

Fishing for Food: Quantifying Recreational Fisheries Harvest in Wisconsin Lakes

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Recreational fisheries have high economic worth, valued at US\$190 billion globally. An important, but underappreciated, secondary value of recreational catch is its role as a source of food. This contribution is poorly understood due to difficulty in estimating recreational harvest at spatial scales beyond a single system, as traditionally estimated from individual creel surveys. Here, we address this gap using 28-year creel surveys of ~300 Wisconsin inland lakes. We develop a statistical model of recreational harvest for individual lakes and then scale-up to unsurveyed lakes (3,769 lakes; 73% of statewide lake surface area). We generate a statewide estimate of recreational lake harvest of ~4,200 metric tons and an estimated annual angler consumption rate of ~1.1 kg, nearly equal to the total estimated United States per capita freshwater fish consumption. An important ecosystem service, recreational harvest makes significant contributions to human diets and plays an often-unheralded role in food security.

INTRODUCTION

Globally, annual recreational fisheries expenditures are valued at US\$190 billion (World Bank 2012), with United States inland recreational fisheries expenditures estimated to have exceeded \$29.9 billion in 2011 (U.S. Department of the Interior 2016). Recreational fisheries now constitute the dominant or sole use of inland fishes in developed nations (Arlinghaus et al. 2013). For many inland fish species in North America and Europe, recreational fisheries have replaced inland commercial fisheries landings and therefore likely contribute significantly as a source of food, but the magnitude is not well understood (de Kerckhove et al. 2015; FAO 2016; Cooke et al. 2018). Studies have found that inland fisheries contribute far more to food security than previously recognized, with potential rates of harvest underreporting as high as 65% (Fluet-Chouinard et al. 2018). Given their immense economic value and role in food security, understanding the magnitude of inland recreational fisheries is vital to conserving and managing these resources as well as ensuring global food security.

Despite increasing evidence of the importance of inland recreational fisheries for food, these systems are rarely considered in food security discussions (Cooke et al. 2016). The United Nations Food and Agriculture Organization (FAO) defines food security as existing when “all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (FAO 2016). Fish have a crucial role in ensuring food security as they provide valuable nutrients and micronutrients of central importance for healthy diets (FAO 2016). In some regions, such as Wisconsin, recreational fisheries are recognized as an important food source for anglers as limited surveys have shown a high reliance on these resources for food, although the magnitude remains unclear (Christensen et al. 2016). Vital to understanding how inland recreational fisheries contribute to food security discussions is accurately quantifying harvest at a meaningful scale.

Inland recreational harvest is difficult to quantify as fisheries are dispersed across the landscape, there are many mobile and transitory anglers, and reporting and monitoring are limited. Although some recreational fisheries harvest estimates have been made, most were either performed at system-specific or global scales (Ryder 1965; de Kerckhove et al. 2015; Cooke et al. 2018). Although single-system estimates are useful for identifying potential drivers of harvest, they have rarely been used to understand the larger-scale magnitude of recreational fisheries harvest beyond a local system. Likewise, broadscale estimates can provide global context as to overall fisheries harvest, but rarely emphasize quantifying recreational fisheries harvest and likely overlook important regional nuances necessary to inform an accurate understanding of the magnitude of recreational fisheries harvest.

In some developed regions, such as parts of the United States, recreational inland fish harvest data are available through time and across many sites. By understanding the implications of temporal and spatial variation in recreational harvest, we can inform the value of inland recreational fisheries given global environmental and social changes. Areas where data are available can be used to elucidate how recreational fisheries contribute to human consumption and overall fisheries harvest. In Wisconsin, over the past 28 years the Wisconsin Department of Natural Resources has conducted extensive creel surveys for 267 inland lakes distributed across the state. Here, we used comprehensive empirical data to develop a robust statistical model predicting Wisconsin lake-specific harvest based on lake predictor variables that includes abiotic and angler access information. We used this model to scale-up and estimate statewide recreational lake fisheries harvest. Such assessments will help guide science, policy, and fisheries management decisions to better balance consumptive use and conservation of fisheries resources.

METHODS

Study Area

The state of Wisconsin includes ~15,000 inland lakes ranging from 0.5 to 53,394 ha (Wisconsin Department of Natural Resources 2009). Most lakes occur in the northern and eastern part of the state as a result of glaciation. Approximately 3,620 lakes are >20 ha and together comprise ~93% of the state's inland lake surface area (Wisconsin Department of Natural Resources 2009). Wisconsin lakes constitute a wide range of physical and biological characteristics. Wisconsin inland lakes (not including the Great Lakes) support valuable recreational fisheries for a variety of species, including Walleye *Sander vitreus*, Northern Pike *Esox lucius*, Muskellunge *E. masquinongy*, Yellow Perch *Perca flavescens*, Largemouth Bass *Micropterus salmoides*, Smallmouth Bass *M. dolomieu*, Lake Sturgeon *Acipenser fulvescens*, and a variety of sunfish *Lepomis* spp.

