Special Issue: Quagga Mussels in the Western United States

Research Article

Abundance and stomach content analysis of threadfin shad in Lake Mead, Nevada: Do invasive quagga mussels affect this prey species?

Eric M. Loomis[1,3*], Jon C. Sjöberg[2], Wai Hing Wong[3] and Shawn L. Gerstenberger[3]

[1]*Bureau of Reclamation, U.S. Department of the Interior, Lower Colorado River Multi-Species Conservation Program Office, PO Box 61470, Boulder City, Nevada 89006 USA*
[2]*Nevada Department of Wildlife, 4747 Vegas Drive, Las Vegas, Nevada 89108 USA*
[3]*Department of Environmental and Occupational Health, University of Nevada, Las Vegas, 4505 Maryland Parkway, Box 453064, Las Vegas, Nevada 89154 USA*

E-mail: eloomis@usbr.gov (EML), sjoberg@ndow.org (JCS), david.wong@unlv.edu (WHW), shawn.gerstenberger@unlv.edu (SLG)

[*]*Corresponding author*

Abstract

Lake Mead, Nevada is the largest reservoir by volume in the United States, as well as a popular sport fishing destination. In January 2007, the invasive quagga mussel *Dreissena rostriformis bugensis* (Andrusov, 1897) was discovered in the reservoir and concerns began to arise about potential alterations to the aquatic environment. The Lake Mead sport fishery is reliant on the sustainability of prey species like the threadfin shad [*Dorosoma petenense* (Günther, 1867)]. This study examined 20-year trends in historic abundance of the threadfin shad, before, and shortly after, the discovery of quagga mussels in the system. Larval shad trawl data collected in Las Vegas Bay and Overton Arm portions of Lake Mead were analyzed in the present study. Two-way analysis of variances showed that the abundance of this prey fish has not changed following quagga mussel invasion ($P > 0.05$). Post-quagga mussel discovery collections of adult threadfin shad from Las Vegas Bay ranged from 113 to 212 mm total length (TL) (mean = 184 mm; n = 170). Shad from Overton Arm ranged from 131 to 197 mm TL (mean = 150 mm; n = 27). Stomach contents were analyzed. The proportion of cladocerans in stomach contents differed significantly from spring to winter in Las Vegas Bay ($P = 0.008$); whereas the proportion of copepods did not show statistically relevant differences regarding seasonality ($P = 0.562$). Initial trends in lower trophic level dynamics in response to quagga mussel invasion has yet to reveal significant effects in Las Vegas Bay or Overton Arm. Long-term monitoring on threadfin shad is needed to evaluate potential impacts from invasive quagga mussels in Lake Mead.

Key words: threadfin shad, Lake Mead, historic trends, stomach contents analysis, *Dreissena rostriformis bugensis*, zooplankton

Introduction

Threadfin shad *Dorosoma petenense* (Günther, 1867), native to the southeastern United States, were introduced into lakes Mead, Mohave, and Havasu in 1954-55 and were found throughout the lower Colorado River system by 1956 (LaRivers 1962; Moyle and Cech 1982). Pelle (1989) attributed such rapid dispersion to high fecundity rates in this species. Threadfin shad are a pivotal component of the Lake Mead food web, serving as prey for introduced game species like striped bass *Morone saxatilis* (Walbaum, 1792) and largemouth bass *Micropterus salmoides* (Lacepède, 1802) (Miller 1950; Haskell 1959; Miller 1961; Deacon et al. 1972; LaBounty et al. 2004). By the time striped bass were introduced in 1969, threadfin shad had

already been well established in parts of Lake Mead where primary productivity was highest (Deacon et al.1972; Allan and Roden 1978). The success of introduced predators in Lake Mead continues to depend largely on the viability and continued production of threadfin shad (Wilde and Paulson 1989). As a result of these introductions, the Lake Mead fishery has experienced sustained popularity in relation to its status as the largest reservoir by volume in the U.S.

Ecological disturbance associated with biological invasions often results in negative alterations of food web dynamics (Vitousek 1990; van Riel et al. 2006). The quagga mussel *Dreissena rostriformis bugensis* (Andrusov, 1897) was first discovered in January 2007 in Boulder Basin of Lake Mead and has established

in great numbers over a short time period (LaBounty and Roefer 2007). Overall, adult and juvenile quagga mussel densities in Lake Mead have increased exponentially, regardless of substrate. In 2007 and 2009, the density of quagga mussels in rocky areas was 624 and 8,925 individuals/m^2, respectively. In sandy and muddy areas, numbers increased from 80 to 3,350 individuals/m^2 (Wong et al. 2011b). Quagga veliger abundance in the Boulder Basin of Lake Mead increased from 0.9 individuals/L in 2007 to 4.5 individuals/L in 2008 (Holdren et al. 2010). It was suspected that the invasive quagga mussels reached Lake Mead from the Great Lakes via recreational boats over land. The initial invasion was thought to have occurred in either 2003 or 2004 based on age structure of mussels at the time of discovery in 2007 (LaBounty and Roefer 2007; McMahon 2011).

Dreissena species can alter ecosystem dynamics by several mechanisms (May and Marsden 1992; MacIsaac 1996). They are highly efficient water filterers, removing substantial amounts of phytoplankton, which in turn decrease the food source for zooplankton (Claxton et al. 1998; Wong et al. 2011a and references therein). Predation by fishes and eels on *Dreissena* veligers have been documented from studies conducted in Europe (Wiktor 1963; Kornobis 1977). However, from a fisheries' perspective, planktivorous fish that mainly rely on zooplankton, especially on microzooplankton, may suffer due to shortage of food as a result of energy transfer from the pelagic community to the benthic community. Therefore, benthic feeding fishes may benefit from the establishment of mussels. Other potential beneficiaries of dreissenid introduction in Great Britain include molluscivorous waterfowl and fishes. However, Aldridge et al. (2004) postulated that British ecosystems would experience negative effects from mussel presence as a whole. Declines in lake fishes due to a collapse in planktonic resources was speculated for the Great Lakes as far back as the early 1990s (Karnaukhov and Karnaukhov 1992). Lake Huron's natural food web was seriously altered because of the mussel invasion. Salmon, alewife, and zooplankton populations have declined, causing an energy shift from pelagic to benthic zones resulting in a $19 million/year decrease in revenues for Lake Huron sport fisheries (Michigan DNR 2010). The influence of dreissenid mussels on fish vary widely across ecosystems as a function of system morphology, factors that limit primary

production, and diets of these fish species (Strayer et al. 2004).

