Using Satellite Imagery for Fisheries Management

Final Report

Lake Erie Protection Fund Project 365-09

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ABSTRACT

The Maumee River plume (MRP) is a dominant feature of western Lake Erie during spring, likely benefiting fish recruitment by providing nursery habitat to pre-recruits. To explore its importance, we quantified MRP size during 2003-2008, using remotely-sensed (satellite imagery) data, and then related size estimates to habitat quality measures and observed yellow perch (*Perca flavescens*) and walleye (*Sander vitreus*) year-class strengths. Specifically, we generated basin-wide maps (250-m x 250-m resolution) of water clarity for all cloud-free days by developing predictive relationships between atmospherically-corrected MODIS spectral (red, green, blue) values and observed Secchi disk transparency. With these habitat maps, we calculated daily estimates of the areal extent of the MRP, which was then converted into an annual index of MRP size during the larval percid production period (April-May). We found that spring-averaged MRP size varied across years due to Maumee River discharge and wind conditions. MRP size was strongly correlated with indices of yellow perch (R^2 = 0.98) and walleye (R^2 = 0.64) recruitment, with year-class strength increasing exponentially as plume size increased. Our study highlights the importance of external physical forces to Lake Erie ecosystem dynamics and demonstrates how satellite imagery can provide information than can benefit fisheries management.

INTRODUCTION

Western Lake Erie provides nursery habitat for many fishes during their first year of life, including walleye (*Sander vitreus*) and yellow perch (*Perca flavescens*), which are Lake Erie's two most recreationally and economically important fisheries. Nursery-habitat quality for these (and other) species is largely dictated by chemico-physical properties (Smith and Ludsin 2009, Zhao et al 2009, Reichert et al. 2010), which, in Lake Erie's western basin, vary spatiotemporally, owing to wind-driven circulation and inputs from tributaries. In turn, intra- and inter-annual variation in nursery habitat quality may have a large influence on growth, survival, and recruitment of larval fish through its changes in the environment (Zhao et al. 2009, Reichert et al. 2010).

Supporting this notion, yellow perch year-class strength (i.e., age-0 juveniles during August) and recruitment to age-2 have been strongly linked to Maumee River discharge during spring (March through May), a time just prior to and during the larval production period (Ludsin 2000). More recently, Reichert et al. (2010) has shown that Maumee River discharge likely influences yellow perch recruitment through the creation of a plume in open waters of western Lake Erie. Using intensive field sampling and otolith microchemical techniques to trace back larval habitat-use patterns, Reichert et al. (2010) demonstrated that disproportionally more yellow perch juvenile recruits emanated from the Maumee River Plume (MRP) than from other areas of the western basin.

Because juvenile abundance in August is a strong predictor of future recruitment to the fishery for both walleye and yellow perch (Ludsin 2000, Walleye Task Group 2010, Yellow Perch Task Group 2010), we hypothesized that increased Maumee River discharge can positively influence percid recruitment by providing suitable nursery habitat for larvae and juveniles. In this way, we would expect that annual average Maumee River discharge during spring and summer would be positively correlated with 1) average annual MRP size during this time, 2) the spatial "spread" of suitable nursery habitat across western Lake Erie, and 3) recruitment of percid larvae to juvenile stages.

Testing these hypotheses requires the ability to quantify the spatial extent of the MRP; however, because the MRP is a spatially and temporally dynamic entity that can encompass the majority of the western basin at times, accurately measuring its size would be near impossible, using conventional sampling techniques (i.e., synoptic field surveys). As a workaround, researchers in other systems have used remotely-sensed data to characterize plume size and dynamics (Walker 1996, Miller and McKee 2004, Horner-Devine et al. 2998, Shi and Wang 2009). For example, Walker (1996) defined the boundaries and spatial extent of the Mississippi River plume in the northern Gulf of Mexico using satellite imagery by utilizing the distinct differences in the spectral quality of plume and non-plume waters. Similar spectral qualities have been measured in Lake Erie, using satellite imagery (Binding et al. 2007, Binding et al. 2008), but never in the context of river plumes.

