Prepared in cooperation with California Department of Water Resources and Bureau of Reclamation

Bivalve Effects on the Food Web Supporting Delta Smelt—A One-Year Study of Bivalve Recruitment, Biomass, and Grazing Rate Patterns with Varying Freshwater Outflow

Open-File Report 2022–1101

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of view from research vessel in the Carquinez Strait, facing west towards the Carquinez Bridge in California. U.S. Geological Survey photograph taken by Emily Zierdt Smith, June 19, 2019.

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Figures

Tables

Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F – 32) / 1.8.

Datum

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Supplemental Information

Biomass units are grams of ash-free dry mass per square meter (g ASDM/m^2). Grazing rate is given as cubic meter per meter squared per day ($m^3/m^2/d$).

Recruits are given as the number of bivalves ≤ 2.5 millimeters in length per meter squared (no./m^2 of bivalves ≤ 2.5 mm in length). The low salinity zone (LSZ)—salinities range from 1 to 6 practical salinity units (psu).

A water year is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends. For example, water year 2020 is the period from October 1, 2019, through September 30, 2020.

Abbreviations

AFDM	ash-free dry mass
CF	*Corbicula fluminea*
DWR	California Department of Water Resources
EMP	Environmental Monitoring Program
GR	grazing rate
GRTO	grazing rate turnover rate
LSZ	low salinity zone
PA	*Potamocorbula amurensis*
POD	pelagic organism decline
PR	pumping rate
Reclamation	Bureau of Reclamation
SWRCB	State Water Resources Control Board
USGS	U.S. Geological Survey

Bivalve Effects on the Food Web Supporting Delta Smelt—A One-Year Study of Bivalve Recruitment, Biomass, and Grazing Rate Patterns with Varying Freshwater Outflow

By Emily L. Zierdt Smith,[1] Kelly H. Shrader,[1] Janet K. Thompson,[1] Francis Parchaso,[1] Karen Gehrts,[2] and Elizabeth Wells[2]

Abstract

Phytoplankton are an important and limiting food source in the Sacramento-San Joaquin Delta and San Francisco Bay in California. Decreasing phytoplankton biomass is one possible factor for the pelagic organism decline and the decline of the protected *Hypomesus transpacificus* (delta smelt). Bivalves *Corbicula fluminea* and *Potamocorbula amurensis* (hereafter *C. fluminea* and *P. amurensis*, respectively) have been shown to control phytoplankton biomass throughout San Francisco Bay and the Sacramento-San Joaquin Delta; therefore, their distribution and population dynamics are of great interest.

We describe the distribution and dynamics of bivalve biomass using samples from California Department of Water Resources' (DWR) 2019 benthic monitoring program. As one element of DWR's and the Bureau of Reclamation's Environmental Monitoring Program (EMP), the DWR benthic monitoring program examines the effect of water project operations on the estuary as prescribed by a series of Water Rights Decisions mandated by the California State Water Resources Control Board (SWRCB).

The biomass and grazing rate values of both bivalves had similar patterns, therefore, comments on biomass distribution can be applied to grazing rate data. Biomass and recruitment values of *C. fluminea* were too low at station C9 (Old River upstream from Clift on Court Forebay Intake) to describe a temporal pattern. *Corbicula fluminea* biomass values were consistently high at station D24 (Sacramento River). Station D4L (confluence of San Joaquin and Sacramento Rivers) biomass values were low during the first half of the year and high the rest of the year. *Corbicula fluminea* biomass values at station P8 (San Joaquin River) were the highest and most consistent on that river. Station D16 (San Joaquin River) and station D28A (central delta) biomass values were near zero with a small peak in May.

Potamocorbula amurensis biomass values were near zero at station D4L (confluence of San Joaquin and Sacramento Rivers). Biomass values were strongly seasonal at station D6 (Suisun Bay). Station D41 (San Pablo Bay) had the highest *P. amurensis* biomass values. Station D7 (Grizzly Bay) and station D41A (San Pablo Bay) had low biomass values in January-June or July and maximum biomass values in August.

Corbicula fluminea recruits in the Sacramento River stations peaked twice, from January to June and from September to December. At the San Joaquin River stations, *C. fluminea* recruitment peaked from May to July or August and from November to December. Peak recruit abundance was higher on the Sacramento River than the San Joaquin River.

Potamocorbula amurensis recruitment was more seasonal than *C. fluminea,* with a high number of recruits followed by periods with no recruits. Station D4L had few recruits except in January. Station D6 had low recruitment from January to February, increased in August, and peaked from November to December. Station D7 had fewer recruits than station D6 but had a similar temporal pattern, although winter recruits continued into April instead of February. Station D41 recruits were sparce and present only from May to July. Station D41A had the most recruits from January to July, and again in September.

