

# Temperature, discharge and development shape the larval diets of threatened green sturgeon in a highly managed section of the Sacramento River

Liam J. Zarri  | Eric P. Palkovacs

Department of Ecology and Evolutionary Biology, University of California, Santa Cruz, California

Correspondence

Liam J. Zarri, Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, NY.

Email: ljjz27@cornell.edu

## Abstract

Feeding at early fish life stages is a key determinant of survival to recruitment. To understand the environmental and developmental determinants of early life stage feeding in ESA-threatened green sturgeon (*Acipenser medirostris*), we performed a diet study in a highly managed section of California's Sacramento River, where temperature and discharge are controlled by dam releases. Utilising field collections from 2012 to 2016, we assessed the impacts of temperature, discharge and morphological development on the composition and number of prey items in larval green sturgeon diets. Results show that there are more empty stomachs at colder temperatures. Higher discharge conditions decreased prey taxon richness and counts, especially the abundance of cyclopoid copepods in diets. Fish smaller than 30 mm had teeth on the oral jaws and showed a strong reliance on zooplankton prey. The developmental loss of teeth in fish greater than 30 mm was associated with decreased zooplankton consumption and increased richness of benthic macroinvertebrates in diets. Our results show that river management through dam releases has the potential to impact the earliest life stage of green sturgeon by reducing the prevalence of favoured zooplankton prey in diets.

## KEY WORDS

*Acipenser medirostris*, benthic macroinvertebrates, dams, Endangered Species Act, environmental flows, jaw morphology, ontogenetic niche shift, prey choice

## 1 | INTRODUCTION

Natural river dynamics, which support native fish species, are altered by dam releases and water diversions. These anthropogenic alterations can impact the scale, regularity, duration and timing of river temperature and river discharge (Poff et al., 1997; Steel, Beechie, Torgersen, & Fullerton, 2017). Early life stage fishes are particularly sensitive to altered environment at the critical stage of initial feeding, and survival at this stage is a driver of fish recruitment (Hjort, 1914; Pepin, 1991; Sanford, Holzman, Haney, Rand, & Bertness, 2006; Sifa & Mathias, 1987). Therefore, it is crucial to understand the anthropogenic impact of altered river regimes on larval fish to better manage fish populations.

The early life stages of sturgeon have been studied extensively in the laboratory over the last 20 years, focusing on growth, behaviour and development (Deng et al., 2003; Gisbert & Williot, 1997; Kynard & Horgan, 2002; Kynard, Parker, & Parker, 2005; Werner, Linares-Casenave, Van Eenennaam, & Doroshov, 2007). Despite the breadth of these laboratory studies, information on the ecological role of early life stage sturgeons is lacking because there are relatively few studies of larval sturgeon in the wild. It is therefore important to understand how the physical river environment may be altering larval sturgeon diets, especially in reference to the ontogeny of key morphological traits. Sturgeon are opportunistic foragers, utilising highly specialised sensory structures and jaw mechanisms to feed on a variety of prey types (Carroll & Wainwright, 2003; Miller, 2004).

Here, we explore the ecology of early life stage larval green sturgeon (*Acipenser medirostris*, Ayres, 1854) in a highly managed section of the Sacramento River, California.

The southern genetically distinct population of green sturgeon has been in decline because of lost and altered habitat and is listed as threatened under the US Endangered Species Act (Adams et al., 2007; Mora, Lindley, Erickson, & Klimley, 2009; National Marine Fisheries Service 2006). Spawning and early life stage development of this population take place in the Sacramento River, which has a watershed encompassing California's northern Central Valley. The present upper extent of anadromy for mainstream spawning fish such as green sturgeon is Keswick Dam, which regulates the hydro-peaking outflow from Shasta Reservoir, a critical source of water for agriculture and urban use for much of California. The hydrological management regime of this region involves controlling the temperature and discharge of the river habitat (MacDiarmid, 1975, USFWS 1999). Spawning habitat of green sturgeon is characterised by deep, turbulent pools with cobble, gravel or sand substrate, and water velocity of 1.0–1.1 m/s (Poytress, Gruber, & Van Eenennaam, 2009; Wyman et al., 2017). Laboratory studies suggest optimal egg development temperatures range from 13°C to 15.5°C (Van Eenennaam et al., 2001). Embryos hatch approximately 8 days after fertilisation and hide in interstitial spaces between gravel and cobble while digesting the yolk sac and then larvae emerge at 10–15 days posthatch (DPH) to begin exogenous feeding and downstream nocturnal migration (Kynard et al., 2005). Larvae have 4–5 days to find food before starvation, and this critical period is one of the primary drivers of sturgeon population growth rate (Gross, Repka, Robertson, Secor, & Van Winkle, 2002). We define larvae as those individuals which have not yet taken on juvenile phenotypes (Balon, 1975), measured by scute count. Optimal growth of early life stage green sturgeon has been found to occur between temperatures of 15–19°C (Mayfield & Cech, 2004). Studies on other sturgeon species, such as shortnose sturgeon (*Acipenser brevirostrum*) and white sturgeon (*Acipenser transmontanus*), have found that larvae consume primarily drifting prey (Buckley & Kynard, 1981; Kynard, Parker, Kynard, & Horgan, 2014; Kynard et al., 2016), while juveniles shift to benthic prey (Radtke, 1966). However, the diet of larval green sturgeon in the Sacramento River is not known. The composition of larval diets has been identified as a priority area of research in recent management reports on green sturgeon (Heublein et al., 2017; Moser et al., 2016).

