Supplementary material

Table S1. Seasonal Mann-Kendall statistics for changes in monthly cyanobacterial spatial extent spanning 2008-2011 for each CONUS climate region. Change over time period represents the change in spatial extent (%) over the entire time period spanning 2008–2011. The γ statistic is an estimate of the number of years of observations required for the observed trend to outweigh variability in the data.

Climate region	Sample size	Change in spatial extent over time period	Kendall's τ	γ (yr)
Northeast	48	2.06%	0.08	42.26
Northwest	48	-1.01%	-0.14	48.07
Northwest Rockies and Plains	48	1.22%	0.03	49.14
Ohio Valley	48	0.91%	0.06	45.02
South	48	-12.08%	-0.17	3.98
Southeast	48	6.90%	0.14	6.89
Southwest	48	-4.52%	-0.25	10.72
Upper Midwest	47	3.89%	0.15	16.79
West	48	-4.33%	-0.14	9.67

Table S2. Seasonal Mann-Kendall ~~s~~statistics for changes in monthly cyanobacterial spatial extent spanning 2008-2011 for each CONUS state spanning with at least one resolvable lake. Bold values represent moderate ($0.3 \leq |\tau| < 0.5$) through strong ($|\tau| \geq 0.5$) Kendall τ strength. Change over time period represents the change in spatial extent (%) over the entire time period spanning 2008–2011. The γ statistic is an estimate of the number of years of observations required for the observed trend to outweigh variability in the data.

State name	State abbreviation	Sample size	Change over time period	Kendall's τ	γ (yr)
Alabama	AL	48	3.39%	0.19	14.37
Arizona	AZ	48	1.10%	0.14	76.37
Arkansas	AR	48	-8.40%	-0.28	7.51
California	CA	48	-0.24%	0	> 100
Colorado	CO	48	-3.31%	-0.08	15.68
Connecticut	CT	46	14.40%	0.27	8.63
Florida	FL	48	5.87%	0.25	8.87
Georgia	GA	48	-0.62%	-0.06	> 100
Idaho	ID	46	-5.04%	-0.07	16.18
Illinois	IL	48	-0.51%	-0.03	> 100
Indiana	IN	48	-2.17%	-0.06	32.89
Iowa	IA	44	7.24%	0.1	12.25
Kansas	KS	48	4.98%	0.17	9.56
Kentucky	KY	48	0.02%	0	> 100
Louisiana	**LA**	**48**	**-16.89%**	**-0.31**	**4.53**
Maine	**ME**	**43**	**-12.87%**	**-0.37**	**8.84**
Maryland	MD	47	0.00%	0.06	*N/A**
Massachusetts	MA	48	2.53%	0.08	51.13
Michigan	MI	47	1.69%	0.03	48.11
Minnesota	MN	41	4.84%	0.23	13.43
Mississippi	**MS**	**48**	**12.91%**	**0.33**	**5.45**
Missouri	MO	48	-8.20%	-0.22	5.99
Montana	MT	47	-6.65	-0.06	11.65
Nebraska	NE	48	7.78%	0.17	8.45
Nevada	NV	48	-16.45%	-0.28	3.84
New Hampshire	NH	42	-0.31%	-0.13	> 100
New Jersey	NJ	48	15.53%	0.25	6.41
New Mexico	NM	48	8.49%	0.28	3.89
New York	NY	48	4.95%	0.11	16.57
North Carolina	NC	48	2.68%	0.22	21.21
North Dakota	ND	41	4.32%	0.07	15.96
Ohio	OH	48	0.49%	0.04	> 100

Oklahoma	OK	48	-5.44%	-0.11	9.05
Oregon	OR	48	-5.08%	-0.11	10.31
Pennsylvania	PA	48	-7.79%	-0.11	11.04
Rhode Island	RI	48	-6.29%	-0.25	18.46
South Carolina	SC	48	-8.02%	-0.19	8.53
South Dakota	SD	47	2.62%	0.09	32.93
Tennessee	TN	48	-0.61%	-0.03	75.92
Texas	TX	48	6.99%	0.11	7.71
Utah	UT	48	-5.34%	-0.25	10
Vermont	VT	43	9.19%	0.26	11.97
Virginia	VA	48	-0.04%	0	> 100
Washington	WA	48	-2.89%	-0.11	19.57
Wisconsin	WI	45	-6.74%	-0.2	12.89
Wyoming	WY	48	0.59%	0.03	> 100
CONUS		48	-0.72	0.03	42.06

* The γ statistic requires the change in spatial extent over the time period as the denominator; thus, with a change of 0%, γ was not computed.

Table S3. Merged Sentinel-3A and -3B seasonal Mann-Kendall statistics for changes in monthly cyanobacteria spatial extent spanning 2017-2020 for each CONUS state with at least one resolvable lake. Bold values represent moderate ($0.3 \leq |\tau| < 0.5$) through strong ($|\tau| \geq 0.5$) seasonal Kendall τ strength. Change over time period represents the change in spatial extent (%) over the entire time period spanning 2017–2020. The γ statistic is an estimate of the number of years of observations required for the observed change to outweigh variability in the data.

State name	State abbreviation	Sample size	Change in spatial extent over time period	Kendall's τ	γ (yr)
Alabama	**AL**	**48**	**5.08%**	**0.39**	**3.39**
Arizona	**AZ**	**48**	**10.44%**	**0.47**	**4.10**
Arkansas	AR	48	2.22%	0.07	19.23
California	**CA**	**48**	**3.88%**	**0.35**	**11.15**
Colorado	CO	47	17.94%	0.27	3.08
Connecticut	CT	47	0%	-0.02	*N/A**
Florida	**FL**	**48**	**22.54%**	**0.44**	**2.92**
Georgia	GA	48	6.20%	0.28	3.80
Idaho	ID	46	3.43%	0.24	14.44
Illinois	IL	48	14.81%	0.25	6.07
Indiana	IN	48	-1.17%	-0.06	54.91
Iowa	IA	46	-3.20%	-0.10	35.26
Kansas	KS	48	11.51%	0.28	6.78
Kentucky	KY	48	2.15%	0.28	12.27
Louisiana	**LA**	**48**	**25.18%**	**0.50**	**2.15**
Maine	**ME**	**44**	**22.79%**	**0.37**	**4.03**
Maryland	MD	48	0.20%	0.24	> 100
Massachusetts	**MA**	**48**	**47.75%**	**0.47**	**2.09**
Michigan	**MI**	**47**	**13.64%**	**0.52**	**3.02**
Minnesota	MN	40	7.04%	0.15	12.21
Mississippi	MS	48	-4.01%	-0.06	23.14
Missouri	MO	48	15.01%	0.25	3.13
Montana	**MT**	**45**	**4.96%**	**0.44**	**4.33**
Nebraska	NE	46	1.47%	0.09	38.31
Nevada	**NV**	**48**	**16.04%**	**0.31**	**3.71**
New Hampshire	**NH**	**39**	**19.05%**	**0.37**	**4.18**
New Jersey	**NJ**	**48**	**32.50%**	**0.54**	**2.36**
New Mexico	NM	48	7.73%	0.26	5.81
New York	NY	48	4.83%	0.19	8.79
North Carolina	**NC**	**48**	**7.34%**	**0.44**	**6.63**
North Dakota	ND	38	-0.39%	-0.15	78.59
Ohio	OH	47	-2.25%	-0.09	38.06

Oklahoma	OK	48	11.74%	0.28	3.18
Oregon	**OR**	**48**	**10.11%**	**0.44**	**6.38**
Pennsylvania	PA	47	3.00%	0.06	24.04
Rhode Island	**RI**	**48**	**21.08%**	**0.36**	**4.55**
South Carolina	SC	48	3.65%	0.26	4.12
South Dakota	**SD**	**42**	**5.58%**	**0.50**	**4.87**
Tennessee	TN	48	0.88%	0.11	25.48
Texas	**TX**	**48**	**6.52%**	**0.31**	**5.99**
Utah	**UT**	**48**	**3.20%**	**0.35**	**9.58**
Vermont	**VT**	**46**	**4.60%**	**0.44**	**5.79**
Virginia	VA	48	1.57%	0.07	25.18
Washington	WA	48	5.35%	0.17	8.32
Wisconsin	WI	43	2.48%	0.17	48.33
Wyoming	**WY**	**43**	**5.48%**	**0.37**	**7.60**

*The γ statistic requires the change in spatial extent over the time period as the denominator; thus, with a change of 0%, γ was not computed.