Calculating Empirical Harvest

A standard angler creel survey was performed on a total of 267 inland lakes from 1990 to 2017 by the Wisconsin Department of Natural Resources (unpublished data). Sampled lakes were selected using a rotating stratified randomized design; therefore, most lakes were sampled once during 1990–2017, but some lakes were resampled during the study period. Total harvest was estimated as the product of angler effort and harvest rate (Rasmussen et al. 1998; Deroba et al. 2007). To estimate effort, instantaneous counts of anglers were conducted, while complete-trip interviews were conducted to estimate harvest rate (Rasmussen et al. 1998). During interviews, creel clerks recorded the number caught and length of fish for each species (Deroba et al. 2007). To estimate species-specific effort, anglers indicated how long they had been fishing and how much of their time was allocated

to a particular species. Creel surveys were conducted beginning the first Saturday in May through March 1 of the following year, a period spanning the legal Walleye angling season (Beard et al. 1997). Survey access points were randomly selected following a random stratified roving access design that was demonstrated to produce unbiased estimates of angling effort and harvest (Pollock et al. 1994; Rasmussen et al. 1998). Survey days were stratified into weekdays and weekend days, with one to three randomly selected weekdays and all weekend days sampled each week (Beard et al. 1997). Throughout the open-water season, surveys were conducted during randomly selected periods. During the ice-fishing season, complete days were sampled as daylight was shortened (Beard et al. 1997). Additionally, creel surveys provided angler counts by type (e.g., boat, shore, ice; Rasmussen et al. 1998).

Annual creel information, including the total number of fish harvested per species (as projected by the Wisconsin Department of Natural Resources based on angler effort and empirical harvest; number per year) as well as species-specific mean lengths, was available for all harvested species for 267 lakes (573 lake–year combinations). In addition to the number of fish harvested annually, we were interested in quantifying the mass of fish harvested; therefore, we compiled species-specific length–weight regressions from multiple sources (Table S1 in the supplemental material provided in the online version of this article). We applied these length–weight relationships to convert species-specific mean length (mm) to mean weight (kg) for species in each lake–year combination of harvested fish. We multiplied the total number of fish harvested per species by the mean weight to estimate the species-specific total biomass harvested (kg) for that lake–year. For each lake–year combination, we summed species-specific harvest values to calculate total annual harvest (kg/year). This value was divided by the area of the lake to estimate total harvest per unit area (kg/ha).

Lake Winnebago, the largest inland lake in Wisconsin, does not undergo a complete creel survey similar to other lakes in the state, but does support Walleye, Lake Sturgeon, Yellow Perch, and sunfish fisheries (Koenigs and Olynyk 2013; Koenigs et al. 2013; Koenigs 2017). We estimated total annual harvest for this lake using a combination of data sources. A limited creel survey was performed in 2012 from June to August, with a total of 35 days of angler interviews (Koenigs and Olynyk 2013). This limited creel survey found that anglers harvested Black Crappie *Pomoxis nigromaculatus*, Bluegill *Lepomis macrochirus*, Walleye, and Yellow Perch (Koenigs and Olynyk 2013). From this information, we calculated the number of fish per species harvested daily, which we multiplied by 365 to estimate the total number harvested for the year. We did this for Black Crappie, Bluegill, and Yellow Perch, but estimated Walleye harvest using more complete information. Mean lengths for Black Crappie and Bluegill were not available in the creel survey; therefore, we calculated the mean length of all Black Crappie and Bluegill present in the statewide creel survey and used that information to estimate mean weights using species-specific length–weight regressions. Yellow Perch mean length was available from creel surveys and therefore, this value was used to estimate mean weight using the species-specific length–weight relationship. Walleye are managed extensively in this system through annual surveys that estimate exploitation rate and other characteristics (Koenigs et al. 2013). The mean abundance of adult (≥ 381 mm) Walleye and the mean exploitation rate from 1993 to 2012 were estimated

(Koenigs et al. 2013). Mean lengths of males and females were also reported (Koenigs et al. 2013). From this information, we calculated the number of Walleye harvested annually using sex-specific abundances multiplied by sex-specific exploitation rates. Sex-specific mean length information was available from annual surveys; therefore, we used this in combination with the species-specific length–weight regression to estimate mean weight and total Walleye harvest. The Lake Winnebago Lake Sturgeon fishery occurs annually and is highly regulated (Koenigs 2017). From available Wisconsin Department of Natural Resources information, we calculated the mean number of Lake Sturgeon harvested between 2002 and 2016 as well as the mean length and weight of harvested individuals (Koenigs 2017).

Evaluating Species Harvest and Angler Effort Trends

We evaluated temporal trends for overall combined harvest (kg/ha) and angler effort (h/ha) from 1990 to 2017. Although 38 species contributed to overall harvest, we evaluated temporal trends for 10 species that comprise ~90% of the harvest and were consistently present in creel surveys. These species included Black Crappie, Bluegill, Largemouth Bass, Muskellunge, Northern Pike, Pumpkinseed *L. gibbosus*, Rock Bass *Ambloplites rupestris*, Smallmouth Bass, Walleye, and Yellow Perch. To determine if species-specific harvest and angler effort changed over the study period, we developed species-specific linear mixed-effects models for standardized harvest (kg/ha) and angler effort (h/ha). We ran Shapiro–Wilk tests to determine whether the distributions for harvest (kg/ha) and effort (h/ha) were normal. Based on findings, harvest and effort were $\log_e$ transformed prior to analysis to meet assumptions of normality. For each model, $\log_e(\text{harvest}+1)$ or $\log_e(\text{effort}+1)$ was the dependent variable, year (centered around the mean) was an independent variable, and lake was a random effect. Models of best fit were first selected based on Akaike information criterion (AIC). If there was no difference between AIC values, the model of best fit was selected based on variance explained.