We examined the impact of larval sturgeon development and river environment (temperature and discharge) on larval green sturgeon diets, including the most abundant diet items by weight and count, total number of food items (diet counts), the number of taxa (richness) and proportion of taxa by count (composition). Food web impacts of river temperature and discharge were not specifically evaluated, as invertebrate samples were not collected from the Sacramento River. Thus, any diet shifts we detect may reflect changes in green sturgeon foraging behaviour, changes in metabolic rate or changes in prey availability. We examined aspects of larval sturgeon development including total length, jaw articulation angle and the presence of teeth. Although

hatchling sturgeon do not have teeth, larvae develop fine, hairlike teeth on the dentary, dermopalatines and palatopterygoid before losing teeth as juveniles (Hilton, Grande, & Bemis, 2011; Laumann, 2016). Jaw articulation angle has been shown to alter diet in other fishes (Higgins & Horn, 2014) as well as other sturgeon species, where piscivorous sturgeon have forward-opening jaws, while benthically foraging sturgeon have downward-opening jaws (Bemis, Findeis, & Grande, 1997). However, the timing of this shift in sturgeon mouth opening direction has not been documented with ontogeny. Based on ontogenetic diet shifts in white sturgeon and shortnose sturgeon (Buckley & Kynard, 1981; Kynard et al., 2014, 2016; Radtke, 1966), we hypothesise that as larval green sturgeons increase in total length, they shift from zooplankton to benthic macroinvertebrates (BMI). We predict that this shift coincides with the development of benthic feeding morphology, including the loss of teeth and the shift from a forward-opening mouth to a downward-opening mouth. We assessed whether larval green sturgeon consume larger diet items with increasing fish size (indicating gape-limitation at small sizes) and whether diet richness increased with increasing fish size (indicating expanding niche breadth). Further, we examined the role of water temperature and discharge in shaping the number and composition of dietary prey items. Given the optimal growth at warmer temperatures observed in early life stage green sturgeon, we hypothesise that the low temperature conditions created by Shasta Dam negatively impact diet metrics such as diet count and proportion of empty stomachs. The highly managed release of water from Keswick Dam during the summer has the effect of increasing discharge and decreasing water temperature, which may impact the diets of larval green sturgeon during this key developmental stage.

## 2 | MATERIALS AND METHODS

### 2.1 | Field collections

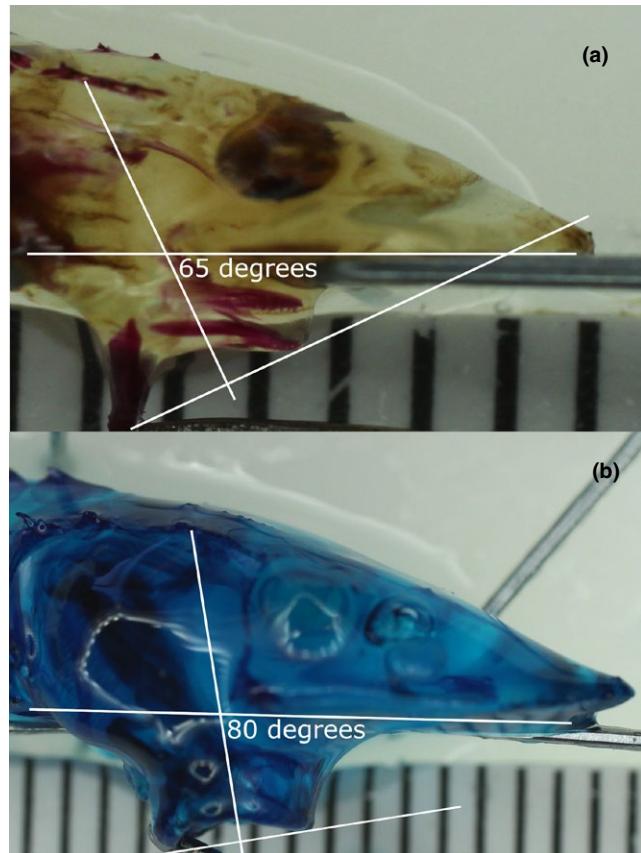
Field collections for this study came from rotary screw traps at Red Bluff Diversion Dam (RBDD; latitude 40.153627, longitude -122.202324), which continuously capture a range of vertebrates, including larval green sturgeon and salmonid fry, and are checked one to two times per day. Given that samples could be in the trap for variable amounts of time, from minutes to just under 24 hours, there is the possibility of a post-capture digestion trap effect (Haywood, 1995). Nonetheless, this sampling method is the only reliable method to collect larval green sturgeon in this part of the Sacramento River. Screw traps are maintained and monitored by the US Fish and Wildlife Service, which preserved trap mortalities in 95% ethanol after total length was recorded. A total of 314 larval green sturgeon samples were collected from 2012 to 2016. All collected fish were less than 100 grams and did not require formalin injection to the gut area for preservation of diet contents (Gelwick & Matthews, 2017). Temperature and discharge measurements at RBDD came from the River Assessment for Forecasting Temperature, a heat budget model which integrates Keswick Dam output and meteorological forcings (Daniels, Sridharan, John, & Danner, 2018; Pike et al., 2013).

## 2.2 | Diet analysis

Using a protocol adapted from Gelwick and Matthews (2017), we extracted diet items from the digestive system and stored them in 70% ethanol. If the stomach tissue appeared to be compromised, that individual's diet was removed from analysis to prevent post-mortality loss of stomach contents from altering results. As the study was focused on the larval life stage, we removed individuals from analysis that had the juvenile phenotype, leaving 314 samples. Juveniles were identified as individuals having less than seven dorsal scutes, 22 lateral scutes or five ventral scutes (North, Farr, & Vescei, 2002). Analyses which used important diet items removed individuals which did not have those diet items, leaving 265 individuals in the sample. We used a dissecting microscope to identify individual diet items to Order (for zooplankton) and Family (for BMI) and measured major axis length. We found primarily hard-bodied diet items and counted head capsules to avoid bias caused by potential differences in rates of digestion among prey items. The mass of each diet item was estimated using length-mass relationships from literature values (Benke, Huryn, Smock, & Wallace, 1999; Malley, Lawrence, & MacIver, 1989). We used counts as a measure of prey choice and weight data as a measure of the relative importance of prey items. Proportion by count of diet items per fish were used to assess how diet shifts with environment and fish development. Laboratory experiments have estimated diet passage time of larval sturgeon as less than 1 day (Silas Hung, *unpublished data*); therefore, we compared stomach contents to temperature and discharge on the day the fish was caught at RBDD.