Introduction

The California State Water Resources Control Board (SWRCB) sets water-quality objectives to protect beneficial uses of water in the Sacramento-San Joaquin Delta and Suisun and San Pablo Bays. To meet these objectives, the SWRCB establishes mandated standards in the water rights permits issued to the California Department of Water Resources (DWR) and Bureau of Reclamation (Reclamation). Water Rights Decisions (stations D-1379, D-1485, and D-1641) have established water-quality criteria and a design for a comprehensive monitoring program to determine water-quality conditions and changes in environmental conditions within the estuary. The benthic monitoring program is one element

[1]U.S. Geological Survey.

[2]California Department of Water Resources.

of DWR and Reclamation's Environmental Monitoring Program (EMP) wherein the potential effects of water project operations on estuary health are determined. These effects are determined by changes in benthic fauna presence, abundance and distribution of the benthos associated with physical factors in the estuary, and the detection of newly introduced species in the estuary. The benthic monitoring program is the foundation of the present study. We used samples collected in 2019 to examine how the biomass and grazing rate of the bivalves changed in distribution throughout 2019.

Large ecological changes that have occurred in San Francisco Bay and the Sacramento-San Joaquin Delta over the past several decades have driven the current interest in bivalve grazing rates and biomass. These ecological changes include the substantial population declines of four species of fish, many macrozooplankton species, and the native *Neomysis mercedis* (mysid shrimp) in the San Francisco Bay estuary (Baxter and others, 2008). Although these reductions in species abundance are problematic, the decline of the *Hypomesus transpacificus* (delta smelt) is of the most concern because of its protected status under the Endangered Species Act. One of the suggested causes for ecological decline, referred to here as the pelagic organism decline (POD), is the reduction of phytoplankton in the northern San Francisco Bay estuary coincident with the 1987 introduction of the exotic, filter-feeding bivalve *Potamocorbula amurensis* (hereafter *P. amurensis*). Phytoplankton biomass immediately declined when *P. amurensis* invaded, and since that time, net phytoplankton growth rates have remained low (Alpine and Cloern, 1992; MacNally and others, 2010). The phytoplankton biomass in the northern San Francisco Bay estuary and the western Sacramento-San Joaquin Delta is now chronically low and is considered a contributor to, if not a major cause of, the POD (Baxter and others, 2008; Hammock and others, 2015).

Two large invasive bivalve species inhabit northern San Francisco Bay and the Sacramento-San Joaquin Delta POD species habitat—the estuarine bivalve, *P. amurensis,* and a freshwater bivalve, *Corbicula fluminea* (hereafter *C. fluminea*). Both bivalve species can limit the availability of phytoplankton biomass to other members of the food web in the San Francisco estuary (Lucas and others, 2002; Lopez and others, 2006; Thompson and others, 2008; Lucas and others, 2009; Kimmerer and Thompson, 2014). In addition, *P. amurensis* can filter zooplankton nauplii (larval crustaceans) and ciliates out of the water column (Kimmerer and others, 1994; Greene and others, 2011), and *C. fluminea* can filter ciliates (Scherwass and others, 2001) and glochidia (larval bivalves; Scherwass and Arndt, 2005) from the water column. Therefore, both bivalves may reduce the food supply to delta smelt and other fish species on at least two levels of the food web. For example, any direct reduction in zooplankton through filtration by bivalves, or indirect reduction in zooplankton owing to food limitation, can affect delta smelt, which feed mostly on calanoid copepods throughout their lives (Nobriga, 2002).

Characterizing the temporal and spatial dynamics of both bivalve species will help to identify possible controls on their distributions. Because *C. fluminea* and *P. amurensis* have almost opposite salinity tolerances, the primary distribution limit for both species is expected to be physiological. Other factors that are likely to affect the bivalves' distribution include (1) physical habitat, which influences reproductive and recruitment success and can also be a stress to adults; (2) food availability, which may limit both species at all ages in this food-limited estuary (Kimmerer and Thompson, 2014); and (3) the effects of predators, which are poorly understood.

Here, we summarize the temporal variability of *C. fluminea* and *P. amurensis* in the northern San Francisco Bay and the Sacramento-San Joaquin Delta area by examining biomass, grazing rate, and recruit density of bivalves in benthic samples that were collected in 2019 from 10 monitoring stations. These samples were collected as part of the monitoring program conducted by the DWR (https://water.ca.gov/Programs/Integrated-Science-and-Engineering/Biological-Monitoring-and-Assessment; Crauder and others, 2016; Zierdt Smith and others, 2021).