The potential impacts quagga mussels pose to the Lake Mead fishery are unknown. The implication of the potential decline in zooplankton that drives energetics is a growing concern. Extensive research in the Great Lakes region where dreissenid mussels, both quagga and zebra mussels *Dreissena polymorpha* (Pallas, 1771), have affected trophic dynamics may not adequately address ecological dynamics encountered in the arid southwest. To address some of these possible differences, we tested for a potential shift in diets of zooplanktivorous fish, specifically threadfin shad, since the introduction of quagga mussels into Lake Mead. Abundance trend data on threadfin shad populations in Lake Mead have largely been lacking in the scientific literature. This paper presents annual larval shad trawl data for comparison with possible ecological effects associated with quagga mussel introduction. Therefore, the objectives of this study were to (i) document historic trends in threadfin shad abundance to assess if this prey fish was affected by quagga mussels, (ii) examine the foraging habits of adult threadfin shad after the discovery of quagga mussels in Lake Mead, and (iii) evaluate if there was any change in abundance of zooplankton in stomach contents of threadfin shad, or in the water column where threadfin shad were caught.

Methods

Study site

Threadfin shad collections have been a routine component of annual lake health assessment since 1988. Sampling locations include two primary areas, the Overton Arm and Boulder Basin of Lake Mead (Figure 1). Overton Arm sites were based on a Lake Mead fertilization study conducted in the late 1980s by Axler et al. (1988) and were named F1 (36°26′00″N; 114°21′9″W), F2 (36°23′46″N; 114°21′56″W), F3 (36°21′43″N; 114°22′51″W) and F4 (36°20′21″N; 114°23′17″W). Nevada Department of Wildlife (NDOW) chose Las Vegas Bay sampling locations based on the Axler et al. (1988) study protocol and named those locations ILV (Inner Las Vegas Bay) (36°7′5″N; 114°50′44″W), MLV (Middle Las Vegas Bay) (36°7′00″N; 114°49′50″W), and BB (Boulder Basin) (36°5′15″N; 114°46′6″W). All fish (larval and adult) were collected as near to these

sampling locations as possible. However, trawl sampling in ILV and MLV have changed from year to year due to declining lake levels (M. Beckstrand, NDOW, June 2008, pers. comm.). Regional sampling from Las Vegas Bay and Overton Arm was established to contrast shad diets from areas with relatively high quagga veliger abundance (Las Vegas Bay) with an area with low veliger abundance (Overton Arm) (LAME 2007).

Larval shad trawls

NDOW shad trawl protocols consist of towing a cone-type-shaped net 6 m long with a 255 mm long collecting bucket on the end. The open end is 1 m in diameter with a 1.6 mm mesh screening. The net is towed approximately 20 m behind the boat in 10 min increments at an engine speed of 1,000 rpm and replicated three times to provide an average number. Flow volume is calculated using a flow meter at the mouth of the net to record water movement. Upon return to the laboratory, fish are counted and abundance converted to fish/100m^3 of water. Fish longer than 20 mm tend to avoid capture in the net so the technique is an estimate of reproductive success and not a population estimate of threadfin shad (NDOW 2006). Samples for this study were collected during spring and early summer from 1988 to 2008, except no data was available for 1990 in Las Vegas Bay.

A one-way ANOVA with Least Squares Determination (LSD) post hoc multiple comparisons was used to evaluate any significant difference in larval threadfin shad abundance among years. Two-way analysis of variance (ANOVA) was used to test for a difference in larval shad abundance before and after quagga mussel invasion between sampling locations in Las Vegas Bay and Overton Arm. Lake Mead's ecosystem has experienced significant natural and human-caused changes in addition to the quagga mussel invasion in recent years. For example, lake levels fluctuate yearly and water surface elevation is in the midst of a severe drought that began in 2000. A large bloom of the green algae *Pyramiclamys dissecta* occurred in the Boulder Basin in February 2001 and ended in late July 2001. Chlorophyll *a* peaked at > 200 mg/m^3 in the middle and outer basins (LaBounty and Burns 2005). To minimize the impacts from the decreasing lake level, nutrient loading, and extremely high algal mass in 2001, the data

collected from 2002-2006 and 2007-2008 were set for pre- and post-quagga mussel periods, respectively, for the present statistical analysis (Wong et al. 2010). The significance level was set at alpha = 0.05 (Zar 1996).

Zooplankton biomass index

To depict a potentially relevant biological relationship between shad and their food source, a biomass conversion was performed on zooplankton abundance (#/L) data reported by the Southern Nevada Water Authority (SNWA). Shad trawl locations were compared to data collected by the SNWA at comparable sampling stations in Boulder Basin. Zooplankton data provided by the SNWA was not readily available prior to year 2000 and thus were not included in the analysis. Contribution to the biomass index was developed from multiple sources (Wells 1970; Dumont et al. 1975; Culver et al. 1985; Pauli 1989; Kane 2004). Length-weight regressions for the bulk of cladocerans and copepods were estimated from Culver et al. (1985):

$$W = aL^b \qquad (1)$$

where *a* and *b* are fitted constants used to calculate weight, *W* represents mass in micrograms (µg), and *L* is length in millimeters (mm). Biomass calculations from the literature were reported directly for rotifers and veligers (Dumont et al. 1975; Pauli 1989; Kane 2004). When available, the length ranges (mm) were averaged at the division level.

Calculated biomass units were multiplied to the raw data provided by SNWA zooplankton counts (#/L) to arrive at a biomass unit (µg/L). Biomass values were then converted to a percent composition and compared to larval shad trawl counts (fish/100m^3) collected by NDOW from 2000 to 2008. Calculated length-weight regressions (µg/individual) for each division of zooplankton were summed and averaged (Table 1).