## 2.3 | Morphological development

Jaw opening direction and teeth presence were assayed for a subset of 46 individuals from 2016, which were double-stained using a protocol adapted from Dingerkus and Uhler (1977). For detailed information on double-staining techniques, see *Supplementary Information*. Following methods in Higgins and Horn (2014), we photographed double-stained individuals with jaws articulated. We calculated jaw articulation angle as the difference between the articulated jawline and the main body axis line (Figure 1). The articulated jawline was digitised by placing points at the distal end of the upper jaw and lower jaw, digitising a line connecting these points and then digitising a perpendicular line (the articulated jawline). Each jaw was articulated and imaged three times to calculate mean and standard deviation of jaw articulation angle. Sampling standard deviation of jaw articulation angle was calculated using the mean of all standard deviations, and individuals were categorised as having either downward-opening mouths (within two standard deviations of 90°) or forward-opening mouths (greater than two standard deviations from 90°). Teeth presence or absence was determined by searching for the hairlike teeth on the oral jaws using high-resolution jaw articulation images.



**FIGURE 1** Jaw articulation angle is the angle between a line on the body axis and a line perpendicular to a line connecting the tips of both jaws. Panel A is a younger fish with forward-opening jaw, and panel B is an older fish with downward-opening jaw

## 2.4 | Statistical analysis

First, we analysed whether development in total length, jaw opening direction (forward or downward) or presence of teeth altered diets. To determine whether total length impacts the maximum prey size found in the diet, we used a linear mixed model. The impact of total length on the presence of any diet items (gut empty versus at least one diet item present) was assessed using a generalised linear mixed model (GLMM), binomial family. We used a GLMM of Poisson family to examine whether sturgeon length is related to diet richness. To determine whether teeth presence or mouth opening direction altered proportion of zooplankton in diet, we used a nonparametric t test (Wilcoxon rank sum test) and calculated effect size using Hedge's g correction to account for small sample sizes. We included year as a random effect for all development analyses.

Next, we assessed the impact of river temperature and discharge on green sturgeon diets. Temperature and discharge measurements were scaled to standard deviations from the mean prior to model fitting. To determine whether river temperature or discharge impacted the presence of important diet items, we used corrected Akaike information criterion (AICc, Hurvich & Tsai, 1989) to select the best binomial generalised linear model (GLM). Important diet items were identified as those

Year	Month	n	$\mu T$ (C)	$\sigma T$ (C)	$\mu D$ (CMS)	$\sigma D$ (CMS)
2012	May	7	13	0.3	314.7	5.1
2012	June	11	12.6	0.7	322.9	12.9
2013	May	9	13.7	0.4	344.1	6.2
2013	June	17	13.7	0.7	391.9	39.2
2013	July	6	14	0.3	419.7	7.4
2013	August	1	13.9	—	336.4	—
2014	May	8	13.7	0.7	224.4	14.6
2015	April	12	14.5	0.5	188.6	25.5
2015	May	17	14.4	0.4	224.7	3.3
2015	June	7	16.4	0.3	210.5	2.4
2015	July	1	16.6	—	211.3	—
2016	April	1	14.3	—	182.7	—
2016	May	150	14.7	0.5	216.1	6.2
2016	June	16	14.4	0.5	253.7	16.3
2016	July	1	13.6	—	296.7	—
2016	Sep.	1	12.9	—	256.8	—

Fish count is n, mean temperature in Celsius is  $\mu T$ , temperature standard deviation is  $\sigma T$ , mean discharge in cubic metres per second is  $\mu D$ , and standard deviation of discharge is  $\sigma D$ . The location of temperature and discharge measurements is Red Bluff Diversion Dam.

**TABLE 1** Fish count, temperature and discharge throughout the 5 years of this study separated by month

Diet item	Life stage	Group	Diet item proportion by count	Diet item proportion by weight
Cyclopoida	A	Zoop	0.42	<0.01
Baetidae	L	BMI	0.30	0.71
Chironomidae	L	BMI	0.22	0.16
Simuliidae	L	BMI	0.03	0.06
Chironomidae	P	BMI	<0.01	<0.01
Tricoptera	L	BMI	<0.01	<0.01
Chironomidae	A	BMI	<0.01	<0.01
Coleoptera	L	BMI	<0.01	<0.01
Heptageniidae	L	BMI	<0.01	<0.01
Nematoda	U	BMI	<0.01	<0.01
Herpacticoida	L	BMI	<0.01	<0.01
Acari	U	BMI	<0.01	<0.01

