How do recent changes in Lake Erie affect birds? Part two: Zebra Mussels and Quagga Mussels

Doug Tozer and Gregor Beck

Figure 1. The non-native invasive Zebra Mussel (shown here) often has a distinctive zig-zag pattern on its shell, which is flattened on one side. By contrast, the non-native invasive Quagga Mussel (not shown) typically lacks the zig-zag pattern and has an all-rounded shell. *Photo: Bird Studies Canada.*

Over the past few decades, Lake Erie has been described as an environmental disaster, as well as a great conservation success. The health of the lake reached a low point in the 1960s and 1970s, but improved greatly by the 1980s (Makarewicz and Bertram 1991). Now, by contrast, we are hearing about harmful algal blooms, botulism, invasive species, climate change and other issues threatening Lake Erie water quality. The health of the lake is now, once again, at a low point. What's happening? Why does the health of the lake keep flip-flopping back-and-forth? What does it all mean for birds? This review article is part two of a series of three articles that will appear in *Ontario Birds*. The articles provide an overview of some of the current environmental and ecological issues for Lake Erie, with emphasis on the implications for the numerous bird species that depend on the lake for nesting and migration. There are dozens of worthy issues to profile. We chose to begin, in part one, with invasive *Phragmites* (Tozer and Beck 2018). In part two, we tackle the invasive Zebra Mussel and Quagga Mussel (*Dreissena polymorpha* and *D. rostriformis bugensis*, respectively). In addition to a review of each issue, the articles will also present new analysis of relevant citizen science data and suggest actions that we, as birders, can take to help alleviate the issues.

The Zebra Mussel and Quagga Mussel are invertebrate bivalve mollusks that live in freshwater (Figure 1). Individuals of both species filter feed with remarkable efficiency, each moving up to 1 L of water per day through their relatively tiny shells (1 mm to 3 cm in length) to their digestive tracts. Food, which is trapped by layers of mucous, consists of phytoplankton and zooplankton that drift through the water. Both species, once mature, anchor themselves with root-like byssal threads to diverse substrates, which for Zebra Mussels usually consist of hard surfaces, such as rock, wood, plastic and fibreglass, and for Quagga Mussels just about any surface (Snyder *et al.* 1990). Less commonly, both species are found on soft substrates, including mud, sand, and aquatic plants, and because of this they are capable of transforming entire substrates from soft to hard bottom (Berkman *et al.* 1998, Petrie and Knapton 1999).

The two species of mussels are native to the Black Sea and Caspian Sea and adjacent regions of the Middle East. They were first detected in North America in Lake Erie during the mid-to-late-1980s (Carlton 2008). Both species probably arrived here in ship ballast water dumped by ocean-going freighters (Griffiths *et al.* 1991). They have since spread throughout much of the Great Lakes, including Lake Erie, where they cover thousands of square kilometres of substrate to depths of several centimetres above the bottom surface (Berkman *et al.* 1998). With the help of free-swimming planktonic larvae and unintended transport by humans, they have spread well beyond the Great Lakes and now occupy 34 US states and three provinces (check out the animated online maps showing the spread across North America over the years provided by Benson *et al.* 2019a,b). The Zebra Mussel has spread farther and faster than the Quagga Mussel (Karatayev *et al.* 2011a), perhaps because its flat side and stronger and faster-growing byssal threads allow it to adhere better to hard substrates, such as recreational boats, that can be transported to new locations by people (Peyer *et al.* 2008). Relatively faster growth of the Zebra Mussel may also contribute to its capacity for rapid population establishment and range expansion (Karatayev *et al.* 2011b). It likely was for those reasons that the Zebra Mussel initially was more common in Lake Erie, reaching peak population density as early as 1989, but since then the Quagga Mussel has become the dominant species, reaching peak density between 1998 and 2002. For example, on a lake-wide basis between 2009 and 2012, Quagga Mussels comprised 87% by density (individuals per m^2) and 98% by biomass (g of tissue and shell per m^2) of Zebra and Quagga mussels combined (Karatayev *et al.* 2014). The increasing dominance of the Quagga Mussel is probably partly due to its higher tolerance of a broader range of conditions (e.g., water depth, temperature) and its slower metabolism which allows for better survival during food shortages as compared to the Zebra Mussel (Karatayev *et al.* 2015).

