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Rapid Communication

The spread of zebra mussel (*Dreissena polymorpha*) from the lower Susquehanna River into the upper Chesapeake Bay, Maryland, USA

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Abstract

The invasion of North American waters by *Dreissena polymorpha* (zebra mussel) and its subsequent ecological impacts has been well documented. Their spread continues to new states and watersheds despite a wealth of research and outreach campaigns, albeit at a slowed pace. We describe the spread and proliferation of zebra mussel into one of the more recently invaded states, Maryland, USA. Veliger counts and fixed hard surface monitoring suggest that a population is established within the lower Susquehanna River to the head of the Chesapeake Bay. A relatively narrow tidal-freshwater habitat envelope with suitable salinity may serve to restrict zebra mussel dispersal further downstream. Dispersal to other freshwater habitats in Maryland seems likely as the current area of infestation is highly used by commercial and recreational boaters, although regulations are in place that could help slow or prevent spread. Successful invasion will likely be a function of water chemistry, which may be limiting in some parts of the state.

Key words: zebra mussel, Susquehanna River, Chesapeake Bay, Maryland, invasive species

Introduction

Zebra mussels (*Dreissena polymorpha* Pallas, 1771) may be the symbolic invasive species of North America. Its introduction in the mid-1980s into the Great Lakes (Carlton 2008) highlighted a lack of preparedness for alien species. Following its introduction, zebra mussels caused considerable economic (Roberts 1990) and ecological damage (Strayer 2009). After 20 years of outreach and regulation the species continues to spread (Benson 2013). Species distribution models predicted that zebra mussels would eventually spread across much of North America including the Chesapeake Bay watershed, but their distribution within it was highly variable (Strayer 1991; Drake and Bossenbroek 2004; Whittier et al. 2008). We describe the relatively recent invasion into Maryland via the Susquehanna River into the Chesapeake Bay.

Study area

The Chesapeake Bay is the largest estuary in the United States. Its 166,543 km² drainage along the Mid-Atlantic coast encompasses major portions of Maryland, Pennsylvania, and Virginia along with smaller parts of Delaware, New York and West Virginia, and all of the District of Columbia. An estimated 17.9 million people live within the watershed (Claggett et al. 2013) and its estuary supports major commercial and recreational fisheries. Considerable effort to rehabilitate the estuary's fisheries and ecosystem health from eutrophication and habitat loss has been ongoing for decades (Kemp et al. 2005).

Invasion of the watershed

In 1991, the first zebra mussels in the Chesapeake Bay drainage were reported from the upper

Susquehanna River in Binghamton, New York (Benson 2013). In an evaluation of water quality data, Christmas et al. (1993) found a sizable portion of both freshwater and oligohaline waters in Maryland were suitable for colonization, which was found by others (Strayer 1991; Drake and Bossenbroek 2004). Restrictions on recreational boats entering water supply reservoirs from other water bodies and treatment facilities with molluscicide dosers were established (Balog et al. 1995). The initial response also included proactive monitoring and public outreach coordinated among the public, academic, and private sectors in an attempt to reduce potential impacts from invasion (Christmas 1995). Over the next ten years, new observations were reported from lakes and streams in New York and Pennsylvania that seemingly dispersed through connected watersheds and may have spread overland by boats and their trailers (Benson 2013). Purposeful introductions were suspected in diving quarries, because of the mussel's ability to increase water clarity.

Dispersal into Maryland

In 2008, a single adult zebra mussel was found attached to an anadromous fish trap upstream of the Conowingo Dam hydroelectric plant (Figure 1, Appendix I). An additional mussel was subsequently found attached to a recreational boat at a marina in Darlington, MD. It is unknown whether this specimen arrived via veliger dispersal down the Susquehanna River or from overland travel from infested waters. One year later, 11 adult mussels were observed downstream of Conowingo Dam (Ashton 2011). In 2010, additional zebra mussels were observed attached to substrate at scattered locations downstream of the dam (Biodrawveristy 2012). Since 2009, monitoring of industrial and municipal water intakes in the area indicated veligers have been increasing by almost an order of magnitude annually (S. Adams, Normandeau Associates, Inc., unpublished data).

As a result of increasing numbers of veligers upstream, the Maryland Department of Natural Resources (MDNR) began inspecting navigational buoys and anchors located in the lower Susquehanna River and upper Chesapeake Bay (Figure 1) while they are removed each fall (e.g., Yoo et al. 2014). Beginning in 2010, we found no mussels attached to 25 buoys or their anchors. No data were collected in 2011 due to a loss of numerous buoys. For 2012 and 2013, only a few zebra mussels were attached to buoy anchors. In 2014, the number of attached zebra mussels removed from anchors increased by five fold (Figure 2). We also observed five times as many anchors colonized with zebra mussels compared to previous years. The increases observed in attached mussels at standardized, artificial substrates strongly corresponded ($p = 0.02$, $df = 2$, $R^2 = 0.97$) with increases in upstream veliger abundance from standardized water samples (Figure 2).