**TABLE 2** Proportion of diet items by weight and count, averaged across all individual fish

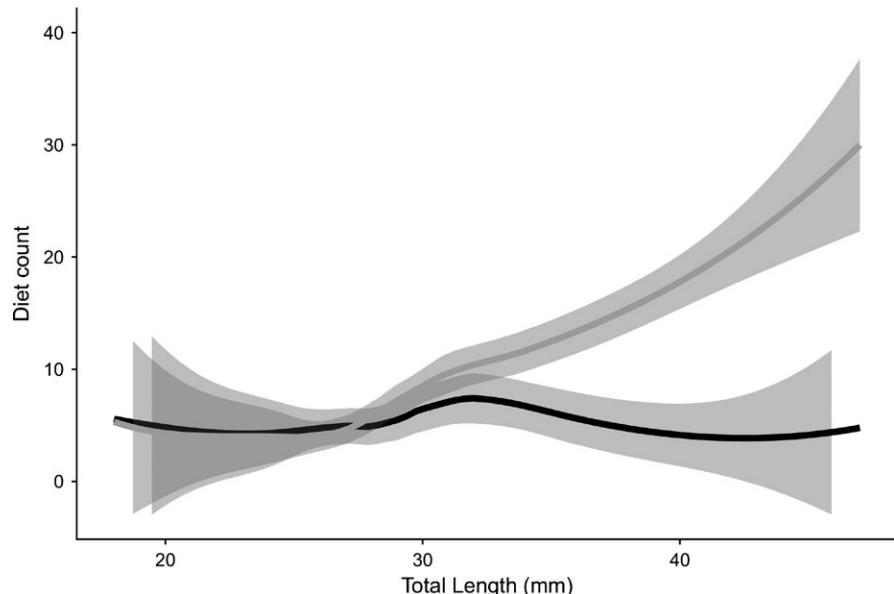
Life stages are larval (L), pupal (P), adult (A) or unknown (U). Group is zooplankton (Zoop) or benthic macroinvertebrate (BMI).

which composed greater than 1% of the diet by count. To determine whether empty vs non-empty stomachs were associated with temperature or discharge, we used AICc to select the best logistic GLM. To determine whether nonzero diet count was impacted by temperature or discharge, we used AICc to select the best negative binomial GLM. To determine whether diet richness was altered by river environment, we used AICc to select the best Poisson GLM. We did not include year as a random effect for environment analyses because much of the temperature variance is between years and doing so would reduce our ability

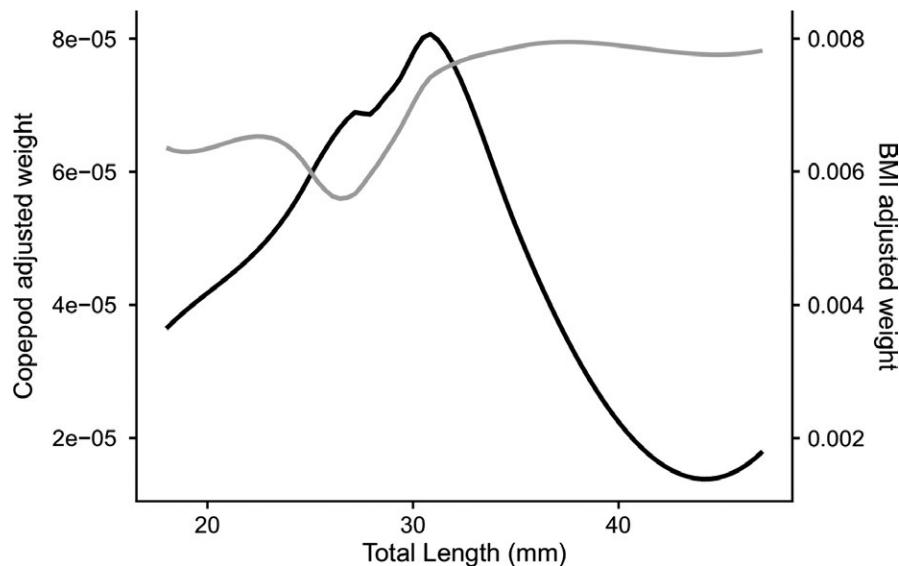
to detect diet shifts resulting from temperature. All statistical analyses were conducted using R statistical language (R Core Team 2017, version 3.4.2).

### 3 | RESULTS

Individuals were analysed across 5 years which represented a range in temperature and discharge regimes (Table 1). The most common diet items were cyclopoid copepods (Copepoda: Cyclopoida), baetid mayflies (Ephemeroptera: Baetidae), chironomids (Diptera:



**FIGURE 2** Association of larval green sturgeon total length with diet by count. Grey line is benthic macroinvertebrates, while black line is zooplankton, fit with a spline of span 1.8. Shading represents standard error



**FIGURE 3** Association of total length and diet of larval green sturgeon by adjusted weight (diet/fish weight). Black line is zooplankton with axis on the left side, while grey line is BMI with axis on the right side. Line fits with a spline of span 1.8

Chironomidae) and simulids (Diptera: Simuliidae; Table 2). Larval green sturgeon developmental features were associated with zooplankton consumption, while total length was associated with diet richness. Although jaw articulation angle was not a significant predictor of diet composition, both total length and teeth presence significantly impacted diets. Total length was positively correlated with maximum diet item length (mixed linear regression:  $df = 259$ ,  $t = 2.8$ , marginal  $r^2 = 0.03$ ,  $p = 0.005$ ), non-empty stomachs (GLMM binomial family: residual  $df = 302$ ,  $z = 3.3$ , marginal  $r^2 = 0.36$ ,  $p < 0.001$ ) and diet richness (GLMM Poisson family: residual  $df = 302$ ,  $z = 3.0$ , marginal  $r^2 = 0.02$ ,  $p = 0.002$ ). Larval green sturgeon consumed equal numbers of BMI and zooplankton until  $\sim 30$  mm total length, when BMI consumption increased but zooplankton consumption remained constant (Figure 2). Although fish consumed greater biomass of BMI through the larval life stage, zooplankton biomass peaked at  $\sim 30$  mm total length (TL) before decreasing (Figure 3). Teeth were found on

smaller individuals and lost at approximately 30 mm (logistic regression prediction: 8.2% error). Larval green sturgeon with teeth consumed a greater proportion of zooplankton than sturgeon without teeth (Figure 4; Wilcoxon rank sum test:  $n = 46$ ,  $p = 0.05$ ; Hedge's g effect size:  $n = 46$ ,  $g = 0.64$  (medium effect), 95% confidence = 0.62).