Evaluating Angler License Trend

To inform angler consumption information, we assessed the temporal trend of the number of fishing licenses purchased in Wisconsin (available: <https://bit.ly/2BFiS3R>) using a linear model. For this model, the number of fishing licenses was the dependent variable and year (centered around the mean) was the independent variable. Using this information, we calculated the mean number of licenses over the study period.

Lake Attributes

Lake surface area was available for all known lakes in the state (Wisconsin Department of Natural Resources 2009). To incorporate lake-specific abiotic characteristics to determine fish yield, we obtained Secchi depth (m) and conductance (uS) measurements from a statewide dataset that averaged measurements from multiple sources (Papes and Vander Zanden 2010). For this analysis, only datasets developed since 1970 were used. To provide an index of angler access for each lake, we calculated the linear distance from the lake shoreline to the nearest mapped road. We did this by calculating the minimum distance from each waterbody to the nearest street in Esri's map of detailed streets (Esri 2011). Winslow et al. (2017) developed estimates of various thermal characteristics for 10,774 Midwestern lakes, including 3,769 lakes in Wisconsin.

We used two modeled characteristics from this dataset in the harvest prediction model: mean temperature at the bottom of the lake in June (°C) and annual growing degree-days (base temperature 5°C) as these predictors contributed to the model of best fit. We evaluated numerous other variables that were not significant (e.g., no statistically significant relationship between angler effort and minimum distance to the nearest road) and did not provide the model of best fit (Table S2 in the supplemental material provided in the online version of this article).

Modeling Statewide Annual Harvest

To estimate statewide recreational annual fish harvest per unit area (areal harvest; kg/ha), we related areal harvest (summed species harvest in a given lake-year; kg/ha) to abiotic intrinsic lake characteristics, as well as waterbody access information using a generalized additive model (using the “gam” function in R package “mgcv,” version 1.8.17; Wood 2011, 2017). Generalized additive models are a flexible, nonparametric technique that employs penalized regression splines to fit smooth relationships between response and explanatory variables (Wood 2017). Distance to nearest road (m) and Secchi depth (m) exhibited linear relationships with harvest. Smooth curves were fit for mean temperature of the lake bottom in June (°C), annual growing degree-days (base temperature 5°C), and conductance (uS) using thin plate splines with a null space penalty (Figure S1 in the supplemental material provided in the online version of this article). Although most lakes were sampled once during 1990–2017, some lakes were resampled; therefore, lake and year were included as random effects (slope and intercept) in the model to account for lake-specific and temporal variation during different sampling periods. Models were fit using restricted maximum likelihood (REML).

Prior to model fitting, we assessed the statistical distribution of each predictor variable and areal harvest (kg/ha) by constructing relative frequency histograms for each statistic and ran Shapiro–Wilk tests to assess distribution normality. The model was fit using the “Tweedie” family such that a log-link function was used for nonnormal statistics and zero values were incorporated as potential predictions (Wood 2017). The model of best fit was selected based on AIC and REML. We applied this model to 3,769 lakes that had information available to predict lake-specific areal annual harvest (kg/ha). We multiplied these values by lake area and summed lake-specific harvest values to calculate total annual harvest (kg) and then converted total annual harvest to metric ton. We used an $\alpha = 0.05$ for all statistical analyses. All calculations and statistical analyses were performed in R version 3.4.3 (R Development Core Team 2017). All data have been made available as part of the Environmental Data Initiative (Embke et al. 2020).

RESULTS

Species Composition of Recreational Harvest

The 38 species harvested were Black Bullhead *Ameiurus melas*, Black Crappie, Bluegill, Bowfin *Amia calva*, Brook Trout *Salvelinus fontinalis*, Brown Bullhead *A. nebulosus*, Brown Trout *Salmo trutta*, Burbot *Lota lota*, Channel Catfish *Ictalurus punctatus*, Cisco *Coregonus artedii*, Common Carp *Cyprinus carpio*, Common Shiner *Luxilus cornutus*, Flathead Catfish *Pylodictis olivaris*, Freshwater Drum *Aplodinotus grunniens*, Golden Shiner *Notemigonus crysoleucas*, Green Sunfish

L. cyanellus, Lake Sturgeon, Lake Trout *S. namaycush*, Lake Whitefish *C. clupeaformis*, Largemouth Bass, Longnose Gar *Lepisosteus osseus*, Muskellunge, Northern Pike, Orangethroat Darter *Etheostoma spectabile*, Pumpkinseed, Rainbow Smelt *Osmerus mordax*, Rock Bass, Shorthead Redhorse *Moxostoma macrolepidotum*, Smallmouth Bass, tiger muskellunge (Muskellunge $\times$ Northern Pike), Walleye, Warmouth *L. gulosus*, White Bass *Morone chrysops*, White Crappie *P. annularis*, White Sucker *Catostomus commersonii*, Yellow Bass *M. mississippiensis*, Yellow Bullhead *A. natalis*, and Yellow Perch. The median harvest values for these species ranged from 0.01 to 0.95 kg/ha (Figure 1). Walleye, Black Crappie, Lake Whitefish, Northern Pike, Bluegill, and Yellow Perch had the largest median harvest values, all exceeding 0.25 kg/ha across all years (Figure 1). Five species accounted for the vast majority (90%) of overall harvest (kg): Walleye, Black Crappie, Bluegill, Northern Pike, and Yellow Perch, although the relative importance of species varied over time (Figure 2A; Figure S2 in the supplemental material provided in the online version of this article). For example, in 1990 Walleye comprised 25% of overall annual harvest, but by 2017 the contribution of Walleye fell to $\sim 9\%$ (Figure 2A). In contrast, the contribution of Black Crappie rose from $\sim 11\%$ to $\sim 22\%$ during the study period (Figure 2A).