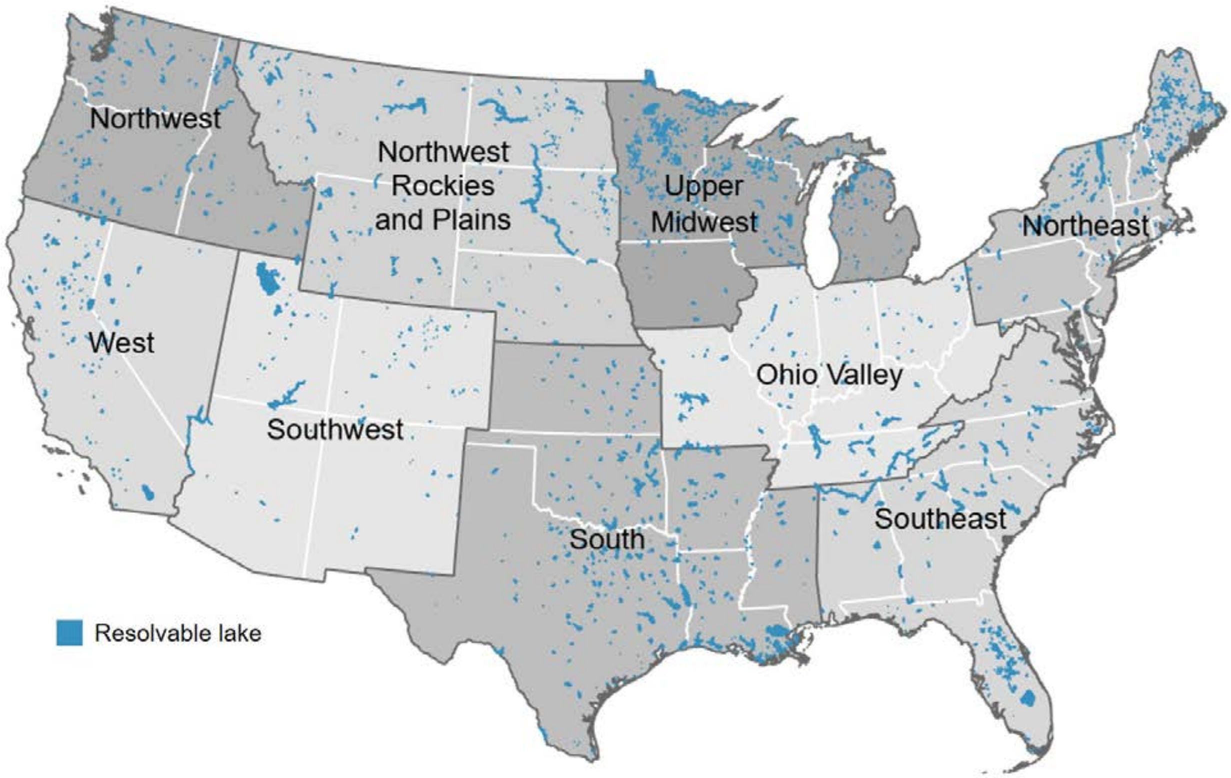

Fig. S1. Nine climatically consistent regions were defined by the National Center for Environmental Information (Karl and Koss, 1984) and were used to assess cyanobacterial spatial extent at a regional scale. Blue polygons represent lakes resolvable with 300-m satellite imagery.

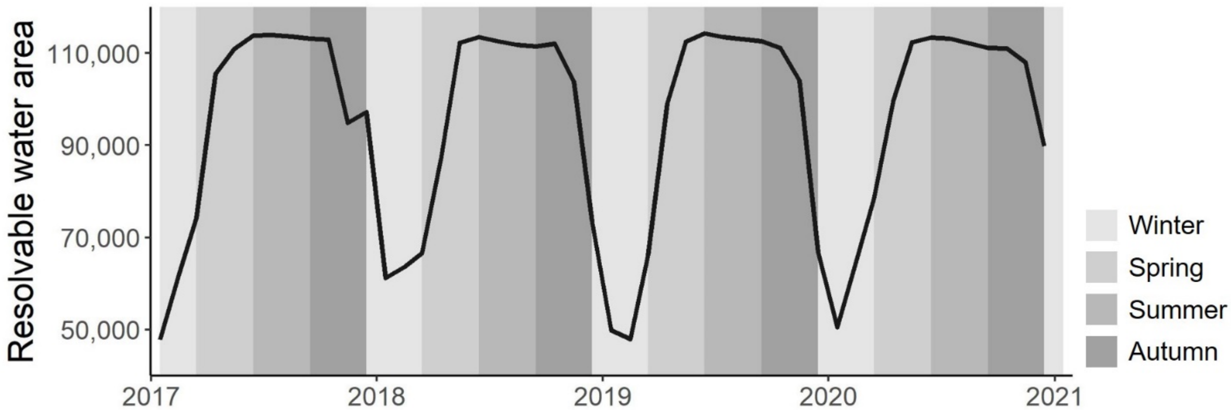

Fig. S2. Monthly CONUS sum of resolvable water area from 2017 through 2020.

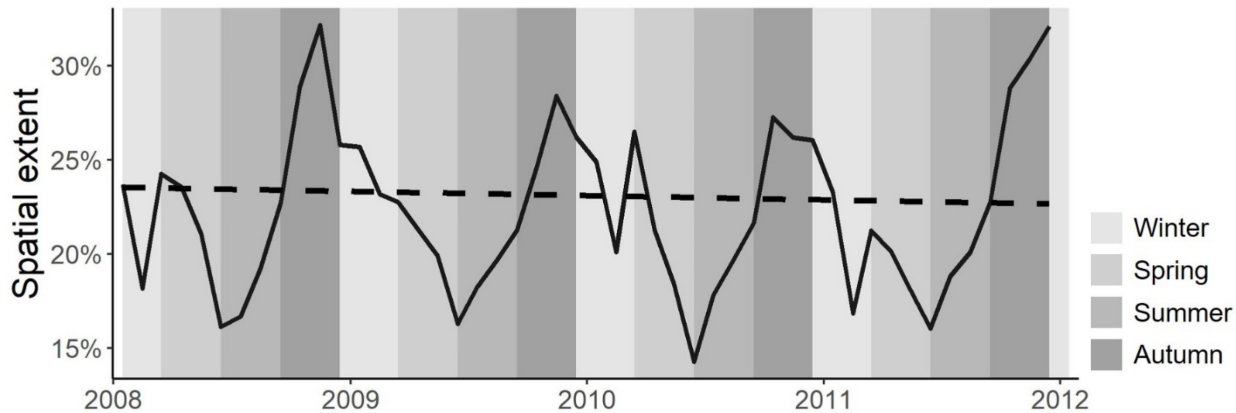

Fig. S3. Monthly spatial extent (%) of any detectable cyanoHAB for CONUS from 2008–2011. Shaded plot regions delineate meteorological seasons. The dashed line represents the seasonal Kendall slope estimator accompanying a seasonal Mann-Kendall test for trend applied to monthly observations.