Stomach contents analysis of adult threadfin shad

To examine the foraging habits of threadfin shad, adults were collected in spring and summer 2008, and in winter 2009 for Las Vegas Bay and Overton Arm, respectively, through standard protocols and immediately fixed in 10% CaroSafe™ in the field in a container large
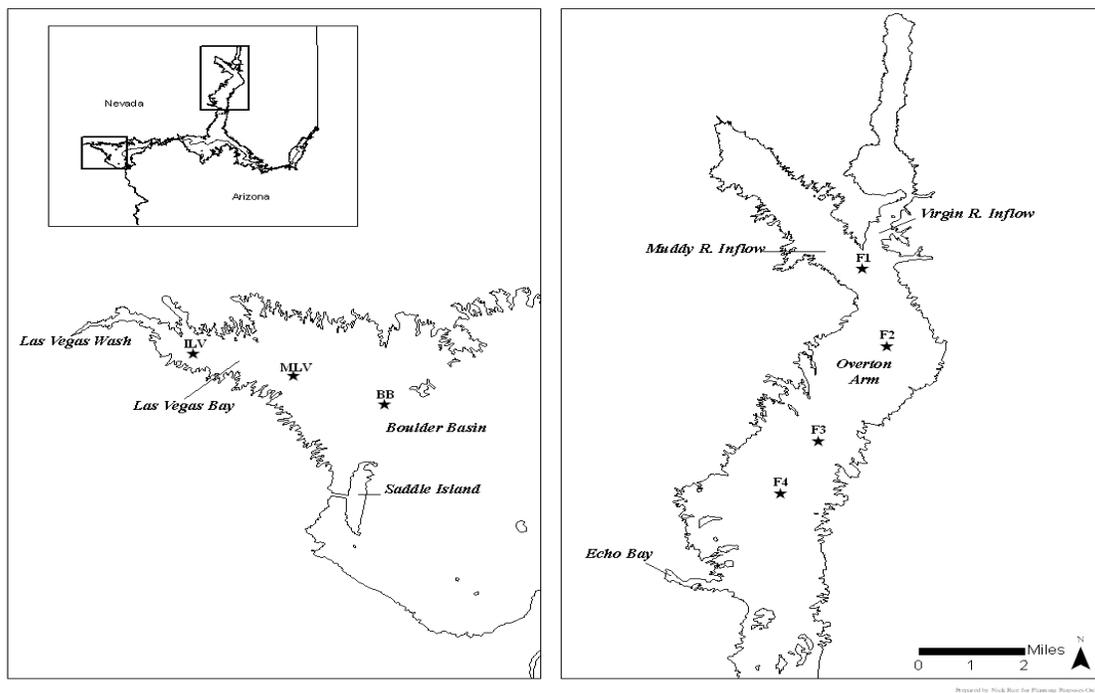
Figure 1. NDOW shad trawl sampling locations in Las Vegas Bay and Overton Arm, Lake Mead since 1988 (Axler et al. 1988; NDOW 2006).

enough to preserve multiple samples (APHA 1995; Haskell 1959; Pelle 1989). Preservation was immediately initiated to maximize the integrity of the stomach contents. After completion of field collection, whole fish were immediately transported to the laboratory and total length measurements were recorded. After lengths of adult fish were recorded, the gut from each fish was removed (from esophagus to anus) and individually preserved in 10% CaroSafe™ in Whirl-Paks™ to minimize possible degradation of the stomachs (Blanco et al. 2003). Extracted samples were stored under refrigeration until stomach contents analysis could be performed (Pinkas et al. 1971).

Stomachs were dissected vertically and the contents placed in a grid-lined sedgwick-rafter cell, suspended in 1ml distilled water (APHA 1995). This method has been employed for water sample analysis conducted by the U.S. Bureau of Reclamation (USBR) (G. Chris Holdren, USBR, Sep 2008, pers. comm.). Frequencies of occurrence of three major taxa of zooplankton common to Lake Mead (rotifers, copepods, and cladoceran) and quagga veligers were recorded under a stereo dissecting microscope (Carl Zeiss SteREO Discovery.V8, Toronto, Ontario, Canada) fitted with a cross-polarized light (CPL) source at magnification suitable for positive identification (Johnson 1995). Using CPL facilitates the identification of veligers due to the birefringent crystalline structure of the calcite in the larval shell (Johnson 1995). A frequency of occurrence method was employed to analyze stomach contents for the determination of diet composition as described by Hyslop (1980):

$$\%F_i = (N_i \, / \, N) \times 100 \qquad (2)$$

where F_i = percent frequency of prey type i, N_i = number of shad with prey i in the stomach, and N is total number of shad with stomach contents. Enumeration of food items were recorded at the division level and included cladocerans, copepods, veligers, or rotifers. Relative percentage occurrence and relative percentage abundance of prey items was determined through modification of the Costello method for interpreting stomach contents data (Amundsen et al. 1996).

160

Table 1. Zooplankton and quagga mussel veliger biomass profile for Lake Mead, Nevada based on Southern Nevada Water Authority count composition. Genus and species are shown when available. Taxa represented encompass non-ovigerous females where applicable. NA refers to a direct biomass conversion from the literature.

Genus	Species	Division	[1]Range (mm)	[1]Mean	[1]b c.i.	[1]a	[1]W (µg)/ind	Source
Daphnia	*galeata*	Cladoceran	0.471-2.172	1.3215	1.5644	7.4997	11.6	Culver et al. 1985
[2]*Daphnia*	*pulex*	Cladoceran	0.471-2.172	1.3215	1.5644	7.4997	11.6	Culver et al. 1985
[2]*Diaphanasoma*	*brachyurum*	Cladoceran	0.471-2.172	1.3215	1.5644	7.4997	11.6	Culver et al. 1985
Acanthocyclops	*vernalis*	Copepod	0.326-1.086	0.706	2.5563	7.0729	2.9	Culver et al. 1985
Mesocyclops	*edax*	Copepod	0.507-1.050	0.7785	2.8945	6.6586	3.23	Culver et al. 1985
Calanoid	*copepodid*	Copepod	0.362-1.176	0.769	2.7766	5.2387	2.53	Culver et al. 1985
Cyclopoid	*copepodid*	Copepod	0.326-1.086	0.706	2.5563	7.0729	2.9	Culver et al. 1985
Epischura	*nevadensis*	Copepod	0.81-2.13	1.47	1.7713	6.4115	12.69	Wells 1970
Leptodiaptomus	*ashlandi*	Copepod	0.724-1.176	0.95	1.9604	6.1927	5.6	Culver et al. 1985; Kane 2004
Nauplii		Copepod	0.144-0.315	0.2295	1.6349	2.5968	0.23	Culver et al. 1985
Euchlanis	*dialata*	Rotifer	NA	NA	NA	NA	0.65	Dumont et al. 1975
Synchaeta	*pectinata*	Rotifer	NA	NA	NA	NA	0.13	Pauli 1989
Conochilus	*unicornis*	Rotifer	NA	NA	NA	NA	0.06	Pauli 1989
Polyarthra	*vulgaris*	Rotifer	NA	NA	NA	NA	0.05	Pauli 1989
Dreissena	*bugensis*	Veliger	[4]0.04-0.41	NA	NA	NA	[3]1.0	Kane 2004

[1] $W = aL^b$, where a and b are constants, L is equal to mean range (mm) (Culver et al. 1985).
[2] Regression equations for cladocerans not significantly different at 0.05 significance level (Culver et al. 1985).
[3] Average individual biomasses used in calculation of veliger biomass values (Kane 2004).
[4] Range(mm) taken from U.S. Army Corps of Engineers.

Prey-specific abundance is a function of the percentage of prey items in only those shad in which the prey occurs and is represented by the following equation:

$$P_i = (\Sigma S_i / \Sigma S_{ti}) \times 100 \quad (3)$$

where P_i is prey-specific abundance of prey type i, S_i total stomach contents (number) comprised of prey i, and S_{ti} is total stomach content in only those shad with prey item i in their stomach (Amundsen et al. 1996). A two proportion z-test was performed to test whether shad were utilizing selected prey items during different seasons (Zar 1996). Prey-specific abundance was also calculated using a proportional z-test, comparing food type variation. Proportional analysis showing variation in prey abundance by site was reported.