Evaluating Select Species Harvest, Angler Effort, and Angler License Trends

Overall combined harvest (kg/ha) and angler effort (h/ha) for all species did not exhibit a significant change over the study period. Although 38 species contributed to the overall harvest, 5 species (Black Crappie, Bluegill, Largemouth Bass, Muskellunge, and Walleye) showed significant temporal harvest trends (Figure 2B; Table S3 in the supplemental material provided in the online version of this article). Harvest of Muskellunge and Walleye declined over the study period (Figure 2B). In contrast, Black Crappie, Bluegill, and Largemouth Bass showed harvest increases (Figure 2B). Northern Pike, Pumpkinseed, Rock Bass, Smallmouth Bass, and Yellow Perch did not display significant temporal harvest trends. Seven species experienced significant changes in angler effort over time (Figure 2C). Walleye, Muskellunge, and Rock Bass showed declines in effort (h/ha), while Black Crappie, Largemouth Bass, Smallmouth Bass, and Pumpkinseed showed increases in effort (h/ha; Table S3 in the supplemental material provided in the online version of this article, Figure 2C). Bluegill, Northern Pike, and Yellow Perch did not show significant changes in effort over the study period.

We found a slight declining relationship in the number of fishing licenses purchased over time (percent change over the study period = -3.6% , $P < 0.01$; Figure S3 in the supplemental material provided in the online version of this article). The mean number of fishing licenses during the study period was 1,405,262, which we used to estimate angler consumption rates.

Statewide Harvest Model Results

From available creel information, areal annual lake-specific harvest (all species-specific harvest combined) ranged from 0.03 to 71.04 kg/ha, with a median value of 5.29 kg/ha [mean $\pm$ 95% CI $\log_e$ (harvest) = 1.57 ± 0.05 kg/ha] (Table S4 in the supplemental material provided in the online version of this article). Lake surface areas ranged from 8.9 to 53,394 ha (median = 216 ha), and locations spanned the state (Figure 3; Table S4 in the supplemental material provided in the online

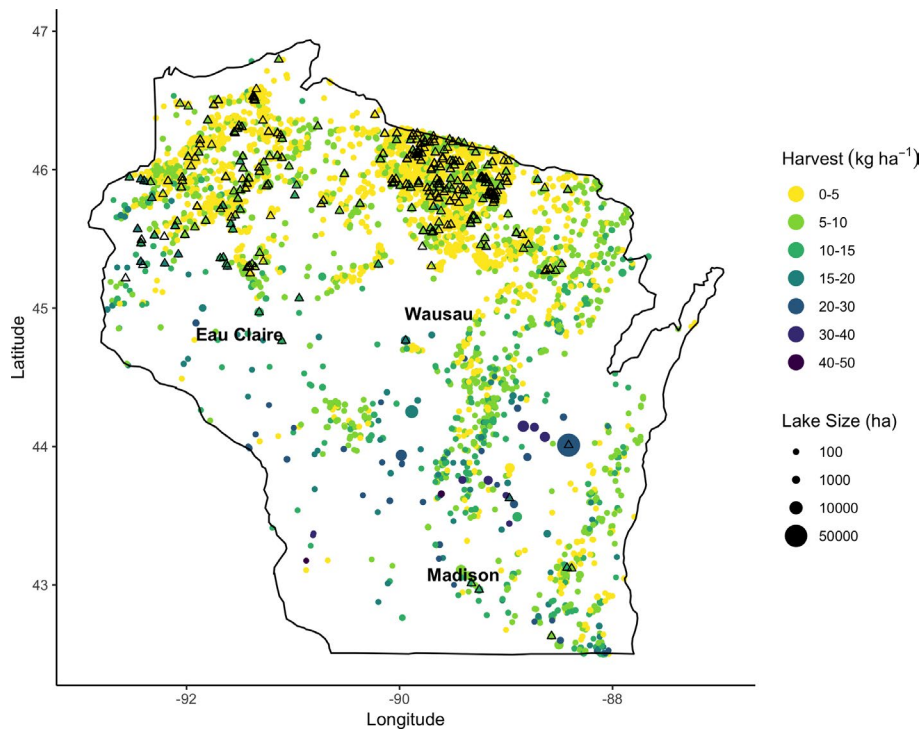


Figure 1. Predicted harvest (kg/ha) and waterbody size (ha) for lakes in Wisconsin predicted using a generalized additive model. Lakes with empirical data from 1990 to 2017 used to fit the model are marked with triangles. Reference cities (Madison, Eau Claire, and Wausau) are shown.

version of this article). Using the generalized additive model ($AIC = 2,936$; $REML = 1,589$; $R^2_{\text{adjusted}} = 0.78$), total annual harvest was estimated for 3,769 lakes with surface areas ranging from 2 to 53,394 ha (median = 15 ha; Table S4 in the supplemental material provided in the online version of this article). Harvest decreased linearly as distance to the nearest road (m) and Secchi depth (m) increased. Thermal predictor variables (i.e., mean bottom temperature of the lake in June, growing degree-days) as well as conductance increased non-linearly with harvest (Figure S1 in the supplemental material provided in the online version of this article).