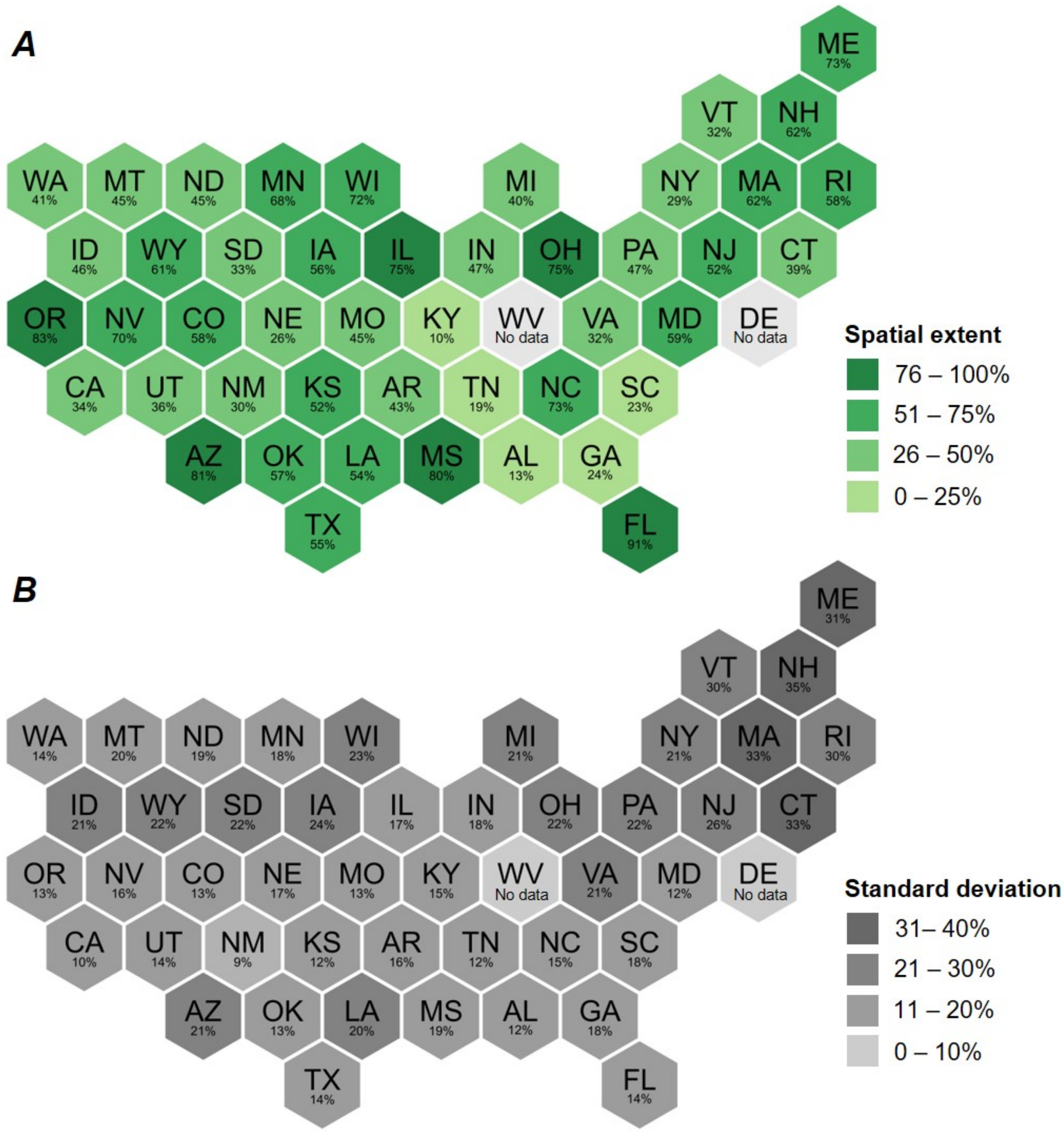

Fig. S4. (A) Median and (B) standard deviation spatial extent for each CONUS state from 2008–2011. Each state is represented as a hexagon labeled with each state's two-letter state abbreviation. WV and DE are presented in light gray as they have no satellite resolvable water at a spatial resolution of 300 m.

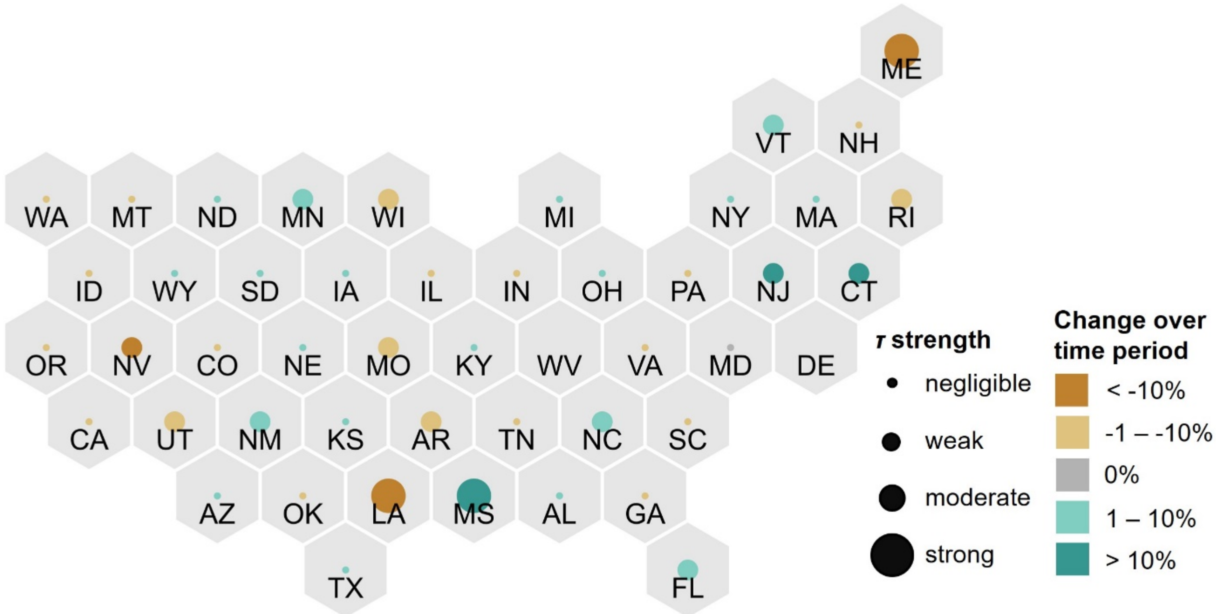

Fig. S5. Change in spatial extent in each CONUS state from 2008–2011 based on results from the seasonal Mann-Kendall test for trend. Each state is represented as a hexagon labeled with each state's two-letter state abbreviation. WV and DE have no trend results as they have no satellite resolvable water at a spatial resolution of 300 m. Color of circles illustrates change over time period, where brown indicates a decrease in bloom area from 2008–2011 and shades of green indicate an increase; size of circles represent categorical Kendall τ, where $|\tau| < 0.2$ denotes a negligible trend, $0.2 \leq |\tau| < 0.3$ denotes a weak trend, $0.3 \leq |\tau| < 0.5$ denotes a moderate trend and $|\tau| \geq 0.5$ denotes a strong trend.

