Estimating Loss of Recreational Angling Trips from Harmful Algal Blooms in Lake Erie

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Abstract

Harmful algal blooms (HABs), which can cause health effects in humans, have been increasing in extent and intensity in Lake Erie. This paper assesses the relationship between HAB occurrence and intensity, and recreational angling trips in Lake Erie using spatially and temporally varying algae measures and daily boat counts in 36 major harbors collected between June and October from 2011 to 2018. We utilize Poisson pseudo-maximum likelihood for the nature of count data, as well as Control function to solve the potential endogeneity from measurement uncertainty and omitted variables. Results indicate a 1% increase of cyanobacteria concentration in the water within 2 miles around the harbors significantly decreases the count of recreational angling boats by 1.47% on weekend days and 2.52% on weekdays. In the western basin, where HAB occurrence is greatest, the numbers are 1.23% on weekend days and 2.03% on weekdays. We also estimate that 163,503 trips in total happened in the western basin of Lake Erie in 2015 during which HABs reached a peak across the ten years, while the numbers go up to 216,703 and 170,547 if we replace the HAB data with 2014 and 2016 respectively. The economic loss of HABs in 2015 on recreational angling is estimated to be at least \$4.6 million if the HAB levels were as same as those in 2014, and at least \$0.6 million if the HAB levels were as same as those in 2016.

Keywords: Water quality, harmful algal bloom, recreational angler, revealed preference, count data, Great lakes

JEL: Q25, Q26, Q51, Q53, Q57

1 Introduction

Harmful algal blooms (HABs) are diverse phenomena when algae - simple photosynthetic organisms that live in the sea and freshwater - grow out of control while producing toxins that can cause acute or chronic health effects in mammals (including humans) and other organisms (Hudnell, 2010). The U.S. national HAB problem is far more extensive than it was decades ago, with more toxic species and toxins to monitor, as well as a larger range of impacted resources and affected areas (Anderson et al., 2021). Lake Erie, the fourth-largest lake (by surface area) of the five Great Lakes in North America possesses an estimated 50% of all fish inhabiting the Great Lakes (Lucente et al., 2012). With its abundant fishery, Lake Erie boasts a wide range of recreational opportunities around fishing and boating. Since the 1990s, Lake Erie has seen a return of the seasonal HABs that were common the in the 1960s and 1970s (Berardo, Turner, and Rice, 2019). It occurs when phosphorus levels are high within the lake mainly due to crop and livestock production in upstream agricultural watersheds (Michalak et al., 2013) and climate change (Cousino, Becker, and Zmijewski, 2015).

Faced with acute HAB problems, National Oceanic and Atmospheric Administration (NOAA) has reported unsafe toxin concentrations in Lake Erie and has advised people (and their pets) to stay away from areas where scum is forming on the water surface. NOAA has also developed the Lake Erie Harmful Algal Bloom Forecast [1] from which people can subscribe and receive forecast information by email. The Ohio Department of Natural Resources (ODNR) also reminds all visitors to beaches to check the Ohio BeachGuard website [2] for any current water quality advisories before swimming. To restore and protect the waters of the Great Lakes, the United States and Canada signed the 2012 Great Lakes Water Quality Agreement (GLWQA) (EPA, 2015), which stipulates completion of revised binational phosphorus reduction targets (40 percent reduction in total phosphorus entering the Western

[1] https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/bulletin.html

[2] https://publicapps.odh.ohio.gov/beachguardpublic/

Basin and Central Basin of Lake Erie – from the United States and from Canada) for Lake Erie.

In light of the increasing frequency and intensity of HABs in Lake Erie, there is a need for information concerning how lake visitors react to HABs to help inform policy, planning, and resource management. A large body of literature has been devoted to evaluating impacts on recreational uses from environmental quality changes (Fisher, Krutilla, and Cicchetti, 1972; Cicchetti, Fisher, and Smith, 1976; Bockstael, Hanemann, and Kling, 1987; von Haefen and Lupi, 2021). Specifically, many studies have examined factors affecting recreational activities in Lake Erie, such as water quality advisories or warnings (Murray, Sohngen, and Pendleton, 2001), perceived water quality (Phaneuf, Kling, and Herriges, 1998; Cheng and Lupi, 2016), and beach closures (Parsons, Jakus, and Tomasi, 1999; Palm-Forster, Lupi, and M. Chen, 2016). More particularly, a few studies examined the impact of HABs on recreational activities in Lake Erie. Most of the current research focuses on estimating people's willingness to pay based on questionnaires. Discrete choice experiments in a mail survey were conducted which found anglers are willing to pay \$8 to \$10 more per trip for one less mile of boating through HABs en route to a fishing site (Zhang and Sohngen, 2018). Another mail survey was conducted to estimate the effects of HABs and E. coli events simultaneously, which found beachgoers and recreational anglers would lose in aggregate \$7.7 million and \$69.1 million, respectively, each year if water quality conditions were to become so poor that Lake Erie's western basin was closed (Wolf, W. Chen, et al., 2019). Interviews and follow-up choice experiment survey on beachgoers' willingness to drive found that the average respondent is willing to drive 260 and 266 miles to avoid sites with either current HAB or bacterial warnings (Boudreaux et al., 2023). To sum up, most of the current research is based on mail survey data, including recall of people's past recreational experiences or stated preference in hypothetical choice experiments. The main reason might be the unavailability of accurate HAB assessment data with spatial and temporal variation.

With the development of empirical relationships derived from measurements of chlorophyll-related band ratios and remote sensing reflectance, satellite raster images became an important data source for HAB severity, making impact evaluation possible. One important data source is 10-day algal-composite satellite images at each map pixel of about 1.1 km by 1.1 km from NOAA (R. Stumpf and Dupuy, 2016) and (Timothy T. Wynne and Richard P. Stumpf, 2015). Using this data, one study looked into the relationship between fishing permit sales and found that monthly permit sales drop between 10% and 13% when algal conditions surpass the World Health's Organization's moderate health risk advisory threshold (Wolf, Georgic, and Klaiber, 2017). Another similar data set is CHLA data, which is 8-day composite satellite raster images derived from NASA'a MODIS-Aqua satellite and is uniformly gridded into 4km by 4km raster cells. Using this data, one study looked into the impacts of HABs in past six months on housing prices in the year and concluded that the impact is spatially limited to properties within 1.2 km of Lake Erie, and a 1 µg/L increase in algae concentration is expected to decrease property values by 1.7% (Wolf, Gopalakrishnan, and Klaiber, 2022).

However, measurement error of the imperfect environmental quality data as well as omitted variables are two longstanding challenges associated with causally identifying the impacts of environmental quality changes (Wolf, Gopalakrishnan, and Klaiber, 2022). For example, for the CHLA data and NOAA data, the maximum for these 10-day or 8-day composites was used to represent the interval because the satellite observes only the surface concentration (nominally within a meter of the surface) while Microcystis blooms tend to float to the surface during calm weather (T. T. Wynne et al., 2013). If one period suffers from a lack of usable days due to cloud coverage, ice coverage, or strong winds, that composite may underestimate the areal biomass since fewer Microcystis blooms will be recorded on the surface. Even worse, pixels next to the shore can have either dense blooms or erroneously high values due to saturation effects (Richard P. Stumpf et al., 2016). Because weather like clouds and winds on the maximum HAB day in the intervals affects both the mismeasurement of algal blooms and the trips, the HAB variable is potentially endogenous. To solve the problems, instrumental variables such as upstream phosphorus concentrations (Keiser, 2019) and loads (Wolf, Gopalakrishnan, and Klaiber, 2022) have been employed for local water pollution. Both are shown to directly influence HABs. Nutrients in Maumee River runoff are mostly considered for Lake Erie while there are still some other tributaries (e.g. Portage, Raisin) often overlooked.

In conclusion, even though the remote-sensing techniques have made the HAB measurement data available, there is a lack of research in terms of direct and instant impact evaluation of HABs on people's recreation trips using satellite rasters. In terms of the available data sources, satellite images from NOAA have smaller grids and fewer missing values than CHLA data do. Meanwhile, more careful consideration and complete solutions to possible endogeneity from measurement error and omitted variables still need to be explored.

In this research, we assess the relationships of HABs on recreational anglers in Lake Erie using NOAA 10-day algal-composite satellite images algae measures and daily boat counts in 36 harbors along the shoreline collected between June and October from 2011 to 2018. We utilize Poisson pseudo-maximum likelihood (PPML) with the count data, and use a control function approach to account for possible endogeneity from measurement uncertainty and omitted variables. The instruments include current and historical nutrient loads from 5 main tributaries of the western basin of Lake Erie (Raisin, Maumee, Portage, Sandusky, and Cuyahoga), current and historical weather, and historical fertilizer prices. Across a number of model specifications, we find that HABs have a significant negative effect on the number of recreational angling boats observed in Lake Erie. Specifically, a 1% increase of cyanobacteria concentration within 2 miles around harbor sites decreases the count of recreational angling boats in a 20-min interval by 1.47% on weekend days and 2.52% on weekdays in Lake Erie. In the western basin, where HAB occurrence is greatest, the numbers are 1.23% on weekend days and 2.03% on weekdays. We also estimate that 163,503 trips in total happened in the western basin of Lake Erie in 2015 during which HABs reached a peak across the ten years, while the numbers go up to 216,703 and 170,547 if we replace the HAB data with 2014 and

2016 respectively. The economic loss of HABs in 2015 on recreational angling is estimated to be at least \$4.6 million if the HAB levels were as same as those in 2014, and at least \$0.6 million if the HAB levels were as same as those in 2016.