Both of these species can wreak havoc just about anywhere populations become established. They clog water intake pipes at electrical power generation stations and drinking water treatment facilities and coat docks, boats and buoys (Connelly *et al.* 2007). Their efficient filter feeding improves water clarity and increases light penetration, which allows for more abundant algae and plant growth. Subsequently, this can lead to large amounts of dead algae washing up on beaches, causing a nuisance for swimmers and other beachgoers (Aur *et al.* 2010). Further, the dense mats of sharp mussel shells found along shorelines and beaches are another reason swimmers detest them. The two mussels are so efficient in their collective filter feeding that they reduce populations of some native invertebrates through competition for the same food. For example, the once abundant bottom-dwelling amphipod *Diporeia* is now likely extirpated from Lake Erie, which has been partially attributed to the mussels (Barbiero *et al.* 2011, Watkins *et al.* 2012). The apparent extirpation of *Diporeia*, in turn, appears to have negatively affected some populations of fish, which depend directly or indirectly on *Diporeia* for food, such as the commercially valuable lake whitefish (*Coregonus clupeaformis*) (Nalepa *et al.* 2005). The high nutrients, warmer temperatures and low oxygen in the water within Zebra Mussel and Quagga Mussel beds stimulate bacteria to produce type-E botulism toxin (Getchell and Bowser 2006) which has been transferred by multiple pathways up the food chain. The botulism toxin can cause large die-offs of mussel-eating and fish-eating birds (Pérez-Fuentetaja *et al.* 2011). There will be more information about this topic in our third and final article in this review series. Zebra Mussels and to a lesser extent Quagga Mussels, attach to and cover the surface of some native mussels to the point of smothering them, effectively cutting off their source of food and ultimately causing their local extinction (Ricciardi *et al.* 1998b). Remarkably, densities of the two non-native mussels combined sometimes reach hundreds of thousands of individuals per m^2 in Lake Erie (Leach 1993) and over 14,000 individual Zebra Mussels have been found attached to the shell of a single native mussel (Schloesser and Nalepa 1994). Indeed, 16 of the 41 (39%) mussel species native to Ontario are currently listed as special concern, threatened, or endangered, and in nearly every case, at least partially due to Zebra Mussels (Ministry of the Environment, Conservation and Parks 2019).

There is, perhaps, a bit of a bright side to some of this. Species richness, density and biomass of native invertebrates like aquatic insects, snails and crustaceans are often many times greater within large, extensive beds of Zebra Mussels and Quagga Mussels compared to adjacent unoccupied lake bottom (Burlakova *et al.* 2012). This is likely because the shells of the mussels provide more abundant and complex substrates for shelter, plus the mussels collect nutrients from the extensive water column and pump them back out in concentrated form in their feces, all of which increases available resources locally for native invertebrates living on the substrate (Ricciardi *et al.* 1998a). The elevated populations of native invertebrates, in turn, appear to benefit certain fish, such as the yellow perch (*Perca flav-escens*), which are sought after by anglers (Cobb and Watzin 2002). The beneficial influence on invertebrates and other wildlife occurs only in relatively shallow water (<20 m); however, in deeper water, the mussels tend to cause declines in populations of invertebrates, like *Diporeia* discussed earlier (Burlakova *et al.* 2018). As noted above, the Quagga Mussel is becoming relatively more common over time in Lake Erie, whereas the Zebra Mussel has been declining. These trends bode well for native mussels because Quagga Mussels are less likely to attach to other mussels, and therefore, are less likely to depress or eliminate populations of native mussels (Burlakova *et al.* 2014b). Indeed, surveys show that as Quagga Mussels increase and Zebra Mussels become less abundant, the number of native mussels with attached Zebra Mussels and Quagga Mussels declines to a third, and the number of non-native invasive mussels attached to native mussels decreases by tenfold (Burlakova *et al.* 2014b). Overall, however, Zebra Mussels and Quagga Mussels have completely altered the entire ecology of the Lake Erie ecosystem, with many negative consequences and relatively few positive ones (Burlakova *et al.* 2014a).

