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Occupancy and detection of Yellow Perch in Great Lakes coastal wetlands

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Dedication

To my husband, Cody, and my friends and family for their support and encouragement throughout this project. I couldn’t have done it without you!

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Abstract

Accurately estimating the distribution of a species is important for managing sustainable populations of fishes. The Yellow Perch *Perca flavescens* is an important sport fish in the Great Lakes region and one of the most abundant fishes in Great Lakes coastal wetlands, which they commonly use for spawning and nursery habitat. Many fisheries management decisions are based on results from sampling fish assemblages, but these methods rarely account for incomplete detection (i.e., presence of a species that is not detected by sampling), which could create biased results. We applied the method of occupancy modeling, which accounts for incomplete detection, to Yellow Perch presence/absence data from coastal wetlands across all five Great Lakes. We used occupancy models with environmental variables to predict the detection probability of fyke-net sampling and the occupancy of Yellow Perch under different environmental conditions. We found that both detection probability and occupancy of Yellow Perch varied among Great Lakes and with changes in other environmental variables. The best statistical model included sampling depth, specific conductivity, wetland hydrologic connection, and Great Lake basin. Yellow Perch occupancy was predicted to be highest in areas with greater depth, lower specific conductivity, and a riverine connection to a Great Lake. All naïve occupancy estimates were lower than the occupancy estimates predicted by our models. Our base model with no covariates predicted an occupancy of 0.68 and detection probability of 0.669 across all sites. Our results predict which coastal wetland habitats were preferred by Yellow Perch (i.e., those with low specific conductivity and greater depth) and emphasize the importance of incorporating detection probability into occupancy estimates. Our results can help provide support for the conservation of coastal wetlands with preferred Yellow Perch habitat, and guidance for future coastal wetland restoration projects.

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Chapter I

Introduction

The Laurentian Great Lakes make up the largest freshwater ecosystem in the world, providing important habitat for many organisms (Jude and Pappas 1992; Lauber et al. 2016). Coastal wetlands are connected to the waters of the Great Lakes, and are found in all five Great Lakes. Coastal wetlands are often used as spawning and nursery habitat for many fishes (Jude and Pappas 1992). Yellow Perch *Perca flavescens* is a freshwater fish species native to the Great Lakes that is both economically and ecologically important to the region (Forsythe et al. 2012; Parker et al. 2009; 2012). Yellow Perch is one of the most abundant species in Great Lakes coastal wetlands (Jude and Pappas 1992; Bhagat et al. 2007; Trebitz et al. 2009) and is known to use these areas as spawning and nursery habitat (Brazner et al. 2004; Janetski et al. 2013; Schoen et al. 2016).

Although Great Lakes Yellow Perch have been studied previously (e.g., Parker et al. 2009; Forsythe et al. 2012; Janetski et al. 2013), there is currently no literature, from the Great Lakes or elsewhere, that addresses the issue of incomplete detection of Yellow Perch (i.e., when a species is present but not detected) with current sampling methods. The method of occupancy modeling uses repeated surveys to account for incomplete detection and can also incorporate environmental covariates to predict the occupancy of a species under certain conditions (MacKenzie et al. 2002). My thesis explains the methods, results, and conclusions of applying the statistical method of occupancy modeling to Yellow Perch data from 5 years of sampling wetlands across the Great Lakes in order to more accurately estimate the spatial distribution of Yellow Perch and the environmental covariates that are driving it. I also provide an overview of some of the current literature on Great Lakes coastal wetlands, Yellow Perch, and the use of occupancy modeling with other organisms, as well as more detail about the materials and methods used for this study.

Purpose

The purpose of this study was to examine the spatial distribution of Yellow Perch in Great Lakes coastal wetlands. I aimed to do this by applying occupancy modeling to determine the detection probability of Yellow Perch in fyke nets fished in coastal wetlands, to account for incomplete detection when estimating Yellow Perch occupancy, and to incorporate environmental covariates into occupancy models to better understand the habitat characteristics that are associated with the presence of Yellow Perch.

Scope

This study focused on coastal wetlands across all five of the Laurentian Great Lakes. Coastal wetlands sites were selected and sampled through the Great Lakes Coastal Wetlands Monitoring Program. Sampleable wetlands included those that had a surface water connection to a Great Lakes, were larger than 4 ha, and were accessible for sampling (Uzarski et al. 2017). Results from this study should be applicable to all Great Lakes coastal wetlands. Results also can be used to inform managers about other freshwater, wetland-dwelling Yellow Perch populations.

Assumptions

I assumed that Yellow Perch captured during sampling were representative of all Yellow Perch in Great Lakes coastal wetlands in that they preferred the same environmental conditions. I also assumed that all Costal Wetland Monitoring Program field crews followed the standard operating procedures when sampling, and correctly identified all Yellow Perch captured during sampling. The Great Lakes Coastal Wetland Monitoring Program has a quality assurance program in place to ensure that all field crews follow the sampling procedures.

Additionally, I followed the assumptions of occupancy modeling stated by Mackenzie et al. (2003) that (1) all parameters associated with occupancy and detection are constant across sites throughout the sampling period, (2) each population at a sampling site is closed during the sampling period, (3) repeated surveys at a site are independent, and (4) there is independence between sampling sites. Not all occupancy modeling assumptions were able to be met throughout my study, so an overdispersion parameter was included in model ranking to correct for violating the independence assumptions (Richards 2008).

Hypothesis

I hypothesized that (1) Yellow Perch are unevenly distributed among the Great Lakes and among wetland types, as not all coastal wetlands contain preferred Yellow Perch habitat (e.g., vegetation or substrate structure for spawning; Robillard and Marsden 2001; Brown et al. 2009; Parker et al. 2012), (2) Yellow Perch are more likely to be present in wetlands with intermediate water-column productivity (Parker et al. 2012), which I predict will be shown by their preference for vegetation structure (Herman et al. 1959), and certain ranges of water quality variables (Herman et al. 1959; Brown et al. 2009), and (3) the detection probability of my sampling method will vary spatially throughout the Great Lakes, as fyke nets in some vegetation zones appear to fish less efficiently than in other vegetation zones.

Significance

Results from this study will help managers gain a better understanding of Yellow Perch distribution in the Great Lakes, identifying the most important environmental conditions in coastal wetlands for providing Yellow Perch habitat. Using occupancy modeling and including the detection probability will create a more accurate representation of the spatial distribution of Yellow Perch in Great Lakes coastal wetlands compared to previous naïve estimates (i.e., occupancy estimates based solely on field detections and the proportion of sites that the species was captured). Results from this study can help managers determine critical areas and wetland characteristics for protection and help guide future wetland restoration efforts to benefit Yellow Perch populations in the Great Lakes.

Definitions

Detection probability (P) – the probability of detecting a species in field sampling when it is present at the sampling site.

Naïve occupancy –the proportion of sites that the species was captured, which does not account for incomplete detection (meaning a species is present at a sampling site but not captured by the sampling gear).

Occupancy (ψ) – the probability that a species is present at a sampling site, which is estimated using occupancy models.

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Chapter II

Occupancy and detection of Yellow Perch in Great Lakes coastal wetlands

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Abstract

Accurately estimating the distribution of a species is important for managing sustainable populations of fishes. The Yellow Perch *Perca flavescens* is one of the most abundant fishes in Great Lakes coastal wetlands, which it commonly uses for spawning and nursery habitat. Many fisheries management decisions are based on results from sampling fish assemblages, but these methods rarely account for incomplete detection (i.e., presence of a species that is not detected by sampling), which could create bias. We applied the method of occupancy modeling, which accounts for incomplete detection, to Yellow Perch presence/absence data from coastal wetlands across all five Great Lakes. We used occupancy models with environmental variables to examine the detection probability of fyke netting and the occupancy of Yellow Perch under different environmental conditions. We found that both detection probability and occupancy of Yellow Perch varied among Great Lakes and was associated with environmental variables. The best statistical model included sampling depth, specific conductivity, wetland hydrologic connection, and Great Lake basin. Yellow Perch occupancy was estimated to be highest in areas with greater depth, lower specific conductivity, and a riverine connection to a Great Lake. All naïve occupancy estimates were lower than the occupancy estimates predicted by our models. Our base model with no covariates predicted an occupancy of 0.68 and detection probability of 0.67 across all sites. Our results predict which coastal wetland habitats were preferred by Yellow Perch and emphasize the importance of incorporating detection probability into occupancy estimates.

Introduction

Knowing the distribution and abundance of species is critical for conservation and management of the freshwater ecosystems of the Great Lakes (Dextrase et al. 2014). Being able to accurately estimate the distribution of a species is especially key for managing sustainable populations of fishes, such as Yellow Perch *Perca flavescens,* that are commonly harvested in the Great Lakes. Fish populations in Great Lakes coastal wetlands have been frequently studied in recent years (e.g., Seilheimer and Chow-Fraser 2006; Bhagat et al. 2007; Trebitz et al. 2009; Cvetkovic et al. 2010; Kovalenko et al. 2014; Uzarski et al. 2005, 2009, 2017), but much still remains to be learned about what factors – such as geographic location, type of wetland, Great Lake, or environmental conditions – affect the distribution of a specific fish species at large spatial scales.

Wetlands that are connected to the waters of the Great Lakes are considered coastal wetlands and are found in all five Great Lakes and their connecting channels (Keough et al. 1999). Coastal wetlands cover an estimated 1214 km^2 throughout the Great Lakes (GLNPO 2002) and provide important habitat for many fishes (Jude and Pappas 1992). An estimated 80 species of fish use coastal wetlands at some point in their life, which includes about 50% of the commercially harvested fishes and more than 80% of the recreationally harvested fishes in the Great Lakes (Herdendorf et al. 1981; Uzarski et al. 2005; Trebitz and Hoffman 2015; Schoen et al. 2016). Coastal wetlands are used by fishes as spawning and nursery habitat, cover for juvenile and forage fish, and feeding grounds for piscivores (Herdendorf et al. 1981; Jude and Pappas 1992). Even though Great Lakes coastal wetlands are ecologically important, in the past they have been lost at alarming rates, with as great as 50% of the historic coastal wetlands lost to agricultural conversion or drainage over the last 100 years (Krieger et al. 1992). Many of the remaining coastal wetlands have been degraded or altered in some way (Jude and Pappas 1992), and nutrient loading and fragmentation from agriculture and urbanization are two of the main factors currently impacting wetlands (Uzarski et al. 2005, 2009; Cooper et al. 2012).