This article makes several contributions to the literature. First, this is the first study to combine the on-site recreational fishing trip count data and the algal-composite satellite images over a long period. It contributes to estimating the recreation value of water using on-site revealed preference data. Second, we build on Wolf, Gopalakrishnan, and Klaiber (2022)'s instrument variables (monthly phosphorus loadings from Maumee River), and develop a model taking nutrient loads from 4 more main tributaries and other environmental and economic factors into consideration. Third, because our dependent variable is counts of boats, we apply a control function method (Wooldridge, 2015) to incorporate the instrument variables, which is the first to apply this methodology to value water quality impacts on recreation activities. Fourth, we showcase that anglers' averting behaviors from HABs are heterogeneous across not only basins but also weekdays or weekends, with weekend goers less sensitive to HABs.

2 Materials and methods

Our study focuses on the implications of HABs on the number of recreational boats returning to 36 major harbor sites along Ohio's portion of the Lake Erie shoreline shown in figure A1. The boat counts in 20-minute intervals were gathered from the Ohio Department of Natural Resources - Division of Wildlife (ODNR-DOW) annual creel surveys during 2011-2018. Creel survey sites were typically surveyed during 3 weekdays and 2 weekend days each week from April to October. The dates and interview schedules were randomly selected within this schema, stratified by day of the week (Natural Resources Division of Wildlife, 2019). Mean boat counts across time and basin are shown in figure 1.

In addition to boat counts information, we acquire the 10-day algal-composite data of the

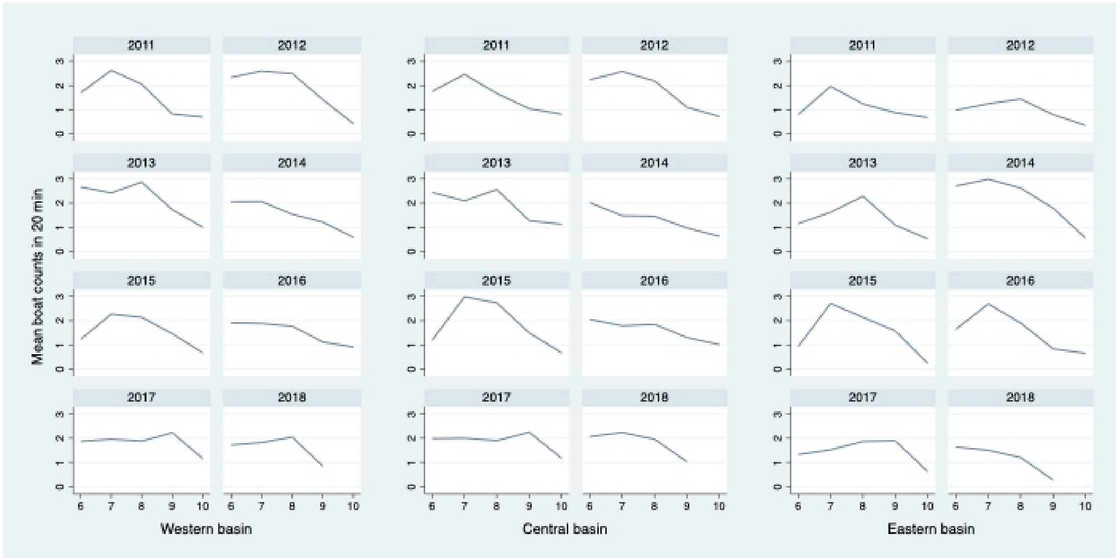

Figure 1: Mean boat counts across time and basin

Great Lakes during 2011-2018 from the NOAA (R. Stumpf and Dupuy, 2016) and (Timothy T. Wynne and Richard P. Stumpf, 2015). Lake Erie HAB raster images are available only for the summer and fall months (June to October) in part due to low or undetectable levels of algae present during much of the winter and spring. A snapshot of the data (2015-08-01 to 2015-08-10) is shown in figure A3. The satellite data sets were processed using a spectral curvature method to obtain the maximum cyanobacterial chlorophyll-related index (CI) value at each map pixel of about 1100 by 1100 m from the individual scenes within sequential (non-overlapping) 10-day periods. The CI corresponds to Microcystis biomass according to empirical models (Timothy T. Wynne, Richard P. Stumpf, et al., 2010).

We use the mean concentration of cyanobacteria within 2 *miles* of each harbor site in each 10-day interval (robustness for different buffer lengths is provided). Mean concentrations of cyanobacteria over time and basins are shown in figure 2. Three observations are evident from this figure. First, 2011, 2013, and 2014 experienced severe HABs, although the highest levels occurred in 2015. Second, there is also substantial inter-annual heterogeneity with some of the HABs peaking in early summer and some peaking in late summer. Third, HABs most frequently occur in the western basin, and are less frequent in the central and eastern

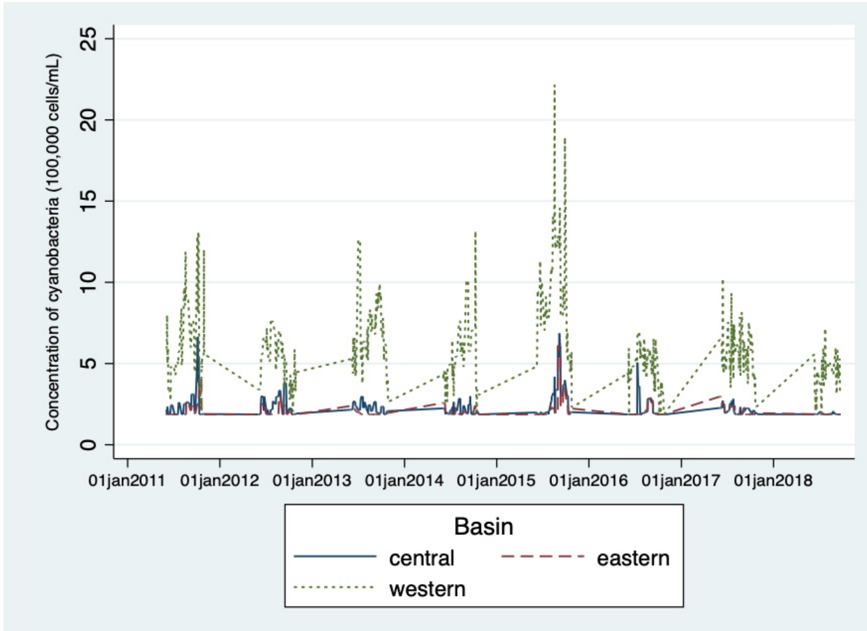

Figure 2: Concentration of Cyanobacteria across time and basin

basins. Looking back to figure 1, we notice that boat counts in the western basin are lower than usual in 2015, the year HABs were extremely high, while boat counts in the central basin are higher than usual. As such, it seems reasonable to expect that HABs variation, coupled with the spatial variation is likely influencing angling behavior along Lake Erie. Anglers might take action to transfer from sites with poor water quality to sites with good water quality or choose not to go angling in Lake Erie as HABs happen.

To form additional control variables, we assembled temporally and spatially varying variables from multiple datasets. First, we obtained weekly Midwest regular conventional retail gasoline prices from U.S. Energy Information Administration. We then calculate the CPI-adjusted gas prices calculated by the weekly gas prices over monthly Core Inflation Rates from US Inflation Calculator. Second, we gathered daily temperature, wind speed, precipitation, and all-sky surface shortwave downward irradiance data at each site's longitude and latitude from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER). Third, we assembled daily mean water surface temperature and daily mean wind speed collected from

Table 1: Summary statistics

	Mean	Std. dev.	Min	Max	N
Boat counts	1.66	2.95	0.00	37.00	23955
Cyanobacteria (cell/ml)	3.0e+05	2.4e+05	1.9e+05	2.5e+06	23955
Weekday (=1)	0.62	0.49	0.00	1.00	23955
CPI adjusted gas price ($/g)	1.58	0.39	0.90	2.40	23984
Survey time (h)	14.49	2.59	10.00	21.00	23955
Shortwave downward irradiance (MJ/m^2/d)	17.94	6.62	1.60	31.90	23955
Temperature (C/d)	20.08	4.56	3.10	32.01	23955
Wind speed (m/s)	3.04	1.50	0.24	11.73	23955
Precipitation (mm/d)	2.97	5.36	0.00	80.53	23955
Buoy wind speed (m/s)	5.34	2.14	1.03	15.35	23412
Buoy water surface temperature (C)	21.25	3.38	11.82	27.41	23412
30-d particulate Phosphorus (mg-P/L)	195.28	368.35	3.08	2964.10	23850
30-d soluble reactive Phosphorus (mg-P/L)	67.31	131.68	0.66	1199.83	23850
30-d total suspended solids (mg/L)	1.2e+05	2.2e+05	911.36	1.8e+06	23850
30-d Nitrite + Nitrate (mg-N/L)	3767.74	7176.04	3.75	68894.11	23850
30-d total Kjeldahl Nitrogen (mg-N/L)	1138.94	1842.40	24.19	14560.77	23850
365-d particulate Phosphorus (mg-P/L)	3434.64	1945.67	176.44	13274.03	23850
365-d soluble reactive Phosphorus (mg-P/L)	1129.79	686.59	29.30	4019.97	23850
365-d total suspended solids (mg/L)	1.9e+06	1.1e+06	1.7e+05	7.2e+06	23850
365-d Nitrite + Nitrate (mg-N/L)	57245.42	33314.51	1485.85	1.8e+05	23850
365-d total Kjeldahl Nitrogen (mg-N/L)	19215.33	10633.66	965.55	66648.73	23850
30-d shortwave downward irradiance (MJ/m^2)	2904.35	519.43	1529.49	3861.18	23955
30-d temperature (C)	91.90	45.63	0.00	150.00	23955
30-d precipitation (mm)	433.66	178.49	89.90	1226.86	23955
30-d wind speed (m/s)	420.94	49.95	334.66	596.20	23955
365-d shortwave downward irradiance (MJ/m^2)	25297.04	650.85	24015.61	26886.14	23955
365-d temperature (C)	466.47	35.76	404.00	563.00	23955
365-d precipitation (mm)	4584.46	358.93	3761.13	5520.59	23955
365-d wind speed (m/s)	6461.93	111.00	6217.60	6667.98	23955
3-m Nitrogenousfertilizer manufacturing price index	1.07	0.18	0.77	1.35	23984
3-m Phosphatic fertilizer manufacturing price index	0.73	0.12	0.55	0.96	23984

