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The re-emergence of seasonal hypoxia in Lake Erie: Causes and implications

Lillian Denecke
ldene1@brockport.edu

Library resources statement:

My research paper was written for ENV 466 (Great Lakes Issues) where the assignment was to perform a literature review on a topic related to environmental issues facing the Laurentian Great Lakes. I chose my topic, the re-emergence of seasonal hypoxia in Lake Erie, because I am interested in how water quality issues can affect ecosystems and am familiar with the topic because I grew up near Lake Erie.

I began my search for sources by utilizing the databases "ScienceDirect" and "JSTOR" to find relevant articles. ScienceDirect was an especially useful database for me because it contained articles from *The Journal of Great Lakes Research* which had numerous articles related to my literature review topic. I often used the advanced search option of the database to search for only articles from this journal to narrow down results. The library database was also crucial for my initial search for articles as it allowed me to search multiple databases at a time if I couldn't find relevant articles on JSTOR or ScienceDirect. Another strategy I used when finding sources was to find one relevant article and then read which articles were cited in that article to find more information on a specific topic. For example, Scavia et al. 2013 was a useful review on Lake Erie hypoxia that I was able to use to find many other relevant articles by looking at what was cited in this review. For journal articles that were not available in any library databases, I was able to utilize the inter-library loan system to gain access to additional articles. Without access to library databases and the inter-library loan system, I would not have been able to find many relevant articles on my topic.

Once I had gathered as many relevant articles as I could, I divided the articles into subcategories related to specific issues surrounding hypoxia in Lake Erie (ex. effects on warmwater fish, effects on coolwater fish, climate change implications, etc.) and was able to eliminate less relevant articles. I also made sure that the articles I only used articles from reliable peer-reviewed journals that frequently published studies related to the Great Lakes. From there, I was able to begin writing my paper. Overall, the online resources made available by the Drake Memorial Library were essential for my success in writing this literature review. I would not have been able to find the resources I did without inter-library loan, the advanced search options of the library databases, and the access I had to a large number of databases containing relevant studies.

The re-emergence of seasonal hypoxia in Lake Erie: Causes and implications

Lillian Denecke

Department of Environmental Science and Ecology, The College at Brockport – State University of New York

Hypoxia is an extreme environmental condition where dissolved oxygen is present at concentrations <2 mg/L. During the mid-late 20th century, Lake Erie began experiencing exaggerated seasonal hypoxia in its central basin as a result of anthropogenic phosphorous loading (Scavia et al. 2014). The seasonal hypoxia began impacting aquatic organisms negatively, such as benthic macroinvertebrates, and the Canada-US Great Lakes Water Quality Agreement (GLWQA) was signed in 1972 to address and combat the issue through monitoring and reduction of phosphorous loading (Watson et al. 2016; Scavia et al. 2014). After 1972, hypoxic conditions were observed to decrease for a short while. However, during the early 1990s, seasonal hypoxia as a result of algal blooms began to emerge once again in the central basin of Lake Erie (Scavia et al. 2013). The goal of this paper is to address and discuss the causes of the re-emergence of hypoxic events, the impact of hypoxia on Lake Erie's ecosystem and aquatic organisms, the implications of climate change as it relates to hypoxic events, and current management efforts relating to hypoxia.

1. The causes of hypoxia

Lake Erie is the shallowest of the five Laurentian Great Lakes, possessing bathymetry that makes it susceptible to seasonal hypoxia (especially in the central basin). Lake Erie is deep enough to stratify during the summer but has a thin hypolimnion and is not able to supply enough dissolved oxygen to make up for decomposition of organic matter in the benthic layer (Watson et al. 2016). Originally, hypoxic events were thought to have been directly related to nutrient loading from nonpoint sources. After Lake Erie responded well to management implemented in 1972, there was confusion as to why cyanobacteria blooms returned in the 1990s while management hadn't changed (Scavia et al. 2014). The exact mechanisms that caused the more recent seasonal hypoxia events have been speculated about but no conclusion has been drawn. Phosphorous loading alone doesn't explain the re-emergence of hypoxia in Lake Erie. Total phosphorous (TP) trends after 1972 showed an initial decrease following the GLWQA, but loading doesn't show a clear trend after 1990 (Figure 1). This lack of explanation of hypoxia events by phosphorous loading was confounding and led to numerous studies exploring various possible mechanisms contributing to the return of hypoxia. Richards et al. (2010) found that while TP loading showed only small changes from the early 1990s to 2005, the proportion of dissolved reactive phosphorous (DRP) in TP increased from 11% to 24%. Since DRP is a more bioavailable form of TP, it is hypothesized that this may have contributed to an increase in algal blooms and therefore also lead to an increase in hypoxia. The reason for the shift in the amount of dissolved phosphorous is unknown, but is thought to most likely be linked to the change in agricultural practices during the late 20th century (Scavia et al. 2014).