What about birds? Might there be a bright side in this story for them? Early in the invasion and for some time thereafter, some waterfowl species, including scaup (*Aythya* spp.), Bufflehead (*Bucephala albeola*), Common Goldeneye (*Bucephala clangula*), scoters (*Melanitta* spp.) and Long-tailed Duck (*Clangula hyemalis*) switched to eating Zebra Mussels and Quagga Mussels, in some cases almost entirely (Figure 2). Prior to the invasion of non-native mussels, Lesser Scaup (*Aythya affinis*) staging in autumn and spring in 1986 in Lake Ontario consumed 86% (aggregate dry mass) native plant-eating snails (Ross *et al.* 2005). The proportion of native snails declined to 16% in 1999 and 2000, well after the arrival of Zebra Mussels and Quagga Mussels, which by then made up 67% of the scaup's diet (Badzinski and Petrie 2006). Similarly, in Lake Erie, the diet of staging scaup consisted of 39-99% Zebra and Quagga Mussels between 1992 and 2000, depending on the location (Custer and Custer 1996, Petrie and Knapton 1999, Badzinski and Petrie 2006). The ducks feed so heavily on the mussels in some places that they significantly reduce the number of mussels by several fold, although it is unlikely that they will reduce the mussel population across all of Lake Erie (Petrie and Knapton 1999, Mitchel *et al.* 2000). It is not surprising that the ducks switch to eating the mussels because the mussels are extremely plentiful, typically occur in dense concentrations and are high in protein. Further, the ducks' gizzards seem to be able to handle processing the hard shells easily enough (Snyder *et al.* 1990). The increased populations of invertebrates

Figure 2. The Common Goldeneye is just one of several species of waterfowl that may have benefited from eating non-native Zebra Mussels and Quagga Mussels since they invaded Lake Erie and the rest of the Great Lakes. The mussels also indirectly benefit these ducks because various invertebrates that the birds are fond of eating are found at higher population levels amongst the mussels' shells. On the negative side, the mussels are a source of contaminants for the ducks, and sometimes a source of the lethal type-E botulism toxin. *Photo: Tim Arthur*

around the mussel beds also benefit diving ducks, like Common Goldeneye (Figure 2), Long-tailed Duck, and especially Bufflehead, because they are particularly fond of eating the elevated numbers of shrimp-like crustaceans and midge fly larvae found amongst the mussel shells (Schummer *et al.* 2008a).

The potential problem with the switch in diet is that the super-efficient filter feeding by the mussels accumulates various contaminants in the mussels at very high levels, including polychlorinated biphenyls (PCBs) and heavy metals (Mazak *et al.* 1997). By contrast, the comparatively less contaminated native plant-eating snails are presumably much healthier for the ducks (Ross *et al.* 2005). Indeed, high levels of contaminants, especially selenium, are found in both the mussels and the ducks (Custer and Custer 2000, Petrie *et al.* 2007, Schummer *et al.* 2010, Ware *et al.* 2011). Selenium is a naturally-occurring element and is required in trace amounts for everyday cell function in animals, but when acquired in large enough doses it causes physiological problems (US Department of Health and Human Services 2003). For instance, elevated body burdens of selenium in birds can cause reduced hatchability of eggs and deformities in