River environment (discharge and temperature) was associated with a shift in larval green sturgeon diets. Because of a temperature control device installed on Shasta Dam in 1996, river discharge and temperature are not collinear at Red Bluff Diversion Dam (variance inflation factor = 1.5). Therefore, we ran models with both temperature and discharge. We found more empty stomachs at colder temperatures (GLM, binomial family: residual  $df = 303$ ,  $z = 2.069$ , Nagelkerke pseudo- $r^2 = 0.03$ ,  $p = 0.04$ ). Using AICc to select the best GLM of binomial family, we found that temperature and discharge impacted the presence of cyclopoid copepods and simulids in diets (Table 3). Then, we used AICc to determine the impact of river



**FIGURE 4** Association of teeth presence with zooplankton proportion by count in diet

environment on nonzero diet count, finding that count decreased with discharge (GLM, negative binomial family: residual  $df = 272$ ,  $z = -6.5$ , Nagelkerke pseudo- $r^2 = 0.11$ ,  $p < 0.001$ ). We calculated the effect of river environment on diet richness with corrected AIC, finding that taxon richness decreased with discharge (GLM, Poisson family: residual  $df = 303$ ,  $z = -3.9$ , Nagelkerke pseudo- $r^2 = 0.14$ ,  $p < 0.001$ ).

## 4 | DISCUSSION

Summer management of dam releases on the Sacramento River is aimed at providing discharge for downstream water users and cold water for winter-run Chinook egg survival (Yates et al., 2008), yet other native species, including threatened green sturgeon, rely on habitat in this highly altered section of river. We examined the effects of morphological development, temperature and discharge on larval diets of threatened green sturgeon. Our results show that green sturgeon decrease zooplankton consumption when teeth are lost and increase diet richness with total length. Mouth width in larval green sturgeon increases non-linearly with length, with an inflection point from rapid to slowed growth just before 30 mm TL, which is the same size that an inflection point indicating decreased barbel

growth occurs (Gisbert & Doroshov, 2006). In support of our first hypothesis, we detected a loss of teeth on the oral jaws at 30 mm, which was also the approximate size at which zooplankton counts in diets decreased and BMI counts increased (Figure 2). However, contrary to our hypothesis, mouth opening direction was not associated with a shift in diet.

The decrease in zooplankton and increase in BMI at 30 mm TL may indicate a shift in the optimal prey for larval green sturgeon. Predators may shift prey items based on prey size (Scharf, Juanes, & Rountree, 2000; Werner & Gilliam, 1984) and/or foraging efficiency of capturing different prey items (Mittelbach, 1981). Cyclopoid copepods represent 40% of larval green sturgeon diets by count but form only 0.6% of diet weight (Table 2). Other sturgeon species have been shown to shift from zooplankton to BMI (Buckley & Kynard, 1981; Dadswell, Taubert, Squiers, Marchette, & Buckley, 1984), and diet analyses indicate gape-limitation in early life stages (Muir, McCabe, Hinton, & Parsley, 2000). Larval green sturgeon diet richness increased with total length, indicating that they widen their niche with increasing size. Although larval green sturgeon increase BMI consumption beginning at approximately 30 mm, zooplankton remain in the diet throughout the larval life stage (Figure 2). Our study identifies a replacement of zooplankton with BMI at 30 mm in

Response	Environmental model terms	df	LogLik	Weight	Marginal $r^2$
Copepod presence	Discharge (-)	2	-149.792	0.696	0.22
Baetid presence	No impact	—	—	—	—
Chironomid presence	Temperature (-) & discharge (-)	3	-153.982	0.714	0.06
Simulid presence	Temperature (+) & discharge (+)	3	-147.629	0.747	0.05

**TABLE 3** Presence of four main diet items as impacted by river environment

In the “Environmental model terms” column, (+) means a positive correlation and (−) means a negative correlation. Predictors standardised, models fit with binomial GLM, best model chosen with corrected AIC. Nagelkerke  $r^2$  fit with MuMIn package in r (Barton, 2017).

larval sturgeons and finds this shift associated with the ontogenetic loss of teeth on the oral jaws.

River temperature and discharge were significantly correlated with the diets of larval green sturgeon. This has important management implications because the discharge of the Sacramento River above Red Bluff is driven by Shasta Dam releases. More empty stomachs were found at colder temperatures, indicating that foraging activity or food availability may be increased at warmer temperatures. Food consumption, growth and metabolism have been previously demonstrated to increase with temperature in early life stage green sturgeon (Mayfield & Cech, 2004). Increasing discharge significantly decreased the total number of prey items in the diets and significantly reduced the presence of cyclopoid copepods in diets. Cyclopoid copepods were an important prey item for green sturgeon below 30 mm, suggesting that fish in this critical life stage may be adversely impacted by dam releases. The density of copepods in the Sacramento River has been found to be inversely associated with discharge (Sommer, Harrell, Solger, Tom, & Kimmerer, 2004), so decreased prey availability may be driving the reduced presence of copepods observed in larval sturgeon diets under high flow. Temperature and discharge had a positive association with simulid presence in diets and a negative association with chironomid presence. Future studies could profitably examine mechanisms by which dam releases impact larval sturgeon diet by simultaneously collecting information on both diets and invertebrate prey availability.