Herein, we developed an approach that links remotely sensed data (satellite imagery) to physical habitat quality measurements (e.g., water clarity) made in western Lake Erie to estimate MRP (nursery habitat) size on a daily basis during spring through summer 2003-2008. To test our hypothesis that MRP influences percid recruitment, we subsequently created annual index of MRP size and related it to percid (yellow perch and walleye) habitat-use patterns and year-class strength. In so doing, we also quantified the influence of Maumee River discharge and wind conditions on MRP size.

In conducting this investigation, we accomplished all of our immediate objectives, which were to 1) help fishery management agencies better understand physical habitat distribution and its influence on habitat use and recruitment of walleye and yellow perch, 2) support an ongoing Great Lakes Fishery Commission (GLFC) project by testing the novel hypothesis that Maumee River discharge regulates yellow perch recruitment through nursery habitat creation, and 3) create a limnological database that will be made available to the research community and public through the Lake Erie GIS. Further, our findings should benefit the joint goal of Lake Erie Committee agencies and the Lake Erie Protection Fund to 1) provide a diversity of recreational fishing opportunities for Ohio anglers on Lake Erie waters and tributaries, 2) sustain a commercial fishing industry in Ohio waters of Lake Erie, and 3) obtain baseline data and fill in data gaps for important and measurable attributes of Lake Erie.

METHODS

Generating habitat maps

We generated basin-wide maps (geotiff images; 250-m x 250-m resolution) of water clarity by developing a predictive relationship between atmospherically-corrected MODIS spectral (red, green, and blue) values and field observations of Secchi disk transparency (Figure 1). MODIS images from all cloud-free days from April through August 2003-2008 (n = 248) were obtained from NASA (http://oceancolor.gsfc.nasa.gov/) and atmospherically-corrected, using the program SeaDas (freely available through NASA). Spectral values were related to Secchi depth using linear regression analysis. Secchi depth measurements (n = 235) were obtained from the Lake Erie Plankton Abundance Study (LEPAS) database (Zhang 2006), which included data collected during April through August 2003-2008 from the western, central and eastern basins of Lake Erie. The variation in location and timing of measurements provided a wide range of Secchi disk values (0.2 to 9.3 m).

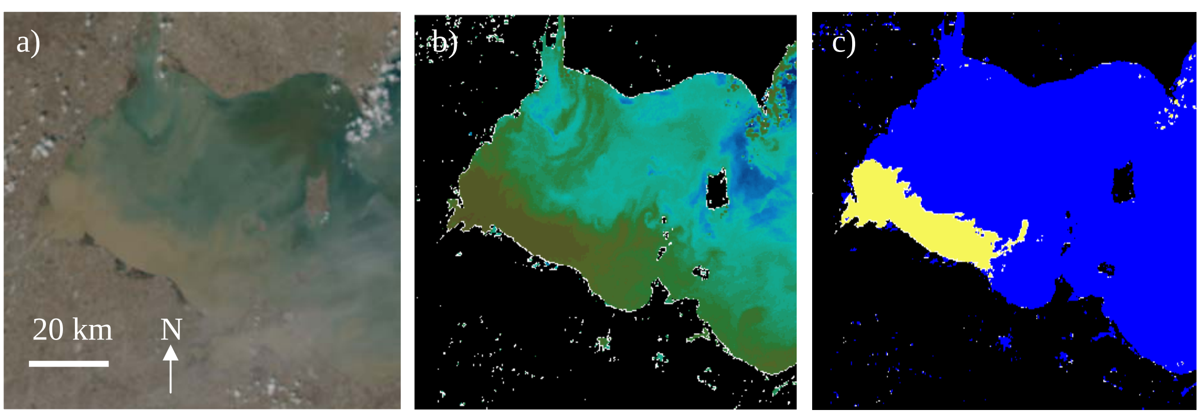

Figure 1. Progression of maps of western Lake Erie. a) True-color values from atmospherically-corrected daily MODIS satellite images were converted into b) predicted water clarity, which became the basis for defining c) the spatial extent of the MRP.