buoys at station 45005 from NOAA's National Data Buoy Center. Fourth, we obtained the time at which boat counting was done from the same creel survey. In order to reflect the phenomenon that most boats depart at around 2 pm, we recentered the time (h) to 14.3 h and calculate the deviation.

We use a Poisson pseudo-maximum likelihood (PPML) model (Correia, Guimaraes, and Zylkin, 2020) to estimate the effect of HABs on angling boat counts mainly for three reasons. First, our dependent variable contains count data, including zeros (figure A2). PPML specification obviates the need to drop zero-valued observations to take natural log or to manipulate the data by adding one to the dependent variable to avoid dropping, both of which have been shown to lead to bias (Silva and Tenreyro, 2011). Second, PPML represents the natural log of the conditional mean of the dependent variable rather than the conditional mean of the natural log of the dependent variable that is estimated by the common log-level specification. The latter has been shown to suffer from bias when heteroskedasticity exists (Silva and Tenreyro, 2006). Third, PPML permits the estimation with high-dimensional fixed effects, which allowed us to control for multiple sources of heterogeneity. For robustness check, we also estimate a Poisson model and a negative binomial model.

We estimate the following regression:

$$\mathbf{Boat}_{it} = \exp\left(\mathbf{b}_0 + \mathbf{b}_1\mathbf{HAB}_{it} + \mathbf{b}_2\mathbf{X}_{it} + \lambda_i + \psi_t\right) + \nu_{it} \tag{1}$$

where i indexed the site and t indexed the day surveyed. The outcome of interest $\mathbf{Boat}_{it}$ is the number of boats returning to the site in the 20 minutes surveyed on that day. Our key variable $\mathbf{HAB}_{it}$ is the concentration of cyanobacteria within 2 *miles* of site i on day t. $\mathbf{X}_{it}$ refers to the spatial and time-varying controls. λ_i and ψ_t are site and time (year and month) fixed effects separately, and ν_{ijt} denotes the remainder error term. To avoid too big values, we recentered and rescaled the concentration of cyanobacteria variable and the controls to zero to one.

However, endogeneity arises due to omitted variables and measurement uncertainty of the estimated concentration of cyanobacteria from satellite images. If the 10-day period suffers from a lack of usable days due to cloud cover or strong winds, that 10-day composite may underestimate the areal biomass since fewer Microcystis blooms will be recorded on the surface. Even worse, pixels next to the shore can have either dense blooms or erroneously high values due to saturation effects. (Richard P. Stumpf et al., 2016). This leads to inconsistency with standard estimation methods that maintain independence between the model's error and the included variables. We utilize control function (CF) methods which were developed to solve the problem of endogenous explanatory variables in both linear and nonlinear models (Wooldridge, 2015). The CF approach is inherently an instrumental variables method, but is more efficient for nonlinear functions. In the first stage, the exogenous variation induced by excluded instrumental variables provides separate variation in the residuals obtained from a reduced form, and these residuals serve as the control functions in the second stage where the endogenous explanatory variables become appropriately exogenous. However, the disadvantage is that it is usually less robust than IV approaches in terms of consistency. Bootstrap can be used to obtain more accurate standard errors.

Two important inputs that influence HAB development are phosphorus and nitrogen released from Lake Erie watersheds (Richard P Stumpf et al., 2012). To measure these, we obtain concentrations of particulate phosphorus, soluble reactive phosphorus, total suspended solids, nitrite and nitrate, total kjeldahl nitrogen, and flow data from the Heidelberg Tributary Loading Program (NCWQR, 2022). Due to data availability, we assemble the observation from 5 sampling stations from 5 main tributaries of the western basin of Lake Erie - Raisin, Maumee, Portage, Sandusky, and Cuyahoga as shown in figure A4. We sum the data from the 5 stations, and calculate the total loads over the previous month and previous year. Second, since the crop and livestock production in the upstream agricultural watershed is an important source of excessive nutrients (Michalak et al., 2013), we obtain the monthly nitrogenous fertilizer manufacturing price index and phosphatic fertilizer manufacturing price index from the U.S. Bureau of Labor Statistics. We use the mean prices over the preceding 3-month period, assuming there is a 3-month lag from farmers making decisions about nutrient applications to the excess nutrients flushing out of the system (Kim, Sohngen, and Sam, 2018). Third, historical weather is another important factor influencing the formation of HABs (Richard P. Stumpf et al., 2016). We obtain the weather data at each tributary station from POWER, including temperature, wind speed, precipitation, and all-sky surface shortwave downward irradiance data at each site's longitude and latitude. Again, we then sum them up and calculate the mean weather data in the past month and past year. No evidence has been found that the tributary P and N loads, fertilizer prices, and historical weather directly influence boat counts.

We estimate the following 2 stages:

$$\mathbf{HAB}_{it} = \mathbf{a}_0 + \mathbf{a}_1\mathbf{Z}_t + \mathbf{resid}_{it} \tag{2}$$

$$\mathbf{Boat}_{it} = \exp\left(\mathbf{c}_0 + \mathbf{c}_1\mathbf{HAB}_{it} + \mathbf{c}_2\mathbf{X}_{it} + \lambda_i + \psi_t + \mathbf{c}_3\mathbf{resid}_{it}\right) + \mu_{it} \tag{3}$$

where we first predict the cyanobacteria concentration using the instrument variables varying across time denoted by $\mathbf{Z}_t$. $\mathbf{resid}_{it}$ denotes the residual we plug into the second stage. Bootstrap was used to estimate the standard error.

3 Results

Table 2 reports results on the first stage regression. Generally, our model performs better for the total sample and the western basin compared to the central basin and eastern basin, which likely relates to the fact that the largest share of nutrients enters Lake Erie in the western basin where most HABs happen. Variables have the expected sign, even after controlling for site, month, and year fixed effects. For loads from tributaries in the past month, higher particulate phosphorus, soluble reactive phosphorus, and nitrite and nitrate loads are

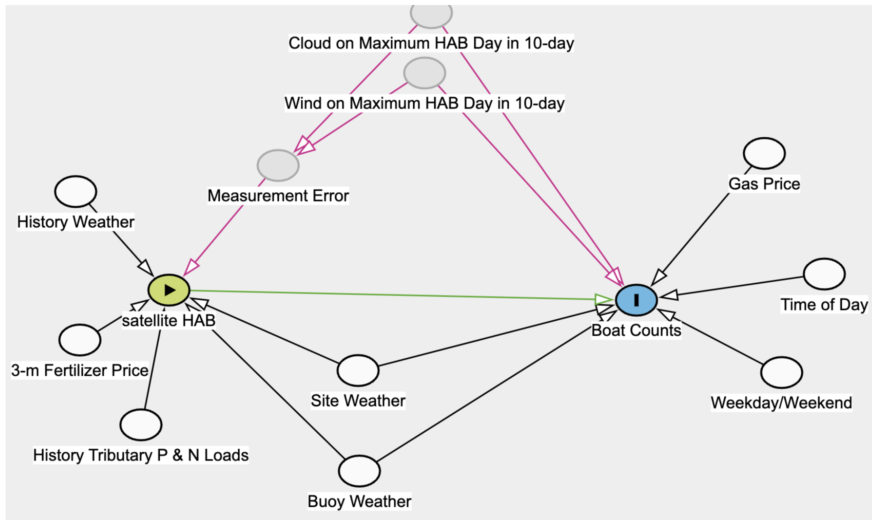

Figure 3: Identification strategy

associated with higher cyanobacteria concentration in Lake Erie while higher total kjeldahl nitrogen and total suspended solids decrease the cyanobacteria concentration. Results for loads from tributaries in the past year are quite different. Higher particulate phosphorus loads are associated with lower cyanobacteria concentration while higher total nitrite and nitrate, and total suspended solids increase the cyanobacteria concentration. For weather in the past month, all the temperature, precipitation, wind speed, and irradiance are positively related to HABs. For weather in the past year, precipitation and irradiance have positive impacts while temperature and wind speed have negative impacts. For fertilizer manufacturing prices in the preceding 3 months, higher phosphatic fertilizer prices will decrease the HABs, while the impact of nitrogenous fertilizer prices is not stable.