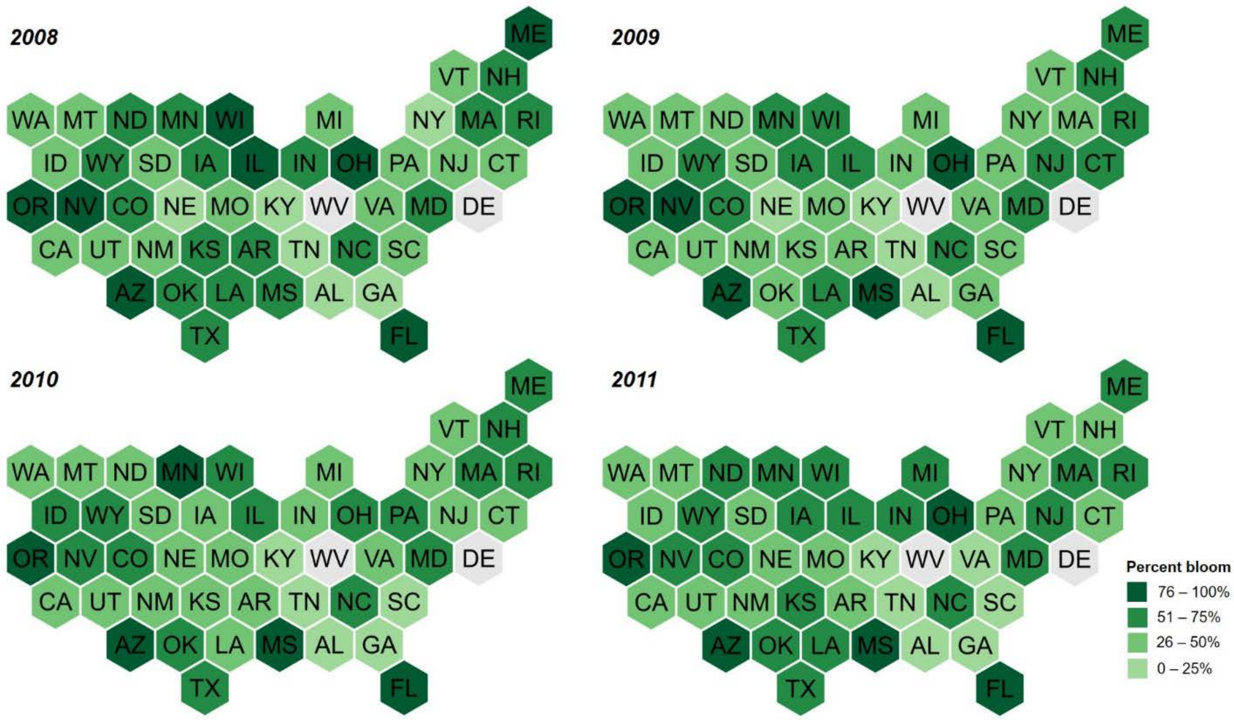

Fig. S6. Spatial extent for each CONUS state for 2008–2011. Each state is represented as a hexagon labeled with each state's two-letter state abbreviation. WV and DE are presented in gray as they have no satellite resolvable water at a spatial resolution of 300 m.

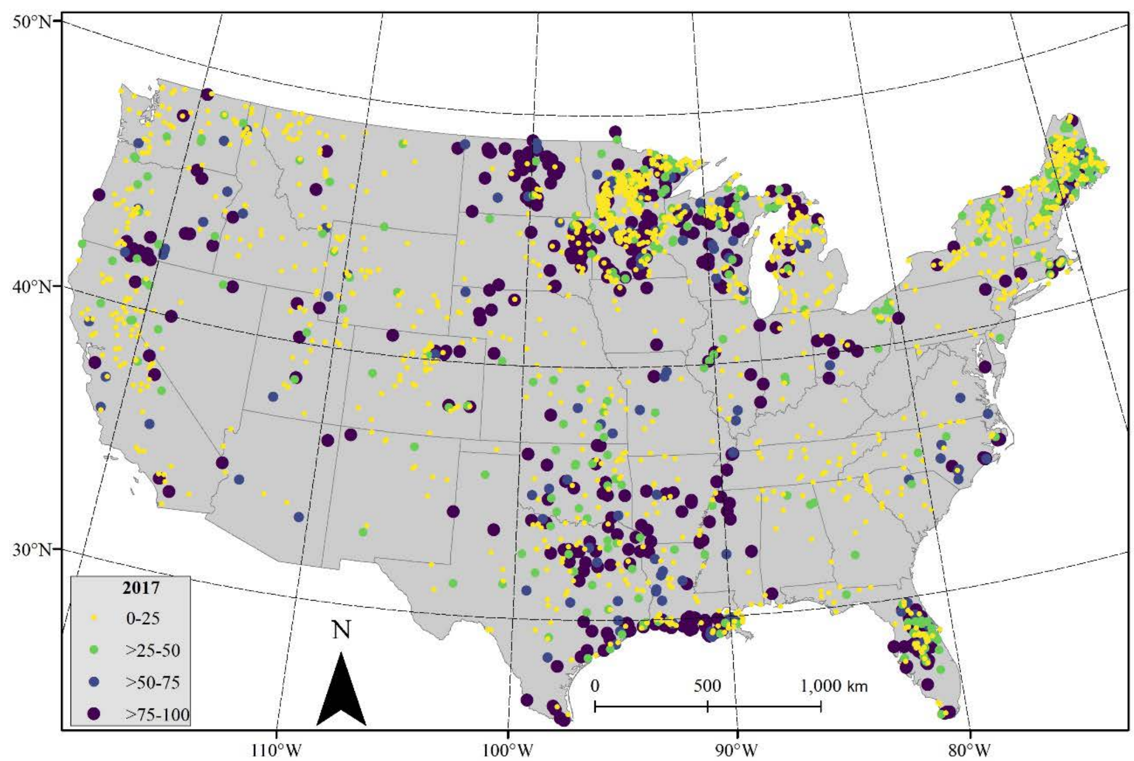

Fig. S7. Median annual spatial extent for each resolvable lake for the year 2017. Each point represents a lake centroid.