Understanding the dynamics of early life stage listed green sturgeon has been identified as an important management priority (Heublein et al., 2017; Moser et al., 2016). Our findings provide information which could be used to refine the current management of environmental flows in the Sacramento River. We found that temperature, discharge and larval development shape green sturgeon diets in ways that may make the smallest larvae potentially vulnerable to the effects of dam releases. The current management regime downstream of Shasta Reservoir uses dam releases to decrease summer temperature for endangered salmonids and increase summer discharge for downstream water users. Our results suggest that this management regime may negatively impact the feeding of threatened green sturgeon in this section of the Sacramento River. Rivers are increasingly being put under pressure to provide water for human use and habitat to support aquatic biodiversity. However, knowledge of habitat requirements for the larval life stages of many fish species is lacking. Understanding the habitat needs of larval fishes and incorporating them into management plans is critical for balancing human water needs and native fish species.

## ACKNOWLEDGEMENTS

Carlos Garza and Bill Poytress provided green sturgeon field collections. Dave Herbst provided support with invertebrate identification. Eric Danner, Katie May Laumann, Colton Deaver, Sarah Mehl, Kevin Bingham, Jacqueline Redinger, Ben Higgins and Chris Law assisted with clearing and staining specimens. Joe Merz, Pete Raimondi, Travis Apgar, Simone Des Roches, Zach Wood, Dave

Fryxell, Krista Oke, Celia Symons and Ben Wasserman provided helpful comments on drafts of the manuscript. We thank three anonymous reviewers for their comments. This study was funded by the NOAA Cooperative Institute for Marine Ecosystems and Climate and the University of California-Santa Cruz.

## ORCID

Liam J. Zarri  <http://orcid.org/0000-0001-8782-6048>

## REFERENCES

- Adams, P. B., Grimes, C., Hightower, J. E., Lindley, S. T., Moser, M. L., & Parsley, M. J. (2007). Population status of North American green sturgeon, *Acipenser medirostris*. *Environmental Biology of Fishes*, 79(3–4), 339–356. <https://doi.org/10.1007/s10641-006-9062-z>
- Ayres, W. O. (1854). Descriptions of three new species of sturgeon from San Francisco. In *Proceedings of the California Academy of Natural Sciences* (Vol. 1, pp. 14–15).
- Balon, E. K. (1975). Terminology of intervals in fish development. *Journal of the Fisheries Board of Canada*, 32(9), 1663–1670. <https://doi.org/10.1139/f75-196>
- Barton, K. (2017). MuMIn: multi-model inference. R package version 1.40.0. <https://CRAN.R-project.org/package=MuMIn>.
- Bemis, W. E., Findeis, E. K., & Grande, L. (1997). An overview of Acipenseriformes. *Environmental Biology of Fishes*, 48(1–4), 25–71. <https://doi.org/10.1023/A:1007370213924>
- Benke, A. C., Huryn, A. D., Smock, L. A., & Wallace, J. B. (1999). Length-mass relationships for freshwater macroinvertebrates in North America with particular reference to the southeastern United States. *Journal of the North American Bentholological Society*, 18(3), 308–343. <https://doi.org/10.2307/1468447>
- Buckley, J., & Kynard, B. (1981). Spawning and rearing of shortnose sturgeon from the Connecticut River. *The Progressive Fish-Culturist*, 43(2), 74–76. [https://doi.org/10.1577/1548-8659\(1981\)43\[74:SAROSS\]2.0.CO;2](https://doi.org/10.1577/1548-8659(1981)43[74:SAROSS]2.0.CO;2)
- Carroll, A. M., & Wainwright, P. C. (2003). Functional morphology of prey capture in the sturgeon, *Scaphirhynchus albus*. *Journal of Morphology*, 256(3), 270–284. <https://doi.org/10.1002/jmor.10095>
- Dadswell, M. J., Taubert, B. D., Squiers, T. S., Marchette, D., & Buckley, J. (1984). *Synopsis of biological data on shortnose sturgeon, Acipenser brevirostrum (Le Sueur 1818)*. National Marine Fisheries Service. <http://spo.nwr.noaa.gov/tr14.pdf>
- Daniels, M. E., Sridharan, V. K., John, S. N., & Danner, E. M. (2018). Calibration and validation of linked water temperature models for the Shasta Reservoir and the Sacramento River from 2000 to 2015. National Marine Fisheries Service. <https://doi.org/10.7289/V5/TM-SWFSC-597>
- Deng, D. F., Koshio, S., Yokoyama, S., Bai, S. C., Shao, Q., Cui, Y., & Hung, S. S. (2003). Effects of feeding rate on growth performance of white sturgeon (*Acipenser transmontanus*) larvae. *Aquaculture*, 217(1–4), 589–598. [https://doi.org/10.1016/S0044-8486\(02\)00461-1](https://doi.org/10.1016/S0044-8486(02)00461-1)
- Dingerkus, G., & Uhler, L. D. (1977). Enzyme clearing of alcian blue stained whole small vertebrates for demonstration of cartilage. *Stain Technology*, 52(4), 229–232. <https://doi.org/10.3109/10520297709116780>
- Gelwick, F. P., & Matthews, W. J. (2017). Trophic relations of stream fishes. In *Methods in Stream Ecology* (Vol. 1, 2nd ed., pp. 611–635). <https://doi.org/10.1016/b978-0-12-416558-8.00022-6>
- Gisbert, E., & Doroshov, S. I. (2006). Allometric growth in green sturgeon larvae. *Journal of Applied Ichthyology*, 22(s1), 202–207. <https://doi.org/10.1111/j.1439-0426.2007.00952.x>