Table 3 provides results for PPML and PPML with the residual from the first stage. As mentioned, the control function model performs better for the total sample and the western basin, and thus we focus more on the first four columns' results. The coefficients of residue from the first stage are significantly positive, which supports our assumption that there exists the endogeneity problem that makes the estimates of HABs from the original ppml underestimate the real effect. Thus, results in column (2) and column (4) are preferred. The coefficients are basically in the same direction and similar in scale for these two columns.

Table 2: Control function 1st stage regression results

	(1) Total	(2) Western basin	(3) Central basin	(4) Eastern basin
30-d particulate Phosphorus (mg-P/L)	0.978***	2.084***	-0.228	0.884***
	(0.274)	(0.432)	(0.193)	(0.168)
30-d soluble reactive Phosphorus (mg-P/L)	0.305***	0.653***	-0.248***	-0.300***
	(0.094)	(0.148)	(0.054)	(0.045)
30-d total suspended solids (mg/L)	-1.015***	-2.111***	0.150	-0.407***
	(0.213)	(0.342)	(0.151)	(0.125)
30-d Nitrite + Nitrate (mg-N/L)	0.209**	0.571***	-0.162***	-0.045
	(0.088)	(0.140)	(0.044)	(0.037)
30-d total Kjeldahl Nitrogen (mg-N/L)	-0.291*	-0.820***	0.516***	-0.213**
	(0.157)	(0.261)	(0.137)	(0.084)
365-d particulate Phosphorus (mg-P/L)	-0.498***	-1.282***	0.118	-0.090
	(0.163)	(0.269)	(0.119)	(0.101)
365-d soluble reactive Phosphorus (mg-P/L)	-0.021	0.070	-0.044	0.068
	(0.077)	(0.126)	(0.052)	(0.049)
365-d total suspended solids (mg/L)	0.444***	1.205***	-0.222***	0.001
	(0.104)	(0.169)	(0.064)	(0.050)
365-d Nitrite + Nitrate (mg-N/L)	0.195**	0.195	0.132**	0.156***
	(0.078)	(0.127)	(0.063)	(0.055)
365-d total Kjeldahl Nitrogen (mg-N/L)	-0.110	-0.135	-0.033	-0.144
	(0.167)	(0.273)	(0.105)	(0.111)
30-d shortwave downward irradiance (MJ/m^2)	0.611***	1.160***	0.126***	0.029
	(0.049)	(0.079)	(0.038)	(0.032)
30-d temperature (C)	0.091***	0.177***	0.021	-0.042***
	(0.023)	(0.040)	(0.015)	(0.016)
30-d precipitation (mm)	0.287***	0.525***	0.067***	0.030
	(0.030)	(0.050)	(0.024)	(0.018)
30-d wind speed (m/s)	0.245***	0.391***	0.054***	-0.027*
	(0.026)	(0.045)	(0.021)	(0.015)
365-d shortwave downward irradiance (MJ/m^2)	0.543***	0.514***	0.607***	0.243***
	(0.068)	(0.108)	(0.046)	(0.045)
365-d temperature (C)	-0.493***	-0.723***	-0.285***	-0.072***
	(0.027)	(0.045)	(0.021)	(0.018)
365-d precipitation (mm)	0.280***	0.284***	0.290***	0.115***
	(0.036)	(0.060)	(0.025)	(0.024)
365-d wind speed (m/s)	-0.356***	-0.336***	-0.301***	-0.201***
	(0.040)	(0.070)	(0.029)	(0.028)
3-m Nitrogenous fertilizer manufacturing price index	-0.411**	-1.531***	0.765***	0.685***
	(0.170)	(0.281)	(0.110)	(0.104)
3-m Phosphatic fertilizer manufacturing price index	-0.215	0.369	-0.500**	-0.423**
	(0.325)	(0.532)	(0.241)	(0.181)
Observations	23307	12166	7195	3946
Adjusted R^2	0.596	0.588	0.242	0.247
Site FE	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Specifically, HABs have a significantly negative impact on recreational angling trips with 1% increase of cyanobacteria concentration within 2 miles around harbor sites significantly decreasing the count of recreational angling boats in a 20-min interval by 1.47% on weekend days and 2.52% on weekdays in Lake Erie. In the western basin, where HAB occurrence is greatest, the numbers are 1.23% on weekend days and 2.03% on weekdays. It might be explained that weekday goers probably take shorter trips, and have less flexibility in general. Weekend trips may be planned weeks in advance and have multiple objectives, so are less sensitive to HABs. It might also be the case that weekday goers are more likely to have more flexible schedules and more experience and knowledge in HABs in Lake Erie compared to weekend goers. Therefore, they are more likely to be informed of the HAB situation in Lake Erie whether by observing HABs by themselves, or by receiving advisory alerts from the Ohio Department of Health after subscribing, or by checking the HAB Forecast Bulletin online by NOAA, and thus are more likely to take actions to avoid the HABs. We also find that weekday and weekend goers respond differently to gas prices, with a 1% increase in gas prices significantly decreasing boat counts by 0.48% on weekends and by 0.63% on weekdays. A weekend itself brings 1.55 % more boats compared to a weekday. Results show that most boats tend to depart at around 2 pm. Evidence also shows that most anglers prefer higher temperatures, milder winds, less precipitation, and brighter days.

Table A2 provides robustness to buffer lengths around sites. The results are quite robust except for the 0.5 miles column, which might be because the sites with distances from sites to the lake larger than 0.5 miles are dropped. Table A1 provides robustness where we first examine the impact of HABs on boat counts in Lake Erie with and without site and time fixed effects. We then change the second stage from PPML to negative binomial and Poison, respectively. Considering the risk of overidentification problem in our control function, we utilize Principle Component analysis (PCA) to transform the large set of variables in the first stage into 6 principal components (Scree plot of eigenvalues after PCA shown in Figure A5). Most of our results are quite robust. We further plot the marginal boat counts distribution

Table 3: Poisson pseudo maximum likelihood - control function 2nd stage results

	Total		Western basin		Central basin		Eastern basin	
	(1) ppml	(2) cf	(3) ppml	(4) cf	(5) ppml	(6) cf	(7) ppml	(8) cf
Cyanobacteria (cell/ml)	0.076	-2.675***	0.079	-1.922***	-0.152	-4.349	-0.148	3.421
	(0.134)	(0.706)	(0.145)	(0.488)	(0.918)	(2.833)	(2.048)	(8.005)
Weekday (=1)	-0.930***	-0.937***	-0.916***	-0.919***	-0.921***	-0.929***	-0.901***	-0.910***
	(0.032)	(0.033)	(0.045)	(0.044)	(0.057)	(0.052)	(0.078)	(0.071)
Cyanobacteria * weekday	-0.562***	-0.541***	-0.516***	-0.501***	-2.902*	-2.896*	-2.466	-2.288
	(0.162)	(0.159)	(0.178)	(0.169)	(1.511)	(1.680)	(3.306)	(3.719)
Log(CPI adjusted gas price ($/g))	0.032	-0.132	0.074	-0.108	0.292	0.155	-0.950***	-0.796*
	(0.126)	(0.127)	(0.175)	(0.188)	(0.211)	(0.240)	(0.335)	(0.480)
Log(CPI adjusted gas price) * weekday	-0.269***	-0.263***	-0.314***	-0.316***	-0.362***	-0.351***	0.034	0.045
	(0.064)	(0.062)	(0.086)	(0.086)	(0.111)	(0.113)	(0.153)	(0.141)
Deviation from 14.3 (h)	-1.533***	-1.547***	-1.766***	-1.787***	-1.020***	-1.028***	-1.797***	-1.799***
	(0.067)	(0.066)	(0.090)	(0.096)	(0.117)	(0.115)	(0.162)	(0.150)
Shortwave downward irradiance ($MJ/m^2/d$)	1.201***	1.274***	1.153***	1.240***	1.189***	1.225***	1.346***	1.347***
	(0.076)	(0.079)	(0.107)	(0.111)	(0.129)	(0.136)	(0.161)	(0.184)
Temperature (C/d)	1.884***	1.880***	1.049***	1.060***	3.434***	3.460***	2.139***	2.085***
	(0.132)	(0.140)	(0.180)	(0.199)	(0.247)	(0.263)	(0.324)	(0.327)
Wind speed (m/s)	-1.427***	-1.470***	-1.425***	-1.381***	-1.406***	-1.447***	-2.998***	-2.967***
	(0.147)	(0.153)	(0.214)	(0.236)	(0.254)	(0.266)	(0.407)	(0.370)
Precipitation (mm/d)	-3.105***	-2.920***	-1.765***	-1.621***	-5.123***	-5.125***	-4.758***	-4.719***
	(0.373)	(0.415)	(0.508)	(0.488)	(0.570)	(0.593)	(0.744)	(0.861)
Buoy wind speed (m/s)	-2.163***	-2.233***	-1.978***	-2.115***	-2.094***	-2.114***	-2.356***	-2.367***
	(0.122)	(0.118)	(0.179)	(0.198)	(0.210)	(0.207)	(0.266)	(0.308)
Buoy water surface temperature (C)	-0.469***	-0.398***	-0.074	-0.000	-1.186***	-1.151***	-0.638**	-0.625**
	(0.112)	(0.105)	(0.150)	(0.147)	(0.203)	(0.240)	(0.285)	(0.243)
resid1		2.831***		2.125***		4.564		-3.910
		(0.708)		(0.462)		(3.030)		(8.285)
Observations	23412	23984	12220	12494	7228	7401	3964	4089
Site FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses
Bootstrapped standard error for cf
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

of weekdays and weekends in Poison and negative binomial model in Figure A6, suggesting the estimates are robust and stable across model specifications.