Another factor that had to be taken into account when the more recent hypoxia events began to occur was the potential role of invasive dreissenid mussels in relation to seasonal hypoxia. Dreissenid mussels graze on phytoplankton and are thought to be a factor in the reduction of the algal blooms and hypoxia events prior to 1972 (Scavia et al. 2014). Carrick et al. (2005) measured TP and phytoplankton trends in Lake Erie central basin after dreissenid mussel invasion and compared them to long term trends. It was found that benthic algal blooms were occurring due to water clarity brought on by dreissenid grazing. The benthic algal blooms may be producing oxygen, but it was observed that a large die-off occurs during June-September and could be contributing to seasonal hypoxia. Furthermore, it was mentioned that sediment oxygen demand (SOD) might be greater than the primary production from benthic algae. This speculation was supported by Edwards et al. (2005) which modeled the vertical oxygen budget in the central basin of Lake Erie and the various factors that might affect it (mixing, oxygen exchange at air-water surface, photosynthesis, respiration, and SOD). It was found that oxygen depletion in the hypolimnion was sensitive to SOD and respiration in the hypolimnion. These findings were significant because both of these factors are not directly related to eutrophication which was previously focused on as the cause of hypoxia.

The idea that hypoxia is predicted by factors other than phosphorous loading is now gaining traction. While phosphorous loading has been observed to have correlation with seasonal hypoxia, other factors such as climate, weather, and the physical processes of lakes should be considered (Watson et al. 2016). Conroy et al. (2011) recognized that there was a gap in knowledge regarding the effect of weather on hypolimnetic oxygen depletion rates. Throughout the summer of 2005, the authors of this study monitored temperature, dissolved oxygen, storm activity, and tributary discharge to create a model of hypolimnetic oxygen depletion rate in Lake Erie based on these factors. The model showed that increased storm activity led to a warmer hypolimnion and a 12% increase in hypolimnion oxygen depletion rate. Therefore, results of this study provide evidence for a linkage of seasonal hypoxia events to increased storms. Another study looking into factors that predict hypoxia other than phosphorous loading was Bouffard et al. (2013) which explored the variability of physical processes in Lake Erie affecting seasonal hypoxia on small- and large-time scales. This study found that the depletion of hypolimnetic oxygen was equally due to respiration in the water column and SOD. Furthermore, SOD was highly dependent on the thickness of the hypolimnion due to the dependence of vertical fluxes of oxygen on hypolimnion thickness. A thicker hypolimnion leads to more oxygen flux to respirating organisms higher in the water column rather than flux of oxygen to fulfill the needs of SOD. Bouffard et al. (2013) provides an example of how physical properties such as extent of hypolimnion thickness in Lake Erie may be factoring into seasonal hypoxia.

More research is needed to be done on the mechanisms that contributed to the return of frequent seasonal hypoxia in the central basin of Lake Erie, but there is some agreement on what is definitely affecting these events. It is agreed upon that hypoxia is related to phosphorous loading, that dreissenid mussels most likely magnified water quality improvements after 1972, SOD needs to be considered as a factor in oxygen depletion, weather has an impact on seasonal hypoxia, and benthic algal blooms play a role in hypolimnetic oxygen depletion (Scavia et al. 2014; Edwards et al. 2005; Bouffard et al. 2013; Conroy et all 2011; Carrick et al. 2005).