Results

Long-term larval shad trend analysis

The annual larval threadfin shad trawl conducted by NDOW has remained consistent by location in Las Vegas Bay and Overton Arm since 1988. Numbers of fish/100m^3 since 1988 were tabulated for all three sampling locations in Las Vegas Bay (Figure 2). The lowest average count occurred in 1989 at 2.78 fish/100m^3 and the highest was observed in 2007, with an average of 445.56 fish/100m^3. There was no difference among years in mean numbers of shad ($F_{19,40,0.05}$ = 1.85, where $F(1.38) < F_{critical}$ (1.85), $P = 0.19$) for Las Vegas Bay based on one-way ANOVA.

Threadfin shad densities ranged from 2.73 fish/100m^3 in 2000 to 256.07 fish/100m^3 in year 2007 for Overton Arm and were significantly different ($F_{20,62,0.05}$ = 1.74, where $F(5.02) > F_{critical}$ (1.74), $P < 0.001$) (Figure 3). The LSD t-test indicated that 2005 and 2007 were significantly different from all other years in the dataset. A separate one-way ANOVA based on trawling locations, as opposed to year, revealed no significant difference in Las Vegas Bay ($F_{2,57,0.05}$ = 3.16, where $F(2.73) < F_{critical}$ (3.16), $P = 0.07$). The same was observed for each of the four trawling locations in Overton Arm ($F_{3,79,0.05}$ = 2.72, where $F(0.39) < F_{critical}$ (2.72), $P = 0.76$).

Figure 2. Larval shad density from 1988-2008 for all three sampling locations in the Las Vegas Bay of Lake Mead (data collected by Nevada Department of Wildlife, Mean ± standard deviation).
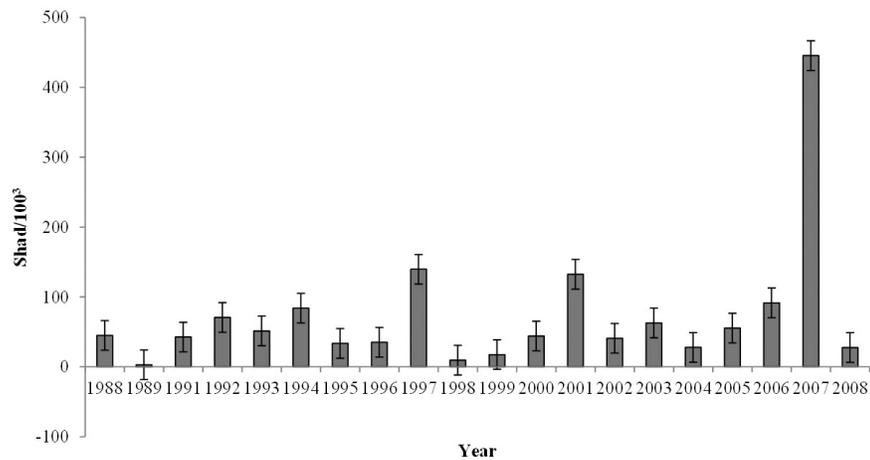
There was no significant difference in larval shad abundance before and after quagga mussel invasion among the three stations in Las Vegas Bay (two-way ANOVA, $df = 3$, $F = 1.82$, $P = 0.18$) and in Overton Arm ($df = 4$, $F = 0.48$, $P = 0.75$). When analyzed together (Las Vegas Bay and Overton Arm), no significant difference (two-way ANOVA, $df = 2$, $F = 1.81$, $P = 0.18$) was found in shad abundance before and after quagga mussel invasion.

Zooplankton biomass

Division means for cladocerans (µg of dry weight/L) were 11.6; for copepods 4.3; rotifers 0.2; and veligers 1.0 (Table 1). Trends in zooplankton biomass were then compared with NDOW shad trawls for sampling location Inner Las Vegas Bay (ILV) from 2000-2008 (Figure 4). Copepod biomass was highest in 2001 comprising over 71% of all zooplankton. Subsequently, mean shad counts peaked with copepod availability during this time at 226.7 fish/100m^3.

Zooplankton biomass and shad distribution in Boulder Basin (BB) differed (Figure 5A) from the inner Las Vegas Bay (ILV) (Figure 4). Copepods dominated representative zooplankton, comprising 76% of all zooplankton biomass over the nine-year dataset. In absolute terms, copepod biomass was the highest of all zooplankton groups. As copepods and cladocerans increased from 2005-2007, a subsequent decrease in shad counts was observed (Figure 5B). From 2006-

2008 shad counts/100m^3 declined as quagga veliger biomass increased. Cladoceran biomass in relation to shad has shown an inverse oscillation from year-to-year (Figure 5A). However, from results of absolute biomass, cladocerans were the least abundant of the zooplankton studied from 2000-2003 (Figure 5B).

Stomach contents analysis

Threadfin shad from Las Vegas Bay ranged in size from 113 to 212 mm total length (TL) (mean = 184 mm; n = 170). Shad from Overton Arm ranged in size from 131 to 197 mm TL (mean = 150 mm; n = 27). The means represent all fish collected from the 2008 and 2009 sampling events. Total identifiable shad stomach contents contained primarily cladocerans and copepods, where some stomachs contained multiple zooplankton food items while others were empty (Table 2). Amorphous debris also contributed a significant portion to the total stomach contents. No quagga mussel veligers were observed under cross-polarizing microscopy. Likewise, no rotifers were observed as food items identified at the division level in Las Vegas Bay or Overton Arm. Visual estimation of abundance revealed that 46 % of Las Vegas Bay stomachs and 85% of Overton Arm stomachs contained either identifiable copepod or cladoceran food items or a combination of zooplankton and other ingested contents.

Figure 3. Larval shad density from 1988-2008 in the Overton Arm of Lake Mead (data were collected by Nevada Department of Wildlife, Mean ± standard deviation).
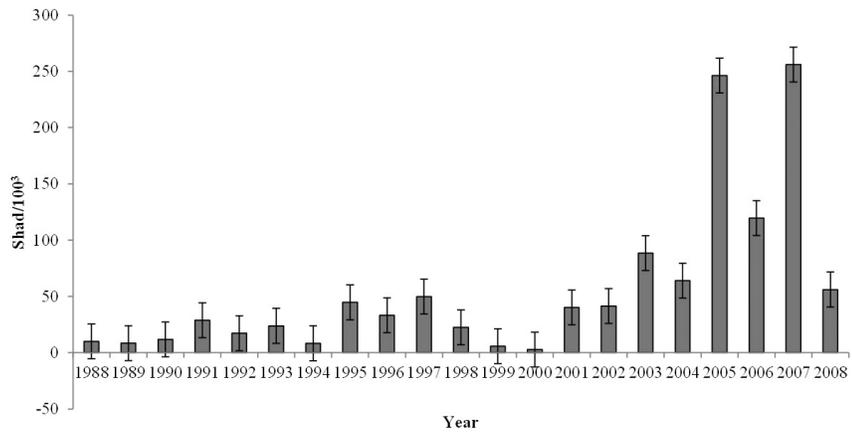