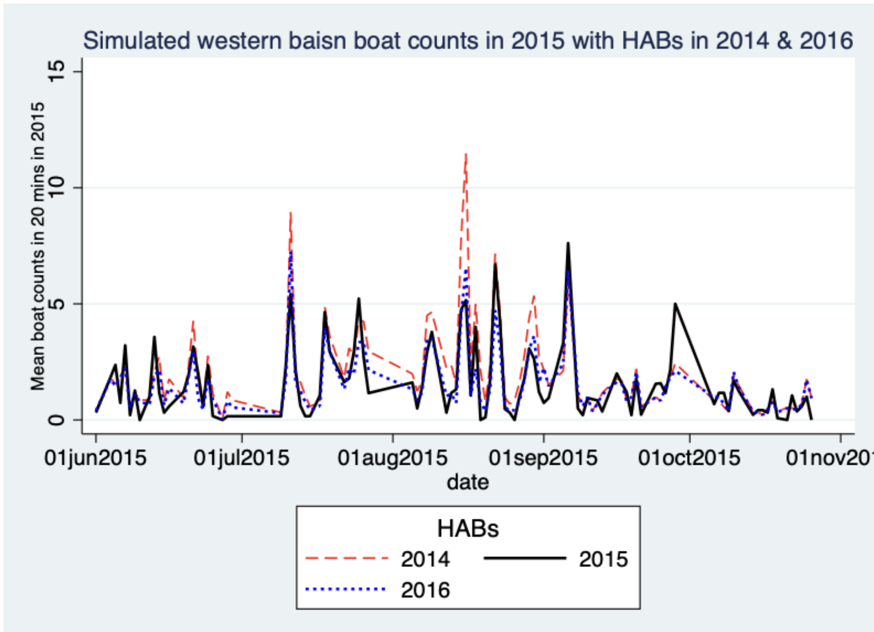

Figure 4: Simulated western basin boat counts in 2015 with HABs in 2014 & 2016

Using the coefficients from Column (4) in table 3, we examine the economic implications of HAB occurrence. From figure 2, we can find that 2011, 2013, and 2014 experienced severe HABs, although the highest levels occurred in 2015. After the peak, the HABs moved down to a comparatively low level in 2016 and 2018. Based on this phenomenon, we try to restore the western basin recreational angling trips in 2015 with the HAB data in 2014 and 2016 respectively. Keeping all the other economic and weather variables in 2015 unchanged, we simulate the boat counts in 2015 shown in figure 4. Compared to the real situation in 2015, we find that the increase in simulated boat counts mainly happens in mid-June to late-August, which is consistent with the time of HAB occurrence. We also calculate the total number of boat trips using multipliers based on sampling strata (Natural Resources Division of Wildlife, 2019). Results show that 163,503 trips happened in the western basin of Lake Erie in 2015, while the numbers go up to 216,703 and 170,547 if we replace the HAB data with 2014 and 2016 respectively. According to a report from a 2014 survey of Lake

Erie anglers (Sohngen et al., 2014), anglers spend around $88 per trip, although those living further away spend around $20 per trip more. The additional money is spent mainly on groceries, restaurants, and other expenditures rather than fuel. Applying the numbers to the total number of trips simulated, we estimate that the HABs in 2015 result in economic losses of at least $4.6 million if the HAB levels were as same as those in 2014, and at least $0.6 million if the HAB levels were as same as those in 2016.

4 Conclusions

HABs in freshwater and marine ecosystems are a growing public environmental concern, both in the U.S. and worldwide. While extensive studies have looked into the cause of HABs, the previous research fails to quantify the impacts of HABs on recreational angling trips, an important outdoor recreation activity for residents and revenue recreational fishing industry. Of particular interest, so far there is no empirical assessment of the impact of HABs on U.S. recreational anglers, especially for the Great Lakes region using revealed preference data. This research helps to fill in this gap by conducting a causal inference on the effect of HABs on recreational boat counts directly. Specifically, we combine the Annual Creel Survey data of 23,139 records of the number of boats leaving the 36 main harbor areas along Ohio's portion of the Lake Erie shoreline in 20-minute intervals and 10-day algal-composite satellite images of the Great Lakes during June to October from 2011 to 2018. We choose PPML for the nature of count data, as well as the Control function to solve the endogeneity from measurement uncertainty and omitted variables.

We find a significantly negative impact of HABs on the number of recreational angling boats in Lake Erie, regardless of model specifications. Specifically, Results indicate a 1% increase of cyanobacteria concentration within 2 miles around harbor sites significantly decreases the count of recreational angling boats in a 20-min interval by 1.47% on weekend days and 2.52% on weekdays in Lake Erie. In the western basin, where HABs mainly happen, the numbers are 1.23% on weekend days and 2.03% on weekdays. We also estimate that 163,503 trips in total happened in the western basin of Lake Erie in 2015 during which HABs reached a peak across the ten years, while the numbers go up to 216,703 and 170,547 if we replace the HAB data with 2014 and 2016 respectively. The economic loss of HABs in 2015 on recreational angling is estimated to be at least \$4.6 million if the HAB levels were as same as those in 2014, and at least \$0.6 million if the HAB levels were as same as those in 2016. We also find the weekday and weekend goers act differently to the gas prices too, with a 1% increase in gas prices significantly decreasing boat counts by 0.48% on weekends and by 0.63% on weekdays. A weekend itself brings 1.55 % more boats compared to a weekday. Results show that most boats tend to depart at around 2 pm. Evidence also shows that most anglers prefer higher temperatures, milder winds, less precipitation, and brighter days.

Our results also help to predict the HABs in Lake Erie with historical weather and tributary nutrient data. For loads from tributaries in the past month, higher particulate phosphorus, soluble reactive phosphorus, and nitrite and nitrate loads are associated with higher cyanobacteria concentration in Lake Erie while higher total kjeldahl nitrogen and total suspended solids decrease the cyanobacteria concentration. Results for loads from tributaries in the past year are quite different. Higher particulate phosphorus loads are associated with lower cyanobacteria concentration while higher total nitrite and nitrate, and total suspended solids increase the cyanobacteria concentration. For weather in the past month, all the temperature, precipitation, wind speed, and irradiance are positively related to HABs. For weather in the past year, precipitation and irradiance have positive impacts while temperature and wind speed have negative impacts. Additionally, higher phosphatic fertilizer prices in the preceding 3 months will decrease the HABs which is in accord with the literature that agricultural nutrient loadings from upstreams are the primary cause of HABs in Lake Erie.

This article provides the first empirical evidence that links remote-sensing HAB data and on-site recreational fishing activities and quantifies the loss of recreational trips from

HABs. Results suggest that policies aimed at eliminating or mitigating algal levels are most beneficial to both the Lake Erie recreational anglers and the angling industry.

Acknowledgement

We would like to thank the Ohio Department of Natural Resources - Division of Wildlife (ODNR-DOW) for providing the annual creel surveys of Lake Erie anglers.