2. The impacts on biota

As mentioned before, hypoxia is considered any conditions where DO < 2 mg/L. This is lethal to fish species for exposure longer than a few hours and to most zooplankton species which have lethal concentrations at 1.0 mg/L DO (Vanderploeg et al. 2009). Seasonal hypoxia has significant impacts on most all aquatic organisms in Lake Erie. Some impacts may be positive such as improved conditions for walleye as prey fish were forced into the walleyes' favorable habitat conditions, while most impacts are negative such as the flip side of this relationship where prey fish such as yellow perch and rainbow smelt are concentrated in less than ideal habitats where they are more vulnerable to predation and exploitative fishing (Brandt et al. 2011; Kraus et al. 2015). Large fish kills as a result of hypoxia are usually only observed in extreme cases when organisms are unable to move out of hypoxic areas or when hypoxic waters are mixed across the water column (Kraus et al. 2015). Most impacts of hypoxia are observed as changes in species interactions and other behavioral responses (Scavia et al. 2014). Here, the impact of seasonal hypoxia on fish, zooplankton, benthic organisms, and changes in food web interactions will be discussed.

2.1 Fish

Cold and coolwater fish are the most vulnerable species to seasonal hypoxia due to their reliance on hypolimnetic habitats during stratified summer months where surface waters are too warm (Kraus et al. 2015). While not a particularly strong fishery in Lake Erie, lake trout (*Salvelinus namaycush*) are still present in small populations and can suffer from the impacts of seasonal hypoxia. A model developed by Evans (2007) measured the effect of temperature and dissolved oxygen on metabolic activity and power capacity of juvenile lake trout. Maximum power output was observed at 12-20 degrees Celsius and above 7 mg/L DO, well beyond dissolved oxygen concentrations present during seasonal hypoxia events. In order to mimic summer hypolimnetic hypoxic conditions, lake trout were exposed to temperatures between 4-8 degrees Celsius and at DO concentrations of 7, 5, and 3 mg/L. Lake trout maximum power capacity was reduced by 33%, 67%, and 100% respectively, indicating significant impact of hypoxia on metabolic activity in lake trout. Hypoxia places additional pressures on an already vulnerable coldwater fish species in Lake Erie.

In multiple studies, seasonal hypoxia has been shown to impact the behavior of an important coolwater fish species: the yellow perch (*Perca flavescens*). Kraus at al. (2015) found that seasonal hypoxia in Lake Erie renders yellow perch vulnerable to commercial fishing because of hypoxia-based habitat compression. The study was done because commercial fishery landings were not reporting lower catches of yellow perch even though seasonal hypoxia was occurring. In addition to the observation of yellow perch migrating vertically and horizontally to avoid hypoxic conditions, this study also found that the hypolimnion location was highly variable with an unstable thermocline. This caused yellow perch habitat quality to shift frequently and rapidly, concentrating yellow perch at the edge of hypoxic zones. Commercial fisheries reported higher catches of yellow perch during these events, exploiting the temporary vulnerability of the yellow perch. The results of Kraus et al. (2015) were reinforced by a previous study, Roberts et al. (2009). Roberts et al. (2009) also found that hypoxia-based habitat compression of yellow perch rendered the species vulnerable to commercial fishing. In addition to this observation, Roberts et al. (2009) also found that seasonal hypoxia caused yellow perch to shift their diets from benthic invertebrates and hypolimnetic zooplankton such as *Bythotrephes longinamus* to pelagic mesozooplankton leading to a benthic-pelagic decoupling in the ecosystem. Interestingly, some yellow perch were observed with benthic prey in their stomachs indicating that they might be diving into the hypoxic hypolimnion to consume their preferred prey. However, more research was suggested to confirm this. This benthic to pelagic diet shift is also observed in Vanderploeg et al. (2009). Yellow perch condition can also be related to hypoxia (Figure 2). As the duration of hypoxia increases, the condition of yellow perch during seasonal hypoxia compared to condition of yellow perch during normoxic conditions decreases (Scavia et al, 2013). This relationship is significant for both male and female yellow perch. The impacts of hypoxia on yellow perch are not considered to be severe and this is hypothesized to be because yellow perch are native in Lake Erie and have evolved with hypoxia (Scavia et al. 2014).

Hypoxia can lead to competition over food resources between different fish species. Pothoven et al. (2008) looked at the diet composition, selectivity, daily ration, and diet overlap of rainbow smelt (*Osmerus mordax*) and emerald shiners (*Notropis atherinoides*) in response to seasonal hypoxia. The two species' diets had low overlap except during the height of hypoxia in

September when rainbow smelt were forced out of the hypolimnion due to oxygen depletion and could no longer consume benthic prey. During this time, emerald shiner consumed 54-68% less than they would during normoxic conditions and began to consume zooplankton to replace the no longer available benthic organisms. Due to the response of emerald shiner to hypoxia, this species was deemed to be equally as important as a regulator of zooplankton abundance as rainbow smelt.

