early summer temperatures can extend the HAB growing season [26], while strong winds and storm events can re-introduce nutrients and dormant seed stocks from the bottom sediment through resuspension [22,48,59–61]. Less research has been conducted to investigate the drivers of the Lake Superior blooms, but initial evidence suggests similar drivers, with more intense blooms in warmer years [14] and years when more extreme storm events result in a greater influx of nutrients and seed stock into the lake [14,15]. River discharge is less predictive of bloom extents in Green Bay and Saginaw Bay [22,29,41], and it is not fully understood what other factors may be driving the bloom extents in these regions. CDOM absorption has been reported as a strong indicator of bloom dynamics in Green Bay [41], while Sayers et al. [22] suggest several other potentially important local factors for these regions, including basin morphometry and local weather patterns. Though the importance of specific drivers varies by region, the complex array of interacting factors that contribute to HAB development is likely responsible for the year-to-year variability. While the specific drivers of anomalously large surface scum years are also not fully understood, the region-specific factors contributing to bloom formation, along with calm wind conditions, may interact to create conditions optimal for surface scum formation even when HAB extent is not unusually high. Given the high degree of interannual variation in bloom conditions, longer time series may be necessary to detect trends in these ecosystems, highlighting the importance of continued monitoring for HABs.

One of the more interesting findings of this study was the lack of coherence in HAB events between regions. If broad scale environmental trends were the primary factor driving blooms, we would expect that the extent peaks and valleys would exhibit significant correlation between regions. However, we did not observe any significant pairwise correlations, and the majority of relationships actually had negative correlations. This result, while perhaps not surprising given the reported differences in drivers between regions, suggests that the bloom is driven more by local factors rather than broad Great Lakes basin-wide drivers, consistent with the conclusions in [22]. The observation that HAB extents are not increasing over the past 21 years, combined with the evidence for the local factor control of HABs in the Great Lakes, suggests that predicting the future extent of HABs in each region may be more difficult due to the complexity of HAB dynamics and that simple explanations for observed changes may not be possible. This aligns with the conclusions in [21], which suggest that while climate change will likely impact many of the HAB drivers, not all of these impacts will be more favorable to HAB growth, and the balance between positive and negative effects is likely to vary between waterbodies.

A unique aspect of this study was the determination of trends in surface HAB scum extents in each study region. Because surface HAB scums are associated with high toxin concentrations, their determination has important water quality and human health implications [21]. Surface HAB scum extents were found to not be increasing across the study period in any of the regions analyzed. Again, this differs from the prior reporting in Lake Erie, which had shown a significant increase in scum extents from 1998 to 2017 [23]. This discrepancy can also be attributed to the lengthened study period, with the years since 2017 experiencing relatively mild surface HAB scums. Scum extents in Green Bay and Saginaw Bay also did not experience any long-term trends, due again in part to the high levels of interannual variability, which masked the ability to detect any long-term trends in these regions. This study failed to observe surface HAB scums in Lake Superior. These scums have been a primary point of concern in the region due to an uptick in reported events [20,62]; however, their ability to be detected with remote sensing may be impeded by their small size and ephemeral nature [14].

Predicting surface HAB scum events from observed HAB extents may be difficult in the Great Lakes due to the high amount of variability between HAB extents and surface scums. Only Green Bay showed a strong correlation between these indices (r = 0.64, $p < 0.01$). The lack of stronger correlation between these metrics is due to several factors. Because surface HAB scums are associated with the most intense blooms, with higher concentrations of chlorophyll and toxins [21,63], we would expect them to have greater coherence with an index targeting bloom severity rather than just extent. Unsurprisingly, the correlation between CI-Max and our WLE surface HAB scum extents (r = 0.87, $p < 0.01$) was stronger than the correlation between CI-Max and WLE HAB extents (r = 0.69) and between WLE HAB extents and WLE surface scum extents (r = 0.35). Additionally, very specific meteorological conditions are required for a HAB event to become a surface HAB scum, with extended quiescent conditions needed for the cells to concentrate at the surface into scums [21,64]. They can also be short-lived, with rapid responses to increased wind and wave conditions [21,65–68], making them more difficult to capture with a once or twice daily satellite overpass. Finally, not all cyanobacteria form surface scums [21], and it has been shown that there are regional differences in *Microcystis* colonies impacting their likelihood of forming surface scums [69].