Appendix

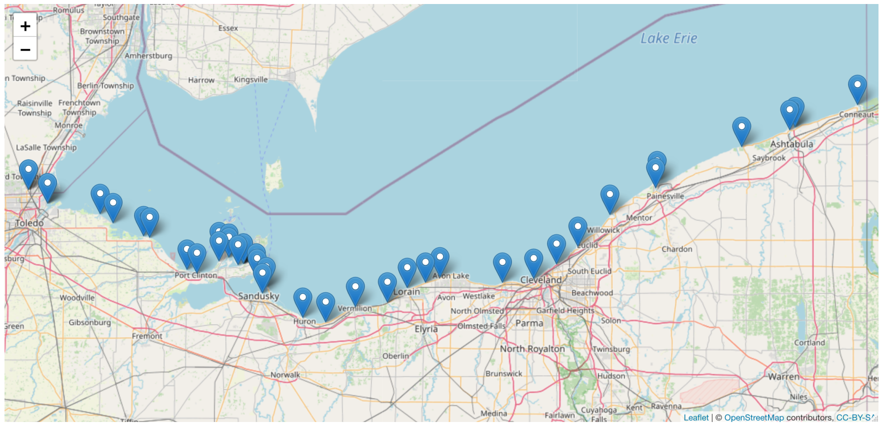

Figure A1: Location of 36 sites in ODNR Annual Creel Survey

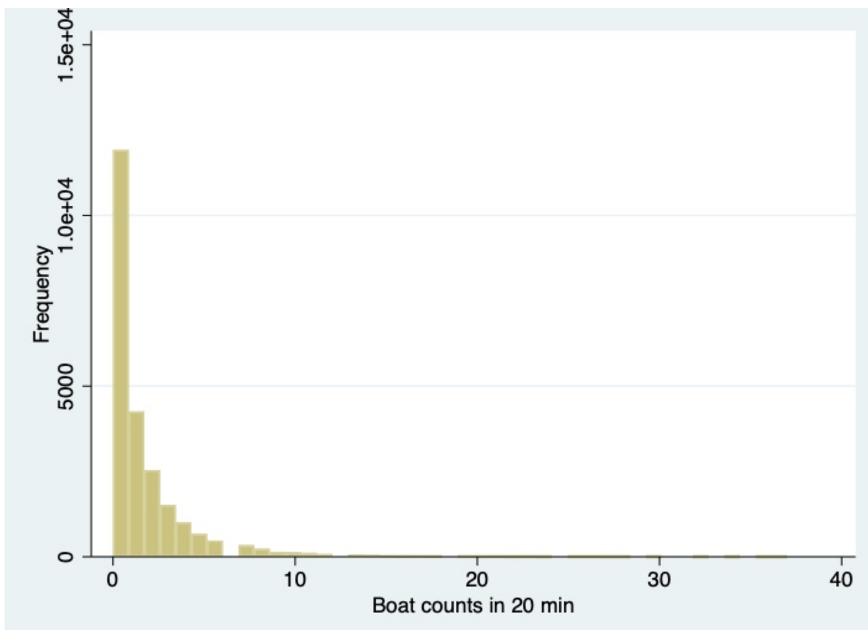

Figure A2: Frequency of boat counts in 20 min

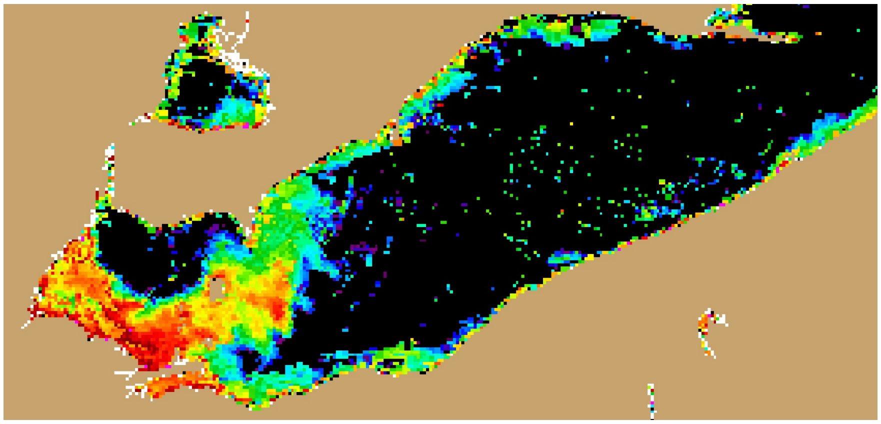
Figure A3: Algal-composite raster image of 2015-08-01 to 2015-08-10

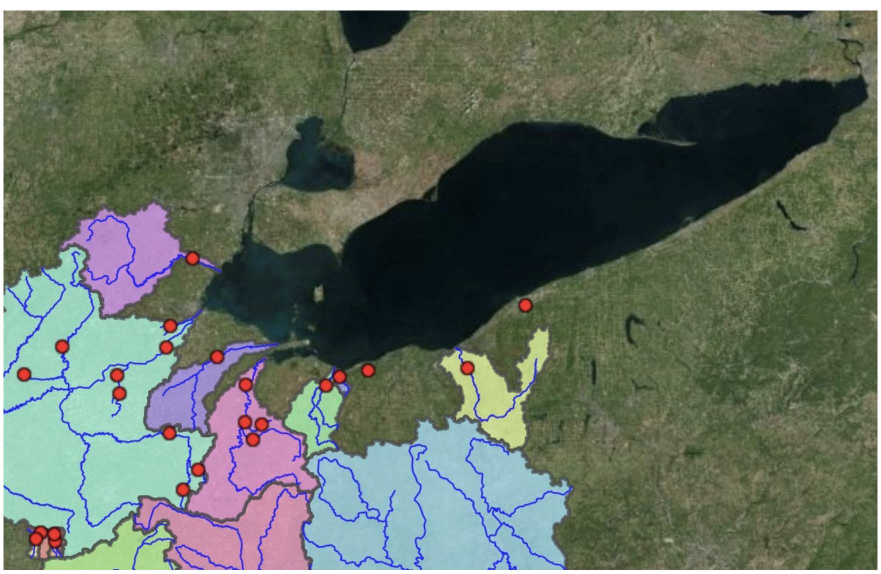
Figure A4: Location of 5 main tributaries ofLake Erie

Table A1: Robustness to functional form specification for the Western basin

	(1) ppml-cf	(2) w/ month	(3) w/ year	(4) w/ site	(5) Negative binomial-cf	(6) Poisson-cf	(7) ppml-cf-PCA
main							
resid1	2.125***	1.061**	0.175	2.293***	2.482***	2.125***	2.125***
	(0.462)	(0.437)	(0.307)	(0.627)	(0.503)	(0.494)	(0.465)
Cyanobacteria (cell/ml)	-1.922***	-0.858**	0.034	-2.213***	-2.304***	-1.922***	-1.922***
	(0.488)	(0.409)	(0.281)	(0.608)	(0.498)	(0.497)	(0.475)
Weekday (=1)	-0.919***	-0.912***	-0.904***	-0.919***	-0.968***	-0.919***	-0.919***
	(0.044)	(0.045)	(0.047)	(0.053)	(0.048)	(0.049)	(0.043)
Cyanobacteria * weekday	-0.501***	-0.519***	-0.504***	-0.469***	-0.356*	-0.501***	-0.501**
	(0.169)	(0.172)	(0.173)	(0.172)	(0.198)	(0.176)	(0.200)
Log(CPI adjusted gas price ($/g))	-0.108	0.039	0.600***	-0.072	0.097	-0.108	-0.108
	(0.188)	(0.166)	(0.069)	(0.210)	(0.166)	(0.175)	(0.168)
Log(CPI adjusted gas price) * weekday	-0.316***	-0.319***	-0.328***	-0.318***	-0.213**	-0.316***	-0.316***
	(0.086)	(0.077)	(0.090)	(0.103)	(0.087)	(0.097)	(0.081)
Deviation from 14.3 (h)	-1.787***	-1.800***	-1.771***	-0.969***	-1.611***	-1.787***	-1.787***
	(0.096)	(0.088)	(0.079)	(0.128)	(0.101)	(0.094)	(0.090)
Shortwave downward irradiance (MJ/m^2/d)	1.240***	1.129***	1.161***	1.243***	1.351***	1.240***	1.240***
	(0.111)	(0.081)	(0.109)	(0.140)	(0.104)	(0.102)	(0.107)
Temperature (C/d)	1.060***	0.897***	1.093***	0.843***	1.267***	1.060***	1.060***
	(0.199)	(0.170)	(0.176)	(0.205)	(0.189)	(0.205)	(0.176)
Wind speed (m/s)	-1.381***	-1.492***	-1.303***	-0.726**	-1.533***	-1.381***	-1.381***
	(0.236)	(0.222)	(0.227)	(0.297)	(0.191)	(0.232)	(0.229)
Precipitation (mm/d)	-1.621***	-1.819***	-1.866***	-1.629***	-1.843***	-1.621***	-1.621***
	(0.488)	(0.521)	(0.559)	(0.542)	(0.432)	(0.465)	(0.506)
Buoy wind speed (m/s)	-2.115***	-1.976***	-1.917***	-2.553***	-2.256***	-2.115***	-2.115***
	(0.198)	(0.189)	(0.202)	(0.225)	(0.159)	(0.188)	(0.187)
Buoy water surface temperature (C)	-0.000	0.245*	0.073	0.120	-0.003	-0.000	-0.000
	(0.147)	(0.129)	(0.146)	(0.167)	(0.168)	(0.158)	(0.137)
Walleye population	0.000	0.000	0.012	0.000	0.270***	0.379***	0.000
	(0.000)	(0.000)	(0.040)	(0.000)	(0.078)	(0.082)	(0.000)
Yellow perch population	0.000	0.000	-0.224***	0.000	0.669***	0.751***	0.000
	(0.000)	(0.000)	(0.048)	(0.000)	(0.233)	(0.173)	(0.000)
Observations	12494	12494	12494	12494	12494	12494	12494
Site FE	Yes	Yes	Yes	No	Yes	Yes	Yes
Month FE	Yes	No	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	No	Yes	Yes	Yes	Yes

Standard errors in parentheses
Bootstrapped standard error for cf
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A2: Robustness to buffer lengths around sites