Linear regression analysis demonstrated a strong relationship between spectral values from the MODIS images and water clarity. Of the three colors, red explained the greatest amount of variation in Secchi depth (Figure 2a, $R^2 = 0.54$, $p < 0.01$), followed by green ($R^2 = 0.52$, $p < 0.01$) then blue ($R^2 = 0.23$, $p < 0.01$). When all colors were included as factors in a multiple linear regression model, explanatory power increased even further ($R^2 = 0.75$, $p < 0.01$). From this particular analysis, we derived the equation:

(1) $$\log_e(\text{Secchi}) = 1.56 - (0.017 * \text{Red}) - (0.033 * \text{Green}) + (0.03 * \text{Blue})$$

where Secchi is water transparency (m) and Red, Green, and Blue represent the intensity of red, green, and blue spectral intensity taken directly from atmospherically corrected geotiff files. This equation was subsequently used to create water transparency (Secchi depth) maps (Figure 1b) from MODIS images.

Although NASA now provides chlorophyll *a* maps of Lake Erie directly from their website, we found that their predictive models intermittently failed to provide estimates in the MRP during high discharge events (owing to highly turbid areas of the lake being perceived as land). Therefore, to fill in these gaps in the NASA maps, we attempted to derive a relationship between atmospherically-corrected MODIS spectral values and chlorophyll *a*. Field observations of chlorophyll *a* (n = 58) were obtained from the LEPAS dataset and ranged from 0.4 to 15.0 mg/L. We related field observations to spectral values, using linear regression analysis. In contrast to water clarity, however, chlorophyll *a* was not significantly correlated to any color intensity (red: $R^2 = 0.02$, p = 0.28; green: $R^2 = 0.00$, p = 0.75; and blue: $R^2 = 0.00$, p = 0.90). Therefore, we used NASA-generated chlorophyll *a* maps for subsequent analyses.

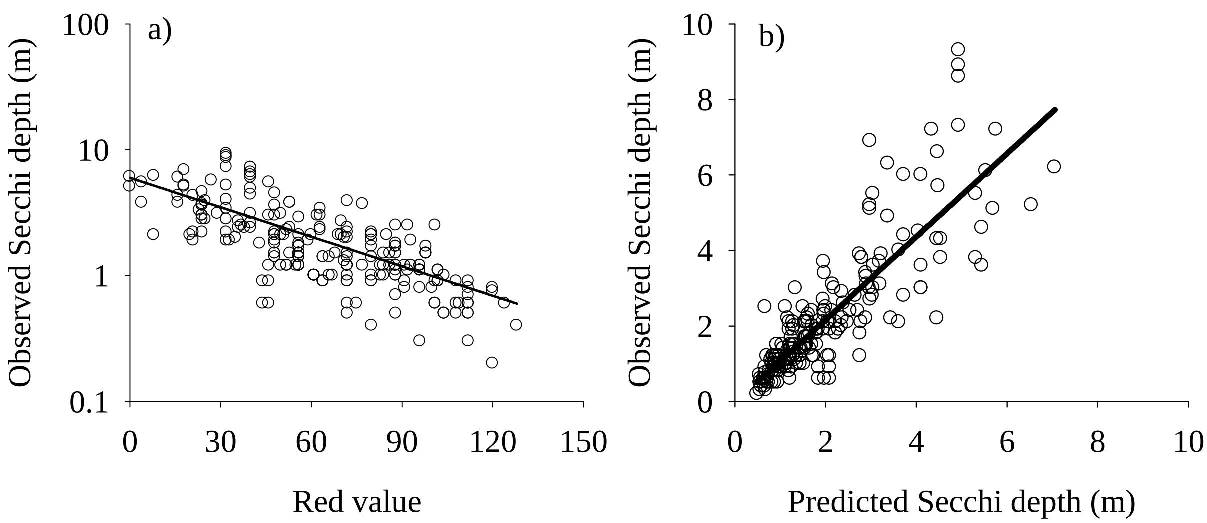

Figure 2. a) Relationship between red intensity values from MODIS images and observed Secchi depth (m) in Lake Erie (n = 248). b) Relationship between predicted and observed Secchi depth. Predictions were generated using Equation 1.