Figure 4. Relative biomass of three types of zooplankton and quagga mussel veligers compared to annual threadfin shad larvae density from 2000-2008 in Inner Las Vegas Bay sampling location.
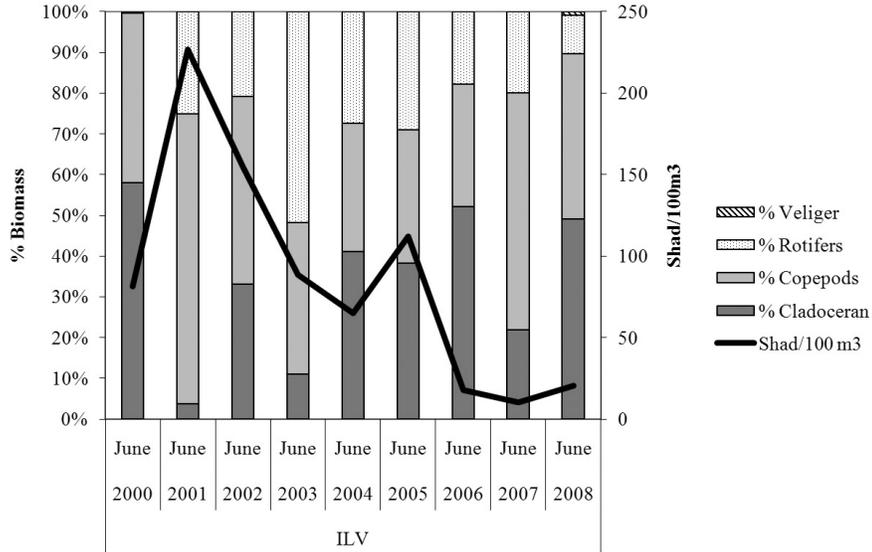

Table 2. Summary of stomach contents collected from 197 adult threadfin shad in Las Vegas Bay and Overton Arm, Lake Mead in spring and summer 2008 and winter 2009. Cladoceran and copepod counts encompass the total number of identifiable specimens in all stomachs examined.

Category	Las Vegas Bay (N = 170)	Overton Arm (N = 27)
Cladocerans	N = 164	N = 16
Copepods	N = 49	N = 32
Stomachs containing food items (including debris)	N = 79 46%	N = 23 85%
Empty stomachs (no gut contents)	N = 91 54%	N = 4 15%

Table 3. Frequency of occurrence and prey-specific abundance percentages of cladocerans and copepods in the stomach contents of adult threadfin shad in Las Vegas Bay, Lake Mead. Prey-specific abundance is a modification of the Costello method (Amundsen et al. 1996).

Location	Frequency of Occurrence	
Las Vegas Bay	$\%F_{cladoceran} = (38_{cladoceran}/79) \times 100$	=48.1%
	$\%F_{copepod} = (24_{copepod}/79) \times 100$	=30.4%

Location	Prey-Specific Abundance	
Las Vegas Bay	$P_{cladoceran} = (\Sigma 164/\Sigma 208) \times 100$	=78.9%
	$P_{copepod} = (\Sigma 49/\Sigma 150) \times 100$	=32.7%

Frequency of occurrence and prey-specific abundance of stomachs that had identifiable cladocerans and copepods were calculated (Table 3). The proportional analysis includes only those stomach contents which contained either cladocerans and/or copepods, respectively. Testing among seasons revealed there was no significant difference in the proportion of cladocerans to copepods in shad stomachs for either spring ($z = 0.70$, $P = 0.484$) or winter ($z = -0.91$, $P = 0.362$) from comparative sampling events in Las Vegas Bay.

The proportion of cladocerans in stomach contents differed significantly between spring and winter in Las Vegas Bay ($z = 2.64$, $P = 0.008$), whereas proportion of copepods counted did not show statistically relevant difference for seasonality ($z = 0.58$, $P = 0.562$). A comparison in prey-specific abundance by site was also analyzed. For Las Vegas Bay, cladocerans were significantly more abundant than copepods ($z = 9.70$, $P < 0.001$).

Discussion

Based on data for shad and zooplankton through 2008, we were unable to detect any changes that are likely to impact the Lake Mead sport fishery specifically with respect to introduction of quagga mussels. Similar results were reported by Mayer et al. (2000) in regards to changes in survival and diet of yellow perch *Perca flavescens* (Mitchill, 1814) in response to zebra mussels *Dreissena polymorpha* (Pallas, 1771) in Oneida Lake, New York. However, studies from the Great Lakes have shown a shift to diet items of a lower energy value as a consequence of dreissenid presence, sometimes feeding on mussels in response to a decline in more energy efficient food items (Pothoven et al. 2001; Hoyle et al. 2008). The presence of quagga mussels in Lake Mead may or may not follow the same trajectory in regards to the health and viability of the fishery. Overton Arm showed a difference between years in the mean number of shad counted ($P < 0.001$). More sample sites to conduct shad trawls in reaches other than Las Vegas Bay and Overton Arm could be considered, especially in areas of Lake Mead where threadfin shad consistently congregate based on historic knowledge (NDOW 2006). The expansion of shad trawls would add significant data to an already comprehensive historical record into the primary food source for valuable

species of game fish such as striped bass and largemouth bass.

A comprehensive zooplankton biomass index specific to Lake Mead was developed in relation to shad abundance and used to compare spatial and temporal variation over the past decade. High relative abundance of copepods, for example, may change dramatically over time as quagga biomass increases, as has recently been observed in the Boulder Basin reach of Las Vegas Bay (Figure 5). Reductions in small bodied zooplankton were observed in the presence of zebra mussel and bluegill *Lepomis macrochirus* (Rafinesque, 1819) from a controlled experimental reservoir pumped from the Black River near La Crosse, Wisconsin (Richardson and Bartsch 1997). Fish/zooplankton trophic interactions in two Swedish lakes showed a shift to more rotifer assemblages when planktivorous fish were present and high numbers of cladocerans when fish were absent (Andersson et al. 1978). Water clarity as a result of mussel influence could show similar dynamics over time. It is unclear how trophic relationships among zooplankton and shad in the years leading up to quagga mussel discovery are affecting Lake Mead. Therefore, it would be premature to conclude there is evidence to suggest quagga mussels have had a negative impact on the shad/zooplankton cycle in Lake Mead. This is in agreement with observations that absolute abundance of zooplankton in the Boulder Basin of Lake Mead has not changed following quagga mussel invasion (Wong et al. 2010).