	(1) 0.5 miles	(2) 1 mile	(3) 1.5 miles	(4) 2 miles	(5) 3 miles	(6) 4 miles	(7) 5 miles	(8) 10 miles
resid1	0.570	1.778***	2.305***	2.831***	2.898***	2.788***	2.837***	2.710***
	(0.585)	(0.605)	(0.567)	(0.597)	(0.697)	(0.670)	(0.598)	(0.687)
Cyanobacteria (cell/ml)	-0.610	-1.699***	-2.153***	-2.675***	-2.805***	-2.808***	-2.794***	-2.459***
	(0.559)	(0.593)	(0.556)	(0.593)	(0.668)	(0.661)	(0.580)	(0.670)
Weekday (=1)	-0.885***	-0.912***	-0.915***	-0.937***	-0.948***	-0.952***	-0.953***	-0.953***
	(0.049)	(0.032)	(0.034)	(0.030)	(0.037)	(0.035)	(0.030)	(0.033)
Cyanobacteria * weekday	-0.372***	-0.403***	-0.559***	-0.541***	-0.406**	-0.389*	-0.436*	-0.599***
	(0.133)	(0.084)	(0.150)	(0.161)	(0.162)	(0.208)	(0.238)	(0.212)
Log(CPI adjusted gas price ($/g))	0.099	-0.141	-0.120	-0.132	-0.104	-0.082	-0.084	-0.107
	(0.217)	(0.135)	(0.121)	(0.125)	(0.124)	(0.120)	(0.122)	(0.133)
Log(CPI adjusted gas price) * weekday	-0.384***	-0.275***	-0.280***	-0.263***	-0.261***	-0.260***	-0.258***	-0.255***
	(0.092)	(0.065)	(0.063)	(0.060)	(0.069)	(0.067)	(0.056)	(0.058)
Deviation from 14.3 (h)	-1.251***	-1.560***	-1.548***	-1.547***	-1.538***	-1.529***	-1.529***	-1.526***
	(0.089)	(0.067)	(0.069)	(0.074)	(0.067)	(0.070)	(0.063)	(0.060)
Shortwave downward irradiance (MJ/m^2/d)	1.247***	1.234***	1.255***	1.274***	1.283***	1.290***	1.292***	1.278***
	(0.095)	(0.090)	(0.067)	(0.073)	(0.077)	(0.085)	(0.073)	(0.080)
Temperature (C/d)	2.401***	1.918***	1.865***	1.880***	1.860***	1.851***	1.850***	1.852***
	(0.212)	(0.136)	(0.140)	(0.142)	(0.116)	(0.129)	(0.129)	(0.130)
Wind speed (m/s)	-1.510***	-1.559***	-1.560***	-1.470***	-1.454***	-1.466***	-1.477***	-1.484***
	(0.240)	(0.154)	(0.153)	(0.154)	(0.137)	(0.164)	(0.138)	(0.138)
Precipitation (mm/d)	-4.270***	-3.019***	-2.966***	-2.920***	-2.847***	-2.857***	-2.868***	-2.988***
	(0.419)	(0.377)	(0.394)	(0.404)	(0.367)	(0.389)	(0.354)	(0.345)
Buoy wind speed (m/s)	-2.023***	-2.102***	-2.119***	-2.233***	-2.260***	-2.252***	-2.244***	-2.230***
	(0.194)	(0.127)	(0.131)	(0.123)	(0.111)	(0.123)	(0.118)	(0.119)
Buoy water surface temperature (C)	-0.431**	-0.373***	-0.359***	-0.398***	-0.398***	-0.393***	-0.396***	-0.445***
	(0.170)	(0.120)	(0.126)	(0.129)	(0.107)	(0.106)	(0.124)	(0.116)
Walleye population	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Yellow perch population	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	10319	22519	23206	23984	24048	24085	24104	24146
Site FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses

Bootstrapped standard error for cf

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

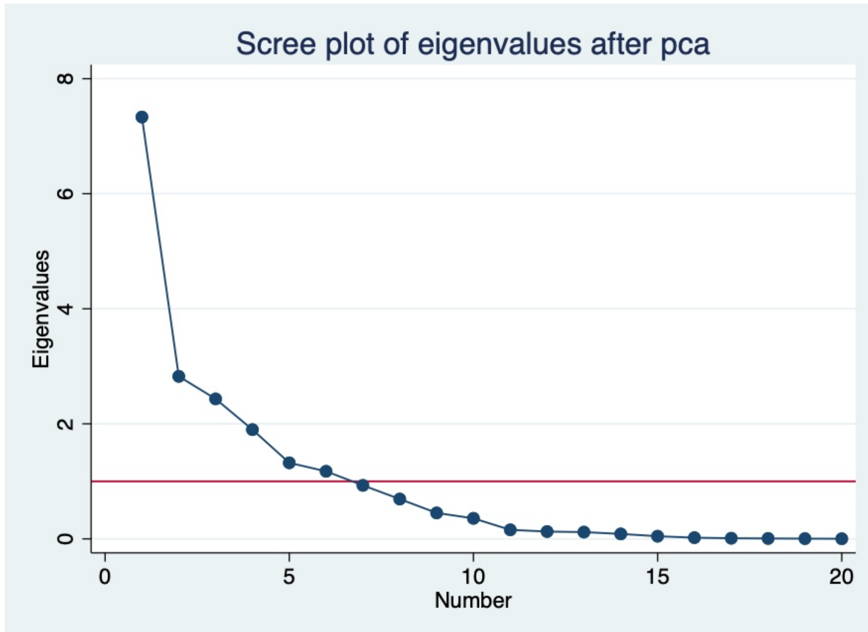

Figure A5: Scree plot of eigenvalues after pca in the first stage

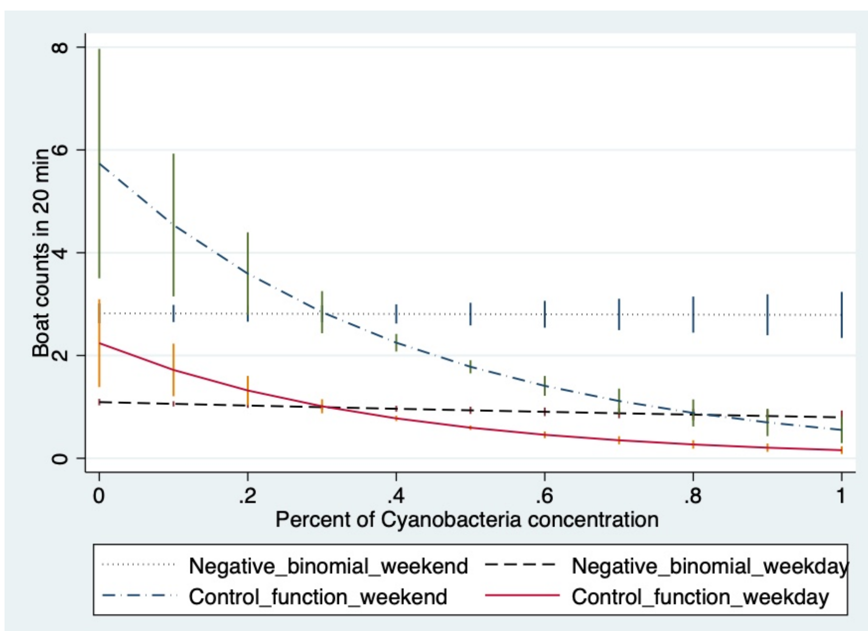

Figure A6: Distribution of marginal boat counts for HABs

References

Anderson, Donald M. et al. (Feb. 1, 2021). "Marine Harmful Algal Blooms (HABs) in the United States: History, Current Status and Future Trends". In: *Harmful Algae*. Global Harmful Algal Bloom Status Reporting 102, p. 101975. ISSN: 1568-9883. DOI: 10.1016/j.hal.2021.101975. URL: https://www.sciencedirect.com/science/article/pii/S1568988321000020 (visited on 05/23/2022).

Berardo, Ramiro, V. Kelly Turner, and Stian Rice (2019). "Systemic Coordination and the Problem of Seasonal Harmful Algal Blooms in Lake Erie". In: *Ecology and Society* 24.3. ISSN: 1708-3087. JSTOR: 26796988. URL: https://www.jstor.org/stable/26796988 (visited on 05/23/2022).

Bockstael, Nancy E., W. Michael Hanemann, and Catherine L. Kling (1987). "Estimating the Value of Water Quality Improvements in a Recreational Demand Framework". In: *Water Resources Research* 23.5, pp. 951–960. ISSN: 1944-7973. DOI: 10.1029/WR023i005p00951. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/WR023i005p00951 (visited on 05/29/2022).

Boudreaux, Greg et al. (Feb. 1, 2023). "Measuring Beachgoer Preferences for Avoiding Harmful Algal Blooms and Bacterial Warnings". In: *Ecological Economics* 204, p. 107653. ISSN: 0921-8009. DOI: 10.1016/j.ecolecon.2022.107653. URL: https://www.sciencedirect.com/science/article/pii/S0921800922003147 (visited on 01/02/2023).

Cheng, Li and Frank Lupi (2016). "Combining Revealed and Stated Preference Methods for Valuing Water Quality Changes to Great Lakes Beaches". In: p. 50.

Cicchetti, Charles J., Anthony C. Fisher, and V. Kerry Smith (1976). "An Econometric Evaluation of a Generalized Consumer Surplus Measure: The Mineral King Controversy". In: *Econometrica* 44.6, pp. 1259–1276. ISSN: 0012-9682. DOI: 10.2307/1914259. JSTOR: 1914259. URL: https://www.jstor.org/stable/1914259 (visited on 05/29/2022).

Correia, Sergio, Paulo Guimaraes, and Thomas Zylkin (2020). "Fast Poisson Estimation with High-Dimensional Fixed Effects". In: *Stata Journal* 20.1, pp. 95–115. URL: https://econpapers.repec.org/article/tsjstataj/v_3a20_3ay_3a2020_3ai_3a1_3ap_3a95-115.htm (visited on 03/08/2023).

Cousino, Luke K, Richard H Becker, and Kirk A Zmijewski (2015). "Modeling the effects of climate change on water, sediment, and nutrient yields from the Maumee River watershed". In: *Journal of Hydrology: Regional Studies* 4, pp. 762–775.