Estimated areal harvest ranged from 0 to 48.35 kg/ha, with a mean $\pm$ 95% CI harvest of 5.3 ± 0.14 kg/ha (Figure 3). For 3,769 lakes (surface area of 305,693 ha), we estimated that $3,580 \pm 1,566$ (mean $\pm$ 95% CI) metric tons of fish were harvested annually by recreational anglers from Wisconsin lakes. These lakes comprised 73% of the entire state's lake surface area. The remaining lakes for which we were unable to estimate harvest due to data limitations were predominantly (80%) small lakes (i.e., surface area < 5 ha). When we applied our median harvest estimate of 5.3 kg/ha to the remaining lakes for which we were unable to estimate harvest using the model (surface area = 113,117 ha), this corresponded to $\sim 4,200$ metric tons harvested annually by recreational anglers in Wisconsin.

DISCUSSION

Though interest in the importance of inland recreational fisheries is growing, information relating to the scope, magnitude, and value of such fisheries is remarkably limited (Lynch et al. 2016; Cooke et al. 2018; Arlinghaus et al. 2019). As a result, major gaps remain in our understanding of the social and economic value of inland recreational fisheries to

humans (Cooke et al. 2018; Arlinghaus et al. 2019). To address one aspect of this gap, we quantified the magnitude of recreational fisheries harvest in Wisconsin to find high levels of harvest resulting in angler consumption rates nearly equal that of the broader United States. Specifically, we developed a robust modeling approach that incorporated abiotic and angler access information to estimate the magnitude of inland recreational fisheries harvest for $\sim 4,000$ Wisconsin lakes. We estimated that anglers in Wisconsin annually harvest $\sim 4,200$ metric ton of fish from lakes, highlighting the important ecosystem service of recreational fisheries as a source of food.

We developed a model for estimating lake-specific recreational harvest, which we then used to approximate statewide recreational harvest. The model we developed incorporated information about angler accessibility, which improved our model predictions, without directly relying on angler effort information as a predictor variable, which restricted model prediction capacity due to data limitations. Other harvest estimation approaches have relied heavily on angler effort information (Deines et al. 2017), but this poses challenges when attempting to extrapolate estimates to a large number of systems as effort data are commonly lacking. Therefore, to incorporate angler access, we found that as lakes were farther from a road, predicted harvest declined. Similar to previous analyses focusing on the interaction between thermal conditions and fish biomass (de Kerchove et al. 2015), we found that warmer thermal conditions (higher summer bottom lake temperatures and higher annual growing degree-days) corresponded with increased harvest (Figure S1 in the supplemental material provided in the online version of this article). Additionally, we found that valuable predictors of fish yield included indicators of the trophic status of the lake (i.e., Secchi depth, conductance). Both variables indicated that more productive