The Yellow Perch is one of the most abundant fishes in Great Lakes coastal wetlands (Jude and Pappas 1992; Bhagat et al. 2007; Trebitz et al. 2009) and they are ecologically and economically important to the Great Lakes region (Forsythe et al. 2012; Parker et al. 2009; 2012). Yellow Perch is an important species in the Great Lakes for both commercial harvest and sport fishing (Trebitz and Hoffman 2015). For example, it is one of the most frequently caught sport fish in Michigan and can be fished throughout the year (MDNR 2016). Recreational fishing in the Great Lakes is estimated to bring in about $7 billion a year for local economies (Lauber et al. 2016). Several life stages (e.g., larval, juvenile, and spawning adult) of Yellow Perch use coastal wetlands as important spawning and nursery habitat as well as areas to provide better foraging and cover for juveniles (Brazner et al. 2004; Janetski et al. 2013; Schoen et al. 2016). Besides being targeted by anglers, Yellow Perch also provide prey for other popular sport fishes, including Walleye *Sander vitreus*, Northern Pike *Esox lucius*, and Largemouth Bass *Micropterus salmoides* (Herman et al. 1959; Brown et al. 2009). During the adult stage, Great Lakes Yellow Perch often form schools in deeper nearshore areas, sometimes returning to coastal wetlands to spawn, although some adults still frequent coastal wetlands throughout the year, and they do not exclusively spawn in coastal wetlands (Brazner et al. 2001; Schoen et al. 2016). Since coastal wetlands are usually warmer than the deeper, nearby areas of the Great Lakes, Yellow Perch typically hatch earlier and have a longer growing season in this habitat, allowing fish to reach larger sizes before winter (Jude and Pappas 1992; Parker et al. 2012). Suitable spawning habitat is an important factor for Yellow Perch hatching success, specifically the presence of substrate or vegetation structure to lay eggs on, and suitable temperatures for development and maturation (Clady 1976; Krieger et al. 1983; Brown et al. 2009).

In order to learn more about a species, individuals must be sampled in nature. Incomplete detection (i.e., the presence of a species that is not detected by sampling) is a common problem with many sampling methods (e.g., minnow traps [Kuehne and Olden 2016], bag seine [Dextrase et al. 2014], backpack electrofishing and angling [MacPherson et al. 2012]) and can make estimates of the proportion of sites occupied by a species biased if not considered (MacKenzie et al. 2003; Anderson et al. 2014; Guillera-Arroita et al. 2014). Naïve estimates (i.e., occupancy estimates based solely on field detections and the proportion of sites that the species was captured) of a species' occupancy will be lower than occupancy estimates that account for incomplete detection. Occupancy modeling can be used to incorporate incomplete detection into occupancy estimates, which allows for more accurate estimation of the distribution of a species (MacKenzie et al. 2002). Distribution information from occupancy models allows for better management and protection of species of concern (e.g., Dextrase et al. 2014; Kuehne and Olden 2016) as well as important sport fishes (MacKenzie et al. 2003; Anderson et al. 2014; Guillera-Arroita et al. 2014).

The goal of our research was to examine the spatial distribution of Yellow Perch in coastal wetlands across the Great Lakes basin. Our objectives were to: (1) estimate the detection probability of Yellow Perch in fyke nets fished in Great Lakes coastal wetlands and account for incomplete detection when estimating site occupancy, and (2) identify wetland types and environmental conditions that are associated with the presence of Yellow Perch by including environmental covariates in occupancy models. We hypothesized that (1) Yellow Perch are unevenly distributed among the Great Lakes and among wetland types, as not all coastal wetlands contain preferred Yellow Perch habitat (e.g., preferred vegetation or substrate structure; Robillard and Marsden 2001; Brown et al. 2009; Parker et al. 2012), (2) Yellow Perch are more likely to be present in wetlands with intermediate water-column productivity (Parker et al. 2012), which we predict will be shown by their preference for vegetation structure (Herman et al. 1959), and certain ranges of water quality variables (Herman et al. 1959; Brown et al. 2009), and (3) the detection probability of our sampling method will vary spatially throughout the Great Lakes, as fyke nets in some vegetation types appear to fish less efficiently than in other vegetation zones (Cvetkovic et al. 2010). Results from this study will help managers gain a better understanding of Yellow Perch distribution in the Great Lakes, emphasizing the importance of specific environmental characteristics in coastal wetlands for maintaining sustainable Yellow Perch populations. Using occupancy modeling and including the detection probability will create a more accurate representation of the spatial distribution of Yellow Perch in Great Lakes coastal wetlands compared to previous naïve estimates. As shown by previous occupancy studies (e.g., Bailey et al. 2014; Guillera-Arroita et al. 2014; Kuehne and Olden 2016), detection probability and the environmental covariates that impact it will be an important component of the model when comparing estimates of occupancy across the basin.

Methods

Study sites

We conducted this study in coastal wetland sites in all five Great Lakes (Figure 1). Data were collected as part of the Great Lakes Coastal Wetlands Monitoring Program, a collaboration of federal, state/provincial, academic, and non-governmental organizations, using standardized methods that was implemented in 2011 (Uzarski et al. 2017). Approximately 1000 coastla wetlands were considered sampleable by the Great Lakes Wetland Consortium (Uzarski et al.

2017). Criteria for a wetland to be sampleable were that it has an area greater than 4 hectares, has a surface water connection to the Great Lakes, and is accessible for sampling (Uzarski et al. 2017). The Great Lakes Coastal Wetlands Monitoring Program used stratified random selection based on wetland type, regions, and Great Lake to determine which wetlands were sampled each year. Each year up to 20% of the total sampleable wetlands were sampled, and the selection is on a 5-year rotation (Uzarski et al. 2016a). We used data collected from 2011 through 2015, which is the first 5-year rotation and includes all of the sampleable sites. “Benchmark” sites, to represent the least impacted and most disturbed wetlands, were also included each year in the sampled sites, and these sites were typically sampled annually (Uzarski et al. 2017).

Data collection

We collected fish and water quality data according to the Standard Operating Procedures (SOP) and Quality Assurance Project Plan (QAPP) created for the Great Lakes Coastal Wetlands Monitoring Program (Uzarski et al. 2016b). We conducted fish sampling between mid-June and early September using 4.8-mm mesh fyke nets (see Uzarski et al. [2017] for fyke net description) that were set overnight (about 24 hours), with three fyke nets set perpendicular to shore at each major vegetation zone at up to three vegetation zones in each wetland site. Vegetation zones were mono-dominant (i.e., a single genus represented at least 75% of the plant community) and at least 400 m^2 in extent with a water depth of 25-100 cm to be sampleable with fyke nets (Uzarski et al. 2016b; 2017). Vegetation zones included cattail (*Typha*), water lily (*Nuphar-Nyphaea*), dense or sparse bulrush (*Schoenoplectus*), wet meadow, arrow-arum-arrowhead-pickerel weed (*Peltandra-Sagittaria-Pontederia*; PSP), *Phragmites*, submersed aquatic vegetation (SAV), and other less-common zones that were not used for our analysis.

At each sampling site we recorded additional site characteristics based on visual observations and aerial imagery of the site. These included the classification of the wetland, the hydrologic connection of the wetland, the vegetation structure of each vegetation zone sampled, if there was any pollution visible at the site, and if there was any recreation activity at the site while we were there sampling (see Table 1 for detailed information on covariates).

We measured the following water quality variables *in situ* with a water quality sonde (e.g., Yellow Springs Instrument model 6600) where each fyke net was set: temperature (°C), dissolved oxygen (mg/L and % saturation), turbidity (Nephelometric Turbidity Units; NTU), pH, and specific conductivity (µS/cm). We collected grab samples of water just below the surface from the same three places per vegetation zone where the fyke nets were set, composited the grabs into one sample per vegetation zone, and put the samples on ice to be processed later or stored for future analysis (see Uzarski et al. [2017] for more detailed water collection and analysis). Laboratory analyses included measurements of total nitrogen (mg/L) and total phosphorus (mg/L) (Axler et al. 2010; Uzarski et al. 2017).

Other variables were also collected from each site as part of the Great Lakes Coastal Wetlands Monitoring program, including additional water quality variables and site characteristics (see Uzarski et al. 2017), but they were not all included in this analysis.

Data analyses

We conducted all data analyses in program R version 3.3.2 (R Core Team 2016). Using the presence or absence of Yellow Perch in each of the three fyke nets fished in a vegetation zone with corresponding site characteristics, we created occupancy models (MacKenzie et al. 2002; MacKenzie and Royle 2005) for Yellow Perch in Great Lakes coastal wetlands using the R package “unmarked” (Fiske and Chandler 2015, 2017). We used the three fyke nets fished in a zone as the “repeated” visits to the site to estimate detection probability (MacKenzie and Royle 2005). Occupancy models analyze not only occupancy and detection probabilities, but also which environmental covariates were associated with occupancy or detection (MacKenzie et al. 2002).

At each site, we sampled all of the vegetation zones that met the sampling criteria. For our analyses, we considered each vegetation zone within a wetland to be a separate site, for a total of 832 vegetation zones sampled during 2011-2015. There were some wetlands that had multiple samples, either from multiple sampling years (e.g., benchmark sites) or multiple vegetation zones within a wetland. To avoid violating the occupancy modeling assumption of independence between sites (MacKenzie et al. 2002; Fiske and Chandler 2011), we used the function “sample” in program R to randomly select which of the sites within a wetland were included in the final analyses. Hereafter, we refer to each sampled vegetation zone as a site. Our final subset of data for model development included 348 sites, which were all separate wetland locations. The vegetation zones in our analyses were: PSP (*n* = 10), sparse bulrush (*n* = 49), dense bulrush (*n* = 44), *Phragmites* (*n* = 10), SAV (*n* = 100), *Typha* (*n* = 57), lily (*n* = 64), and wet meadow (*n* = 14).