Quantifying a MRP index

With the daily water clarity and chlorophyll *a* habitat maps, we next sought to quantify the areal extent of the MRP on a daily basis (cloud-free days only). Preliminary comparisons between habitat maps and satellite images of the MRP indicated that the plume was defined more by water clarity (Secchi depth) than chlorophyll *a*. Subsequently, we used only Secchi depth maps to assess MRP size. To define the areal extent of the MRP, we derived a classification rule, using Secchi depth maps, which distinguished areas of the western basin inside and outside of the MRP. This rule had to satisfy the following criteria: 1) the MRP had to be a contiguous shape; 2) the MRP had to emanate from Maumee River mouth; and 3) the Detroit River plume (emanating from the north shore) was excluded. We found that the MRP was best defined using a Secchi- depth cutoff value of 0.5 m with Secchi disk values above 0.5 m indicating non-MRP waters. Using this classification rule, an index of potential suitable nursery habitat for yellow perch and walleye was calculated for every cloud-free day during April through August 2003-2008 (see Figure 1c) where the total area of nursery habitat (measured in km^2) was defined as the MRP (*sensu* findings from Zhao et al. 2009 and Reichert et al. 2010).

Drivers of MRP size

We evaluated potential drivers of the spatial extent of the MRP by relating our plume index values to key environmental variables. In general, river plumes are extraordinarily dynamic features of the Great Lakes (Rao and Schwab 2007, Reichert et al. 2010), with high discharge events often being a necessary precursor for the occurrence of a large plume. However, other physical processes (e.g., wind conditions, lake circulation) may magnify or negate a plume's size and dispersal (Masse and Murthy 1990). Here, we focused on Maumee River discharge and western basin wind conditions as factors potentially dictating plume size. Daily discharge measurements were obtained from a USGS stream gauge located on the Maumee River at Waterville, OH. Daily wind conditions (average velocity and direction) were obtained from an airport near Windsor, ON.

We related river discharge and wind conditions to our MRP index using linear regression. We expected lags to exist between changes in environmental factors and changes in MRP size. For example, a large plume may possibly take several days to develop following a high discharge event. To account for time lags, we related MRP size to environmental factors on the day that the plume was indexed, as well as on each of the 10 days prior to the plume indexing.

Importance of the MRP to percid habitat use and recruitment

To assess the effect of the MRP on the western basin ecosystem, we related our MRP index to Lake Erie habitat characteristics and recruitment of both juvenile yellow perch and walleye. We focused on the effect of the MRP during the springtime (April-May), when individuals were in the larval stage, a period that appears critical to their eventual recruitment into the fishery (Smith and Ludsin 2009, Zhao et al. 2009, Reichert et al. 2010). The habitat attributes that we considered included total phosphorus and chlorophyll *a* concentrations and zooplankton biomass. Habitat data were obtained from the LEPAS dataset and averaged over April and May across the western basin to derive a springtime basin-wide mean for each year. Mean springtime habitat characteristics were related to the average MRP size index over the same period using linear regression. Although not included in the analysis, water clarity also was implicitly considered, as the MRP size index was based on a measure of water clarity (Secchi depth).

To understand the MRP's effect on yellow perch and walleye recruitment, we used linear regression to relate our springtime-averaged MRP index to the abundance of age-0 yellow perch and walleye during August, which again has been shown to be a strong predictor of recruitment to the fishery at age-2 for both species (R^2=0.75; p<0.001 during 1987-2004, S. Ludsin, J. Tyson, and T. Johnson, unpubl. data; also see Ludsin 2000, Walleye Task Group 2010, Yellow Perch Task Group 2010). Juvenile abundance data on percids were collected as a part of annual trawling surveys (n = ~80 sites/year) conducted across western Lake Erie by the Ohio Division of Wildlife and the Ontario Ministry of Natural Resources (Walleye Task Group 2010, Yellow Perch Task Group 2010).