Results from stomach contents analysis of threadfin shad were under-represented in Overton Arm collections (n = 27). Our use of trammel and gill nets of varying mesh size probably allowed smaller shad to avoid capture in the two and three inch portions of the nets. The bulk of threadfin shad were located in the smallest one-third of nets. Therefore, smaller shad were most likely under-represented due to variability in mesh size.

Multiple studies have recognized the problem of rapid digestion in fish guts of soft-bodied larval tissue due to mechanical and chemical processes (Hunter 1981; Folkvord 1993; Kim and DeVries 2001; Schooley et al. 2008). As a result, the ability to efficiently quantify quagga veligers by this method has proved problematic. Although preservation techniques used were adequate for large-bodied cladocerans and copepods, it was not practical for the delicate nature of veligers and may have explained

Figure 5. Relative biomass of three types of zooplankton and quagga mussel veligers compared to annual larval shad density (A) and zooplankton biomass (µg/L) compared with shad from 2000-2008 in Boulder Basin, Las Vegas Bay, sampling location (B).
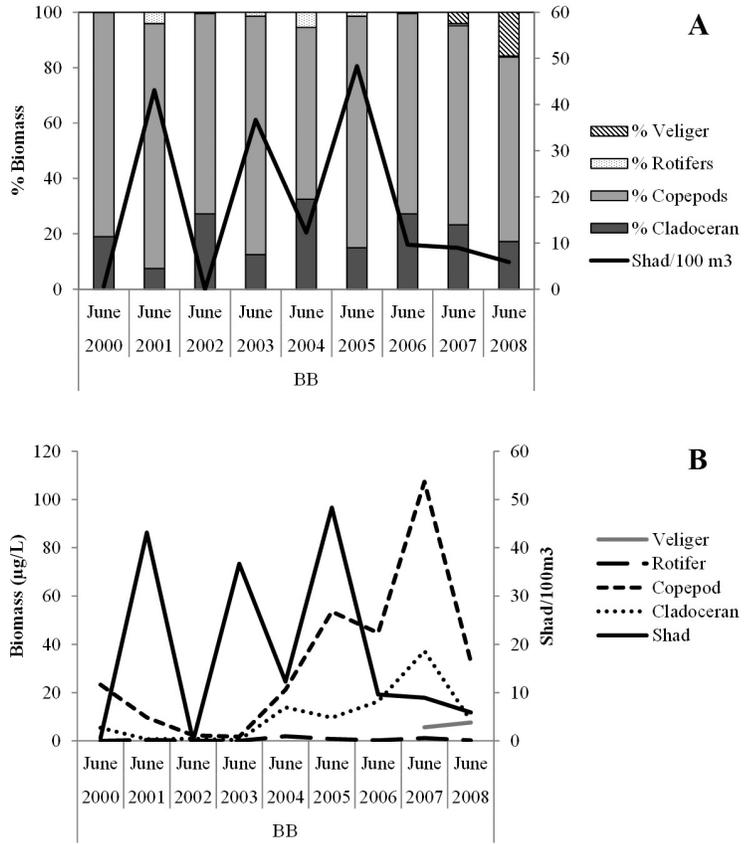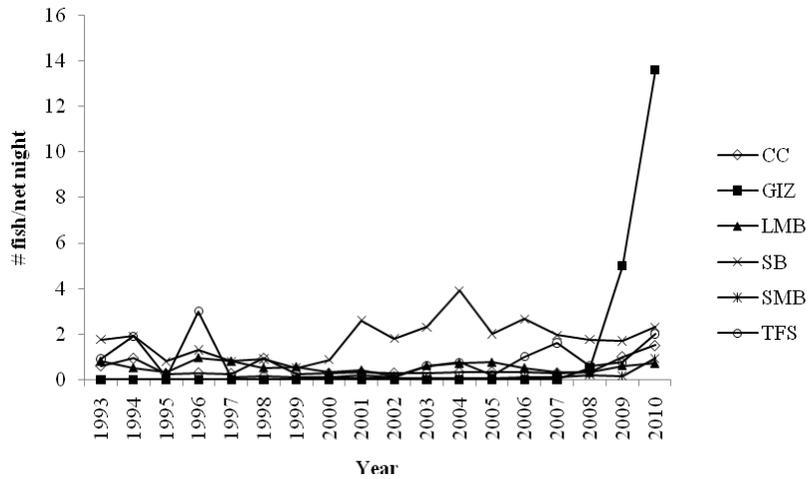
Figure 6. Lake Mead fish abundance (catch per unit effort with gill net) from 1993 to 2010 (CC: Common Carp; GIZ: Gizzard Shad; LMB: Large Mouth Bass; SB: Striped Bass; SMB: Small Mouth Bass; TFS: Threadfin Shad

the lack of identifiable rotifers in gut contents of shad as well. Based on previous studies, immediate examination of stomach contents is critical. Archived retention time of stomach contents from this study varied from a maximum of ten months from collections gathered in April, 2008 to as little as three weeks in the case of samples collected in February, 2009. Use of active capture methods such as electro fishing, angling, or seining could reveal better results than the passive method of trammel and gill netting (Schooley et al. 2008).

Since quagga mussel invasion is a recent phenomenon in the western U.S., many protocols and research needs on fisheries have yet to be developed. One recommendation would be to study assimilation of a quagga veliger once it enters the stomach of the threadfin shad. The soft-bodied, miniscule properties of this organism make it difficult to identify (Johnson 1995; Frischer et al. 2002). Studies related to degradation over time could be administered in a controlled environment in an attempt to evaluate the future plausibility of conducting gut content analysis in the targeted search for veligers. Additional biological introductions to Lake Mead may further impact long-term trends regarding abundance of threadfin shad, zooplankton, and quagga mussels.

Other recent notable introductions that may impact Lake Mead ecology were the discovery in 2007 of gizzard shad *Dorosoma cepedianum* (Lesueur, 1818) in Overton Arm (Herndon 2010) and the New Zealand Mud snail *Potamopyrgus antipodarum* (J.E. Gray, 1853), first detected in 2008 (Davis and Moeltner 2010). Although no significant change was found in threadfin shad, the gizzard shad has experienced exponential increase since then (Figure 6). In 2010, the biomass of this prey fish was 42.5% among all species. Benthic organisms are a major food component for gizzard shad (Judge 1973), and their dominance may be associated with invasive quagga mussels in Lake Mead. However, it would be premature to conclude gizzard shad will impact the Lake Mead fishery due to uncertainties this early in the invasion cycle. The closely coupled timing in spread and growth between gizzard shad and quagga mussels in Lake Mead needs to be addressed for future studies. The high numbers of larval shad collected in 2005 and 2007 from Overton Arm could be due to increases in larval gizzard shad and not threadfin (Figure 3). Because gizzard

and threadfin shad larvae are morphologically similar (Miller 1950; Santucci and Heidinger 1986), speciation was likely overlooked and all specimens were assumed to be threadfin shad during data analysis.