To determine which environmental covariates to test in occupancy models, we identified factors that likely impact habitat suitability of Yellow Perch. We then analyzed the environmental covariates for correlation with each other to avoid redundancy in our models. Environmental covariates included in our analyses were: vegetation structure, presence of pollution (i.e., public litter, commercial refuse, petroleum, large equipment, household appliances, or sewage), presence of recreation activity (i.e., swimming, sailing, fishing, boating, or personal watercraft), latitude of sampling site, wetland class, hydrologic connection, specific conductivity, and lake basin (see Table 1 for more detail about environmental covariates). Several other covariates, such as dissolved oxygen, temperature, pH, vegetation type, turbidity, total phosphorus, and Julian day were considered for our models but ultimately removed from analyses because they either had a strong correlation with other covariates, had too many missing observations, or had no impact on model rank. Once we determined which environmental covariates to include, we created occupancy models with sets of covariates we had determined *a priori*, and also tested all possible combinations of the covariates for our complete basin-wide dataset, and also with our sites divided by each Great Lake. This resulted in six different suites of models. Some additional covariates were removed from the individual lake models due to small sample size. We created a global model (i.e., model that included all of the possible covariates for occupancy and detection), and determined the $\hat{c}$ value, or overdispersion parameter, for our basin-wide dataset and each individual lake dataset (Richards 2008). All of our data except for Lake Huron had evidence of overdispersion (i.e., $\hat{c} > 1.0$) so we used the quasi-likelihood Akaike's information criterion corrected for sample size ($QAIC_C$) to rank models, which accounts for overdispersion (Richards 2008). We used Akaike's information criterion corrected for sample size (AIC_C) to rank the models for Lake Huron because there was no evidence of overdispersion. If overdispersion is present but not accounted for, it can lead to the selection of overly complex models when ranked by AIC (Richards 2008). We compared all models to a base model with no covariates and determined the models that had the best fit based on AIC_C or $QAIC_C$ rank (MacKenzie and Bailey 2004). Once we developed our models, we were able to predict Yellow Perch occupancy or detection for a set of environmental conditions, and also determine which covariates had the strongest association with Yellow Perch occupancy or detection probability.

Results

Yellow Perch were detected at 228 of 348 sites for a naïve occupancy estimate of 0.655 across all wetlands. A total of 69,648 Yellow Perch were collected across the 348 sites, ranging from 0 to 40,169 individuals collected at a site. Of the 348 sites we examined, no Yellow Perch were collected at 120 sites, one individual was collected at 43 sites, and two or more Yellow Perch were collected at 185 sites; the median number of Yellow Perch captured at a site was one. Lake Michigan had the highest number of Yellow Perch collected among the Great Lakes, although 40,169 Yellow Perch were collected at a single site in Green Bay in 2013. Yellow Perch had the highest naïve occupancy in Lake Ontario and Lake Superior, where they were collected at 78 out of the 104 sites and 33 out of the 44 sites, respectively (Table 2 and Figure 2).

Occupancy

All basin-wide models with covariates ranked better than the base models (Table 3). The basin-wide base model predicted Yellow Perch occupancy to be 0.68, which was only slightly higher than the naïve occupancy estimate. For Yellow Perch occupancy on a basin-wide scale, depth, specific conductivity, and hydrologic connection appeared in many of the top models, suggesting that they were important for predicting Yellow Perch occupancy (Table 3). Depth appeared to have the strongest connection to Yellow Perch occupancy basin wide (Table 4). Depth was in 8 out of the top 10 basin-wide models for Yellow Perch occupancy, and an increase in depth was associated with an increase in Yellow Perch occupancy (Figure 3c). For specific conductivity, an increase was associated with a decrease in Yellow Perch occupancy (Figure 3a). Yellow Perch occupancy was highest in wetlands that had a riverine connection or were fully exposed (i.e., a or b [see Table 1]), and decreased as the connectivity of the wetland decreased

(Table 5). Vegetation structure, wetland classification, pollution, and recreation also appeared as covariates for Yellow Perch occupancy (Table 3).

When our analysis was divided by lake basin, different top covariates emerged for each of the Great Lakes. For Lake Superior, latitude was the most common occupancy covariate, and specific conductivity, depth, and recreation also were included in several models (Table 3). Contrasting with the basin-wide models, specific conductivity in Lake Superior had a small but positive association with Yellow Perch occupancy (Table 7). For Lake Michigan, hydrologic connection was the most common covariate associated with occupancy, and specific conductivity, vegetation structure, pollution, and recreation also were included in top models (Table 3). Similar to the basin-wide models, a riverine hydrologic connection had the greatest Yellow Perch occupancy in Lake Michigan (Table 7). For Lake Huron, depth strongly affected occupancy (Table 7), similar to the basin-wide models. Hydrologic connection and specific conductivity also appeared in most top models (Table 3). Yellow Perch occupancy was also highest in wetlands with a riverine connection in Lake Huron (Table 7). Contradictory to the basin-wide models, specific conductivity had a small but positive relationship with Yellow Perch occupancy for Lake Huron (Table 7). For Lake Erie, specific conductivity was the primary covariate in the top models, hydrologic connection appeared in one model, and one top model had occupancy held constant (i.e., no covariates; Table 3). Similar to the basin-wide models, Yellow Perch occupancy in Lake Erie also had a negative relationship with specific conductivity (Table 7). For Lake Ontario, latitude, depth, and specific conductivity were in the top models, as well as a constant occupancy with no covariates (Table 3). Depth and latitude both had strong, positive associations with Yellow Perch occupancy in Lake Ontario (Table 7).

Detection

The detection probability of Yellow Perch in the basin-wide base model was 0.669. On the basin-wide scale, lake and depth primarily influenced Yellow Perch detection. Although depth was an important covariate for detection, the relationship with depth was chaotic with no clear direction (Figure 3d). Latitude and vegetation structure also appeared in top models for Yellow Perch detection. Yellow Perch detection had a small, positive relationship with sampling latitude (Table 4). Lake Michigan had the highest detection probability, which was similar to Lakes Huron, Ontario and Superior, while the Lake Erie detection probability was much lower (Table 2).

Similar to Yellow Perch occupancy, covariates for detection probability for each individual Great Lake varied from each other and the basin-wide models. For Lake Superior, only the covariates latitude and depth were included for Yellow Perch detection probability in the top models (Table 3). Depth had a strong, positive association with Yellow Perch detection probability for Lake Superior, which was similar to the basin-wide models (Tables 4 and 7). However, latitude had a negative relationship with detection probability for Lake Superior, compared to a positive relationship for the basin-wide model (Tables 4 and 7). For Lake Michigan, models included depth, latitude and recreation for Yellow Perch detection probability (Table 3). The top model for Lake Michigan included latitude, which had a similar relationship to Yellow Perch detection probability as the basin-wide model (Tables 4 and 7). For Lake Huron, detection probability was related to pollution, depth, and vegetation structure (Table 3). The association of depth with detection probability was similar between the basin-wide models and Lake Huron (Tables 4 and 7). For Lake Erie, specific conductivity, recreation, and pollution were the only covariates included for Yellow Perch detection probability, along with a constant detection probability in several models (Table 3). However, the top model for Lake Erie only had a constant detection probability (Tables 3 and 7). Lake Ontario models had more covariates associated with detection probability, with latitude, hydrologic connection, pollution, vegetation structure, and specific conductivity appearing in top models (Table 3). Lake Ontario was the only lake to have vegetation structure included in the top model.

Discussion

Yellow Perch occupancy and detection probability in coastal wetlands varied across Great Lakes and wetland types. Yellow Perch had a greater probability of being present in coastal wetlands in with a riverine connection, areas with a greater depth, and a lower specific conductivity. However, detecting the species was least likely in Lake Erie. Although depth was an important covariate for detection probability, there was no clear trend.

We predicted that Yellow Perch detection probability would vary among the Great Lakes, which our results seem to agree with. The lake covariate appeared in every basin-wide model for detection probability (Table 3) and was very similar among all of the Great Lakes, except for Lake Erie (Table 2). In addition, the top models for each of the Great Lakes had many different covariates for Yellow Perch detection, suggesting that there are different factors within Great Lakes that influence the detection probability of Yellow Perch with our fyke net sampling method (Table 3). In the instances where covariates appeared in models for detection probability for more than one of the Great Lakes, some of the covariates, such as pollution, had a positive association for one lake (e.g., Lake Huron) and a negative association for another lake (e.g., Lake Ontario; Table 7).

Although we predicted that wetland class would be an important covariate for Yellow Perch occupancy and detection, class only appeared as a covariate in one of our top basin-wide models. However, hydrologic connection, which appeared in many top models, is related to wetland class. The hydrologic connection “strictly riverine connection to the lake” had the highest occupancy among all of the wetland classifications, which essentially means riverine wetlands (Table 6). Our results showed that wetlands with a riverine connection had the highest occupancy. This contradicts findings by Parker et al. (2012), who also sampled for Yellow Perch with fyke nets and found that Yellow Perch were more abundant in lacustrine than riverine wetlands. We only used presence/absence in our analyses and not catch per unit effort like Parker et al. (2012), which could be responsible for some differences, but we found that Yellow Perch had a greater association with wetlands that had a riverine connection compared to wetlands that were fully exposed or protected by a barrier (i.e., barrier or lacustrine wetlands). However, Parker et al. (2012) included only wetlands in Lake Michigan and Saginaw Bay, Lake Huron, and not across the entire Great Lakes basin.

The hydrologic connection of the wetland was an important variable for Yellow Perch occupancy and detection at the basin-wide scale as well as for several of the Great Lakes. The connectivity of a wetland is a characteristic that is often altered by anthropogenic disturbances, such as adding or removing dikes or sandbars by dredging, adding break walls or channels, etc. (Albert et al. 2005). When a wetland is separated from the Great Lake (i.e., barrier wetland), it likely limits fish movement between the wetland and the nearshore Great Lake habitat, which we hypothesize could be the reason for decreased Yellow Perch occupancy in wetlands with less of a hydrologic connection to the Great Lake.

Specific conductivity was the only chemical/physical variable that showed up in the top models. In general, as specific conductivity increased the occupancy of Yellow Perch decreased (Figure 3c). Specific conductivity has been shown to be positively correlated with disturbance (Uzarski et al. 2005). We also investigated the effect of total phosphorus in our models, but it was not a strong covariate for Yellow Perch occupancy or detection, so we excluded it from our models. It is difficult to make conclusions for some of the water chemical/physical parameters that we investigated (i.e., temperature, dissolved oxygen) because they were only measured as a snapshot of one time at a site, and the time of measurement is not standardized across all sites and can be taken at any point during the day. Many water chemical/physical variables, such as dissolved oxygen, temperature and pH, vary throughout a diel cycle in Great Lakes coastal wetlands (Nelson et al. 2009; Cooper et al. 2013) so time of measurement could impact our results. However, previous research by Cvetkovic et al. (2010) found that fish in Great Lakes coastal wetlands had a stronger response to the plant community than water quality variables.