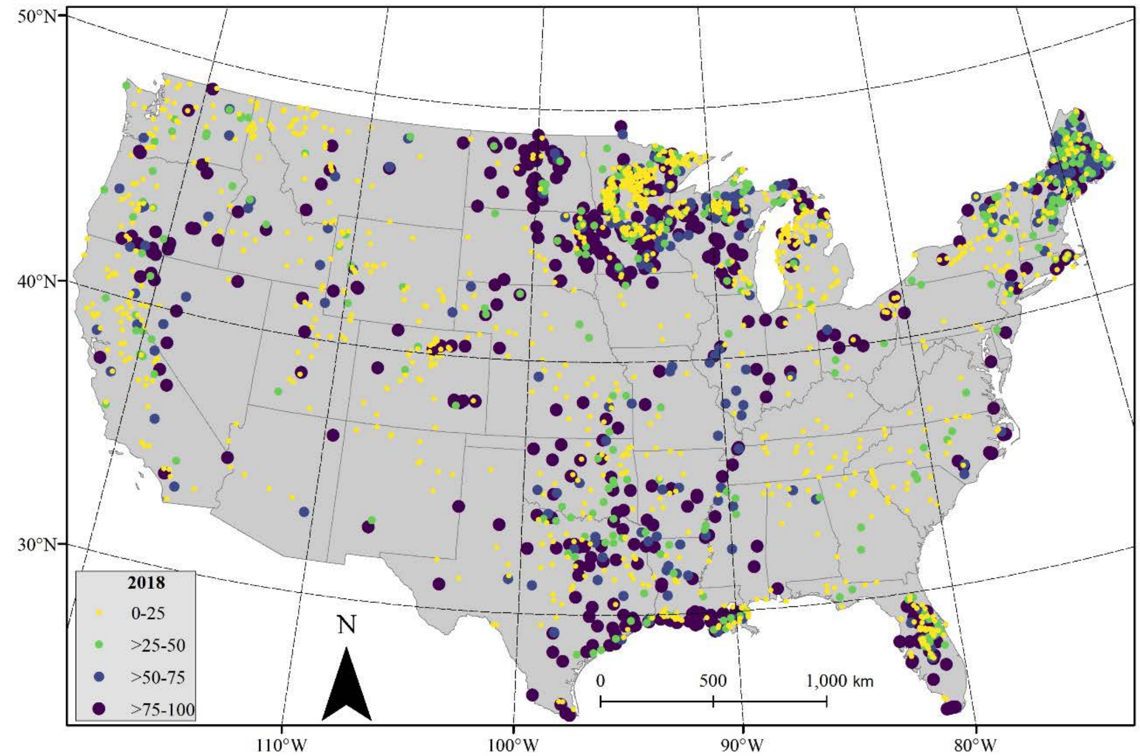

Fig. S8. Median annual spatial extent for each resolvable lake for the year 2018. Each point represents a lake centroid.

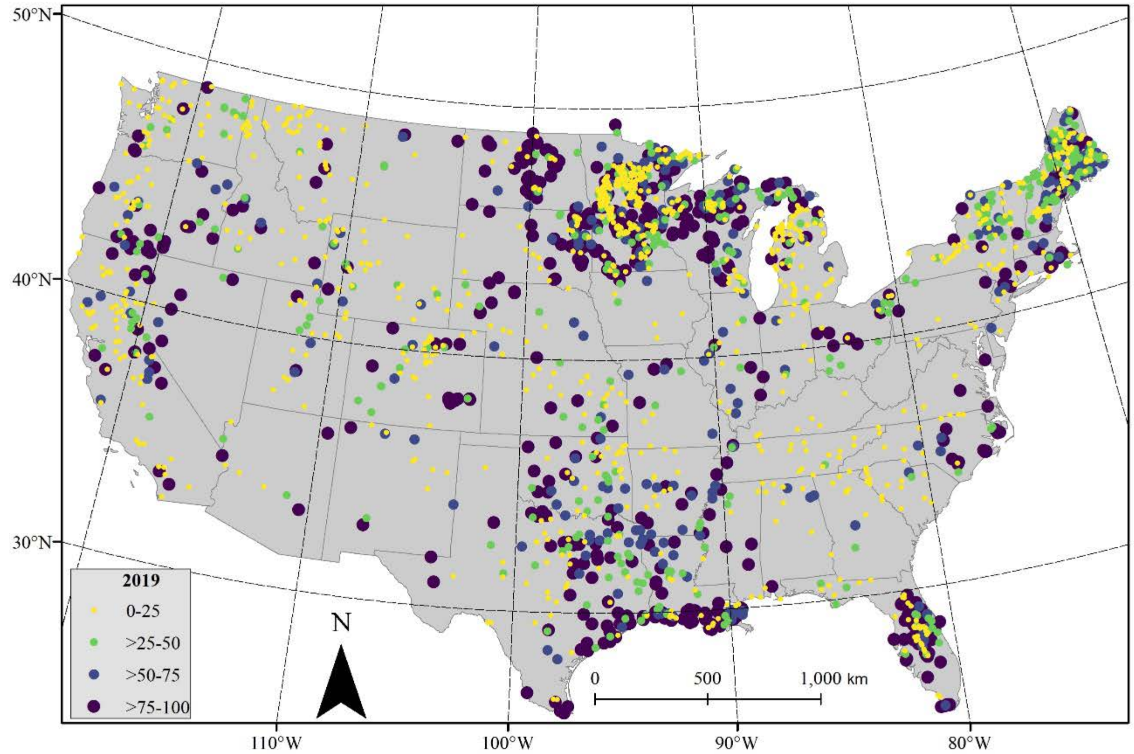

Fig. S9. Median annual spatial extent for each resolvable lake for the year 2019. Each point represents a lake centroid.

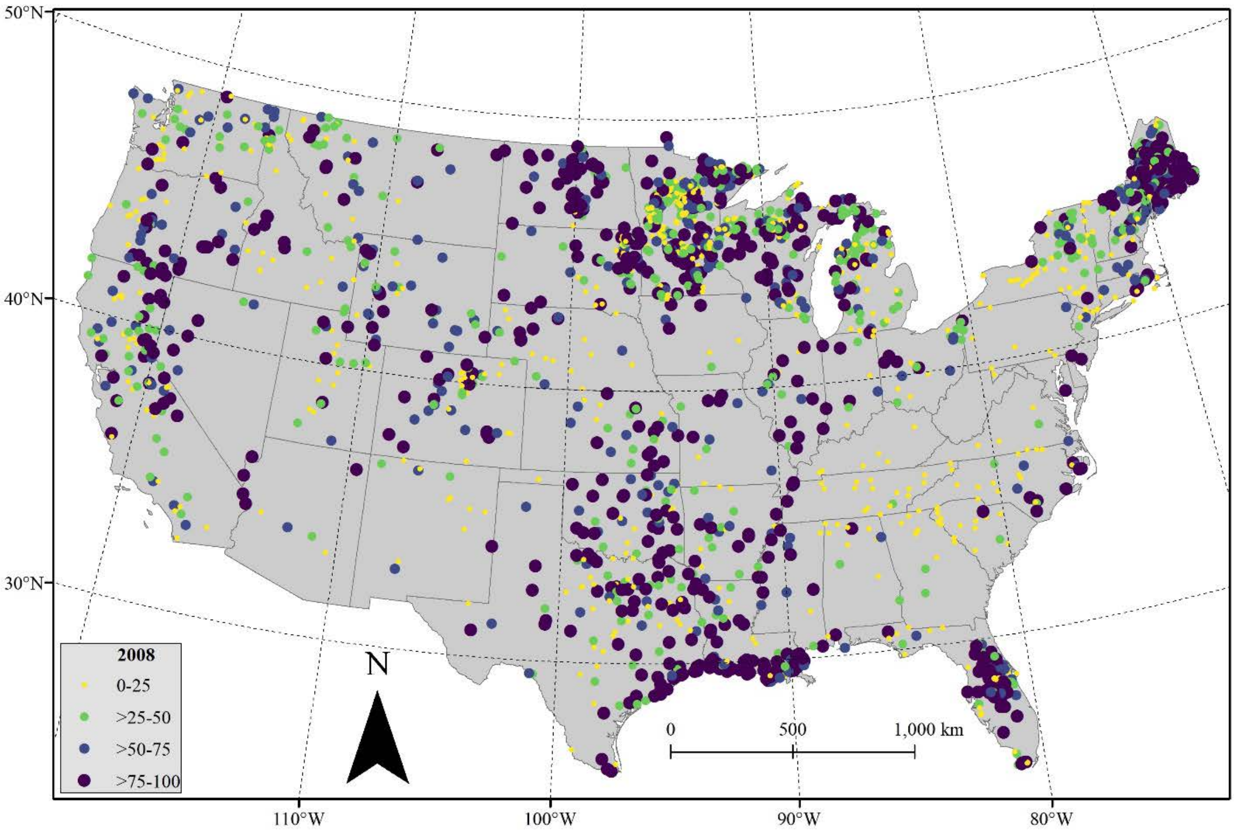

Fig. S10. Median annual spatial extent for each resolvable lake for the year 2008. Each point represents a lake centroid.