RESULTS

Drivers of MRP size

Effects of Maumee River discharge and wind velocity (regardless of direction) on MRP size were evident, but only after consideration of time lags. For example, the correlation between the index and Maumee River discharge on the same day was not significant (r = 0.02, p = 0.22); however, correlations using river discharge measured two to four days prior to plume size estimation were statistically significant with the strongest correlation (r = 0.33, p < 0.01) found three days prior (Figure 3a). In other words, a three-day lag generally existed between a high discharge event and subsequent large plume formation. Similarly, the correlation between our MRP size index and wind velocity on the same day was only marginally significant (Figure 3b, r = 0.22, p = 0.05), whereas a correlation using wind velocity from one day prior to plume size determination was stronger (r = 0.41, p < 0.01).

Using multiple linear regression analysis, we simultaneously considered Maumee River discharge (three days prior) and wind velocity (one day prior) as factors in explaining variation in our MRP size index. In addition, we considered wind direction (i.e., N, NE, etc.) as a discrete factor in this analysis within which wind velocity was nested. We found that together these factors explained 32% of the variation in the plume size index.

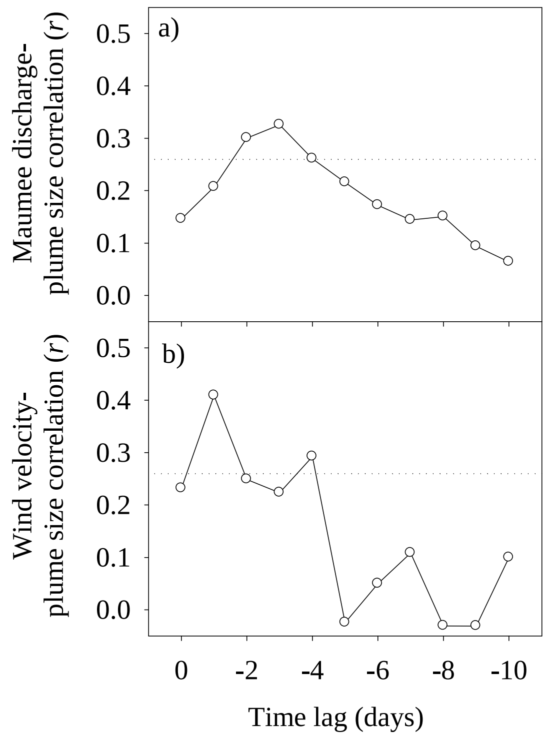

Figure 3. Correlations between the MRP size index and a) Maumee River discharge and b) wind velocity. Environmental factors were measure 0 to 10 days prior to MRP size determination (y-axis).

Importance of the MRP to percid habitat and recruitment

The springtime-averaged MRP size index varied considerably across 2003-2008, ranging from 114 km^2 in 2004 to 787 km^2 in 2003. Despite this variation, MRP size was a strong predictor for only one of the three evaluated habitat variables (Figure 4). Specifically, a significant ($F_{1,4}$ = 12.51, p = 0.02) positive relationship was found between plume size and total phosphorus (TP) in the western basin, with concentrations in the year of largest plume twice that found in the year of the smallest plume (Figure 4a). Interestingly, the mean springtime MRP size explained more variation in TP than simply mean springtime Maumee River discharge (76 and 64%, respectively). Despite the greater nutrients, no effect of MRP size on chlorophyll concentrations ($F_{1,4}$ = 0.00, p = 0.99) or zooplankton biomass ($F_{1,4}$ = 0.05, p = 0.84) was observed (Figure 4b and c, respectively).

Finally, percid year-class strength was strongly related to springtime-averaged MRP size (Figure 5). August age-0 yellow perch abundance was positively related ($F_{1,4}$ = 21.16, p = 0.01) to the mean springtime plume size index with the index explaining 98% of the variation in abundance (Figure 5a). August age-0 walleye abundance also was positively related ($F_{1,4}$ = 7.24, p = 0.05) to the index with our index, in this case, explaining 64% of the variation in abundance (Figure 5b). Importantly, these analyses were performed on the $\log_{10}$ of abundances, indicating that a linear increase in MRP size led to an exponential increase in percid abundance.