The sampling depth of our fyke nets was also an important variable for Yellow Perch occupancy and detection at the basin-wide scale and in several individual Great Lakes. The depth that fyke nets were set increased from 2011 to 2015, as water levels in the Great Lakes continually fluctuate, with an overall trend of increasing during our study (Uzarski et al. 2017). Monitoring of Great Lakes water levels has shown that Lake Superior rose about 0.6 m and lakes Michigan and Huron rose almost 1.0 m in just two years from 2012 to 2014 (Gronewold et al. 2015). Our results suggest that changes in water levels that we observed during our study can have a substantial impact on Yellow Perch occupancy and detection in Great Lakes coastal wetlands.

The importance of water depth for Yellow Perch occupancy also brings up the concern of water use within the Great Lakes basin. Historically, there have been many disagreements and court cases about water withdrawals outside of the Great Lakes basin and water use within the basin (Annin 2009). Even though we have seen water levels in the Great Lakes rising in recent years, with growing populations, an increased need for water for human consumption, and the threat of warming temperatures due to climate change (Kling et al. 2003), we could start to see declines in Great Lakes water levels in the near future. Based on the occupancy models we developed, a decrease in water depth in Great Lakes coastal wetlands could lead to a decrease in Yellow Perch occupancy.

The importance of both hydrologic connection and specific conductivity for Yellow Perch occupancy suggests that Yellow Perch have a strong response to anthropogenic disturbances in or around Great Lakes coastal wetlands. Maintaining a natural connection to a Great Lake can be directly tied in with depth, both of which are important for the presence of Yellow Perch. Whereas disturbing a wetland, whether for development, dredging, etc., and increasing the specific conductivity through that disturbance has the potential to decrease Yellow Perch occupancy in the area. In order to provide the best Yellow Perch habitat, we need to protect coastal wetlands from future anthropogenic disturbances.

There were changes in the importance of covariates in our models for both Yellow Perch occupancy and detection changed when we changed the spatial scale of our analysis from the basin-wide scale to each individual Great Lake. The basin-wide models were different from the individual lake models, and the individual lake models also differed from each other, although there was some overlap. This suggests that there is a different suite of factors within each Great Lake that influence Yellow Perch occupancy and detection at the spatial scale of individual lakes. Since lake was an important covariate for detection probability at the basin-wide scale, and the covariates for Yellow Perch detection probability vary among the Great Lakes, this emphasizes that researchers and managers must be aware of potential biases when comparing Yellow Perch catch across Great Lakes. Habitat can be quite different between Great Lakes, and Yellow Perch populations within coastal wetlands of different Great Lakes are facing different threats and levels of disturbance. Although we do not have to worry about false positives with research like this because we will never catch a fish when it is not there, it is still important to know when we are getting false negatives in our sampling so our research can be as accurate as possible. Although in most cases our naïve estimates were close to our model predicted estimates, using occupancy modeling to determine key characteristics of wetlands that Yellow Perch commonly use could also help guide future coastal wetland restoration or protection efforts. In addition, using occupancy modeling to monitor trends in species occupancy instead of species abundance can be an order of magnitude cheaper for managers because less effort is needed (MacKenzie 2002; Steenweg et al. 2016).

With climate change (Kling et al. 2003), increased development, and the constant possibility of new aquatic invasive species entering the Great Lakes (e.g., bighead carps or snakeheads; Lauber et al. 2016), it is important to understand how native species, such as Yellow Perch, might be impacted. Mortsch et al. (2006) used possible climate change scenarios to predict the impacts on Great Lakes coastal wetlands, and they ranked Yellow Perch as highly vulnerable to the predicted habitat changes. Using occupancy models, we could similarly estimate changes in Yellow Perch occupancy with changing environmental conditions. Trebitz and Hoffman (2015) found that Yellow Perch responded negatively to an anthropogenic disturbance gradient in Great Lakes coastal wetlands, which they state could make Yellow Perch useful as an indicator species for these areas. Uzarski et al. (2005) also found that specific conductivity, which was in many of our top models, was associated with greater anthropogenic disturbance. Similarly, Brazner (1997) captured more Yellow Perch at undeveloped wetland sites compared with developed sites. Lauber et al. (2016) predicted possible scenarios of various aquatic invasive species entering the Great Lakes, and many scenarios predicted a decrease in Yellow Perch populations. They also proposed the scenario that Yellow Perch populations may be unharmed or even increased by an invasion of bighead carps because they have a wide enough niche and could avoid competition. However, other scenarios, such as invasion by the aquatic macrophyte *Hydrilla*, showed a decline in Yellow Perch populations of up to 30% in some areas of the Great Lakes (Lauber et al. 2016). Such a strong response to changing vegetation coincides with our results that vegetation structure is an important component of Yellow Perch habitat. Applying occupancy models with data from large scale projects like the Great Lakes Coastal Wetlands Monitoring Program will allow us to continue to monitor Yellow Perch populations as they face the effects of climate change, aquatic invasive species, and anthropogenic disturbances that are impacting the Great Lakes.

Conclusions

Our results showed that the Yellow Perch is unevenly distributed across Great Lakes coastal wetlands with respect to depth, specific conductivity, and hydrologic connection at the basin-wide scale. We also predicted that there would be a greater chance of Yellow Perch being present in wetlands with intermediate water-column productivity, which was partially supported by our results. Due to sampling inconsistency, we were unable to use many of the covariates related to water column productivity, which we had predicted would affect Yellow Perch occupancy. In addition, vegetation type did not appear in any of our top models like we had predicted, suggesting that other wetland habitat factors (e.g., water quality) influence Yellow Perch occupancy more than the vegetation type. Vegetation structure did appear in several top models though, so perhaps Yellow Perch prefer to have vegetation, but are not as selective about which vegetation type is present. However, our results showed that Yellow Perch occupancy is strongly related to specific conductivity, suggesting that Yellow Perch do respond to the level of disturbance in a wetland. Additionally, our results also supported the idea that there is spatial variation in the detection probability of Yellow Perch with the fyke-net sampling method used throughout the Great Lakes. The detection probability of Yellow Perch in fyke nets was not consistent across our study area, but the detection probability was very similar among four of the five Great Lakes, and among the different wetland types. We predicted that vegetation type would influence Yellow Perch detection, but it did not appear in any top models, suggesting that fyke nets can be consistent when sampling across different vegetation types. Our results showed that fyke nets can still be a reliable method for sampling Yellow Perch in Great Lakes coastal wetlands, even when sampling different vegetation types or wetlands in different Great Lakes, although caution should be used when comparing Lake Erie to the other Great Lakes. Fish have been considered to be an important indicator of water quality (Hubbs and Lagler 2004), which stresses the need to monitor and maintain populations of Great Lakes fishes, such as Yellow Perch.

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Table 1. Covariates used in occupancy models for Yellow Perch in Great Lakes coastal wetlands.

Covariate Name	Description	Possible Values
class	Classification of the wetland	Barrier, lacustrine, riverine
depth	Average of net depth when set and net depth when pulled	0.19 – 1.13 meters (mean = 0.64 m)
hc	Hydrologic connection of the wetland	a = strictly riverine connection to the lake; b = fully exposed to deep water portion of the lake c = fully exposed; partially protected from direct wave action d = partially protected; opening is a large river e = partially protected; opening is a small stream f = fully separated from lake, but seasonal inundation possible g = fully separated from lake
lake	Great Lake basin the wetland is located in	Erie, Huron, Michigan, Ontario, Superior
lat	Latitude of the sampling site	41.3750 – 48.2074
pol	Pollution observed at the site (i.e., public litter, commercial refuse, petroleum, large equipment, household appliances, or sewage)	0 = no pollution 1 = pollution observed
rec	Recreation observed at the site (i.e,, swimming, sailing, fishing, boating, or personal watercraft)	0 = no recreation 1 = recreation observed
sc	Average specific conductivity of 3 measurements in a vegetation zone	60.0 - 2147.9 µS/cm (mean = 316.4)
vs	Vegetation structure of the sampling zone	zones by depth, uniform distribution, or patchwork mosaic

Table 2. The estimated occupancy (ψ) and detection probability (*P*) with standard errors for Yellow Perch in Great Lakes coastal wetlands for each of the Great Lake basins. Estimates were made with a model that only included lake as a covariate to remove any effects from other covariates. Naïve occupancy was calculated by the number of sites that Yellow Perch were captured divided by the total number of sites sampled for each lake (Lake Superior: *n* = 44; Lake Ontario: *n* = 104; Lake Michigan: *n* = 60; Lake Huron: *n* = 103; Lake Erie: *n* = 37).

Lake	Naïve ψ	Predicted ψ	ψ SE	Predicted *P*	*P* SE
Superior	0.75	0.7841	0.0696	0.6799	0.0524
Ontario	0.75	0.7756	0.0447	0.6792	0.0341
Michigan	0.67	0.6845	0.0631	0.7037	0.0459
Huron	0.62	0.6403	0.0497	0.6909	0.0369
Erie	0.35	0.5721	0.2019	0.2720	0.1055

Table 3. Yellow Perch occupancy models using basin-wide data, and subsets of Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario data. The quasi-likelihood Akaike's information criterion adjusted for sample size (QAIC$_C$) was used for model selection for the datasets with overdispersion, and AIC$_c$ was used for those without overdispersion (i.e., $\hat{c} \leq 1$). ΔQAIC$_C$/ ΔAIC$_C$ indicates the difference from the top model within each suite of models for each Great Lake, and the w_t is the weight of each model. Occupancy (ψ) and detection probability (P) were analyzed with a base model (.), which held occupancy and/or detection probability constant, and also using covariates, which included depth, specific conductivity (sc), hydrologic connection to the lake (hc), wetland class (class), vegetation structure (vs), Great Lake basin (lake), latitude of the site (lat), recreation observed at the site (rec), and pollution observed at the site (pol). Each variable is defined in Table 1. The overdispersion parameter ($\hat{c}$) = 3.23 for the basin-wide dataset, $\hat{c}$ = 1.3 for Lake Superior, $\hat{c}$ = 1.41 for Lake Michigan, $\hat{c}$ < 1 for Lake Huron, $\hat{c}$ = 2.4 for Lake Erie, and $\hat{c}$ = 1.5 for Lake Ontario.