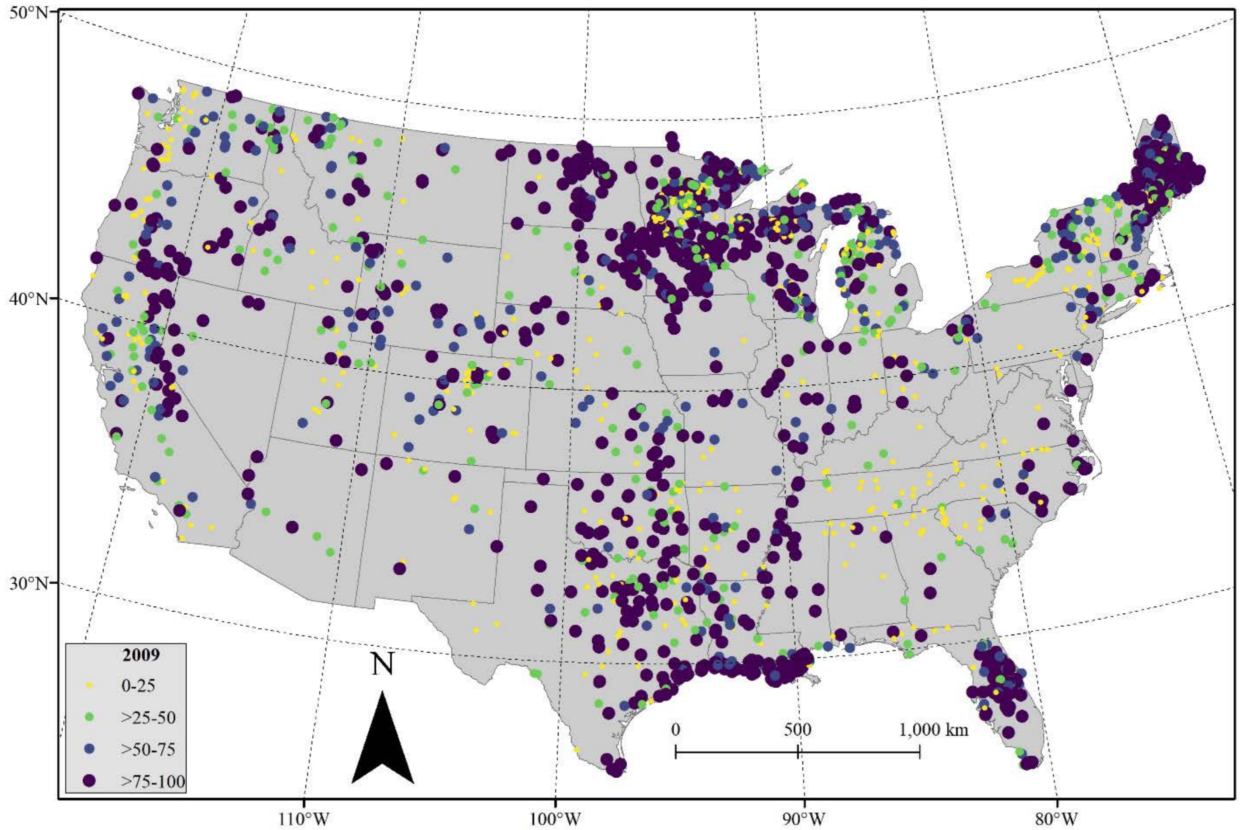

Fig. S11. Median annual spatial extent for each resolvable lake for the year 2009. Each point represents a lake centroid.

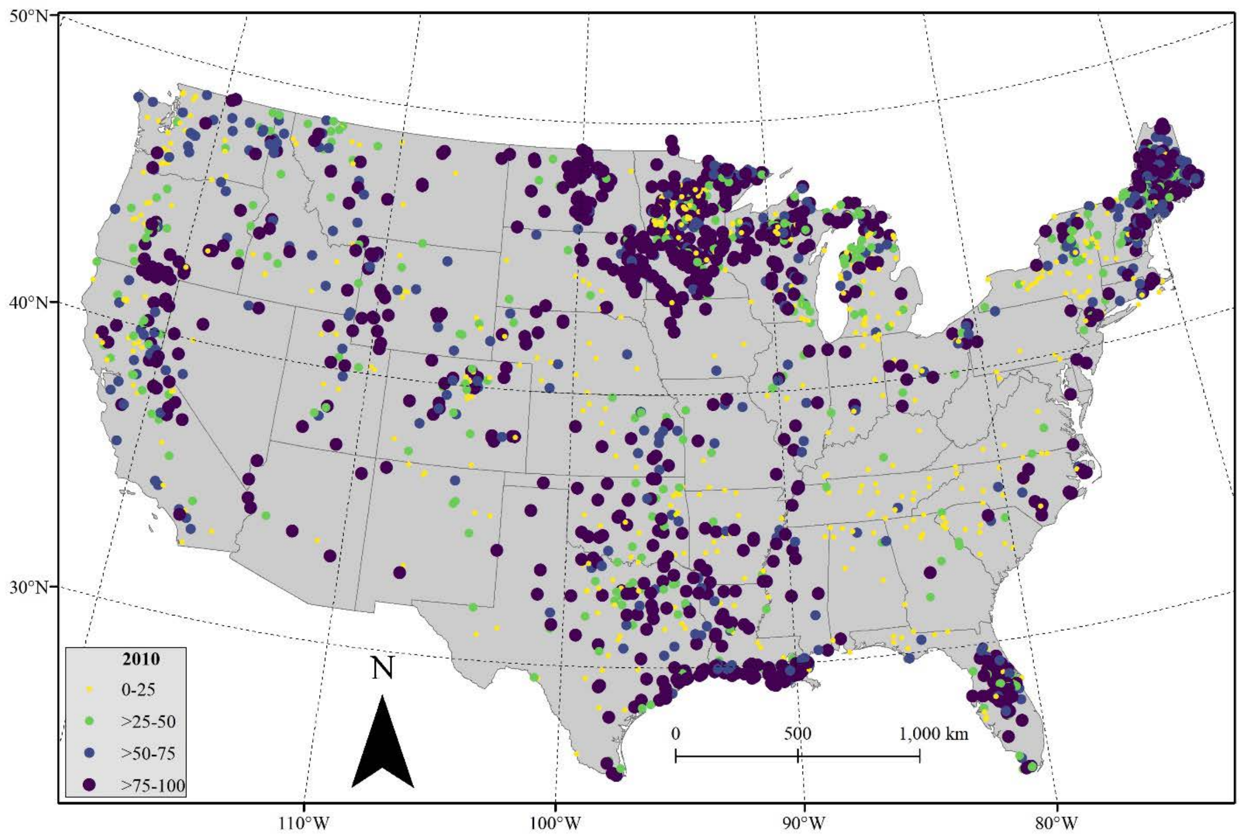

Fig. S12. Median annual spatial extent for each resolvable lake for the year 2010. Each point represents a lake centroid.