Project Background and the Conceptual Model

All POD models have recognized that food limitation may be contributing to the decline of delta smelt (Baxter and others, 2008). The new, spatially explicit conceptual model for 2011 (California Water Boards-, 2011) highlights the importance of the biotic habitat as well as the abiotic habitat as measured by the position of X2 (a point given in kilometers [km] upstream from the Golden Gate Bridge where a daily average salinity at 1 meter [m] off the bottom is 2 parts per thousand; Jassby and others, 1995). The X2 position is tidally influenced and varies with season. The longitudinal salinity distribution estimated by X2 helps determine the available habitat for each bivalve and the potential for limiting grazing rates along the longitudinal axis.

Phytoplankton is a critical component of food production and its growth is controlled by a combination of light and nutrient availability, residence time, and benthic and pelagic grazing losses (Kimmerer and others, 2012). The high turbidity of the San Francisco Bay and Sacramento-San Joaquin Delta limits positive net phytoplankton production to shallow areas where accelerated vertical mixing rates expose phytoplankton cells to more light than in the channel (Cloern and others, 1985). Grazing losses to bivalves may also be greater in shallow water because increased mixing rates afford the bivalves more access to pelagic food. However, the results of Thompson and others (2008) and Lucas and others (2009) indicated that bivalves in deep water (≥ 5 m) can have high grazing rates and can depress the phytoplankton biomass transported from the shallows.

How food availability for delta smelt has changed with the onset of the POD and what factors are responsible for those changes have not been resolved. Variability in salinity has decreased since the beginning of the POD in fall (August through November) in the low salinity zone (LSZ), a favored habitat of the delta smelt during fall. Several components of the LSZ food web, including the wider distribution of bivalves and increased magnitude of bivalve grazing, might be affected by this change in salinity variability.

Bivalve biomass, grazing rates, and recruitment patterns were analyzed at all monitoring stations by examining freshwater flow at the time of the sample and prior to the sample. Water year 2018 (October 1, 2018 to September 30, 2019) was a below normal water year (less than normal freshwater flowing into the San Francisco Bay and Sacramento-San Joaquin Delta; water year type designation available at http://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST) and water year 2019 was a wet year (table 1) and thus the salinity was lower in water year 2019 than water year 2018. We examined bivalve recruitment patterns to understand how the increasing freshwater flow in water year 2019 influenced the distribution of each species.

Table 1. Water year type in Sacramento and San Joaquin Rivers from 2000 to 2020.

[The water year spans from October 1 to September 30; Categorization is defined by the California Department of Water Resources (DWR). W, wet year type; AN, above normal year type; BN, below normal year type; D, dry year type; C, critical year type. See http://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST for explanation of calculation of water year type]

Water Year	Sacramento River	San Joaquin River
2000	AN	AN
2001	D	D
2002	D	D
2003	AN	BN
2004	BN	D
2005	AN	W
2006	W	W
2007	D	C
2008	C	C
2009	D	BN
2010	BN	AN
2011	W	W
2012	BN	D
2013	D	C
2014	C	C
2015	C	C
2016	BN	D
2017	W	W
2018	BN	BN
2019	W	W
2020	D	D

The data in this report are from the 2019 data of the EMP. Data from 1976 to 2013 have been published by Crauder and others (2016), and the data from 2014 to 2019, including the data from this report are available in a data release (Zierdt Smith and others, 2021).

Methods

Stations and Samples

The California Department of Water Resources Environmental Monitoring Program sampled 10 benthic stations throughout San Francisco Bay and Sacramento-San Joaquin Delta from January 2019 to December 2019 (fig. 1; table 2). Five samples were collected at each station. Details of station location and sample collection are available at the EMP website: https://emp.baydeltalive.com/wiki/12294.

Field Collection Methods

The California Department of Water Resources Environmental Monitoring Program uses a 0.052-square meter (m^2) Ponar dredge to sample the bottom to a depth that varies with the type of sediment and the ability of the dredge to penetrate it. At all sites, DWR collected four samples for species identification and an extra sample to determine the monthly length-to-weight (ash-free dry mass, [AFDM]) relation for each bivalve species. Each sample was sieved through a U.S. Standard No. 30 stainless steel mesh screen (0.595 millimeter [mm] openings) to remove sediment and detritus that was less than (<) 0.595 mm. The remaining sample (eqal to or greater than [$\geq$] 0.595 mm) was preserved in a solution of approximately 10–20 percent buffered formaldehyde (depending on the substrate) with Rose Bengal dye added for laboratory analysis. We received sorted samples (animals removed from sediment and detritus) from DWR after their routine laboratory analyses were completed.