While most fish species seem to experience negative impacts of hypoxia, some species may benefit from it. Walleye (*Sander vitreus*) are a crucial game fish species in Lake Erie's lucrative recreational fishery. Brandt et al. 2011 found that hypoxia may be improving walleye habitat quality by concentrating prey in conditions favorable to walleye. This study collected data on walleye to input into a spatial arrangement model of prey availability, DO, temperature, and irradiance. While the monthly average amount of optimal habitat for walleye decreased during hypoxic events, the quality of the habitat was increased. Hypoxia-based habitat compression forced prey fish (yellow perch, emerald shiner, and rainbow smelt) into the lower epilimnion and metalimnion where they were preyed on at night by walleye. Table 1 shows increased proportion of emerald shiner and rainbow smelt (walleye prey fish) sampled in walleye habitat during and after hypoxia. These increased concentrations of prey fish improve habitat conditions for walleye. However, in this study it is addressed that persisting hypoxia in Lake Erie may eliminate the benefits for walleye because the ecosystem cannot sustain heavy, consistent predation and overly warm years may decrease the quality of walleye habitat. Moreover, if walleye habitat quality decreases then they will become more concentrated and may become targets of exploitative commercial fishing, similar to yellow perch.

2.2 Zooplankton

While zooplankton may have a higher tolerance to oxygen depletion than fish, it does not make them completely immune to the impacts of hypoxia. The impact of hypoxia on zooplankton is similar to the hypoxia-based habitat compression observed with yellow perch. Vanderploeg et al. (2009) studied the vertical migration of zooplankton in response to hypolimnetic oxygen depletion. Zooplankton are able to tolerate hypoxic conditions down to 1 mg/L DO and are sometimes observed to congregate in the 1-3 mb/L DO range that is too low for fish to tolerate but not yet lethal for zooplankton. This offers a refuge from predation, especially when hypoxia is forcing fish to concentrate into pelagic zones normally inhabited by zooplankton. The utilization of the 1-3 mg/L DO area was observed in this experiment as a portion of zooplankton remained in the hypoxic hypolimnion to avoid predation. Vertical and horizontal compression of planktivorous fish most likely lead to localized reduction in zooplankton populations.

Pothoven et al. (2012) provides opposing results to Vanderploeg et al. (2009). Where Vanderploeg et al. (2009) found that zooplankton utilized the hypoxic hypolimnion as a refuge from predation, Pothoven et al. (2012) observed a large shift of zooplankton into the epilimnion as a result of hypoxia. A focus was placed on *Bythotrephes longinamus* (an invasive predatory zooplankton) and *Leptodora* (a native predatory zooplankton). *Bythotrephes* underwent high predation pressure prior to hypoxia and also has a low tolerance to oxygen depletion, leading to their disappearance in the water column if Lake Erie by late summer. *Leptodora,* however, persisted despite heavy predation pressure. Although not mentioned in the study, the benefit of being native to Lake Erie and evolving with hypoxia may be playing a role in the survival of *Leptodora* during seasonal hypoxia similarly to the yellow perch. However, this is just speculation.

2.3 Benthic organisms

Dreissenid mussels were discussed previously as a possible contributor to the return of seasonal hypoxia and they are definitely suffering from impacts of hypoxia. A 50-year historical dataset monitoring benthic organisms in Lake Erie included information on the population dynamics of dreissenid mussels in response to hypolimnetic oxygen depletion (Burlakova et al. 2014). Populations of dreissenid mussels were lowest in the central basin, an area that is the most heavily impacted by hypoxia. Dreissenid mussels have a low tolerance for anoxic conditions and were therefore unable to tolerate conditions in the central basin. Burlakova et al. (2014) also found that snails were absent from benthos in parts of the central basin, further supporting the argument that hypolimnetic oxygen depletion negatively impacts benthic invertebrate species. Because dreissenid mussels are sensitive to oxygen depletion, the study suggests that they can be used as an indicator species for benthic hypoxic conditions.