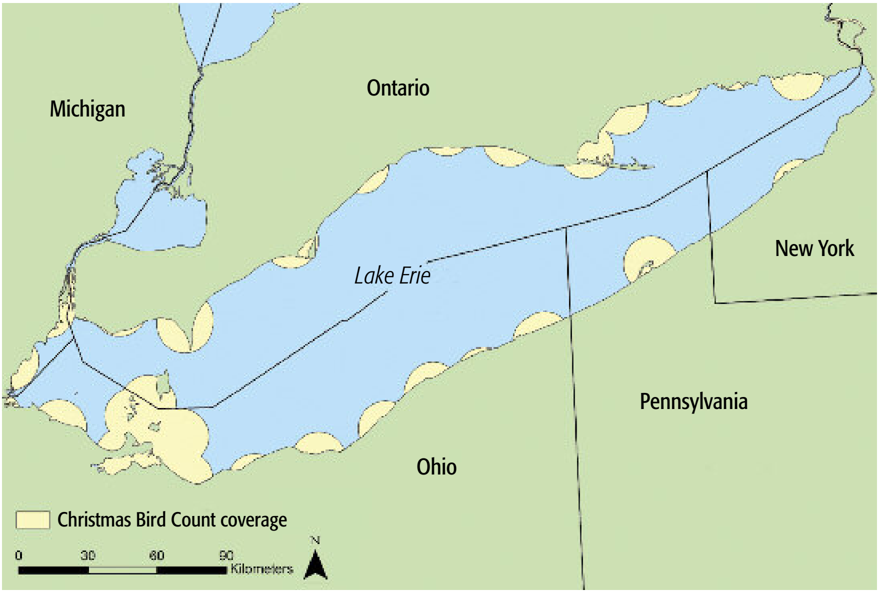


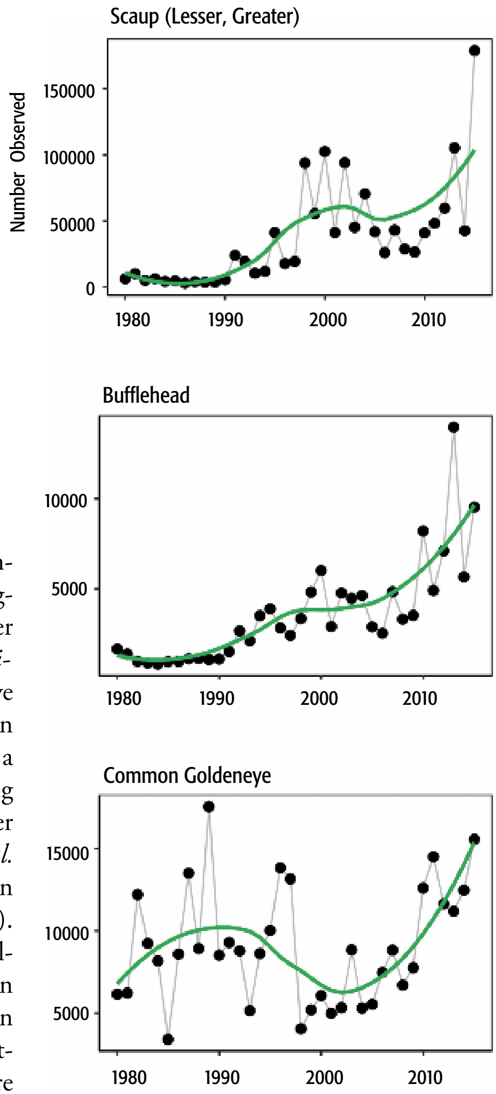
Figure 3. Areas surveyed by the Christmas Bird Count on Lake Erie.
Data source: Bird Studies Canada and Audubon.

in embryos, and oxidative stress can inhibit enzyme and protein function, all of which can lead to reductions in reproductive success and survival (Spallholz and Hoffman 2002). The main source of selenium in the water of the lower Great Lakes is likely various industrial activities, such as coal-fired power generation and fossil fuel combustion, which are known to produce selenium as a by-product, although other sources such as agricultural runoff are possible. The selenium then makes its way to air, then water, and is subsequently taken up by the mussels (Lemly 2004). Reflective of this pattern is the observation that selenium levels in ducks staging on the lower Great Lakes are higher closer to heavy industrial areas compared to farther away (Schummer *et al.* 2010). This leads to the question of whether the elevated contaminant levels in the ducks are high enough to significantly affect the ducks' reproduction and survival?