Analytical Methods

Measuring Bivalves

U.S. Geological Survey (USGS) personnel measured the bivalves to the nearest millimeter using handheld calipers and a microscope micrometer. Bivalves were then returned to DWR for archiving. Biomass (AFDM) estimates were based on relations between length and dry tissue mass calculated by DWR and the USGS during each field sampling using the standard techniques described in Thompson and others (2008).

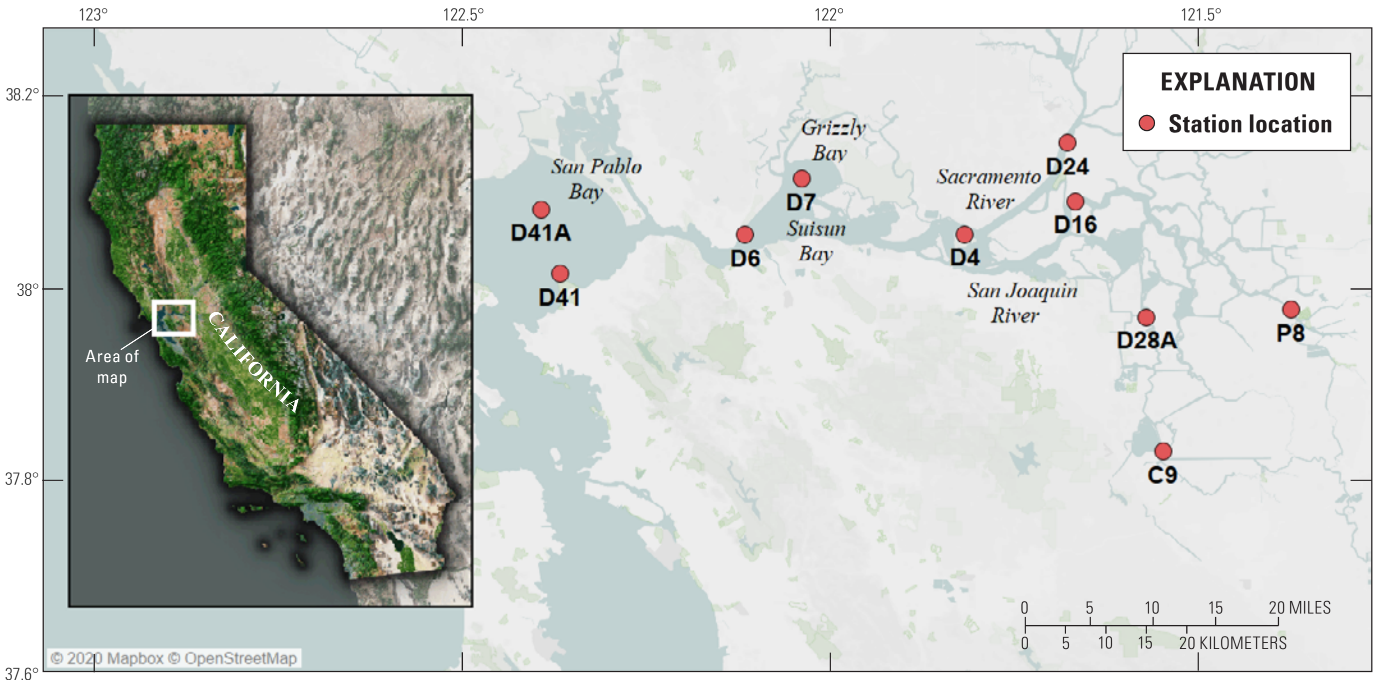

Figure 1. Map of the California Department of Water Resources' benthic monitoring program station locations for benthic samples, Sacramento–San Joaquin Delta, California, 2019. Labels on round dots are station numbers and locations supplied by the California Department of Water Resources. The image contains a regional indicator that shows where the Sacramento-San Joaquin River Delta is in California. The blue box on the California map indicates where in the state the study took place, and the red box indicates the study area within the San Francisco Bay and Sacramento-San Joaquin River Delta.

Table 2. The benthic monitoring stations, their location descriptions, names, and latitude and longitude coordinates of the California Department of Water Resources and the Bureau of Reclamation's Environmental Monitoring Program.