- Gisbert, E., & Williot, P. (1997). Larval behaviour and effect of the timing of initial feeding on growth and survival of Siberian sturgeon (*Acipenser baeri*) larvae under small scale hatchery production. *Aquaculture*, 156, 63–76. [https://doi.org/10.1016/S0044-8486\(97\)00086-0](https://doi.org/10.1016/S0044-8486(97)00086-0)
- Gross, M. R., Repka, J., Robertson, C. T., Secor, D. H., & Van Winkle, W. (2002). Sturgeon conservation: Insights from elasticity analysis. In *American Fisheries Society Symposium* (Vol. 28, pp. 13–30). <https://doi.org/10.1.1.503.8853>
- Haywood, M. D. E. (1995). Rates at which post-larval prawns are digested by a small predatory fish and the implications for predation studies. *Journal of Fish Biology*, 47(2), 337–340. <https://doi.org/10.1111/j.1095-8649.1995.tb01901.x>
- Heublein, J. C., Bellmer, R. J., Chase, R. D., Doukakis, P., Gingras, M., Hampton, D., ... Luis, S. (2017). *Improved Fisheries Management Through Life Stage Monitoring: The Case for the Southern Distinct Population Segment of North American Green Sturgeon and the Sacramento-San Joaquin River White Sturgeon*. National Marine Fisheries Service, <https://doi.org/10.7289/V5/TM-SWFSC-588>
- Higgins, B. A., & Horn, M. H. (2014). Suction among pickers: Jaw mechanics, dietary breadth and feeding behaviour in beach-spawning *Leuresthes* spp. compared with their relatives. *Journal of Fish Biology*, 84(6), 1689–1707. <https://doi.org/10.1111/jfb.12385>
- Hilton, E. J., Grande, L., & Bemis, W. E. (2011). Skeletal anatomy of the shortnose sturgeon, *Acipenser brevirostrum* Lesueur, 1818, and the systematics of sturgeons (*Acipenseriformes*, *Acipenseridae*). *Fieldiana Life and Earth Sciences*, 1–168, <https://doi.org/10.3158/2158-5520-3.1.1>
- Hjort, J. (1914). Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. *RAPPORTS ET PROCRS-VERBAUX Volume XX*.
- Hurvich, C. M., & Tsai, C. L. (1989). Regression and time series model selection in small samples. *Biometrika*, 76(2), 297–307. <https://doi.org/10.1093/biomet/76.2.297>
- Kynard, B., Bolden, S., Kieffer, M., Collins, M., Brundage, H., Hilton, E. J., ... Peterson, D. (2016). Life history and status of Shortnose Sturgeon (*Acipenser brevirostrum* LeSueur, 1818). *Journal of Applied Ichthyology*, 32(S1), 208–248. <https://doi.org/10.1111/jai.13244>
- Kynard, B., & Horgan, M. (2002). Ontogenetic behavior and migration of Atlantic sturgeon, *Acipenser oxyrinchus oxyrinchus*, and shortnose sturgeon, *A. brevirostrum*, with notes on social behavior. *Environmental Biology of Fishes*, 63(2), 137–150. <https://doi.org/10.1023/A:1014270129729>
- Kynard, B., Parker, E., Kynard, B. E., & Horgan, M. (2014). Effect of velocity regime on ontogenetic dispersal and habitat use of Kootenai River White Sturgeon (*Acipenser transmontanus*, Richardson, 1836) early life stages: An artificial stream study. *Journal of Applied Ichthyology*, 30(6), 1160–1167. <https://doi.org/10.1111/jai.12595>
- Kynard, B., Parker, E., & Parker, T. (2005). Behavior of early life intervals of Klamath River green sturgeon, *Acipenser medirostris*, with a note on body color. *Environmental Biology of Fishes*, 72(1), 85–97. <https://doi.org/10.1007/s10641-004-6584-0>
- Laumann, K. M. (2016). *Sturgeon (Acipenseridae) phylogeny, biogeography, & ontogeny*. Doctoral Dissertation, The College of William and Mary. Retrieved from Virginia Institute of Marine Science.
- MacDiarmid, J. M. (1975). The State Water Plan and Salinity Control in the Sacramento-San Joaquin Delta of California. *Yearbook of the Association of Pacific Coast Geographers*, 37(1), 39–54. <https://doi.org/10.1353/pcg.1975.0003>
- Malley, D. F., Lawrence, S. G., & MacIver, M. A. (1989). Range of variation in estimates of dry weight for planktonic Crustacea and Rotifera from temperate North American lakes. Department of Fisheries and Oceans, Central and Arctic Region.
- Mayfield, R. B., & Cech, J. J. Jr. (2004). Temperature effects on green sturgeon bioenergetics. *Transactions of the American Fisheries Society*, 133, 961–970. <https://doi.org/10.1577/T02-144.1>
- Miller, M. J. (2004). The ecology and functional morphology of feeding of North American sturgeon and paddlefish. In *Sturgeons and paddlefish of North America* (pp. 87–102). Netherlands: Springer. [https://doi.org/10.1007/1-4020-2833-4\\_5](https://doi.org/10.1007/1-4020-2833-4_5)
- Mittelbach, G. G. (1981). Foraging efficiency and body size: A study of optimal diet and habitat use by bluegills. *Ecology*, 62(5), 1370–1386. <https://doi.org/10.2307/1937300>
- Mora, E. A., Lindley, S. T., Erickson, D. L., & Klimley, A. P. (2009). Do impassable dams and flow regulation constrain the distribution of green sturgeon in the Sacramento River, California? *Journal of Applied Ichthyology*, 25(S2), 39–47. <https://doi.org/10.1111/j.1439-0426.2009.01297.x>
- Moser, M. L., Israel, J. A., Neuman, M., Lindley, S. T., Erickson, D. L., McCovey, B. W., & Klimley, A. P. (2016). Biology and life history of green sturgeon (*Acipenser medirostris* Ayres, 1854): State of the science. *Journal of Applied Ichthyology*, 32(S1), 67–86. <https://doi.org/10.1111/jai.13238>
- Muir, W. D., McCabe, G. T. Jr., Hinton, S. A., & Parsley, M. J. (2000). Diet of first-feeding larval and young-of-the-year white sturgeon in the lower Columbia River. *Northwest Science*, 74(1), 25. <http://hdl.handle.net/2376/1075>
- National Marine Fisheries Service. (2006). Endangered and threatened wildlife and plants: Threatened status for southern distinct population segment of North American Green Sturgeon. *Federal Register*, 67 (71), 17757–17766.
- North, J. A., Farr, R. A., & Vescei, P. (2002). A comparison of meristic and morphometric characters of green sturgeon *Acipenser medirostris*. *Journal of Applied Ichthyology*, 18(4–6), 234–239. <https://doi.org/10.1046/j.1439-0426.2002.00373.x>
- Pepin, P. (1991). Effect of temperature and size on development, mortality, and survival rates of the pelagic early life history stages of marine fish. *Canadian Journal of Fisheries and Aquatic Sciences*, 48(3), 503–518. <https://doi.org/10.1139/f91-065>
- Pike, A., Danner, E., Boughton, D., Melton, F., Nemani, R., Rajagopalan, B., & Lindley, S. (2013). Forecasting river temperatures in real time using a stochastic dynamics approach. *Water Resources Research*, 49(9), 5168–5182. <https://doi.org/10.1002/wrcr.20389>
- Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., ... Stromberg, J. C. (1997). The natural flow regime. *BioScience*, 47(11), 769–784. <http://www.jstor.org/stable/1313099>
- Poytress, W. R., Gruber, J. J., & Van Eenennaam, J. P. (2009). *2008 Upper Sacramento River Green Sturgeon spawning habitat and larval migration surveys*. Final Annual Report to US Bureau of Reclamation, US Fish and Wildlife Service.
- R Core Team (2017). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. <https://www.R-project.org/>
- Radtkne, L. D. (1966). Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento-San Joaquin Delta with observations on food of sturgeon. *Ecological Studies of the Sacramento-San Joaquin Estuary, Part II*, 115–119.
- Sanford, E., Holzman, S. B., Haney, R. A., Rand, D. M., & Bertness, M. D. (2006). Larval tolerance, gene flow, and the northern geographic range limit of fiddler crabs. *Ecology*, 87(11), 2882–2894. [https://doi.org/10.1890/0012-9658\(2006\)87\[2882:LTGFAT\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2006)87[2882:LTGFAT]2.0.CO;2)
- Scharf, F. S., Juanes, F., & Rountree, R. A. (2000). Predator size-prey size relationships of marine fish predators: Interspecific variation and effects of ontogeny and body size on trophic-niche breadth. *Marine Ecology Progress Series*, 208, 229–248. <http://www.jstor.org/stable/24863819>
- Sifa, L., & Mathias, J. A. (1987). The critical period of high mortality of larvae fish—a discussion based on current research. *Chinese Journal of Oceanology and Limnology*, 5(1), 80–96. <https://doi.org/10.1007/BF02848526>
- Sommer, T. R., Harrell, W. C., Solger, A. M., Tom, B., & Kimmerer, W. (2004). Effects of flow variation on channel and floodplain biota