The stakes associated with the question are high. Much larger numbers of some waterfowl species now stage or overwinter on Lake Erie since Zebra Mussels and Quagga Mussels have become common (Petrie and Badzinski 2007). This of course means that much larger numbers of ducks are also now exposed to the potentially negative effects of selenium and other contaminants picked up from eating the mussels. To illustrate these stakes, we used data from the Christmas Bird Count (coordinated in Canada by Bird Studies Canada, and in the US by the National Audubon Society) to plot numbers of waterfowl

Figure 4. Number of individuals of some mussel-eating ducks observed during Christmas Bird Counts on Lake Erie between 1980 and 2015. See Figure 3 for survey locations. Dots are grand totals of all individuals observed on all counts in a particular year; lines of best fit are superimposed on observed counts to show overall trajectory. All species show major or moderate increases in the most recent years, with scaup and Bufflehead relatively scarce before the mussel invasion (~late-1980s) and dramatically more common afterwards.

Raw sums of observed individuals are shown because adjustments for differences among years in effort and area surveyed (e.g., birds per party hour per ha of lake surveyed) yielded nearly identical patterns.



observed over the years in late autumn-early winter throughout Lake Erie (Figure 3). Our analysis shows that Lesser Scaup and Greater Scaup (*Aythya marila*), Bufflehead and Common Goldeneye all show major or moderate increases in the most recent years, probably due to a variety of factors, including decreasing coverage and duration of ice cover over the years (Wang *et al.* 2012, Mason *et al.* 2016), as well as increasing reliance on invasive mussels for food (Figure 4). Notably, scaup and Bufflehead were relatively scarce before the mussel invasion and became substantially more common afterwards (Figure 4). Some of these patterns have been noted by others before and after the mussel invasion at Long Point and Point Pelee on Lake Erie (Wormington and Leach 1992, Petrie and Knapton 1999). The degree to which certain duck species consume mussels varies depending on time and location, particularly for Bufflehead and Common Goldeneye (i.e., sometimes in some places they eat lots of the two mussels, and sometimes they do not) (Petrie and Knapton 1999, Schummer *et al.* 2008b). It seems likely, however, that the patterns we observed in our analysis for Lesser Scaup and Greater Scaup especially, and Bufflehead, were caused, at least in part, by a switch to eating mainly Zebra Mussels and Quagga Mussels (Petrie and Knapton 1999). Our analysis shows that hundreds of thousands of individuals of mussel-eating ducks are likely exposed to contaminants while staging or overwintering on Lake Erie.