3. Climate change and hypoxia

Climate change is now frequently studied to determine its potential impacts on physical and biological processes on Earth. As with many other environmental issues, hypoxia is expected to become more exaggerated and extreme with climate change (Scavia et al. 2013). Discussed earlier, the study done by Conroy et al. (2011) found that increased storm events lead to a warmer hypolimnion and increases hypolimnetic oxygen depletion rate by 12%. Within the context of climate change where more frequent and extreme weather events are predicted to occur, hypoxia can be expected to worsen. In addition to this, an increase of strong winds has been shown to result in a deeper thermocline and a thinner hypolimnion, a known factor that contributes to the occurrence of seasonal hypoxia (Scavia et al. 2013). Other studies that have modeled changes in lake processes in response to climate change have predicted that water levels will be lower which will also result in a thinner hypolimnion (Scavia et al. 2013).

Many of the studies previously discussed in this review also mentioned how climate change would lead to more extreme impacts of hypoxia on aquatic organisms. For example, Evans 2007 (studied lake trout metabolic activity in response to hypoxia) pointed out that lake trout are extremely vulnerable to the impacts of climate change due to loss of habitat associated with summer water temperatures and hypolimnetic oxygen depletion. Some models have shown that climate change may benefit some warmwater species due to temperature dependent growth, but these models may not be accurate for Lake Erie because of the extensive hypoxia (Scavia et al. 2013). Overall, it is agreed upon that climate change will cause hypoxia to become more extensive and will further contribute to negative impacts of hypoxia on aquatic organisms in Lake Erie (Conroy et al. 2011; Evans 2007; Scavia et al. 2013).

4. Management

After the re-emergence of hypoxia despite phosphorous loading reductions after 1972, it became clear that new management actions were needed to control seasonal hypoxia. In 2012, the International Joint Commission commissioned the Lake Erie Ecosystem Priority taskforce to respond to issues such as hypoxia (Watson et al. 2016). New management has been based on models of different factors contributing to hypoxia such as phosphorous loading, SOD, and temperature (Scavia et al. 2013). While an acceptable goal for target DO concentrations has not been set yet, a popular option is to set this goal as pre-1990 concentrations. Currently, the main method of management is to reduce phosphorous loading, especially DRP (Watson et al. 2016; Scavia et al. 2013). As mentioned earlier, DRP is mostly bioavailable meaning it has a greater capacity to lead to algal blooms and hypoxia. Scavia et al. (2013) reviewed studies focused on the management of DRP and it was found that current agricultural best management practices (BMP) such as no-till has actually increased the proportion of DRP in TP runoff by a factor of four compared to traditional till practices. Current BMPs are only reducing nutrient and sediment loading by 0-11% (Figure 3). Bosch et al. (2013) found that regular BMPs were only minimally effective in reducing nutrient runoff. In order to reduce phosphorous loading, agricultural BMPs need to be modified to become more effective.

To conclude, seasonal hypoxia in Lake Erie is a natural process that has been exaggerated by anthropogenic activity and is now changing the ecosystem within Lake Erie. The causes of the re-emergence of hypolimnetic oxygen depletion are still debated, with more scientists now focusing on physical processes besides phosphorous loading that may be contributing to hypoxia. Aquatic organisms inhabiting Lake Erie such as fish, zooplankton, and benthic invertebrates are all effected by these hypoxic events, both positively and negatively depending on the species. Finally, the threat of climate change has serious implications for seasonal hypoxia as it could cause more extreme hypoxic events in the future with more detrimental affects to Lake Erie's biota. Effective management is needed for the reduction of seasonal hypoxia in Lake Erie.