Discussion

The Chesapeake Bay is a partially mixed estuary with a salt wedge that varies longitudinally in relation to seasonal patterns in precipitation (Kemp et al. 2005). Monthly salinity measured over a 30-year period in the area of colonized anchors averages 0.01 to 1.71 PSU. In comparison, the average salinity where anchors were not colonized ranges from 0.86 to 4.75 PSU and reaches a maximum of 10.89 PSU (MDNR 2015). In other North American estuaries and laboratory studies, higher salinity over prolonged periods of time effected zebra mussel growth, condition, reproduction, and survival (Mackie and Claudi 2010). Thus, the relatively small and temporally dynamic tidal-freshwater habitat envelope in the upper Chesapeake Bay may restrict the spread of zebra mussels further south. However, the currently infested area is frequented by recreational and commercial fisherman and some barge traffic. Dispersal to other freshwater habitats in Maryland at some point in the future seems likely, although existing regulations could help slow or prevent spread. Successful invasion is thought to be a function of water chemistry (Naddafi et al. 2011), which may be limiting in parts of the state (Strayer 1991; Whittier et al. 2008; Methratta et al. 2014).

The dark false mussel (*Mytilopis leucophaeta* Conrad, 1831) is another small bivalve that inhabits the oligohaline and mesohaline portions of the Chesapeake Bay. They are typically an uncommon bivalve, but experience unpredictable population irruptions (Kennedy 2011). There appears to be almost no overlap in the distribution of dark false mussels with the distribution of zebra mussels in Maryland. Because distinguishing between the settled stages of these species can be difficult, we visually inspect internal and external features of mussel shells to verify their identity (e.g., Pathy and Mackie 1993) when we receive reports of bivalve fouling from boaters or commercial fisherman.

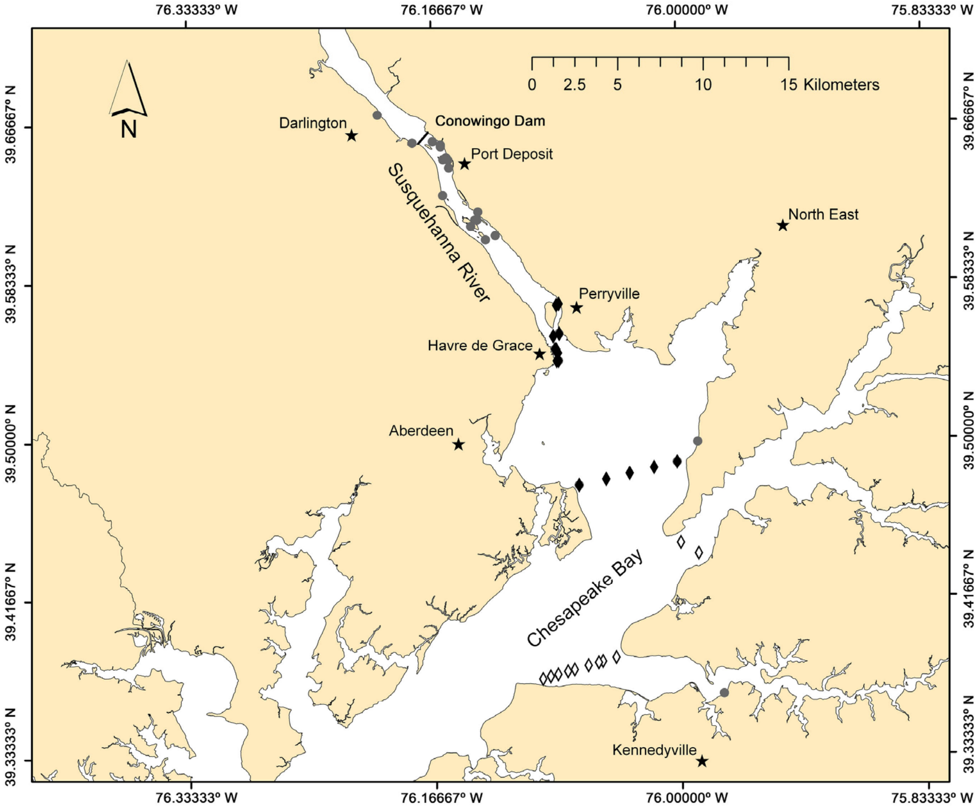
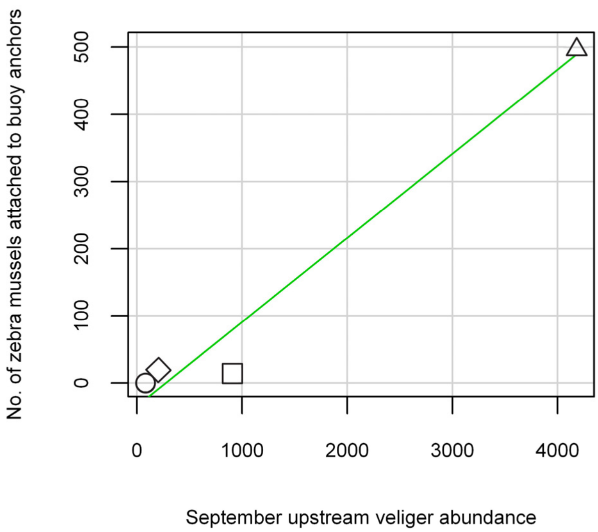


Figure 1. Geographic locations of zebra mussel observations made within the lower Susquehanna River and upper Chesapeake Bay, Maryland, USA since 2008. Observations reported by citizens or *in situ* are denoted with gray circles. The locations of navigational buoy anchors with attached zebra mussels are denoted with closed diamonds. Locations of anchors not colonized by zebra mussels are denoted with open diamonds. Records with uncertain locality information (Appendix I) downstream of the confluence of the Susquehanna River with Chesapeake Bay are not shown.