		Within suite	
Spatial scale	Model	ΔQAIC$_C$/ ΔAIC$_C$	w_t
Basin-wide (n = 348)	ψ(depth+sc+hc), P(lake+depth)	0.00	0.24
	ψ(depth+hc), P(lat+depth)	0.20	0.21
	ψ(depth+sc), P(depth+lake)	1.20	0.13
	ψ(depth+hc), P(depth+lake+vs)	1.25	0.13
	ψ(depth+sc), P(lake)	2.09	0.08
	ψ(sc+depth+hc+vs), P(lake+depth)	2.66	0.06
	ψ(class+depth), P(lake+depth)	3.07	0.05
	ψ(depth), P(depth)	3.40	0.04
	ψ(sc), P(depth+lake)	3.59	0.04
	ψ(pol+rec), P(depth+lake)	5.30	0.02
	ψ(.), P(.)	9.02	0.00
Superior (n = 44)	ψ(lat+sc), P(lat+depth)	0.00	0.47
	ψ(lat), P(lat+depth)	1.09	0.27
	ψ(depth), P(depth)	2.29	0.15
	ψ(lat+rec), P(lat+depth)	2.77	0.12
	ψ(.), P(.)	16.4	0.00
Michigan (n = 60)	ψ(hc), P(depth+lat)	0.00	0.23
	ψ(hc), P(depth+rec)	0.34	0.19
	ψ(hc+sc+vs), P(depth+lat)	0.72	0.16
	ψ(hc+sc), P(rec)	0.99	0.14
	ψ(hc+pol), P(depth+lat)	1.27	0.12
	ψ(rec), P(rec)	2.38	0.07
	ψ(hc), P(hc+rec)	2.61	0.06
	ψ(.), P(.)	3.62	0.04
Huron (n = 103)	ψ(depth+hc+sc), P(pol+depth)	0.00	0.44
	ψ(depth+hc+sc), P(pol)	0.03	0.44
	ψ(depth+hc), P(pol+vs+depth)	2.61	0.12
	ψ(.), P(.)	26.81	0.00
Erie	ψ(sc), P(.)	0.00	0.35

(*n* = 37)	ψ(.), P(sc)	1.01	0.21
	ψ(sc), P(rec)	2.20	0.12
	ψ(sc), P(sc)	2.65	0.09
	ψ(sc+hc), P(.)	2.67	0.09
	ψ(sc), P(pol)	2.68	0.09
	ψ(.), P(.)	3.68	0.05
Ontario (*n* = 104)	ψ(lat+depth), P(lat+hc+pol+vs+sc)	0.00	0.30
	ψ(lat), P(lat+hc+pol+vs)	0.49	0.24
	ψ(lat), P(lat)	1.15	0.17
	ψ(.), P(pol+vs)	1.49	0.14
	ψ(sc), P(sc)	2.54	0.08
	ψ(.), P(.)	3.04	0.07

Table 4. Coefficients for model parameters with 95% confidence interval for the two top-ranked, basin-wide models for Yellow Perch occupancy (Ψ) and detection (*P*) in Great Lakes coastal wetlands (*n* = 348).

covariate	top model	second model
Ψ (intercept)	-0.07 (-0.96, 0.70)	-0.59 (-1.50, 0.32)
Ψ (sc)	-0.001 (-0.003, 0.0002)	
Ψ (depth)	3.13 (1.72, 4.24)	3.29 (1.81, 4.78)
Ψ (hc)	-0.32 (-0.51, -0.13)	-0.33 (-0.51, -0.14)
P (Intercept)	-2.27 (-3.26, -1.27)	-11.02 (-17.49, -4.55)
P (lake: LH)	2.00 (1.29, 2.72)	
P (lake: LM)	2.27 (1.50, 3.05)	
P (lake: LO)	1.75 (1.07, 2.43)	
P (lake: LS)	1.92 (1.15, 2.68)	
P (lat)		0.24 (0.10, 0.38)
P (depth)	1.65 (0.55, 2.74)	1.38 (0.36, 2.39)

Table 5. The estimated occupancy (ψ) and detection probability (*P*) with standard errors for Yellow Perch in Great Lakes coastal wetlands for the variable hydrologic connection. Estimates were made with a model that only included hydrologic connection as a covariate to remove any effects from other covariates. Naïve occupancy was calculated by the number of sites that Yellow Perch were captured at divided by the total number of sites sampled for each hydrologic connection option (a: *n* = 85; b: *n* = 103; c: *n* = 64; d: *n* = 40; e: *n* = 41; f: *n* = 12; g: *n* = 3). See Table 1 for hydrologic connection descriptions.

hydrologic connection	Naïve ψ	Predicted ψ	ψ SE	Predicted *P*	*P* SE
a	0.73	0.7729	0.0529	0.6312	0.0405
b	0.70	0.7125	0.0463	0.7334	0.0327
c	0.63	0.6455	0.0632	0.6833	0.0473
d	0.65	0.6726	0.0791	0.6775	0.0593
e	0.56	0.6536	0.1020	0.4786	0.0763
f	0.42	0.4230	0.1437	0.7929	0.1020
g	0.00	<0.0001	NA	0.0298	NA

Table 6. The estimated occupancy (ψ) and detection probability (*P*) with standard errors for Yellow Perch in Great Lakes coastal wetlands for each wetland classification (class) using the basin-wide dataset. Estimates were made with a model that only included class as a covariate to remove any effects from other covariates. Naïve occupancy was calculated by the number of sites that Yellow Perch were captured divided by the total number of sites sampled for each class. Riverine wetlands had the largest sample size with 169 (*n* = 22 in Lake Michigan; *n* = 33 in Lake Superior; *n* = 22 in Lake Erie; *n* = 53 in Lake Ontario; *n* = 39 in Lake Huron), 140 sites were lacustrine (*n* = 30 in Lake Michigan; *n* = 5 in Lake Superior; *n* = 11 in Lake Erie; *n* = 33 in Lake Ontario; *n* = 61 in Lake Huron), and 39 sites were barrier wetlands (*n* = 8 in Lake Michigan; *n* = 6 in Lake Superior; *n* = 4 in Lake Erie; *n* = 18 in Lake Ontario; *n* = 3 in Lake Huron).

Classification	Naïve ψ	Predicted ψ	ψ SE	Predicted *P*	*P* SE
riverine	0.69	0.7393	0.0395	0.6072	0.0303
lacustrine	0.65	0.6623	0.0413	0.7350	0.0290
barrier	0.51	0.5255	0.0825	0.7109	0.0646

Table 7. Coefficients for model parameters with 95% confidence interval for the top model for Yellow Perch occupancy (Ψ) and detection (*P*) in Great Lakes coastal wetlands for each Great Lake basin subset (Lake Superior: *n* = 44; Lake Ontario: *n* = 104; Lake Michigan: *n* = 60; Lake Huron: *n* = 103; Lake Erie: *n* = 37).

covariate	Superior	Michigan	Huron	Erie	Ontario
Ψ(intercept)	16.35 (-129.97, 162.67)	1.92 (0.66, 3.18)	-1.71 (-3.60, 0.19)	8.34 (0.51, 16.17)	-114.41 (-200.11, -28.70)
Ψ(sc)	0.04 (-0.02, 0.10)		0.004 (-0.001, 0.01)	-0.02 (-0.04, -0.002)	
Ψ(depth)			5.16 (1.98, 8.35)		4.32 (0.53, 8.10)
Ψ(hc)		-0.51 (-0.97, -0.05)	-1.00 (-1.62, -0.38)		
Ψ(lat)	-0.42 (-3.52, 2.68)				2.58 (0.64, 4.52)
P(intercept)	50.99 (-7.85, 109.83)	-25.67 (-46.32, -5.02)	-0.44 (-1.59, 0.72)		-21.34 (-65.22, 22.54)
P(depth)	7.38 (4.33, 10.42)	3.19 (0.53, 5.85)	1.28 (-0.38, 2.93)		
P(lat)	-1.1 (-2.44, 0.08)	0.55 (0.11, 1.00)			0.50 (-0.49, 1.49)
P(pol)			1.22 (0.44, 2.00)		-0.77 (-1.40, -0.14)
P(vs: patchwork)					-0.93 (-1.98, 0.12)
P(vs: uniform)					0.77 (0.05, 1.49)
P(sc)					0.002 (-0.001, 0.004)
P(hc)					-0.18 (-0.37, 0.01)
P(.)				-0.78 (-1.48, -0.08)	

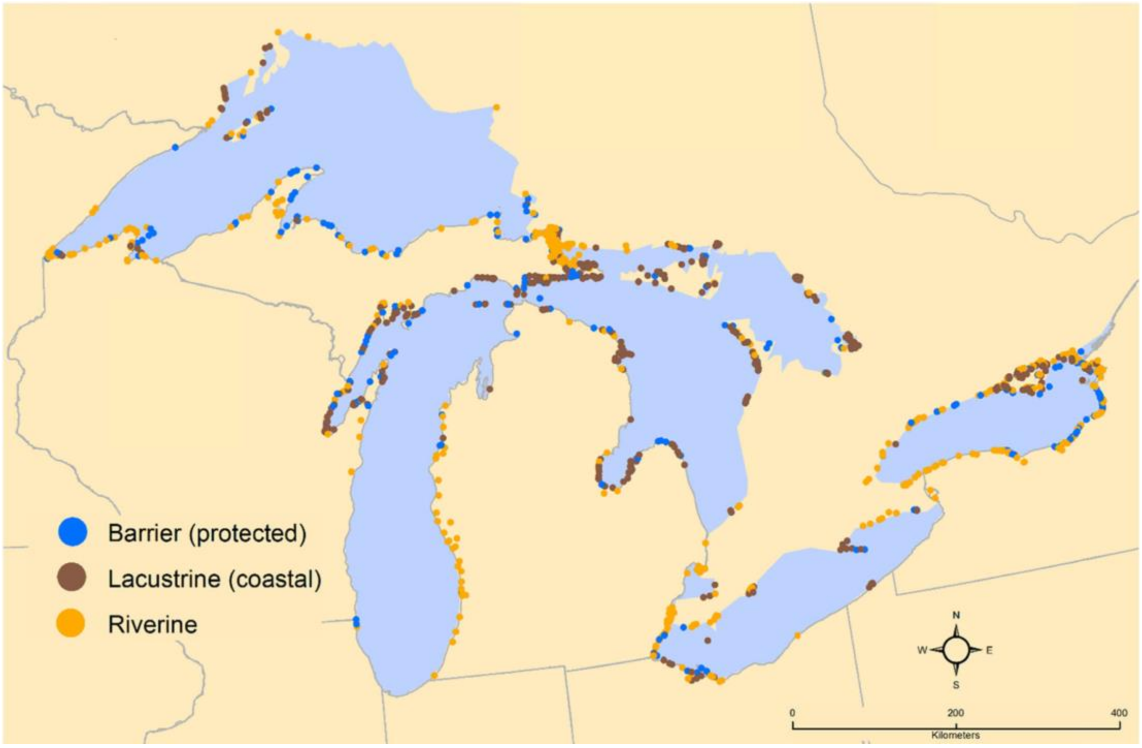


Figure 1. Locations and classifications of the Great Lakes Coastal Wetlands Monitoring Program sampling sites (Uzarski et al. 2017).