Post-invasion monitoring and continued data collection are perhaps most critical to further understanding potential effects quagga mussels may be having in Lake Mead. Since quaggas were first discovered in 2007, little data are available to gauge the long-term impact. We recommend continuation and expansion of larval shad trawls by NDOW and zooplankton monitoring by the SNWA and USBR if trends are to be determined. Long-term monitoring goals for Lake Mead based on quagga mussel influence (Wong et al. 2011a) need to be implemented as the invasion persists and possible depletion of the sport fishery is threatened by an altered trophic structure.

Acknowledgements

References

Aldridge DC, Elliott P, Moggridge GD (2004) The recent and rapid spread of the zebra mussel (*Dreissena polymorpha*) in Great Britain. *Biological Conservation* 119: 253–261, doi:10.1016/j.biocon.2003.11.008

Allan RC, Roden DL (1978) Fish of Lake Mead and Lake Mohave. Nevada Department of Wildlife (NDOW), Reno. Biological Bulletin No 7

Andersson G, Berggren H, Cronberg G, Gelin C (1978) Effects of planktivorous and benthivorous fish on organisms and water chemistry in eutrophic lakes. *Hydrobiologia* 59: 9–15, doi:10.1007/BF00017602

APHA (1995) Standard Methods for the Examination of Water and Wastewater, 19th ed. American Public Health Association, American Water Work Association, Water Environment Association Washington DC

Amundsen PA, Gabler HM, Staldvik FJ (1996) A new approach to graphical analysis of feeding strategy from stomach contents data – modification of the Costello (1990) method. *Journal of Fish Biology* 48: 607–614, doi:10.1006/jfbi.1996.0060

Axler R, Paulson L, Vaux P, Sollberger P, Baepler DH (1988) Fish aid — The Lake Mead fertilization project. *Lake and Reservoir Management* 2: 125–135, doi:10.1080/07438148809354820

Blanco S, Romo S, Villena MJ, Martinez S (2003) Fish communities and food web interactions in some shallow Mediterranean lakes. *Hydrobiologia* 506-509: 473–480, doi:10.1023/B:HYDR.0000008583.05327.da

Claxton WT, Wilson AB, Mackie GL, Boulding EG (1998) A genetic and morphological comparison of shallow and deep water populations of the introduced dreissenid bivalve *Dreissena bugensis*. *Canadian Journal of Zoology* 76: 1269–1276, doi:10.1139/cjz-76-7-1269

Culver DA, Boucherle MM, Bean DJ, Fletcher JW (1985) Biomass of freshwater crustacean zooplankton from length-weight regressions. *Canadian Journal of Fisheries and Aquatic Sciences* 42: 1380–1390, doi:10.1139/f85-173

Davis A, Moeltner K (2010) Valuing the prevention of an infestation: The threat of the New Zealand mud snail in northern Nevada. *Agricultural and Resource Economics Review* 39: 56–74

Deacon JE, Paulson LJ, Minckley CO (1972) Effects of Las Vegas Wash effluents upon bass and other game fish reproduction and success. Nevada Department of Fish and Game. Final Report, 74 pp

Dumont HJ, Van de Velde I, Dumont S (1975) The dry weight estimate of biomass in a selection of Cladocera, Copepoda, and Rotifera from the plankton, periphyton and benthos of continental waters. *Oecologia* (Berlin) 19: 75–97, doi:10.1007/BF00377592

Folkvord A (1993) Prey recognition in stomachs of cannibalistic juvenile cod (*Gadus morhua* L.). *Sarsia* 78: 97–100

Frischer ME, Hansen AS, Wyllie JA, Wimbush J, Murray J, Nierzwicki-Bauer SA (2002) Specific amplification of the 18S rRNA gene as a method to detect zebra mussel (*Dreissena polymorpha*) larvae in plankton samples. *Hydrobiologia* 487: 33–44, doi:10.1023/A:1022971918673

Haskell WM (1959) Diet of the Mississippi threadfin shad, *Dorosoma petenense atchafalyae*, in Arizona. *Copeia* 4: 298–302, doi:10.2307/1439886

Herndon D (2010) Lake Mead preliminary gill net survey results. Interagency Quarterly Quagga Mussel Meeting, Henderson, NV

Holdren GC, Wong WH, Hosler D (2010) Spread and abundance of quagga mussel veligers in Lake Mead, Nevada-Arizona from 2007 to 2009. Aquaculture 2010 (American Fisheries Society / National Shellfisheries Association / World Aquaculture Society Triennial Conference), San Diego, CA, March 1-5, 2010

Hoyle JA, Bowlby JN, Morrison BJ (2008) Lake whitefish and walleye population responses to dreissenid mussel invasion in eastern Lake Ontario. *Aquatic Ecosystem Health and Management* 11: 403–411, doi:10.1080/14634980802530392

Hunter JR (1981) Feeding ecology and predation of marine fish larvae. In: Lasker R (ed), Marine fish larvae: Morphology, ecology, and relation to fisheries. Washington Sea Grant Program, Seattle, Washington, pp 33–71

Hyslop EJ (1980) Stomach contents analysis—A review of methods and their application. *Journal of Fish Biology* 17: 411–429, doi:10.1111/j.1095-8649.1980.tb02775.x

Johnson LE (1995) Enhanced early detection and enumeration of zebra mussel (*Dreissena* spp.) veligers using cross–polarized light microscopy. *Hydrobiologia* 312: 139–146, doi:10.1007/BF00020769

Judge DJ (1973) Food and Feeding Habits of Gizzard Shad in Pool 19, Mississippi River. *Transactions of the American Fisheries Society* 102: 378–383, doi:10.1577/1548-8659(1973)102<378:FAFHOG>2.0.CO;2

Kane DD (2004) The development of a planktonic index of biotic integrity for Lake Erie. PhD Thesis, Ohio State University, Columbus, Ohio, 277 pp

Karnaukhov VN, Karnaukhov AV (1992) Perspectives on the ecological impacts of the zebra mussel (*Dreissena polymorpha*) in the former European USSR and in North America. In: Nalepa TF, Schlosser DW (eds), Zebra Mussels: Biology, Impacts, and Control. Lewis Publishers, Boca Raton, Florida, pp 729–732

Kim GW, DeVries DR (2001) Adult fish predation on freshwater limnetic fish larvae: A mesocosm experiment. *Transactions of the American Fisheries Society* 130: 189–203, doi:10.1577/1548-8659(2001)130<0189:AFPOFL>2.0.CO;2

Kornobis S (1977) Ecology of *Dreissena polymorpha* (Pall.) (Dreissenidae Bivalvia) in lakes receiving heated water discharges. *Polish Archives of Hydrobiology* 24: 531–545

LaBounty JF, Burns NM (2005) Characterization of boulder basin, Lake Mead, Nevada–Arizona, USA – Based on analysis of 34 limnological parameters. *Lake and Reservoir Management* 21: 277–307, doi:10.1080/07438140509354435