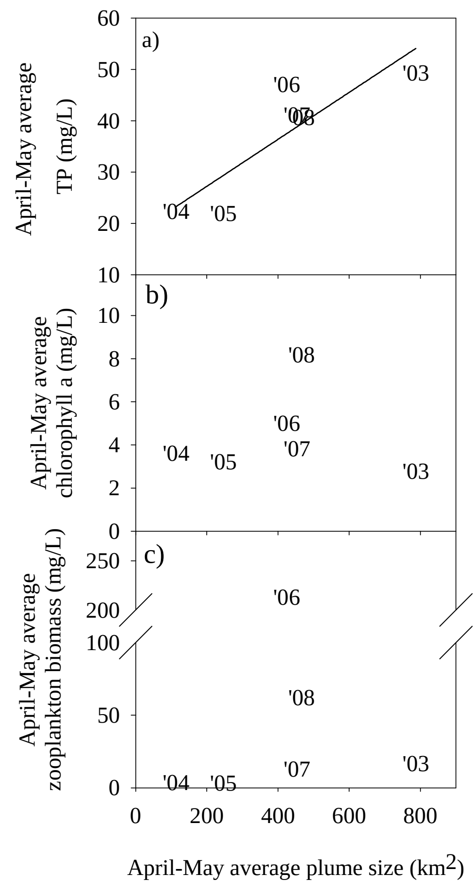

Figure 4. Relationships between the MRP size index and habitat characteristics. A regression line was added to significant (p<0.05) relationships.

DISCUSSION

Our study has revealed the environmental factors that shape the MRP, and in turn, how the MRP itself influences the western Lake Erie ecosystem. Below, we discuss some of our findings, as well as their implications for fisheries management and sustainability in Lake Erie. We also discuss how our research, and the spatially-explicit data that have been amassed, can be used to fill in data/information gaps for important and measurable attributes of Lake Erie, as well as benefit other Lake Erie investigators.

The MRP has been shown to be a highly dynamic feature of western Lake Erie, the size of which depends heavily on the magnitude of discharge from its source river, as well as wind conditions. Specifically, our analyses demonstrated that the response of the MRP to changes in Maumee River discharge and wind forcing were not instantaneous with three- and one-day time lags observed, respectively. However, our analyses also point to the importance of other factors (e.g., magnitude of Detroit River discharge, lakewide seiches, bathymetric features that influence water currents) in driving the spatial extent of the MRP, as we were only able to account for 32% of the variation in MRP size with consideration of Maumee River discharge and wind velocity/direction. This inability to explain the spatial extent of the MRP solely with knowledge of Maumee River discharge and wind conditions points to the need for hydrodynamics modeling approaches, which consider these and other external (e.g., solar radiation) and internal (e.g., thermal stratification, diffusion gradients) factors.

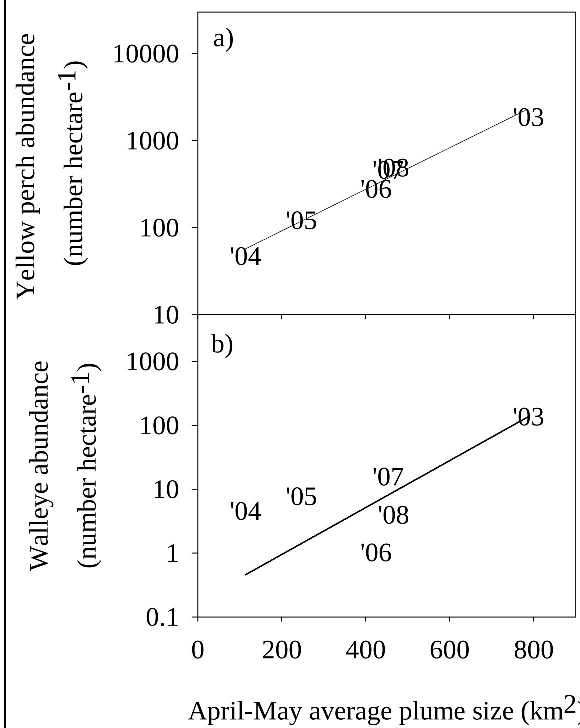

Figure 5. Relationships between our springtime-averaged MRP size index and age-0 a) yellow perch and b) walleye year-class strength during August, 2003-2008. A regression line was added to significant ($p<0.05$) relationships.