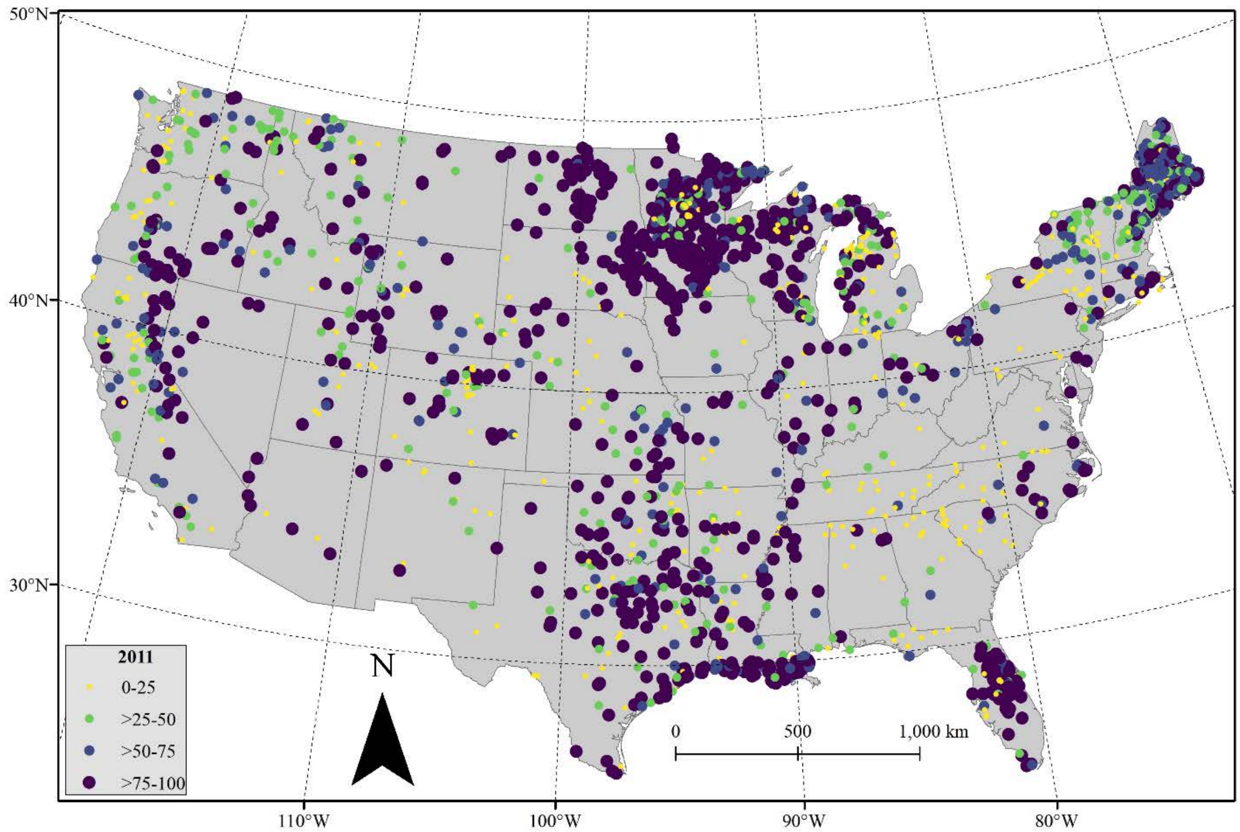

Fig. S13. Median annual spatial extent for each resolvable lake for the year 2011. Each point represents a lake centroid.

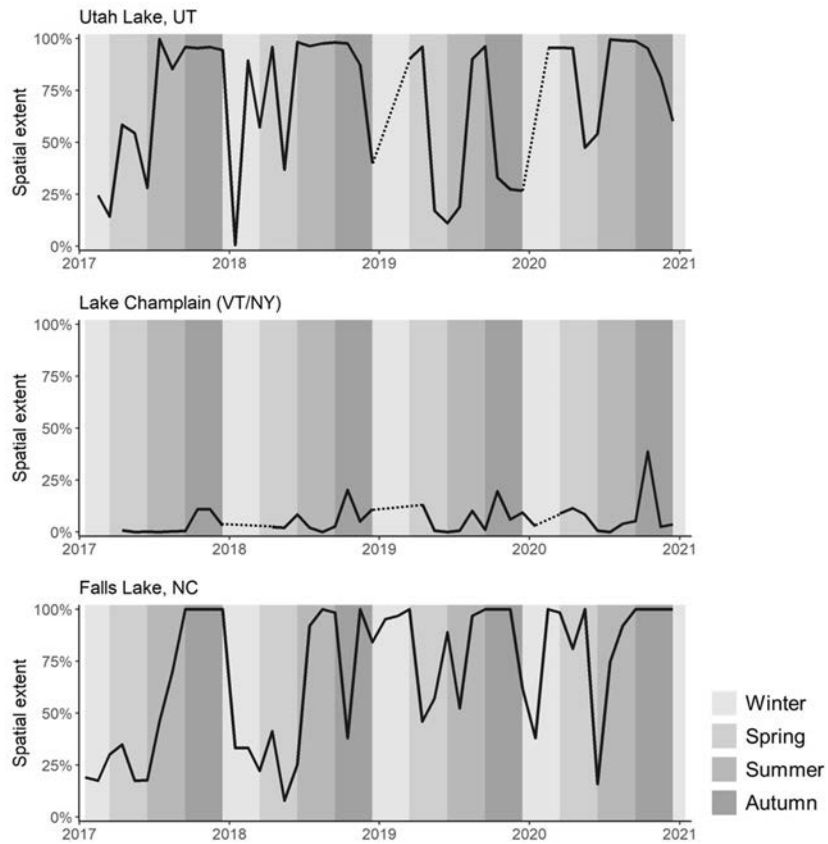

Fig. S14. Monthly spatial extent time series variation example from a few select single lakes. Dotted line represents data gaps due to snow and ice quality flags.