LaBounty JF, Roefer P (2007) Quagga mussels invade Lake Mead. *LakeLine* 27: 17–22

LaBounty JF, Holdren GC, Horn MJ (2004) The limnology of Boulder Basin, Lake Mead, Arizona-Nevada: Report of Findings 1990-1998. U.S. Bureau of Reclamation (USBR) Technical Service Center. USBR Technical Memorandum No 8220–04–10

LAME (2007) Lake Mead National Recreation Area. Lake Mead National Recreation Area draft quagga mussel initial response plan. National ParkService Lake Mead National Recreation Area, Boulder City, Nevada

LaRivers I (1962) Fishes and fisheries of Nevada. Nevada State Fish and Game Commission, State Printing Office, Carson City, Nevada, 781 pp

MacIsaac HJ (1996) Potential abiotic and biotic impacts of zebra mussels on the inland waters of North America. *American Zoologist* 36: 287–299

McMahon RF (2011) Quagga mussel (*Dreissena rostriformis bugensis*) population structure during the early invasion of Lakes Mead and Mohave January-March 2007. *Aquatic Invasions* 6: 131–140, doi:10.3391/ai.2011.6.2.02

May B, Marsden JE (1992) Genetic identification and implications of another invasivespecies of dreissenid mussel in the Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 49: 1501–1506, doi:10.1139/f92-166

Mayer CM, VanDeValk AJ, Forney JL, Rudstam LG, Mills EL (2000) Response of yellow perch (*Perca flavescens*) in Oneida Lake, New York, to the establishment of zebra mussels (*Dreissena polymorpha*). *Canadian Journal of Fisheries and Aquatic Sciences* 57: 742–754, doi:10.1139/cjfas-57-4-742

Michigan DNR (2010) Changes in Lake Huron's ecosystem and foodweb cause Chinook salmon collapse summer 2010. Michigan Department of Natural Resources, Lansing, Michigan, 17 pp

Miller RR (1950) A review of the American clupeid fishes of the genus *Dorosoma*. *Bulletin U.S. Natural Museum* 100: 387–410

Miller RV (1961) The food habits and some aspects of the biology of the threadfin shad, *Dorosoma petenense* (Gunther). Master's Thesis, University of Arkansas, Fayetteville, Arkansas, 46 pp

Moyle PB, Cech JJ Jr (1982) Fishes: An introduction to ichthyology. Prentice-Hall, Englewood Cliffs, New Jersey, 593 pp

NDOW (2006) Nevada Department of Wildlife. Statewide fisheries management: Federal aid job progress reports: F-20-38, Lake Mead Southern Region, Nevada, USA: F–20–38, 27 pp

Pauli H-R (1989) A new method to estimate individual dry weights of rotifers. *Hydrobiologia* 186-187: 355–361, doi:10.1007/BF00048932

Pelle WL (1989) Temporal and spatial patterns of abundance of age 0 threadfin shad (*Dorosoma petenense*) in Overton Arm, Lake Mead. Master's Thesis, University Nevada, Las Vegas, Nevada, 41 pp

Pinkas L, Oliphant MS, Iverson ILK (1971) Food habits of albacore, bluefin tuna, and bonito in California waters. *California Fish and Game* 152: 1–105

Pothoven SA, Nalepa TF, Schneeberger PJ, Brandt SB (2001) Changes in diet and body condition of lake whitefish in southern Lake Michigan associated with changes inbenthos. *North American Journal of Fisheries Management* 21: 876–883, doi:10.1577/1548-8675(2001)021<0876:CIDABC>2.0.CO;2

Richardson WB, Bartsch LA (1997) Effects of zebra mussels on food webs: Interactions with juvenile bluegill and water residence time. *Hydrobiologia* 354: 141–150, doi:10.1023/A:1003048431234

Santucci VJ Jr., Heidinger RC (1986) Use of total myomere numbers to differentiate larvae of threadfin and gizzard shad. *Transactions of the Illinois Academy of Science* 79: 197–202

Schooley JD, Karam AP, Kesner BR, Marsh PC, Pacey CA, Thornbrugh DJ (2008) Detection of larval remains after consumption by fishes. *Transactions of the American Fisheries Society* 137: 1044–1049, doi:10.1577/T07-169.1

Strayer DL, Hattala KA, Kahnle AW (2004) Effects of an invasive bivalve (*Dreissena polymorpha*) on fish in the Hudson River estuary. *Canadian Journal of Fisheries and Aquatic Sciences* 61: 924–941, doi:10.1139/f04-043

van Riel MC, van der Velde G, Rajagopal S, Marguillier S, Dehairs F, bij de Vaate A (2006) Trophic relationships in the Rhine food web during invasion andafter establishment of the Ponto-Caspian invader *Dikerogammarus villosus*. *Hydrobiologia* 565: 39–58, doi:10.1007/s10750-005-1904-8

Vitousek PM (1990) Biological invasions and ecosystem processes: Towards anintegration of population biology and ecosystem studies. *Oikos* 57: 7–13, doi:10.2307/3565731

Wells L (1970) Effects of alewife predation on zooplankton populations in Lake Michigan. *Limnology and Oceanography* 15: 556–565, doi:10.4319/lo.1970.15.4.0556

Wiktor J (1963) Research on the ecology of *Dreissena polymorpha* Pall. in the Szczecin Lagoon (Zalew Sczcecinski). *Polish Journal of Ecology* 11: 275–280

Wilde GR, Paulson LJ (1989) Food habits of subadult striped bass in Lake Mead, Nevada-Arizona. *The Southwestern Naturalist* 34: 118–123, doi:10.2307/3671816

Wong WH, Tietjen T, Gerstenberger SL, Holdren GC, Mueting S, Loomis EM, Roefer P, Moore B, Turner K, Hannoun I (2010) Potential ecological consequences of nvasion of the quagga mussel (*Dreissena bugensis*) into Lake Mead, Nevada-Arizona, USA. *Lake and Reservoir Management* 26: 306–315, doi:10.1080/07438141.2010.n504071

Wong WH, Gerstenberger SL, Miller JM, Palmer CJ, Moore B (2011a) A standardized design for quagga mussel monitoring in Lake Mead, Nevada-Arizona. *Aquatic Invasions* 6: 205–215, doi:10.3391/ai.2011.6.2.09

Wong WH, Holdren GC, Gerstenberger SL, Tietjen T, Moore B, Turner K, Hickman G, D Wilson (2011b) Effects of invasive quagga mussels (*Dreissena rostriformis bugensis*) on chlorophyll and water clarity in the lower Colorado River. In: Nalepa TF, Schloesser DW (eds) Zebra Mussels: Biology, Impact, and Control, 2nd Edition (accepted)

Zar JH (1996) Biostatistical analysis, 3rd edn. Prentice Hall, Upper Saddle River, New Jersey, 662 pp