Similar to previous studies in marine systems (Grimes and Finucane 1991, Grimes and Kingsford 1996, Le Pape et al. 2003), we expected the physical, chemical, and biological attributes of the MRP to differ from surrounding waters. In particular, we expected increased plume size to lower water clarity, increase nutrient (phosphorus) concentrations, and enhance phytoplankton (as measured by chlorophyll *a*) and crustacean zooplankton biomass in the western basin. Our expectations were only partially supported. Most striking was the reduction in water clarity associated with the MRP, which was the best metric to define the MRP's spatial extent. Likewise, we found that basin-wide average total phosphorus concentrations to be greater as plume size increased. Both of these findings support other studies of the MRP, both past (Reichert et al. 2010) and ongoing (Ludsin et al.'s ongoing Great Lakes Fishery Commission study entitled "River discharge as a predictor of Lake Erie yellow perch recruitment"). These effects are clearly linked to the high concentrations of suspended material and nutrients transported by the Maumee River, particularly during high flow events, due in part to the prevalent agricultural use of its watershed (Richards et al. 2001, Baker and Richards 2002).

Despite higher total phosphorus levels caused by the MRP, which could potentially fuel lower trophic level production, we did not find evidence for higher phytoplankton (as measured by chlorophyll *a*) or crustacean zooplankton biomass with increased MRP size. In support of our findings, Reichert et al. (2010) found no differences in crustacean zooplankton biomass between MRP and non-MRP waters of western Lake Erie during May-June 2006-2007, although these authors did find zooplankton productivity (not explored herein) to be greater in the MRP than outside of it. Perhaps the disconnect between nutrients and phytoplankton production is due to low light conditions in the turbid plume, which limits photosynthetic activity, or possibly due to a time lag, such that large spring plume may lead to summer blooms that were not considered in our analysis. Indeed, previous research has shown south-shore areas of western Lake Erie, which are likely influenced extensively by discharge from the Maumee River, tend to have higher crustacean zooplankton biomass during late summer than the more offshore waters of the basin, which are more likely influenced by the nutrient poorer Detroit River (Frost and Culver 2001).

Importantly, our results indicate that large spring plumes appear to be positively related yellow perch and walleye recruitment in western Lake Erie, likely through creation of nursery habitat that benefits percid growth and/or survival. The MRP may affect larval fish, and in turn future recruitment, through two general mechanisms. First, the nutrient-rich waters of the MRP could enhance the production of larval food resources (i.e., zooplankton) leading to faster growth and higher survival of larvae (Houde 1987; Grimes and Kingsford 1996; Ludsin 2000), which then could benefit future growth and survival success (*sensu* Ludsin and DeVries 1997). Although this explanation has been supported in other plume-dominated systems (Grimes and Finucane 1991, Grimes and Kingsford 1996, Le Pape et al. 2003), it seems unlikely here, as crustacean biomass was unrelated to plume size. A second possible mechanism is that the turbid waters of the plume could provide larvae a refuge from visual predators (Rice et al. 1993; Gregory and Levings 1998; De Robertis et al. 2003). Supporting this notion, the MRP, by our definition, was always turbid, with a Secchi depth less than 0.5 m. In addition, Reichert et al. (2010) showed that predator (e.g., age-1+ yellow perch, walleye, white perch *Morone Americana*, and white bass *M. chrysops*) densities in the MRP were lower than non-MRP water during the spring, suggesting that predators may avoid the plume possibly because turbidity has been shown to hamper foraging by piscivores more than planktivores (DeRobertis et al. 2003).

The observed relationship between MRP size and percid recruitment has major implications for fisheries management in Lake Erie and the Great Lakes in general. First, no Great Lakes fishery is currently managed with consideration of forces external to the aquatic realm, such as climate and nutrient inputs. Instead, the fisheries that are actively managed in Lake Erie are managed primarily through harvest regulations (quota management). Although we cannot say for certain, we believe that a lack of mechanistic understanding concerning linkages between the broader ecosystem (e.g., watershed) and fish production is one primary reason why ecosystem-based management strategies have not been adopted as of yet, despite a call by the Great Lakes Fishery Commission for ecosystem-based fisheries management.