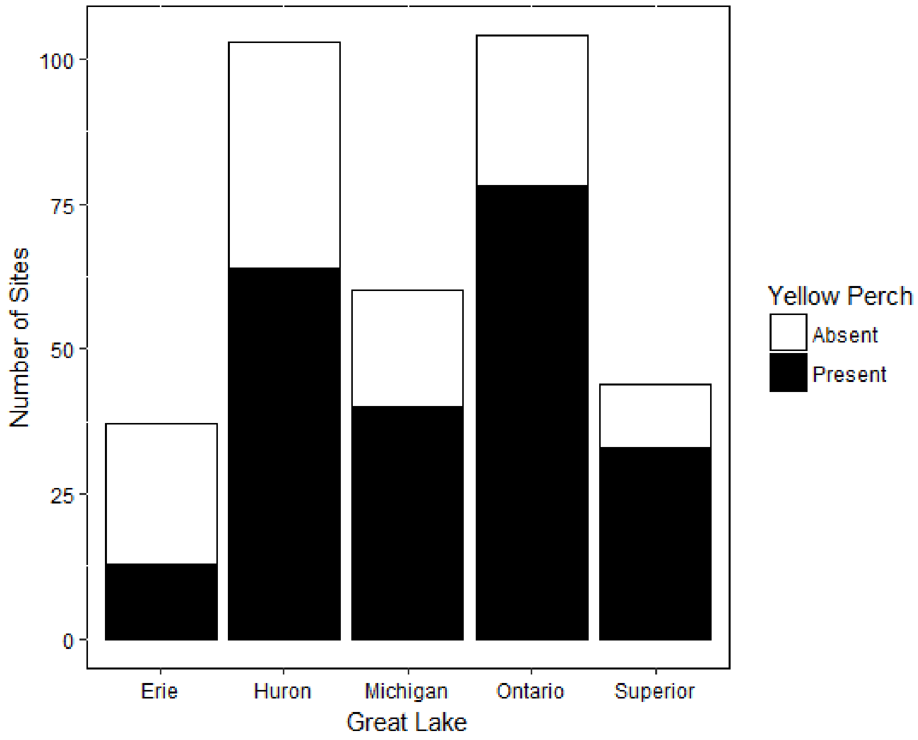
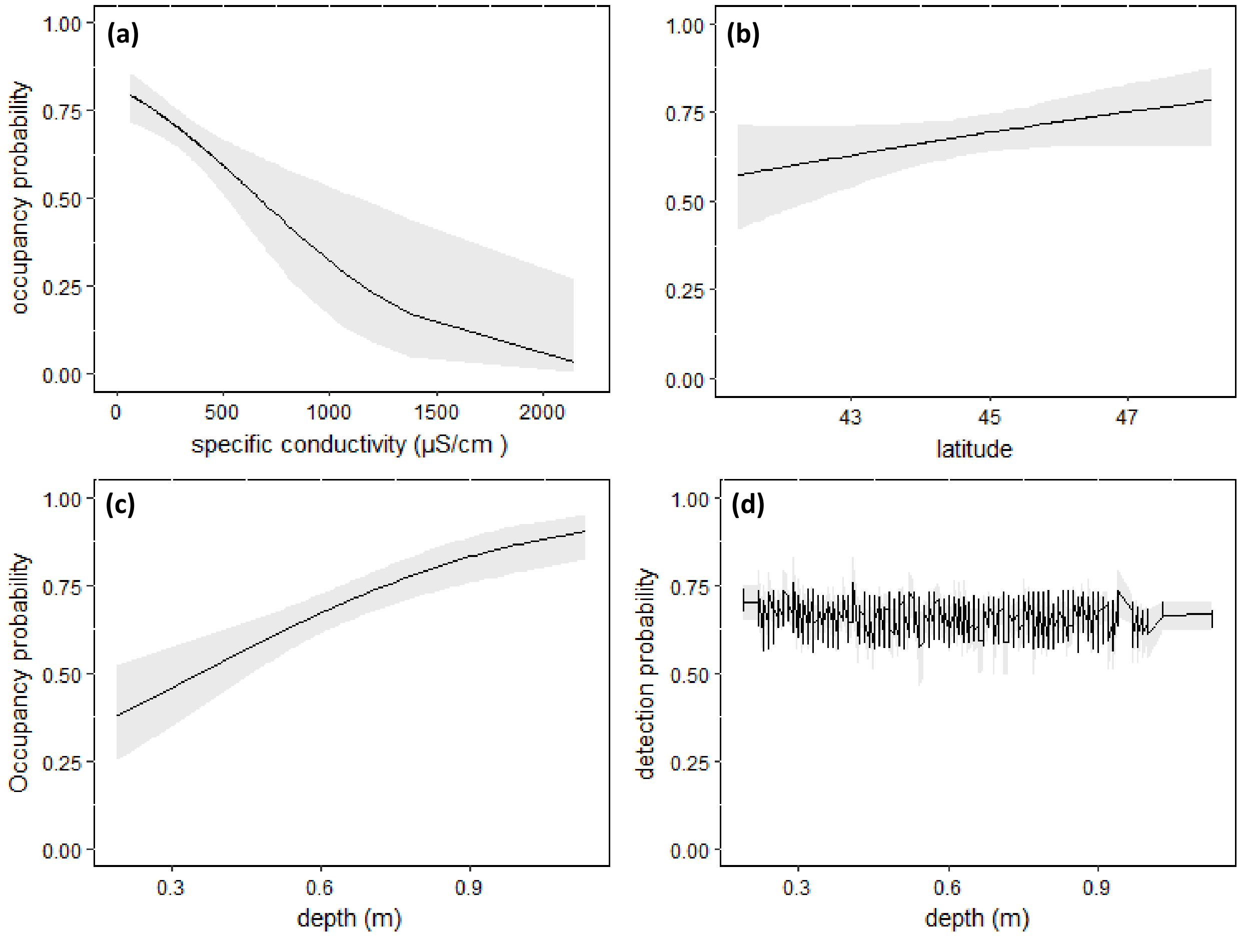


Figure 2. Presence/absence of Yellow Perch in coastal wetlands across the Great Lakes between 2011 and 2015 (*n* = 348).

Figure 3. Predicted Yellow Perch occupancy with 95% confidence interval for **(a)** specific conductivity measured at the sampling site (µS/cm), **(b)** latitude of the sampling site, **(c)** water depth (m) fyke nets were fished in, and **(d)** predicted detection probability for the water depth fyke nets were fished in. The response is based on an occupancy model with only the covariate of interest in order to avoid confounding effects.



Chapter III

Extended Review of Literature

Great Lakes Coastal Wetlands

The Laurentian Great Lakes are located halfway between the equator and the North Pole with shorelines in both the United States and Canada, consisting of lakes Erie, Huron, Michigan, Ontario, and Superior (Hubbs and Lagler 2004). They hold one fifth of the world's surface freshwater and cover an area of roughly 244,000 km^2 (Lauber et al. 2016). The Great Lakes are bordered by eight U.S. states and one Canadian province, with over 17,000 km of shoreline (Hubbs and Lauber 2004), which is more than the combined shoreline of the entire east coast and west coast of the United States (Cooper and Uzarski 2016).

A wetland is defined "as land where the water table is at, near, or above the land surface long enough to promote the formation of hydric soils or to support the growth of hydrophytes" (Cowardin et al. 1977, Herdendorf et al. 1981). Wetlands that are connected to the waters of the Great Lakes are often called coastal wetlands, and they are found in all five Great Lakes and their connecting channels (Keough et al. 1999). Great Lakes coastal wetlands are an important feature for the surrounding environment as they provide water retention, sediment removal, nursery areas for wildlife and fish, and invertebrate prey for juvenile and adult fishes (Jude and Pappas 1992). Great Lakes coastal wetlands can be broken down into three hydrogeomorphic classifications: lacustrine, riverine, and barrier-protected (Albert et al. 2005; Uzarski et al. 2016a). Albert et al. (2005) describes lacustrine being directly controlled by Great Lakes waters, riverine wetlands as associated with creeks and rivers connected to the Great Lakes, and barrier-protected as wetlands protected from the Great Lakes by some kind of natural or artificial barrier (Albert et al. 2005). The hydrology and geomorphic features of these different types of wetlands along with factors such as the water temperature, dissolved oxygen (DO), turbidity, fetch, direction and extent of currents, watershed drainage, and nearby urban development impact wetland productivity and ultimately the macrophyte and organism diversity (Keough et al. 1999). While water quality does impact aquatic communities (Keough et al. 1999), Cvetkovic et al. (2010) found that fish communities in Great Lakes coastal wetlands have a greater association with the macrophyte community present than the water quality.