- and habitats of the Sacramento River, California, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 14(3), 247–261. <https://doi.org/10.1002/aqc.620>
- Steel, E. A., Beechie, T. J., Torgersen, C. E., & Fullerton, A. H. (2017). Envisioning, quantifying, and managing thermal regimes on river networks. *BioScience*, 67(6), 506–522. <https://doi.org/10.1093/biosci/bix047>
- US Fish and Wildlife Service. (1999). *Effects of temperature on early-life survival of Sacramento River fall-run and winter-run Chinook salmon*. Final Report.
- Van Eenennaam, J. P., Webb, M. A., Deng, X., Doroshov, S. I., Mayfield, R. B., Cech, J. J., ... Willson, T. E. (2001). Artificial spawning and larval rearing of Klamath River green sturgeon. *Transactions of the American Fisheries Society*, 130(1), 159–165. [https://doi.org/10.1577/1548-8659\(2001\)130<0159:ASALRO>2.0.CO;2](https://doi.org/10.1577/1548-8659(2001)130<0159:ASALRO>2.0.CO;2)
- Werner, E. E., & Gilliam, J. F. (1984). The ontogenetic niche and species interactions in size-structured populations. *Annual Review of Ecology and Systematics*, 15(1), 393–425. <https://doi.org/10.1146/annurev.es.15.110184.002141>
- Werner, I., Linares-Casenave, J., Van Eenennaam, J. P., & Doroshov, S. I. (2007). The effect of temperature stress on development and heat-shock protein expression in larval green sturgeon (*Acipenser medirostris*). *Environmental Biology of Fishes*, 79(3–4), 191–200. <https://doi.org/10.1007/s10641-006-9070-z>
- Wyman, M. T., Thomas, M. J., McDonald, R. R., Hearn, A. R., Battleson, R. D., Chapman, E. D., ... Pagel, M. D. (2017). Fine-scale habitat selection of green sturgeon (*Acipenser medirostris*) within three spawning locations in the Sacramento River, California. *Canadian Journal of Fisheries and Aquatic Sciences*, 75(5), 779–791. <https://doi.org/10.1139/cjfas-2017-0072>
- Yates, D., Galbraith, H., Purkey, D., Huber-Lee, A., Sieber, J., West, J., ... Joyce, B. (2008). Climate warming, water storage, and Chinook salmon in California's Sacramento Valley. *Climatic Change*, 91(3–4), 335. <https://doi.org/10.1007/s10584-008-9427-8>

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**How to cite this article:** Zarri LJ, Palkovacs EP. Temperature, discharge and development shape the larval diets of threatened green sturgeon in a highly managed section of the Sacramento River. *Ecol Freshw Fish*. 2018;00:1–9. <https://doi.org/10.1111/eff.12450>