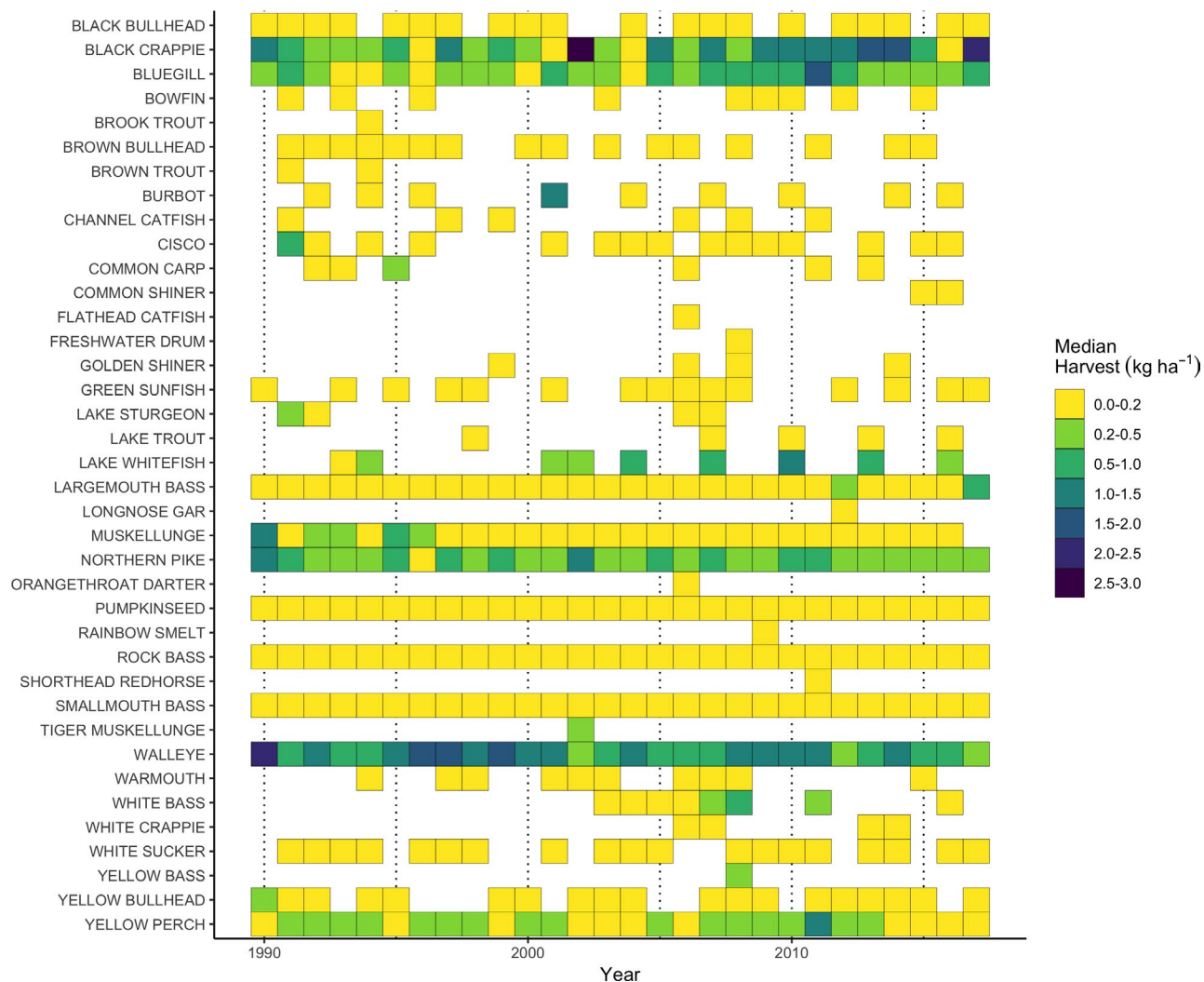


Figure 2. Species-specific annual median harvest (kg/ha) values for lakes in Wisconsin calculated from creel data from 1990 to 2017. Vertical dotted lines indicate 5-year intervals.

systems (i.e., lower Secchi depth, higher conductance) resulted in higher levels of harvest, corresponding to literature predictors of fish harvest (Ryder 1965; Deines et al. 2017). Our approach leveraged robust empirical information across both time and space through the incorporation of random effects to account for temporal variability and among lake variation. Many of the lakes for which we estimated harvest were small lakes (<10 ha, $n = 1,391$), which comprise a portion of systems rarely considered in large-scale harvest analyses but contribute substantially to total harvest.

Our analyses do not extend beyond Wisconsin, but the approach we developed can be used to inform broadscale analyses. Additionally, the majority of recreational fisheries occur within developed countries and therefore, our estimates may be applicable to similar landscapes if we assume recreational anglers harvest fish in similar fashion in other regions (Arlinghaus et al. 2013). This presents an opportunity for future evaluation, wherein if angler harvest patterns across varying landscapes were compared, it could be used to inform overall recreational harvest. Global estimates often overlook regional differences, but this variation may be substantial and therefore regional estimates like that performed in this study have the potential to inform data-poor scenarios.

We extrapolated empirical harvest information to estimate total statewide recreational harvest; however, we acknowledge limitations of our approach. First, we limited our analyses to inland lakes due to data limitations, even though other waterbodies, including ~51,500 km of rivers (<https://bit.ly/2VitD2T>), as well as wetlands and the Laurentian Great Lakes contribute substantially to global harvest and food security (Lymer et al. 2016; McIntyre et al. 2016). Improved harvest estimates of these systems utilizing similar approaches to those we employed are greatly needed to more accurately understand the role of recreational fisheries in fisheries harvest.

Second, although we considered spatiotemporal creel sampling variation by incorporating lake and year as random effects in our model, there was additional variation in the empirical creel estimates we did not consider when scaling-up to the statewide level. As our intention was to understand broadscale patterns in recreational fishing harvest in Wisconsin, we used mean species-specific annual harvest estimates to inform our model, but understand that these estimates were variable. This variation may influence our estimates and would be an avenue for further research in refining recreational harvest estimates. Finally, the lakes in our study were potentially biased towards lakes in northern Wisconsin