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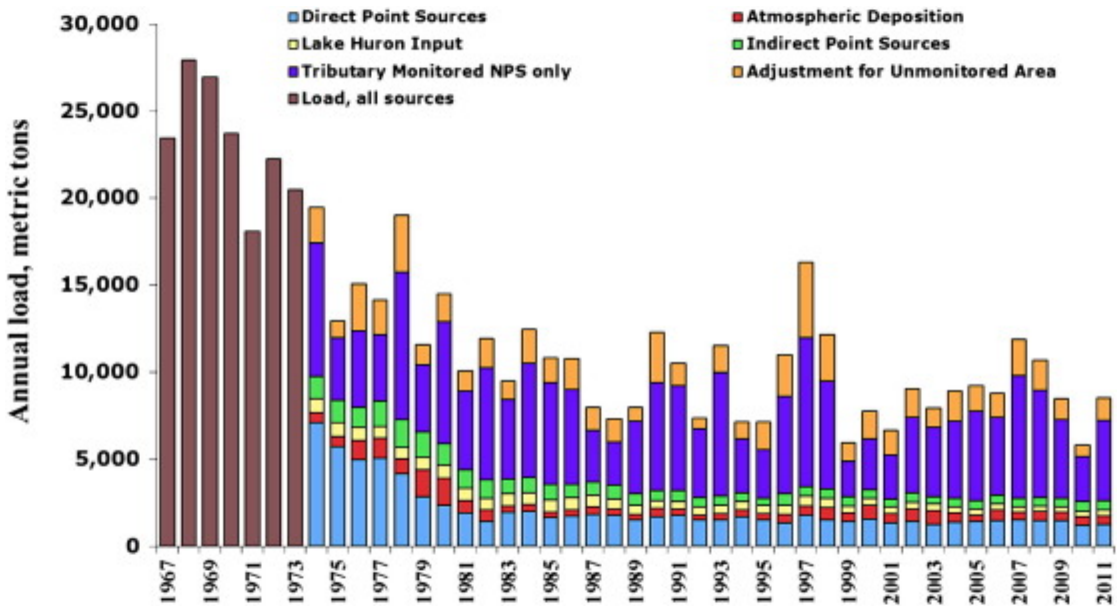

Figure 1. "Total phosphorus loads (TP) into Lake Erie during 1967–2011 from municipal and industrial point sources, monitored and estimated non-point sources (NPS), atmospheric deposition, and inter-lake transfers. Sources of TP loads: Dolan (1993); Dolan and McGunagle (2005), Dolan and Chapra (2012), and D. Dolan, unpublished data. Current GLWQA loading goal is 11,000 metric tons per year." (Scavia et al. 2013)