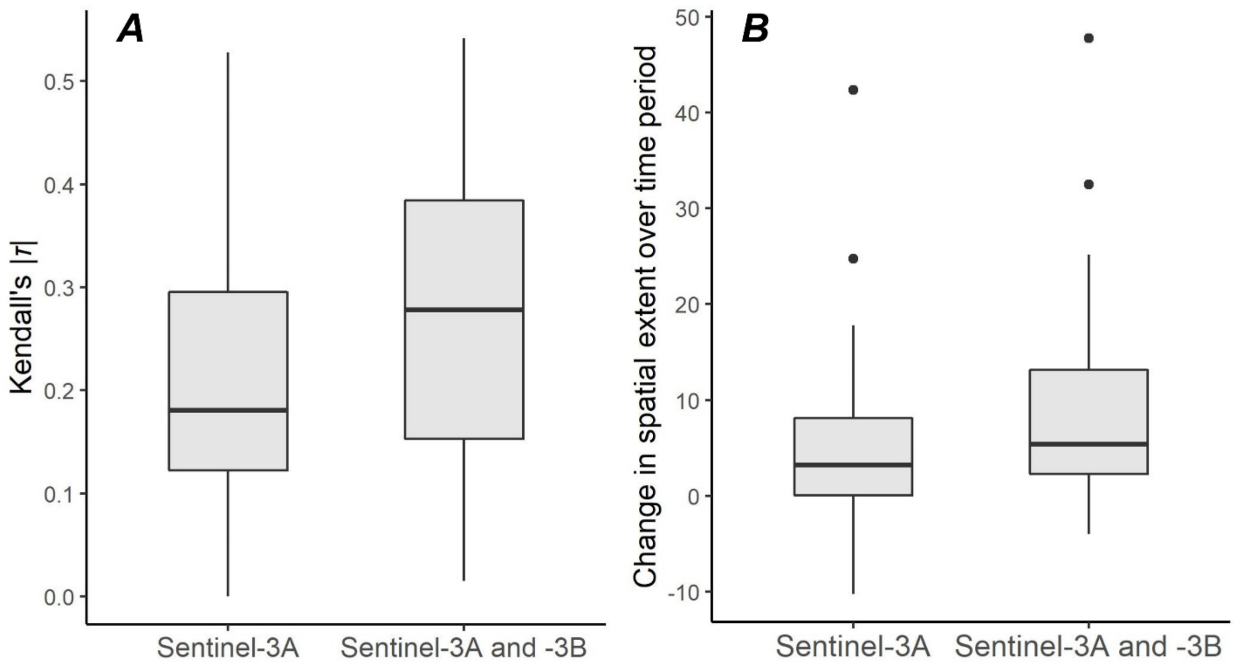

Fig. S15. Comparison of only Sentinel-3A and merged Sentinel-3A and -3B for (A) Kendall $|\tau|$ strength and (B) change in spatial extent over time period.

Data Description

ICE_output: IMS Daily Northern Hemisphere Snow and Ice Analysis data (4km) were obtained from the National Snow and Ice Center (currently at http://nsidc.org/). We temporally binned the daily 2008-2011 and 2017-2020 GeoTIFF imagery into weekly time composites consistent with the end-of-week day from the satellite derived cyanoHAB abundance data. Weekly GeoTIFF data were converted to ESRI shapefiles with polygon holes removed. File naming convention is Syyyydddyyyyddd_ice.shp, where yyyy=four-digit calendar year and ddd=three digit calendar day.

MERIS_monthly: A total of 208 full resolution (300m at nadir), weekly MERIS maps of the continental US spanning 2008 through 2011 were obtained from the NASA Ocean Biology Processing Group (OBPG). The OBPG prepared these data using their standard satellite ocean color software package (l2gen; distributed publicly within the SeaWiFS Data Analysis System, SeaDAS, https://seadas.gsfc.nasa.gov/), the Shuttle Radar Topography Mission (SRTM) static land mask, and a transformation to Albers Equal Area with an area-weighted interpolation to match the projections of the National Hydrography Dataset High Resolution (https://nhd.usgs.gov/). Each 300m satellite pixel in a weekly CONUS map represents the maximum Cyanobacteria Index (CI) value retrieved in the specific time period. The CI was calculated using a spectral shape (SS) algorithm detailed and validated elsewhere. Original files are publicly available at https://oceancolor.gsfc.nasa.gov/projects/cyan/. File naming convention is Xyyyymm_masked.tif, where yyyy=four digit calendar year and mm=two digit calendar month 01-12.

OLCI_3A_only_monthly: Full resolution (300m at nadir), weekly Sentinel-3A only OLCI maps of the continental US spanning 2017 through 2020 were obtained from the NASA Ocean Biology Processing Group (OBPG). The OBPG prepared these data using their standard satellite ocean color software package (l2gen; distributed publicly within the SeaWiFS Data Analysis System, SeaDAS, https://seadas.gsfc.nasa.gov/), the Shuttle Radar Topography Mission (SRTM) static land mask, and a transformation to Albers Equal Area with an area-weighted interpolation to match the projections of the National Hydrography Dataset High Resolution (https://nhd.usgs.gov/). Each 300m satellite pixel in a weekly CONUS map represents the maximum Cyanobacteria Index (CI) value retrieved in the specific time period. The CI was calculated using a spectral shape (SS) algorithm detailed and validated elsewhere. Original files are publicly available at https://oceancolor.gsfc.nasa.gov/projects/cyan/. File naming convention is Xyyyymm_masked.tif, where yyyy=four digit calendar year and mm=two digit calendar month 01-12.

OLCI_3A&3By_monthly: Full resolution (300m at nadir), weekly Sentinel-3A and Sentinel-3B OLCI maps of the continental US spanning 2017 through 2020 were obtained from the NASA Ocean Biology Processing Group (OBPG). The OBPG prepared these data using their standard satellite ocean color software package (l2gen; distributed publicly within the SeaWiFS Data Analysis System, SeaDAS, https://seadas.gsfc.nasa.gov/), the Shuttle Radar Topography Mission (SRTM) static land mask, and a transformation to Albers Equal Area with an area-weighted interpolation to match the projections of the National Hydrography Dataset High Resolution (https://nhd.usgs.gov/). Each 300m satellite pixel in a weekly CONUS map represents the maximum Cyanobacteria Index (CI) value retrieved in the specific time period. The CI was calculated using a spectral shape (SS) algorithm detailed and validated elsewhere. Original files are publicly available at https://oceancolor.gsfc.nasa.gov/projects/cyan/. File naming convention is Xyyyymm_masked.tif, where yyyy=four digit calendar year and mm=two digit calendar month 01-12.

Climate_Regions/climate_regions.shp: Shapefile of nine climate regions defined by the National Center for Environmental Information (Karl and Koss, 1984) which represent climatically consistent states across the contiguous United States (CONUS).

CONUS_Boundary/conus_boundary.shp: Shapefile indicating the boundary of CONUS.

CONUS_States/state_48.shp: Shapefile indicating the boundary of each of the 48 states within CONUS.

Invalid_Pixels/invalidMixed.tif: Raster indicating pixels along the land-water interface which are quality flagged.

Resolvable_Lakes/LakeswithStats11_14.shp: Shapefile

Resolvable_Lakes/UpdatedLakes11_13.shp: Shapefile indicating the boundary of all resolvable lakes across CONUS.

Sentinel-3A_Swaths/YYYYMMDD_DOY_selection.shp: Shapefiles delineating Sentinel-3A swath paths formated as year (YYYY) month (MM) day (DD) and day of year (DOY) for all dates after the incorporation of Sentinel-3B data.

Coding_Scripts/parallel.step1plus2.R: R script used to mask weekly satellite data to just CONUS, just resolvable lakes, and to remove invalid satellite pixels.

Coding_Scripts/cyanoCONUS_ice_step3.R: R script used to bin daily snow and ice data to weekly data matching each week of satellite imagery.

Coding_Scripts/hole_chop.R: R script used as input in cyanoCONUS_ice_step3; fills in holes in snow and ice shapefiles.

Coding_Scripts/cyanoCONUS_ice_step4.R: R script used to set any satellite pixels to a quality flag if they correspond to snow and ice cover as indicated by output from cyanoCONUS_ice_step3.

Coding_Scripts/cyanoCONUS_monthly_step5.R: R script used to aggregate weekly satellite data into monthly composites preserving the average CI-cyano value for each month.

Coding_Scripts/cyanoCONUS_extent1_lakes_updated.R: R script used to compute lake-scale cyanobacterial spatial extent for each month of data and for each resolvable lake across CONUS.

Coding_Scripts/cyanoCONUS_extent1_updated.R: R script used to compute state-, regional-, and national-scale cyanobacterial spatial extent for each month of data across CONUS.

Coding_Scripts/PYTHON: Python script used to preserve satellite pixels that fall within swath paths of Sentinel-3A.