EPA, US (2015). "Great Lakes Water Quality Agreement (GLWQA)". In: *https://www.epa.gov/glwqa*.

Fisher, Anthony C., John V. Krutilla, and Charles J. Cicchetti (1972). "The Economics of Environmental Preservation: A Theoretical and Empirical Analysis". In: *The American*

Economic Review 62.4, pp. 605–619. ISSN: 0002-8282. JSTOR: 1806102. URL: https://www.jstor.org/stable/1806102 (visited on 05/29/2022).
Hudnell, H. Kenneth (May 1, 2010). "The State of U.S. Freshwater Harmful Algal Blooms Assessments, Policy and Legislation". In: *Toxicon*. Harmful Algal Blooms and Natural Toxins in Fresh and Marine Waters – Exposure, Occurrence, Detection, Toxicity, Control, Management and Policy 55.5, pp. 1024–1034. ISSN: 0041-0101. DOI: 10.1016/j.toxicon.2009.07.021. URL: https://www.sciencedirect.com/science/article/pii/S004101010900378X (visited on 05/23/2022).
Keiser, David A (2019). "The missing benefits of clean water and the role of mismeasured pollution". In: *Journal of the Association of Environmental and Resource Economists* 6.4, pp. 669–707.
Kim, Sei, Brent Sohngen, and Abdoul Sam (Sept. 1, 2018). "The Implications of Weather, Nutrient Prices, and Other Factors on Nutrient Concentrations in Agricultural Watersheds". In: *Science of The Total Environment* 650. DOI: 10.1016/j.scitotenv.2018.09.012.
Lucente, Joseph E. et al. (2012). "Ohio's 2010 Lake Erie Charter Fishing Industry". In: *Fisheries* 37.12, pp. 532–541. ISSN: 1548-8446. DOI: 10.1080/03632415.2012.742805. URL: https://onlinelibrary.wiley.com/doi/abs/10.1080/03632415.2012.742805 (visited on 05/23/2022).
Michalak, Anna M. et al. (Apr. 16, 2013). "Record-Setting Algal Bloom in Lake Erie Caused by Agricultural and Meteorological Trends Consistent with Expected Future Conditions". In: *Proceedings of the National Academy of Sciences of the United States of America* 110.16, pp. 6448–6452. ISSN: 0027-8424. DOI: 10.1073/pnas.1216006110. pmid: 23576718. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3631662/ (visited on 05/30/2022).
Murray, Chris, Brent Sohngen, and Linwood Pendleton (Oct. 1, 2001). "Valuing Water Quality Advisories and Beach Amenities in the Great Lakes". In: *Water Resources Research* 37, pp. 2583–2590. ISSN: 0043-1397. DOI: 10.1029/2001WR000409. URL: https://ui.adsabs.harvard.edu/abs/2001WRR....37.2583M (visited on 04/29/2022).
Natural Resources Division of Wildlife, Ohio Department of (2019). *Ohio's Lake Erie Fisheries Annual Status Report*. Ohio Department of Natural Resources, Division of Wildlife, Lake Erie Fisheries Units, Fairport and Sandusky. URL: https://ohiodnr.gov/static/documents/wildlife/fish-management/ODW+LE+Angler+Report+2018.pdf.
NCWQR (June 2022). "Heidelberg Tributary Loading Program (HTLP) Dataset". Version 20220330. In: Funding for the HTLP is continually pursued from a variety of sources including federal and state agencies and public utilities, as well as private organizations.

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Palm-Forster, Leah H., Frank Lupi, and Min Chen (Aug. 2016). "Valuing Lake Erie Beaches Using Value and Function Transfers". In: *Agricultural and Resource Economics Review* 45.2, pp. 270–292. ISSN: 2372-2614. DOI: 10.1017/age.2016.15. URL: https://www.cambridge.org/core/journals/agricultural-and-resource-economics-review/article/valuing-lake-erie-beaches-using-value-and-function-transfers/7118CA96FF77278C3EFE464055E8F720 (visited on 04/28/2022).

Parsons, George R., Paul M. Jakus, and Ted Tomasi (Sept. 1, 1999). "A Comparison of Welfare Estimates from Four Models for Linking Seasonal Recreational Trips to Multinomial Logit Models of Site Choice". In: *Journal of Environmental Economics and Management* 38.2, pp. 143–157. ISSN: 0095-0696. DOI: 10.1006/jeem.1999.1083. URL: https://www.sciencedirect.com/science/article/pii/S0095069699910835 (visited on 05/11/2022).

Phaneuf, Daniel J., Catherine L. Kling, and Joseph A. Herriges (1998). "Valuing Water Quality Improvements Using Revealed Preference Methods When Corner Solutions Are Present". In: *American Journal of Agricultural Economics* 80.5, pp. 1025–1031. ISSN: 0002-9092. DOI: 10.2307/1244199. JSTOR: 1244199. URL: https://www.jstor.org/stable/1244199 (visited on 04/29/2022).

Silva, JMC Santos and Silvana Tenreyro (2006). "The log of gravity". In: *The Review of Economics and statistics* 88.4, pp. 641–658.

— (2011). "Further simulation evidence on the performance of the Poisson pseudo-maximum likelihood estimator". In: *Economics Letters* 112.2, pp. 220–222.

Sohngen, Brent et al. (2014). "Results from a 2014 Survey of Lake Erie Anglers". In: p. 32.

Stumpf, R and D Dupuy (2016). "Experimental lake erie harmful algal bloom bulletin". In: *Bulletin 28/2016*.

Stumpf, Richard P et al. (2012). "Interannual variability of cyanobacterial blooms in Lake Erie". In.

Stumpf, Richard P. et al. (Dec. 1, 2016). "Forecasting Annual Cyanobacterial Bloom Biomass to Inform Management Decisions in Lake Erie". In: *Journal of Great Lakes Research*

42.6, pp. 1174–1183. ISSN: 0380-1330. DOI: 10.1016/j.jglr.2016.08.006. URL: https://www.sciencedirect.com/science/article/pii/S0380133016301484 (visited on 03/15/2023).

Von Haefen, Roger H. and Frank Lupi (Dec. 27, 2021). “How Does Congestion Affect the Evaluation of Recreational Gate Fees? An Application to Gulf Coast Beaches”. In: *Land Economics*, pp. 082721–0102. ISSN: 0023-7639, 1543-8325. DOI: 10.3368/le.98.3.082721-0102. URL: http://le.uwpress.org/lookup/doi/10.3368/le.98.3.082721-0102 (visited on 05/09/2022).

Wolf, David, Wei Chen, et al. (2019). “The Impacts of Harmful Algal Blooms and E. Coli on Recreational Behavior in Lake Erie”. In: *Land Economics*, p. 18.

Wolf, David, Will Georgic, and H. Allen Klaiber (Sept. 2017). “Reeling in the Damages: Harmful Algal Blooms’ Impact on Lake Erie’s Recreational Fishing Industry”. In: *Journal of Environmental Management* 199, pp. 148–157. ISSN: 03014797. DOI: 10.1016/j.jenvman.2017.05.031. URL: https://linkinghub.elsevier.com/retrieve/pii/S0301479717304905 (visited on 04/03/2022).

Wolf, David, Sathya Gopalakrishnan, and H. Allen Klaiber (2022). “Staying Afloat: The Effect of Algae Contamination on Lake Erie Housing Prices”. In: *American Journal of Agricultural Economics* 104.5, pp. 1701–1723. ISSN: 1467-8276. DOI: 10.1111/ajae.12285. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/ajae.12285 (visited on 10/24/2022).

Wooldridge, Jeffrey M (2015). “Control function methods in applied econometrics”. In: *Journal of Human Resources* 50.2, pp. 420–445.

Wynne, T. T. et al. (2013). “Evolution of a Cyanobacterial Bloom Forecast System in Western Lake Erie: Development and Initial Evaluation.” In: *Journal of Great Lakes Research* 39 (Suppl. 1), pp. 90–99. ISSN: 0380-1330. URL: https://www.cabdirect.org/cabdirect/abstract/20133356790 (visited on 03/15/2023).

Wynne, Timothy T. and Richard P. Stumpf (May 12, 2015). “Spatial and Temporal Patterns in the Seasonal Distribution of Toxic Cyanobacteria in Western Lake Erie from 2002–2014”. In: *Toxins* 7.5, pp. 1649–1663. ISSN: 2072-6651. DOI: 10.3390/toxins7051649. pmid: 25985390. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4448166/ (visited on 11/09/2022).

Wynne, Timothy T., Richard P. Stumpf, et al. (2010). “Characterizing a Cyanobacterial Bloom in Western Lake Erie Using Satellite Imagery and Meteorological Data”. In: *Limnology and Oceanography* 55.5, pp. 2025–2036. ISSN: 1939-5590. DOI: 10.4319/lo.2010.55.5.2025. URL: https://onlinelibrary.wiley.com/doi/abs/10.4319/lo.2010.55.5.2025 (visited on 03/28/2023).

Zhang, Wendong and Brent Sohngen (2018). "Do U.S. Anglers Care about Harmful Algal Blooms? A Discrete Choice Experiment of Lake Erie Recreational Anglers". In: *American Journal of Agricultural Economics* 100.3, pp. 868–888. ISSN: 1467-8276. DOI: 10.1093/ajae/aay006. URL: https://onlinelibrary.wiley.com/doi/abs/10.1093/ajae/aay006 (visited on 04/28/2022).