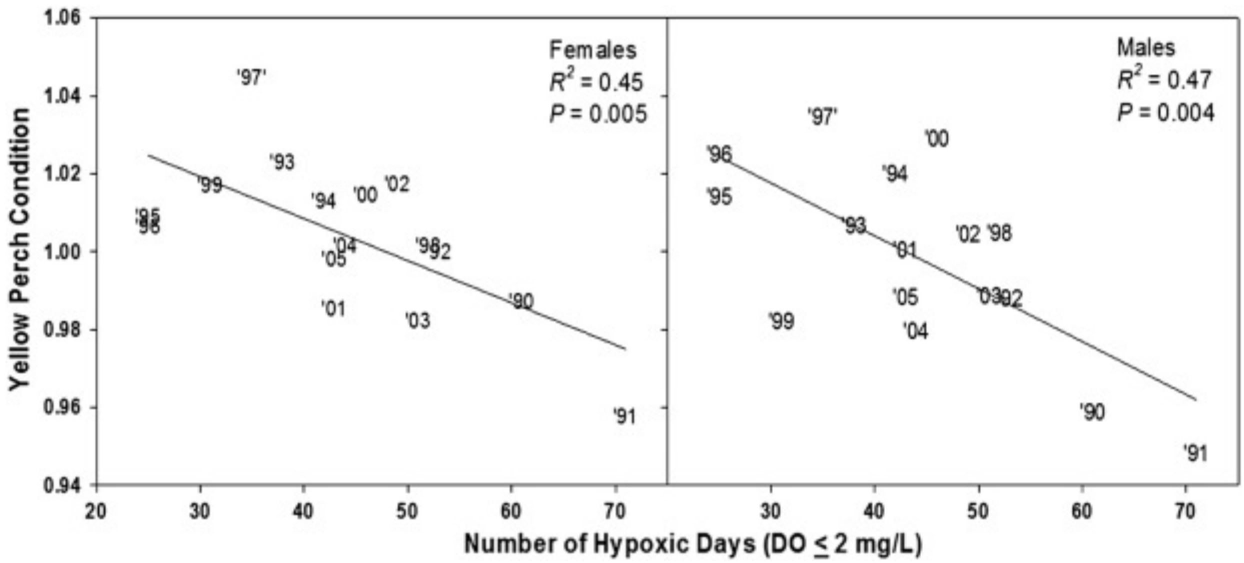

Figure 2. "Relationship between the number of hypoxic days in the central basin of Lake Erie and the condition (relative weight) of yellow perch captured in central basin bottom trawls during fall (September–October), 1990–2005. Condition was defined as the mean relative weight, i.e. observed mass divided by predicted mass, which was estimated from a sex-specific length–mass relationship developed for Lake Erie yellow perch during this time period. Condition values greater than or less than one signifying above-average or below-average condition, respectively. Data sources: hypoxic days (Rucinski et al., 2010); fish condition (Troy Farmer and the Ohio Division of Wildlife, unpublished data)." (Scavia et al. 2013)

Table 1. (Brandt et al. 2011) See below for caption.

Table 1. Percentage of prey fish species caught in north–south transect trawl samples before hypoxia (August), during hypoxia (September), and after hypoxia (October) in central Lake Erie during 2005.

	Percent of catch				
	August B	August D	September A	September B	October B
Burbot	0.0	0.2	0.0	0.0	0.0
Emerald shiner	0.0	0.0	89.4	12.2	28.9
Freshwater drum	0.0	0.2	0.0	0.0	1.7
Gizzard shad	0.0	0.0	0.2	0.1	4.6
Lake whitefish	0.0	0.0	0.4	0.0	0.0
Rainbow smelt	16.0	4.6	4.7	72.7	37.6
Round goby	0.5	1.7	2.2	1.4	0.4
Trout-perch	2.1	0.5	0.0	0.0	0.0
Walleye	0.0	0.0	0.0	0.0	0.4
White bass	0.0	0.0	0.2	0.2	2.5
White perch	1.1	0.0	0.0	8.3	13.0
Yellow perch	80.1	92.8	2.9	5.2	10.8

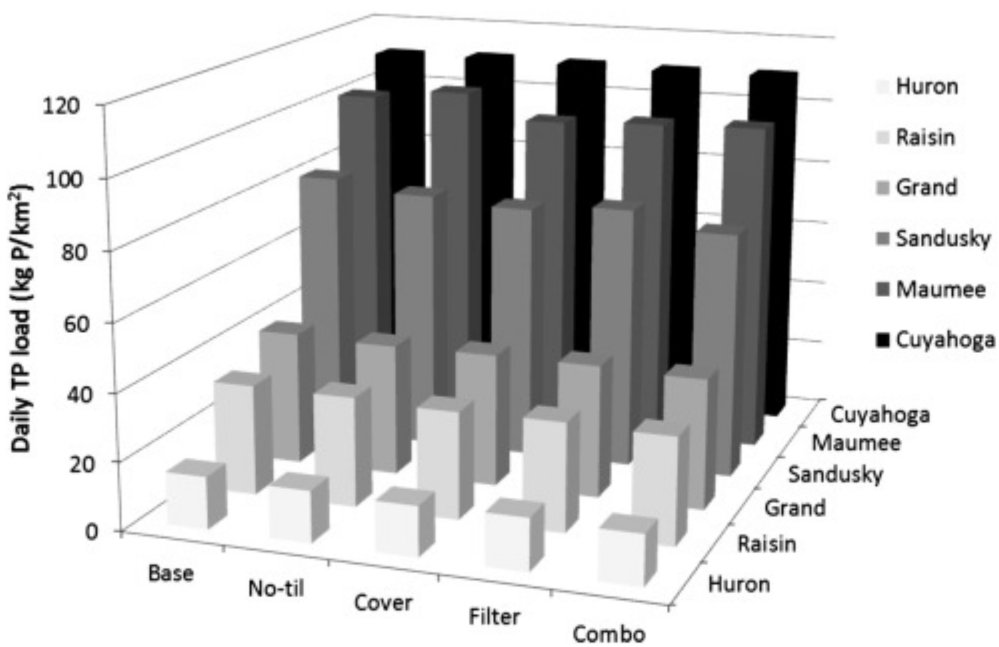

Figure 3. “Comparison of reduction in daily TP yield from implementing “feasible” best management practices, including no-till, cover crop, filter strips and a combination of all three, for six Lake Erie Watersheds as predicted by SWAT model scenarios.” (Bosch et al. 2013).