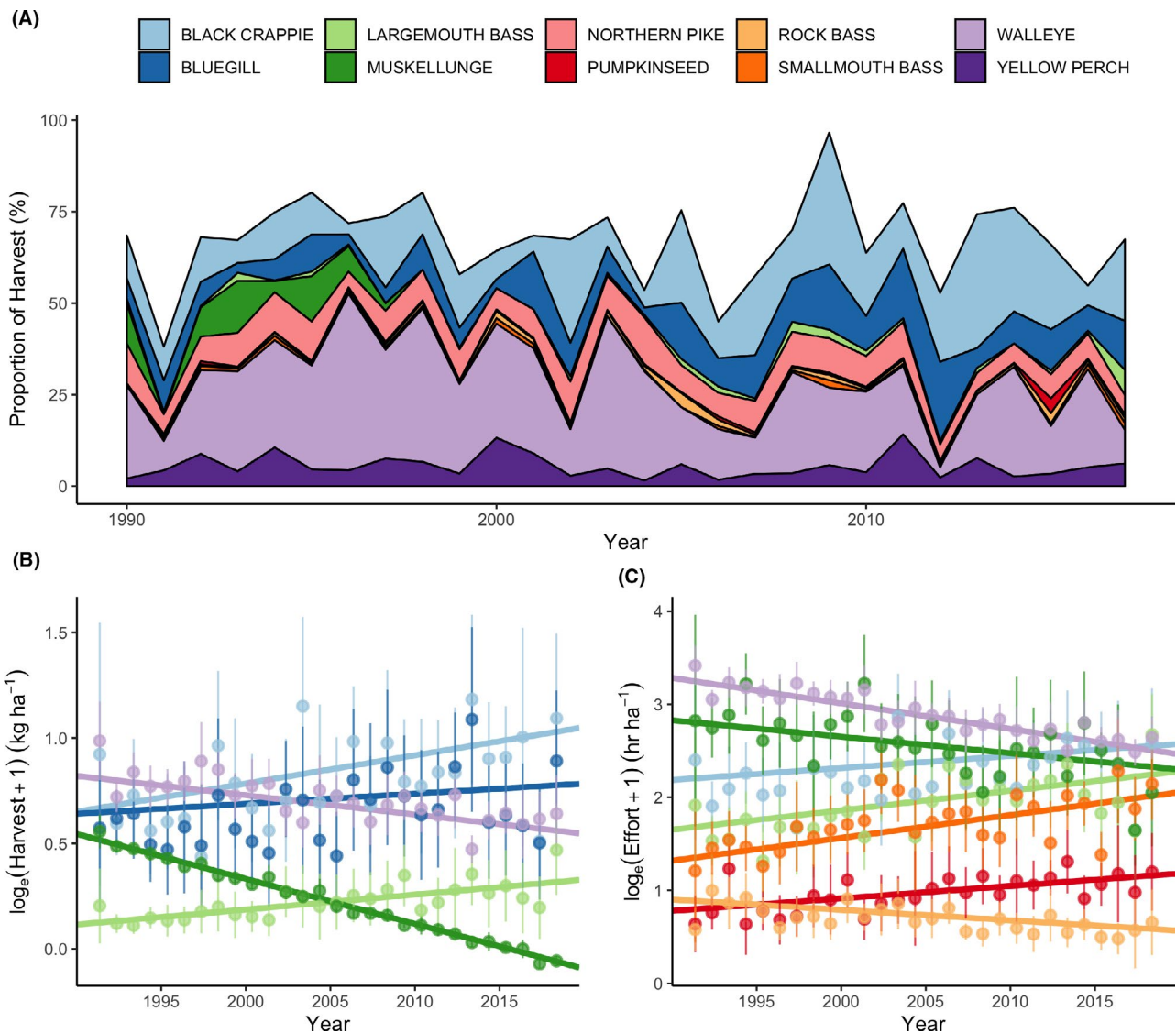


Figure 3. Species-specific proportion of harvest (%) (panel A), mean $\pm$ 95% confidence intervals $\ln(\text{harvest} + 1)$ (kg/ha) (panel B), mean $\pm$ 95% confidence intervals $\ln(\text{effort} + 1)$ (hr/ha) (panel C) from 1990 to 2017. Only statistically significant temporal harvest trends are shown in panel B and C, with trend lines corresponding to linear mixed effects models. Species include Black Crappie (*Pomoxis nigromaculatus*; light blue), Bluegill (*Lepomis macrochirus*; dark blue), Largemouth Bass (*Micropterus salmoides*; light green), Muskellunge (*Esox masquinongy*; dark green), Northern Pike (*E. lucius*; light red), Pumpkinseed (*L. gibbosus*; dark red), Rock Bass (*Ambloplites rupestris*; light orange), Smallmouth Bass (*M. dolomieu*; dark orange), Walleye (*Sander vitreus*; light purple), and Yellow Perch (*Perca flavescens*; dark purple).

as these are much more commonly surveyed and certain species in these lakes (e.g., Walleye) are more selectively targeted (Cichosz 2017). However, the variables used to predict harvest were spatially independent and spanned the range of values used to estimate harvest. Lakes in southern Wisconsin are commonly warmer, more productive systems and thus likely contribute higher harvest in combination with the fact that anglers in southern lakes potentially target different species (e.g., *Lepomis* spp., which are viewed more consumptively) than those in northern lakes. Overall, our analysis provides a novel approach to estimate the contribution of inland recreational fisheries to overall fisheries harvest.

The creel survey revealed that 38 species were harvested over the past 28 years from lakes in Wisconsin (Figure 1), a much larger number than those species actively managed by state agencies. Harvest was largely comprised of

commonly targeted taxa, including Walleye, Northern Pike, Lake Whitefish, and sunfishes, but many other species contributed to the overall harvest (Figure 1). Additionally, our findings demonstrated species-specific harvest trends (Figure 2). As harvest and angler effort of Muskellunge and Walleye declined, harvest and effort increased for other species, in this case Black Crappie and Largemouth Bass (Figure 2). These species-specific trends align with species abundance shifts (Hansen et al. 2017). In contrast, Bluegill harvest increased but effort did not, indicating anglers may be choosing to keep additional Bluegill that they previously released (Figure 2). Some species, including Smallmouth Bass and Pumpkinseed, showed significant changes in effort but no changes in harvest, indicating that while these species may be important recreational target species, they may not be of interest to consumptive anglers (Figure 2).