Figure 2. Scatter plot of total monthly veliger abundance versus total number of zebra mussels attached to navigational anchor buoys in the lower Susquehanna River and upper Chesapeake Bay. Veliger abundance data come from the Peach Bottom Atomic Power Station approximately 25 to 40 km upstream of navigational buoys. Triplicate 1000-L veliger net samples are taken bi-weekly within intake canals from May through November each year (S. Adams, Normandeau Associates, Inc., unpublished data). Number of attached zebra mussels is the total from all colonized buoy anchors observed during annual inspection. Sample years are denoted by polygons as: circle (2010), diamond (2012), square (2013), and triangle (2014). The solid line represents an ordinary least squares regression ($y = 0.125x - 34.256$).



As of January 2015, live zebra mussels have not been documented in any Maryland waters except for the lower Susquehanna River and upper Chesapeake Bay. Increasing reports of fouling, evidence of regular recruitment, and the current trajectory of abundance suggests the zebra mussel population in the study area may be exhibiting signs of an early invasion (Strayer et al. 1996). Existing strategies to contain zebra mussels to the lower Susquehanna River and upper Chesapeake Bay and prevent their spread are being re-evaluated. Regulations to prevent the spread of aquatic invasive species in Maryland have been in place since 2006 (COMAR 08.02.08.01, 08.02.19.01). However, there is no regular enforcement of recreational boats leaving infested waters or entering uninfested waters and decontamination procedures are voluntary. It will be important to communicate the efficacy of policies to control zebra mussel spread and their costs, along with the ecological and economic trade offs that could result from any decision.

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Appendix I. Localities of zebra mussel collection in Maryland since 2008. Nature of observation is categorized as citizen (C), *in situ* (I), or buoy anchors (A).

Date	Latitude	Longitude	Water body	Location	Number of specimens	Nature of observation
Nov-08	39.6567	-76.1772	Susquehanna River	Darlington, MD	1	C
Dec-08	39.6713	-76.2017	"	"	1	C
6-Jul-10	39.6163	-76.1360	Susquehanna River	Port Deposit, MD	2	I
"	39.6164	-76.1375	"	"	2	I
7-Jul-10	39.6577	-76.1659	"	"	2	I
"	39.6558	-76.1605	"	"	2	I
"	39.6206	-76.1354	"	"	1	I
8-Aug-10	39.6577	-76.1659	"	"	2	I
1-Oct-11	39.3662	-75.9712	Sassafras River	Kennedyville, MD	1	C
13-Sep-12	39.6549	-76.1605	Susquehanna River	Port Deposit, MD	6	I
1-Nov-12	39.4989	-75.9875	Chesapeake bay	North East, MD	1	C
3-Dec-12	39.5479	-76.0839	Susquehanna River	Havre de Grace, MD	7	A
"	39.5417	-76.0815	"	"	7	A
"	39.4763	-76.0683	Susquehanna River	Aberdeen, MD	6	A
11-Jun-13	39.6571	-76.1798	Susquehanna River	Darlington, MD	6	I
4-Nov-13	39.5532	-76.0898	Susquehanna River	Havre de Grace, MD	7	A
"	39.5562	-76.0810	Susquehanna River	Perryville, MD	6	A
"	39.4883	-76.0016	Chesapeake Bay	North East, MD	1	A
9-Sep-14	39.6571	-76.1798	Susquehanna River	Darlington, MD	3	I
17-Sep-14	---	---	Chesapeake Bay	North East, MD	52	C
11-Nov-14	---	---	Chesapeake Bay	Havre de Grace, MD	21	C
17-Nov-14	39.4794	-76.0498	Chesapeake Bay	Aberdeen, MD	33	A
"	39.4854	-76.0173	"	"	92	A
"	39.4763	-76.0683	"	"	59	A
"	39.4823	-76.0339	"	"	2	A
"	39.4883	-76.0016	"	"	81	A
"	---	---	"	"	6	A
17-Nov-14	39.5562	-76.0847	Susquehanna River	Perryville, MD	91	A
"	39.5712	-76.0829	"	"	6	A
"	39.5561	-76.0810	"	"	9	A
"	39.5480	-76.0838	Susquehanna River	Havre de Grace, MD	4	A
"	39.5482	-76.0833	"	"	11	A
"	39.5416	-76.0827	"	"	29	A
"	39.5459	-76.0827	"	"	9	A
"	39.5413	-76.0808	"	"	70	A