Because HABs mitigation is a part of Great Lakes water quality management, the results of our study warrant consideration in future management decisions. Phosphorus load targets have been in place for WLE, Saginaw Bay, and Green Bay since the 1972 GLWQA was implemented, with more restrictive targets established for Lake Erie after the 2012 GLWQA update. Management actions to reduce phosphorus loads are ongoing and expected to alleviate algal growth once targets are met. While the results of this study show that HAB extents have not increased over the last two decades, more long-term HAB monitoring is needed before a definitive conclusion can be made about the effectiveness of these actions to reduce phosphorus loads, especially since several of these regions still exhibit a water quality that is indicative of eutrophic conditions [70] and recurring and localized HABs still pose a risk to human and animal health, foul coastlines, and negatively impact communities and businesses.

Looking to the future, we believe it is important to continue monitoring the state of the blooms throughout the lakes. The regular assessment and public reporting of long-term HAB trends, such as performed via the triennial State of the Great Lakes reports pursuant to the GLWQA [70], help inform stakeholders and assess progress in efforts to restore and protect Great Lakes water quality. Routine in situ HAB monitoring has been ongoing in Lake Erie and Saginaw Bay for over 10 years. While new monitoring networks are being established in some parts of the Great Lakes, including Lakes Superior and Ontario, the historic dataset is limited in these areas, with sampling largely reactive to observations and reports from local resource managers and the public. The remote sensing approaches used in this study have the benefit of a much higher spatial and temporal coverage than can be attained through traditional field sampling and serve as a valuable complement to these existing programs. Because of the ephemeral nature of surface scums both spatially and temporally [21], remote sensing has distinct advantages over traditional in situ monitoring methods and may be the most appropriate tool for monitoring the prevalence of Great Lakes scums. Continued monitoring will help us to understand if the bloom peaks in WLE and Lake Superior were outliers or if they could be part of a cyclic pattern in the drivers. Additionally, there is evidence that nutrient inputs can impact Lake Erie HAB growth for nearly a decade after they enter the basin [54,56], so tracking the impact of any nutrient load reductions will require many years of additional monitoring. Extending the dataset into the future will also allow for the incorporation of newer satellite sensors to improve the results, including the ability to better monitor nearshore waters with higher resolution sensors and more accurately discern cyanobacteria from other phytoplankton groups with the use of the forthcoming NASA PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) hyperspectral satellite, which launched in February 2024.

While the results of this study indicate that the extents of HABs and surface HAB scums in these four areas of the Great Lakes are not increasing, it is important to reiterate that this study looked at broad regional scales. There may be locations within each region where HABs are increasing or historically uncontaminated sites that are now starting to experience HABs. Distinct hot spots for scum formation have been reported within WLE, with increased prevalence in shallow waters, areas with protection from winds, and areas near high nutrient loading sites [23]. Historically, WLE blooms also tend to persist longest in the nearshore waters along the Michigan and Ohio coastlines and rarely extend to the Canadian shorelines [23]. Future analyses are planned to partition the four broad regions in this study into sub-regions in order to investigate spatial variability in these long-term trends. Additionally, we plan to parse the annual data to determine if there have been changes to bloom phenology over time, such as bloom start or end dates or season length.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w16141944/s1: Figure S1: Example WLE HAB Classification; Figure S2: Example Saginaw Bay HAB Classification; Figure S3: Example Green Bay HAB Classification; Figure S4: Example Lake Superior algal bloom classification; Figure S5: Distribution of image dates used in analysis- WLE; Figure S6: Distribution of image dates used in analysis- Saginaw Bay; Figure S7: Distribution of image dates used in analysis- Green Bay; Figure S8: Distribution of image dates used in analysis- Lake Superior; Table S1: Annual WLE HAB and Surface Scum extents; Table S2: Annual Saginaw Bay HAB and Surface Scum extents; Table S3: Annual Green Bay HAB and Surface Scum extents; Table S4: Annual Lake Superior algal bloom extents.

Author Contributions: Conceptualization, K.R.B., G.L.F., C.D.B., M.B.P., A.E.S., E.K.H. and M.J.S.; methodology, K.R.B. and M.J.S.; formal analysis, K.R.B.; writing—original draft preparation, K.R.B. and C.D.B.; writing—review and editing, G.L.F., C.D.B., M.B.P., A.E.S., E.K.H. and M.J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Great Lakes Restoration Initiative between the United States Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration (NOAA) under Agreement DW-013-92560501 and in part by the Cooperative Institute for Great Lakes Research (CIGLR) through the NOAA Cooperative Agreement with the University of Michigan (CIGLR contribution number is 1205) under Grant NA17OAR4320152.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank Steve Ruberg and Dr. Andrea Vander Woude from NOAA GLERL for supporting this research and Santina Wortman for providing feedback on the draft.

Conflicts of Interest: The authors declare no conflicts of interest.

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