Overall pooled harvest and effort did not change over time even though species-specific shifts occurred, indicating anglers consistently harvested the same amount of fish, but the species that comprised that harvest did change. Additionally, total harvest and effort remained constant as the number of fishing licenses declined, potentially indicating that the dominant proportion of harvest is driven by a smaller group of highly skilled anglers who continued to harvest fish despite large-scale changes (e.g., species abundance shifts). We did not explore relationships between angler types (e.g., boat, bank, ice), but it would be an interesting area for future research to understand the harvest dynamics of different consumptive anglers as they are known to target different species and to understand how this relates to broadscale ecosystem changes (Kaemingk et al. 2020). Although much management focus is put on specific species, consumptive anglers may target a variety of species and compensate to other species as a food source if they are primarily motivated by subsistence, even if a preferred species declines. Harvest switching by anglers to compensate and maintain overall harvest levels has significant implications for natural resource managers and our understanding of ensuring food security.

Few have assessed the magnitude of recreational fisheries harvest beyond individual systems, yet many have estimated global lake fisheries harvest (Welcomme 2011; Lymer et al. 2016; Deines et al. 2017). Employing a variety of extrapolation methods, including simple relationships between lake size and harvest and theoretical habitat-specific yields, global inland lake fisheries harvest was estimated to range between 20.7 to 93.0 million metric tons annually (Welcomme 2011; Lymer et al. 2016). Others have used waterbody productivity and human populations to estimate that over 11 metric tons were harvested from inland lakes (Deines et al. 2017). These broadscale approaches overlook important fine-scale processes that influence the dynamics of specific fisheries sectors, such as recreational, that are not considered in these aggregated estimates. Others have focused exclusively on recreational fisheries harvest, using Canadian average harvest (4.5 kg/ha) to extrapolate global recreational harvest to be 10.86 metric tons annually, with recreationally harvested fish contributing 9.3% to total fish harvest (Cooke and Cowx 2004; Cooke et al. 2018). These estimates relied on significant assumptions (e.g., that Canadian harvest patterns apply globally, which is likely not the case given international variation in angler dynamics and fisheries ecology). Using our modeling approach that goes beyond applying a local average and considers small-scale dynamics, we estimated a slightly higher median harvest level (5.3 kg/ha), indicating that global recreational harvest estimates may be underestimating the contribution of recreational fisheries, although understanding regional harvest dynamics is critical to accurately estimating this magnitude.

We found that a substantial amount of fish, ~4,200 metric tons, was recreationally harvested annually from lakes in Wisconsin. Although angler-specific consumption rates are highly uncertain given data limitations, assuming the people harvesting the fish are eating them, if we convert our harvest estimate to edible portion given an average filet yield of ~35% (Summerfelt et al. 2010; Lyons et al. 2017), this corresponds to ~1.1 kg/angler annually. For the United States, combined freshwater and estuarine annual finfish consumption rates were estimated to be ~1.8 kg/adult and ~0.4 kg/youth (50th percentile, edible portion; Environmental Protection Agency 2014). These consumption rates did not consider the source of consumed fish

(e.g., commercially versus recreationally harvested), but given that our coarse estimate stemming solely from recreational lake harvest is nearly equal to total freshwater fish consumption, it is clear that recreational fisheries contribute substantially to overall fish consumption. Although precise consumption rates in the region are unclear, the sizeable contribution of recreational fisheries to overall per-angler fish consumption highlights the significant and overlooked ecosystem service that the recreational fisheries sector provides as a source of food and highlights a critical avenue for future research.

Given the magnitude of harvest and consumption we estimated, these findings provide context for a potentially hidden and additional source of value that is not represented in these analyses. Much emphasis has been placed on quantifying the economic impact of the recreational fisheries sector as anglers contribute economically in a variety of ways, including purchasing fishing licenses and equipment and chartering boats, generating \$2.3 billion annually in Wisconsin alone (U.S. Department of the Interior 2016). Using our estimates, when we compare the average price of a kilogram of fish in a Wisconsin grocery store (~\$15), it results in a value of ~\$65 million annually that is contributed by recreational fisheries, but goes unmeasured. More research is needed to accurately value inland recreational fisheries, but studies like ours can serve as starting points to begin to understand the hidden contribution this sector provides to many economies.

Our findings have implications for understanding the effect of recreational fisheries on local economies, ecosystems, and management, as well as a source of food. Recreational fisheries have the potential to greatly affect fish communities; therefore, understanding the magnitude of harvest can inform the conservation and management of these populations (Post et al. 2002). Others have emphasized the nutritional value that fish contribute to fishing communities; therefore, estimating the magnitude of recreational harvest can inform our understanding of the often-hidden role recreational fisheries play in food security issues (Cooke et al. 2018). Given that regional differences are highly influential in these harvest patterns, we suggest that a mosaic approach wherein harvest is estimated at smaller scales, such as was done in this study, and then combined can provide a greater understanding of the role recreational fisheries play in overall harvest. The approach we developed can be used to guide science, policy, and management decisions on harvest levels to satisfy consumption needs as well as conserve natural resources.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.
Supplementary Material [AFS](#)