Herein, we have demonstrated a strong linkage between Lake Erie's watershed and its fisheries through the allochthonous inputs of sediments (and perhaps nutrients) that create the MRP. Although the exact mechanisms underlying the strong relationship between Maumee River discharge and recruitment in western Lake Erie remain uncertain (and are the primary focus of Ludsin et al.'s ongoing Great Lakes Fishery Commission study, at least for yellow perch), knowledge of this linkage in-and-of-itself will be valuable in future research and may help guide Lake Erie management agencies in their search for watershed management plans (e.g., regulations on nutrient or sediment inputs from rivers) that eventually could be used to reduce inter-annual recruitment variation, or perhaps even enhance fisheries production in future. Such a management strategy would be of great value to these agencies, complementing their existing set of management tools.

Importantly, our results also point to tradeoffs that might arise in the future, if regulations are implemented to limit the magnitude of the delivery of water from the Maumee River into the western basin or the delivery of sediment/nutrient runoff into the Maumee River (e.g., best management practices on agricultural lands). With the growing concern that non-point source runoff is contributing to harmful algal bloom (e.g., *Microcystis*) production in western Lake Erie, ways to reduce allochthonous inputs of nutrient-laden sediments into the lake are likely being considered. Such management practices, however, may have unanticipated negative effects on production of walleye and yellow perch in Lake Erie, given the apparent dependence of both species on nursery habitat provided by the MRP (Zhang et al. 2009, Reichert et al. 2010, this study). Given these tradeoffs, any decisions made regarding land or water management that could affect the timing or magnitude of delivery of water, sediments, and nutrients into western Lake Erie need to consider the potential impact on the whole Lake Erie ecosystem, including its fisheries.

Our study also most certainly will benefit fisheries management on Lake Erie through tool development in two different capacities. First, our results demonstrate that MRP size is an excellent, early indicator of the quality of future year-classes of percids, particularly yellow perch. If our process of predicting MRP size is automated such that plume size could be predicted in near real-time, Lake Erie Committee agencies could be provided with knowledge of upcoming recruitment three months in advance of what is currently possible (i.e., year-class strength, and hence future recruitment, could be predicted by the end of May as opposed to late August). This knowledge could perhaps benefit quota management decision-making in some capacity, particularly when used with other management strategies being considered by lake managers, or at a minimum would allow future fisheries management planning to start earlier than is currently possible. Second, our study clearly demonstrates how remotely sensed data can be used as a tool by fisheries management agencies (as well as the Lake Erie research community as a whole) to provide important limnological information at a scale and resolution that could not have been collected through any other means. Lastly, our study demonstrates that dynamics of aquatic organisms are well correlated with spatially and temporally dynamic habitat created by physical drivers, and knowledge of these relationships could be useful for projecting future trajectories of these populations given physical outputs from many of the climate change models. With hopeful automation of the production of habitat maps (from image download to map production), in combination with continued discovery of how organisms distribute themselves in relation to dynamic habitat features such as water clarity, it may be possible to provide anglers or commercial fishers with real-time predictions of where fish might be distributed.

INFORMATION DISSEMINATION

Results of this research have been presented at the 2010 Ohio DNR-Division of Wildlife / Aquatic Ecology Laboratory (AEL) research review meeting (attended by >100 Ohio DNR biologists and Lake Erie researchers), the 2010 Ohio Charter Captains Conference, and the 2010 International Association of Great Lakes Research conference. Movies of MRP formation, created using satellite imagery, also have been posted at the OSU Aquatic Ecology lab website (http://www.ael.osu.edu/ael-KevinPangle.html#) and YouTube (http://www.youtube.com/user/aquaticecologylab).

We are currently completing two manuscripts that include results of this research, one that describes the approach that we used to quantify MRP dynamics, and one that focuses on the effect of pulsed inputs from the MRP on the ecology of the Lake Erie ecosystems. We also have initiated the process (with Edward Rutherford, Lake Erie GIS coordinator) of making monthly habitat maps available to other researchers and the general public through the Lake Erie GIS.

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