Great Lakes coastal wetlands provide habitat for more than 80 species of fish, including fishes important to recreational and commercial harvest, and waterfowl, amphibians, reptiles, birds, mammals, and over 300 genera of invertebrates (Herdendorf et al. 1981; Uzarski et al. 2005; Cooper and Uzarski 2016). It is estimated that recreational fishing in the Great Lakes brings in about $7 billion a year for local economies (Lauber et al. 2016). A recent survey of Great Lakes coastal wetlands estimated that approximately 50% of the commercially harvested fish and more than 80% of the recreationally harvested fish in the Great Lakes use coastal wetland habitat at some point in their life (Trebitz and Hoffman 2015). Coastal wetlands provide nursery habitat, cover for juvenile and forage fish, and feeding grounds for predatory fish (Herdendorf et al. 1981). Some of these important sport fishes that use coastal wetlands, typically as juveniles, include walleye (*Sander vitreus*), smallmouth bass (*Micropterus dolomieu*), and Yellow Perch (*Perca flavescens*) (Herdendorf et al. 1981). Several fishes (e.g., Yellow Perch, alewife (*Alosa pseudoharengus)*, and spottail shiners (*Notropis hudsonius*)) will spawn in wetlands earlier in the spring, and then spawn again in the Great Lakes once the water temperature increases to their preferred range (Jude and Pappas 1992).

Even though Great Lakes coastal wetlands are important, they have been lost at alarming rates, with as great as 50% of the historic coastal wetlands lost to agricultural conversion or drainage over the last 100 years (Parker et al. 2012; Uzarski et al. 2017). Many of the remaining coastal wetlands have been degraded or altered in some way (Jude and Pappas 1992), and nutrient loading and fragmentation are two of the main factors currently impacting wetlands (Parker et al 2012). The Great Lakes Environmental Indicators Program identified the main anthropogenic disturbances currently affecting coastlines of the Great Lakes to be sediment, nutrient, and chemical pollution from agricultural activities, increased population densities and development (including natural land cover alteration and shoreline modifications), and point source pollution (Bhagat et al. 2007).

Ecology of Yellow Perch

The Yellow Perch is a native freshwater fish species found in the Great Lakes. They are members of the Percidae family, which is a group of spiny-rayed fishes with ctenoid scales, thoracic pelvic fins, and typically two separated dorsal fins (Hubbs and Lagler 2004). Yellow Perch are typically yellow with dark vertical bars. Adults are typically less than 35 cm and weigh less than 500 g (Hubbs and Lagler 2004). Yellow Perch are often associated with shallow depths, heavy aquatic vegetation, and are relatively tolerant of low dissolved oxygen (DO [Brown et al. 2009]), which makes wetlands very suitable habitats for them. Yellow Perch are slow swimmers (Herman et al. 1959), so it is important that they have vegetation structure to hide from predators. The diet of Yellow Perch typically consists of small, live animal foods. Their diet generally shifts from zooplankton in the larval stage, to insects, invertebrates and juvenile fish as an adult (Herman et al. 1959; Brown et al. 2009; Parker et al. 2009). Yellow Perch have comb-like gill rakers, which allow them to strain out small foods such as plankton or midge larvae (Herman et al. 1959). Yellow Perch spawn in the spring, and lay their eggs in a protective casing, or skein, which they drape over a structure such as vegetation (Treasurer 1981; Becker, 1983; Almeida et al. 2017). The chemical composition of Yellow Perch egg skeins has been shown to reduce the predation on the eggs by other fishes, such as round goby (*Neogobius melanostomus*), by making them less appealing than other fish eggs (Almeida et al. 2017). Individual round goby were observed attempting to consume Yellow Perch egg skeins during their first exposure to them, but they would spit them back out and did not attempt to feed on them during any following exposures (Almeida et al. 2017). Thus, Yellow Perch egg skeins can increase survival by reducing predation (Almeida et al. 2017). Suitable spawning habitat is an important factor for Yellow Perch hatching success, specifically the presence of substrate or vegetation structure to lay eggs on, and suitable temperatures for development and maturation (Clady 1976; Krieger et al. 1983; Brown et al. 2009).

The Yellow Perch is one of the most abundant fishes in Great Lakes coastal wetlands (Jude and Pappas 1992) and they are ecologically and economically important to the Great Lakes region (Becker 1983). The Yellow Perch is an important species in the Great Lakes for commercial harvest and sport fishing (Trebitz and Hoffman 2015), and it is one of the most frequently caught sport fishes in Michigan (MDNR 2016). Yellow Perch also serve as prey for other popular sport fishes, including walleye, northern pike (*Esox lucius*), and largemouth bass (*Micropterus salmoides*; Herman et al. 1959; Brown et al. 2009).

Several life stages (e.g., larvae, juvenile, and spawning adult) of Yellow Perch use coastal wetlands as important spawning and nursery habitat as well as areas to provide better foraging and cover for juveniles (Brazner et al. 2004; Janetski et al. 2013; Schoen et al. 2016), although Yellow Perch do not exclusively spawn in coastal wetlands. During the adult stage, Great Lakes Yellow Perch often form schools in deeper nearshore areas, returning to coastal wetlands to spawn, although some adults still frequent coastal wetlands throughout the year (Brazner et al. 2001; Schoen et al. 2016). Since coastal wetlands are usually warmer than the deeper, nearby areas of the Great Lakes, Yellow Perch typically hatch earlier and have a longer growing season in coastal wetlands, allowing fish to reach larger sizes before winter (Jude and Pappas 1992; Parker et al. 2012). Wetland productivity can be crucial for larval Yellow Perch, as Dettmers et al. (2003) found that zooplankton biomass is strongly linked to Yellow Perch recruitment.

In lakes Huron and Michigan, Yellow Perch have been found to be more abundant in coastal fringing wetlands than drowned river mouth wetlands, likely because of the intermediate productivity combined with a lower chance of hypoxic conditions due to more water flow (Parker et al. 2012), but previous studies only examined distributions between wetland types, not within wetlands. Within wetlands of the same classification, many other factors can vary and impact habitat suitability such as vegetation type and structure, water chemical factors (e.g., pH, alkalinity, nitrogen, phosphorus, etc.), and even latitude can have an impact because the Great Lakes cover such a large area.

Although Great Lakes Yellow Perch and their habitats have been studied in recent years, knowledge gaps still remain in the literature. Previous Yellow Perch studies in the Great Lakes have typically been on smaller spatial scales than the entire Great Lakes basin, and also have not accounted for incomplete detection. For example, Janetski et al. (2013) studied Yellow Perch recruitment patterns in a drowned river mouth lake, Muskegon Lake, which is connected to Lake Michigan, and found that warmer conditions during early larval stages seemed to increase Yellow Perch recruitment. However, catch per unit effort was used for analysis without accounting for the less than perfect detection probability of the fyke nets or bottom trawls used for sampling.

Occupancy Modeling

Incomplete detection (i.e., the presence of a species that is not detected by sampling) is a common problem with many sampling methods and can make estimates of occupied sites inaccurate or biased if not accounted for (MacKenzie et al. 2003; Bailey et al. 2013; Guillera-Arroita et al. 2014). Previous studies on fishes in the Great Lakes or Yellow Perch have not explicitly accounted for the detection probability of the sampling method.

Occupancy modeling, developed by MacKenzie et al. (2002), is one of the newest, most accurate methods for estimating species occurrence and abundance because it accounts for incomplete detection (Bailey et al. 2013). For occupancy modeling, presence or absence data are collected for a species at multiple sampling sites, with repeated surveys at each site, along with site characteristic variables (MacKenzie et al. 2002). Sampling sites must have repeated visits for occupancy modeling to work, and most studies will use three visits, although there is not a required number and it can work with more or fewer visits. Visits can be separate sampling events, or occupancy modeling can also work with increased sampling effort in one visit (i.e., three fyke nets set at one sampling site can count as three “visits”; MacKenzie and Royle 2005). Site occupancy data are represented by a vector of 1s and 0s for each site, representing detection and non-detection, respectively. These data are then analyzed to create models that predict occupancy of a species (MacKenzie et al. 2002; 2003; MacKenzie and Royle 2005). Models are ranked to determine the models with the best fit for the data. Occupancy models have been developed to account for false negatives and determine the detection probability of a sampling method, and site characteristics can be included to estimate the detection probability or occupancy under certain site conditions (Bailey et al. 2013). This allows for more accurate estimation of the distribution of a species compared to traditional naïve estimates (MacKenzie et al. 2002).

Typically, occupancy modeling is used to answer questions about what sites a species occupies, and how effective the sampling method is at detecting the species when it actually is present. There are four main assumptions for occupancy models: 1) sites are closed to changes in occupancy during the sampling period (MacKenzie et al. 2002); 2) all parameters are constant across sites throughout the sampling period (MacKenzie et al. 2003); 3) repeated visits to a site are independent; and 4) there is independence between sampling sites (MacKenzie et al. 2002; Fiske and Chandler 2011). Violating any of these assumptions can result in biased results and inaccurate models (MacKenzie et al. 2002). Additional methods have been developed to work around unavoidable violations of some of the occupancy modeling assumptions. For example, it can be difficult in some instances to sample with complete independence between sites, so an overdispersion parameter can be used to reduce bias in the estimate of occupancy if a lack of independence is suspected (MacKenzie and Bailey 2004; DeVoe et al. 2015).

Occupancy modeling has a wide range of ecological applications, such as habitat relationships, population dynamics, species relationships, community dynamics, and species distribution (MacKenzie and Royle 2005; Bailey et al. 2013). It also has been used to test the efficiency of different sampling methods on a species (Haynes et al. 2013). Occupancy models are useful for population monitoring, especially for large-scale monitoring cases (Efford and Dawson 2012). Occupancy models are also applicable for a variety of organisms, both aquatic and terrestrial, and have been used with Atlantic sturgeon (*Acipenser oxyrinchus*; Flowers and Hightower 2013), Mohave ground squirrels (*Xerospermophilus mohavensis*; Logan 2015), mountain goats (*Oreamnos americanus*; DeVoe et al. 2015), darter species (*Etheostoma* spp.; Magoulick and Lynch 2015; Potoka et al. 2016; Anderson et al. 2012), and many others.