The problem is potentially quite big, but is it actually negatively affecting the reproduction and survival of the ducks? On the reproduction side of things, studies have measured selenium and other contaminants in female scaup when they arrive on their boreal breeding grounds and found levels low enough to be of little or no concern (Fox *et al.* 2005, Matz and Rocque 2007, DeVink *et al.* 2008a, Badzinski *et al.* 2009). This may occur because as the ducks head north, and get farther away from the Great Lakes, they no longer take on contaminants because they are no longer eating contaminated mussels, and the more the ducks' livers and kidneys are able to eliminate the high amounts of selenium from their bodies (Petrie and Badzinski 2007). Thus, they are able to reproduce without jeopardizing the hatchability of their eggs or the health of their embryos. What about survival? To get at this one, researchers got quite ambitious. It seemed clear that selenium was at high levels in the ducks because they were eating tainted Zebra Mussels and Quagga Mussels, but how to know if the ducks' health and survival was being negatively affected because of it? The clincher: experimentally feed captive scaup with low, medium, and high doses of selenium over the range found in the wild and directly measure their health and survival, including measures of oxidative stress and immune function. This huge undertaking was accomplished with 54 captive scaup housed in outdoor pens at a facility near Aylmer, Ontario (Brady *et al.* 2013), plus another 46 captive birds kept in similar cages in Laurel, Maryland (DeVink *et al.* 2008b). Surprisingly, no differences were found among the treatment groups. The survival and health of the high-dose birds was no different than the low-dose birds (DeVink *et al.* 2008b, Brady *et al.* 2013). The researchers also found no relationship between high levels of selenium and various health measures in wild, free-living scaup wintering in Hamilton Harbour on Lake Ontario (Ware *et al.* 2012). Conclusion: the ducks take on lots of selenium from the mussels, but it is not enough to negatively affect their health and survival. All the available evidence to date suggests that mussel-eating ducks on Lake Erie and the rest of the lower Great Lakes are not at risk from the high levels of selenium they acquire as a result of eating Zebra and Quagga Mussels. Indeed, numbers of breeding scaup and other duck species that often consume the two species of mussels, such as Bufflehead, have increased by several fold throughout their ranges over the past decade or so (Canadian Wildlife Service Waterfowl Committee 2017, US Fish and Wildlife Service 2018).

Figure 5. The number of staging and overwintering scaup (shown here) and other species of mussel-eating ducks has increased dramatically to hundreds of thousands of birds on Lake Erie since the invasion by non-native invasive Zebra Mussels and Quagga Mussels.

It is sobering to consider "what could have been" if the high levels of selenium that these birds ingest when eating the mussels were to seriously negatively affect their reproduction and survival.

Photos: Jeremy Bensette

So what does this all mean? Probably the most important and sobering message for waterfowl is "what could have been." Just imagine if the reproduction and survival of the hundreds of thousands of scaup and other species of waterfowl that eat contaminated Zebra Mussels and Quagga Mussels on Lake Erie and the rest of the lower Great Lakes (Figure 5) had been seriously negatively affected. Those species might be experiencing population declines large enough for them to be listed as species at risk. Therefore, as with invasive *Phragmites*, the take-home message is that we need to be extremely careful when it comes to invasive species and take preventative measures to avoid their establishment and spread (Tozer and Beck 2018). In the case of Zebra Mussels and Quagga Mussels, we may have gotten off somewhat easy, at least with respect to the ducks and selenium issue, but that is only part of the story since these invasive mussels have had broader environmental and social impact. We recommend collectively taking the time to learn more about invasive species issues and ways to prevent them. Some good ways to start include reviewing actions that can be taken while birding or pursuing other recreation in or near lakes to prevent the spread of invasive species, such as cleaning gear and boats before moving between locations (see summary at Ministry of Natural Resources and Forestry 2019). Also, learning more about government policies and recommended policy changes to deal with invasive species in Ontario (read Environmental Commissioner of Ontario 2019) would be a good idea. Spreading the message about ways to limit the spread of invasives around the Great Lakes is an important task for all of us. Currently, at least, Zebra Mussels and Quagga Mussels do not appear to be an issue for mussel-eating ducks, as far as selenium in their diet is concerned; in fact, the mussels are likely a dietary benefit to them, as long as they are not tainted with botulism toxin. By contrast, the very negative effects of these two invasive species on native mussels especially, and the Lake Erie ecosystem as a whole, is something that is too easily forgotten in the larger scheme of things.

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Doug Tozer
Long Point Waterfowl and Wetlands Research Program
Bird Studies Canada
P.O. Box 160
Port Rowan, Ontario N0E 1M0
E-mail: dtozer@birdscanada.org

Gregor Beck
Bird Studies Canada
P.O. Box 160
Port Rowan, Ontario N0E 1M0