For example, occupancy modeling was used to investigate habitat use by a sensitive species, the Olympic mudminnow (*Novumbra hubbsi*), by identifying habitat features that affect occupancy and detection probability (Kuehne and Olden 2016). An occupancy model for the eastern sand darter (*Ammocrypta pellucida*) was used to assess the biotic and abiotic factors that influence their distribution in order to help restore populations (Dextrase et al. 2014). Occupancy models also were used on six different fish species and sampled with five different gear types in Arctic lakes on the North Slope, Alaska to investigate detection probability and sampling accuracy for both small- and large-bodied fish species (Haynes et al. 2013). DeVoe et al. (2015) used occupancy modeling to determine the accuracy of visual surveys for non-native mountain goats (*Oreamnos americanus*) in the greater Yellowstone area, and also to determine suitable habitat in the area to predict possible range expansion and competition with native Rocky Mountain bighorn sheep (*Ovis canadensis canadensis*). Distribution information from occupancy models allow for better management and protection of species of concern (e.g., Dextrase et al. 2014; DeVoe et al. 2015; Kuehne and Olden 2016) as well as important sport fishes (MacKenzie et al. 2003; Anderson et al. 2012; Guillera-Arroita et al. 2014).

Extended Methodology

Field Methods

Study sites. We conducted this study in coastal wetland sites in all five Great Lakes (Figure 1). Coastal wetlands are considered to be wetlands that are connected to the waters of one of the Great Lakes (Keough et al. 1999). Data were collected as part of the Great Lakes Coastal Wetlands Monitoring Program, a bi-national (U.S. and Canada) collaboration of federal, state/provincial, academic, and non-government organizations, using standardized methods that began sampling in 2011. Through this monitoring program, data are collected for water quality, aquatic macrophytes, aquatic macroinvertebrates, birds, anurans, and fishes, although the focus of this study is primarily on fish, more specifically Yellow Perch. More detail on sampling methods can be found in Uzarski et al. (2017). Coastal wetlands sampled consisted of the roughly 1000 major coastal wetlands that were considered sampleable by the Great Lakes Wetland Consortium. Criteria for a wetland to be sampleable were that it has an area greater than 4 hectares, has a surface water connection to the Great Lakes, and is accessible for sampling (Uzarski et al. 2017). The Great Lakes Coastal Wetlands Monitoring Program used stratified random selection based on wetland type (i.e., riverine, lacustrine or barrier), region (i.e., northern or southern), and Great Lake (i.e., Erie, Huron, Michigan, Ontario, or Superior) to determine which wetlands were sampled each year. Each year up to 20% of the total sampleable wetlands were sampled, and the selection is on a 5-year rotation (Uzarski et al. 2016a). We used data collected from 2011 through 2015, which is the first 5-year rotation and includes all of the sampleable sites. "Benchmark" sites, to represent the least impacted and most disturbed wetlands, or to help monitor the effectiveness of restoration or conservation efforts, were also included each year in the sampled sites, and these sites were typically sampled annually and made up about 10% of the sites sampled each year (Uzarski et al. 2017).

Data collection. We collected fish and water quality data according to the Standard Operating Procedures (SOP) and Quality Assurance Project Plan (QAPP) created for the Great Lakes Coastal Wetlands Monitoring Program (Uzarski et al. 2016b). We conducted fish sampling between mid-June and early September using 4.8-mm mesh fyke nets in either a large net or small net style depending on water depth. We typically used large fyke nets when the water depth was between 0.5 and 1.0 m, and small fyke nets when the water depth was 0.25 to 0.5 m. Both size nets have the same design and mesh size – the only difference is the dimensions. Large fyke nets have a 7.62 m long by 0.91 m tall lead extended from the mouth of the net. The box at the mouth is 1.22 m wide by 0.91 m tall. Wings extend from each side of the mouth of the box at a 45° angle from the lead and are 1.83 m long by 0.91 m tall. Five 0.76-m diameter hoops come off the box, after which the net ends with a closeable cod-end. The first and third hoops have an inner mesh funnel to prevent fish from swimming back out once they reach the cod end of the net. Small fyke nets have a 0.91 m wide by 0.46 m tall box frame with a center lead of 7.62 m long by 0.46 m tall. The wings from the box extend at a 45° angle from the lead and are 0.46 m tall by 1.83 m long. The small fyke nets also have five hoops, with a 0.30 m diameter and an inner funnel on the first and third hoops with a diameter of 0.075 m. Leads and wings for both the small and the large fyke nets have floats along the top and weights on the bottom (Uzarski et al. 2017). We set fyke nets overnight (about 24 hours), with three fyke nets set perpendicular to shore at each major vegetation zone at up to three vegetation zones in each wetland site. Replicate fyke nets in a zone were separated by at least 25 m. Vegetation zones were monodominant and at least 400 m^2 in extent with a water depth of 25-100 cm to be sampleable with fyke nets (Uzarski et al. 2016b; 2017). Possible vegetation zones included cattail (*Typha*), water lily (*Nuphar-Nyphaea*), dense or sparse bulrush (*Schoenoplectus*), wet meadow, arrow-arum-arrowhead-pickerel weed (*Peltandra-Sagittaria-Pontederia*; PSP), bur-reed (*Sparganium*), *Phragmites*, submersed aquatic vegetation (SAV), and floating bog mat.

We measured the following water quality variables *in situ* (typically mid to late morning, but timing was not standardized) with a water quality sonde (e.g., Yellow Springs Instrument model 6600) where each fyke net was set: temperature (°C), dissolved oxygen (mg/L and % saturation), pH, specific conductivity (µS/cm), chlorophyll-*a* (µg/L), turbidity (Nephelometric Turbidity Units; NTU), total dissolved solids (mg/L), and oxidation-reduction potential (mV). We collected two 1-L grab samples of water just below the surface with an acid-washed polypropylene bottle attached to the end of an extension pole from the same three places per vegetation zone where the fyke nets were set. We pre-filtered each 1-L sample with 500-µm mesh to removed debris and transferred the sample to an acid-washed polypropylene carboy, creating a 6-L composite sample for a single vegetation zone. We mixed the sample and transferred it to a 4-L acid-washed, deionized water rinsed, polypropylene Cubitainer and placed the sample on ice in a dark cooler to be processed later or stored for future analysis. We transferred the remaining sample water in the carboy to a 100-cm transparency tube to measure water clarity. Laboratory analyses of the water samples included measurements of alkalinity (mg/L $CaCO_3$), soluble reactive phosphorus (SRP, mg/L), ammonium-N (mg/L), [nitrate+nitrite]-N (mg/L), total nitrogen (mg/L), total phosphorus (mg/L; TP), chloride (mg/L), and color (see Uzarski et al. (2017) for more detailed water collection and analysis methodology).

We also recorded observations on physical data at each site. We used aerial imagery and ground observations to determine the surrounding land use, wetland classification, and hydrologic connection (Uzarski et al. 2017). In addition, ground observations were used to report any signs of recreational activities at the site or pollution visible at the site.

Data analysis

We conducted all data analyses in program R version 3.3.2 (R Core Team 2016). Using the presence or absence of Yellow Perch in each of the three fyke nets fished at a vegetation zone with corresponding site characteristics, we created occupancy models for Yellow Perch in Great Lakes coastal wetlands (MacKenzie et al. 2002; MacKenzie and Royle 2005) using the R package "unmarked" (Fiske and Chandler 2011, 2017). We used the three fyke nets fished in a vegetation zone as the required repeated visits to the site, which is how detection probability was determined (MacKenzie and Royle 2005). For example, if Yellow Perch were captured at two out of the three nets at a site, then we know Yellow Perch are present at that specific site, but our detection probability is not 100%. In this instance, detection probability would be 66%. Occupancy models analyze not only occupancy and detection probability, but also which environmental covariates are associated with occupancy or detection probability (MacKenzie et al. 2002).

At each site, we sampled all of the vegetation zones that met the sampling criteria. For our analyses, we considered each vegetation zone within a wetland to be a separate site, for a total of 832 vegetation zones sampled during 2011-2015. Hereafter, we refer to each sampled vegetation zone as a site. Due to small sample sizes for some vegetation zones, we removed any that had fewer than 10 sites sampled across the 5-year sampling period. The vegetation zones left in our analyses were: PSP (n = 11), sparse bulrush (n = 63), dense bulrush (n = 47), *Phragmites* (n = 12), SAV (n = 105), *Typha* (n = 61), lily (n = 74), and wet meadow (n = 14). After removing the less common vegetation zones, there were still some wetlands that had multiple samples, either from multiple sampling years (e.g., benchmark sites) or multiple vegetation zones within a wetland. To avoid violating the occupancy modeling assumption of independence between sites (MacKenzie et al. 2002; Fiske and Chandler 2011), we used the function "sample" in program R to randomly select one site within a wetland to keep in our data subset for analyses. Our final subset of data for model development included 387 sites, which were all separate wetland locations.

To determine which environmental covariates to test in occupancy models, we identified factors that likely impact habitat suitability of Yellow Perch. We then analyzed the environmental covariates for correlation with each other to avoid redundancy in our models. Environmental covariates included in our analyses were: vegetation structure; presence of pollution (i.e., public litter, commercial refuse, petroleum, large equipment, household appliances, or sewage), presence of recreation activity (i.e., swimming, sailing, fishing, boating, or personal watercraft), latitude of sampling site, wetland class, hydrologic connection; specific conductivity; and lake basin (see Table 1 for more detail about environmental covariates). Several other covariates, such as dissolved oxygen, temperature, pH, vegetation type, turbidity, total phosphorus, and Julian day were considered for our models but ultimately removed from analyses because they either had a strong correlation with other covariates, had too many missing observations, or had no impact on model rank. Once we determined which environmental covariates to include, we created occupancy models with sets of covariates we had determined *a priori*, and also tested all possible combinations of the covariates for our complete basin-wide dataset, and also with our sites divided by each Great Lake. This resulted in 5 different suites of models. Some additional covariates were removed from the individual lake models due to small sample size. We created a global model (i.e., model that included all of the possible covariates for occupancy and detection), and determined the ĉ value, or overdispersion parameter, for our basin-wide dataset and each individual lake dataset (Richards 2008). All of our data except for Lake Huron had evidence of overdispersion (i.e., ĉ > 1.0) so we used the quasi-likelihood Akaike's information criterion corrected for sample size (QAICc) to rank models, which accounts for overdispersion (Richards 2008). We used Akaike's information criterion corrected for sample size (AICc) to rank the models for Lake Huron because there was no evidence of overdispersion. We compared all models to a base model with no covariates and determined the models that had the best fit based on AICc or QAICc rank (MacKenzie and Bailey 2004). Once we developed our models, we were able to predict Yellow Perch occupancy or detection for a set of environmental conditions, and also determine which covariates had the strongest association with Yellow Perch occupancy or detection probability.

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