[Samples were collected and sorted for the bivalves *Corbicula fluminea* and *Potamocorbula amurensis*. All depths are in meters (m), left and right refer to which side of the channel (looking downstream) samples were collected]

Station code	Location	Latitude	Longitude	Depth
C9	Old River upstream from Clift on Court Forebay Intake (left)	37.8271	−121.5522	1.7
D16	San Joaquin River at Bradford Island (left)	38.0930	−121.6697	3.0
D24	Sacramento River downstream from Rio Vista bridge (left)	38.1547	−121.6814	8.0
D28A	Old River upstream from Rock Slough (left)	37.9701	−121.5741	4.5
D4L	Sacramento River at Sherman Island upstream from Point Sacramento (left)	38.0581	−121.8193	4.9
D41A	San Pablo Bay- north central (shallow)	38.0847	−122.3906	2.5
D41	San Pablo Bay near Pinole Point (deep)	38.0160	−122.3647	4.9
D6	Suisun Bay upstream from I-680 bridge (right)	38.0577	−122.1149	3.5
D7	Grizzly Bay at Dolphin near Suisun Slough (center)	38.1171	−122.0395	3.0
P8	San Joaquin River at Buckley Cove (right)	37.9778	−121.3799	3.0

Estimating Grazing Rates

Grazing rates were calculated using the method described in Thompson and others (2008) for *P. amurensis* and in Lopez and others (2006) for *C. fluminea*. Pumping rates were adjusted for temperature and were estimated as conservative rates (assuming the development of a concentration boundary layer). Species pumping rates were based on published relations: *P. amurensis* pumping rates (400 liters per gram [g] AFDM/day, where AFDM = dry mass – ash mass) were based on those measured by Cole and others (1992). Pumping rates were converted to grazing rates by reducing the pumping rate to adjust for the presence of a concentration boundary layer. This adjustment is based on the refiltration relation of O'Riordan and others (1995, figure 7b):

$$(GR = PR\,(1 - n_{max}));\ (n_{max} = 2.5(s(d_o)^{-1})^{-1})) \qquad (1)$$

where

- GR is grazing rate (m^3/m^2/day);
- PR is pumping rate (L/day);
- n_{max} is the maximum refiltration proportion—the proportion of water previously filtered by one square meter of bivalves;
- s is distance between siphon pairs—a proxy for animal density; and
- d_o is the average diameter of the excurrent siphon of the animals collected at each site—a proxy for animal size (cm).

The diameter of the excurrent siphon was changed throughout the study to reflect the change in average size of animals as the study progressed, and the distance between siphon pairs was based on the density of animals observed in our benthic sampling, assuming equidistant spacing within the 0.05-m^2 sample area. Benthic grazing rates calculated in this manner represent the minimum grazing rates, as they assume that the near-bottom boundary layer is depleted of phytoplankton and mixing of the water column is inadequate to replenish that lower layer with phytoplankton biomass. We assumed all bivalves grazed continuously.

Corbicula fluminea dry weight was used to estimate their temperature-corrected pumping rates. Pumping rate expressed relative to dry tissue weight (PR_{wt} in milliliters per milligram of AFDM per hour) was derived from data published by Foe and Knight (1986) for *C. fluminea* from the Sacramento-San Joaquin Delta:

$$PR_{wt} = 0.4307\ e^{0.1113(\text{water temperature})} \qquad (2)$$

Pumping rate for *C. fluminea* is calculated for water temperatures between 16 and 30 degrees Celsius using equation 2. Pumping rate (in liters per day) for each individual bivalve as shown in equation 1 was re-assigned as:

$$PR = (PR_{wt}) \qquad (3)$$

Calculated pumping rates were converted to grazing rates using equation 1 assuming a maximum effect of a concentration boundary layer by decreasing pumping rate using the refiltration relation derived by O'Riordan and others (1995) for a similar bivalve, *Venerupis philippinarum*—a bivalve with similar pumping rates (about 8 milliliters per milligram per hour [$mL\ mg^{-1}\ hr^{-1}$]) as *C. fluminea*.

$$n_{max} = 3(s(d_o)^{-1})^{-1} \qquad (4)$$

where

- n_{max} is the maximum refiltration proportion
- s is a proxy for animal density, and
- d_o is a proxy for animal size (cm)

GR was then estimated using the new estimation of n_{max} from equation 4 within equation 1.

Estimating Recruitment

Recruits were considered to be animals ≤2.5 mm in length for this study. This estimate will not include the smallest sized recruits due to the screen size (0.5 mm) that was used to sieve the samples. Initial recruitment is likely to be at least a month earlier than is observed using this size range.

Data Analysis

Once calculated, biomass, recruitment, and grazing rate were graphed using a visual analysis software package Tableau 2022.1 (http://www.tableau.com/). Data are shown in graphs (figs. 2–11) and can be found in Crauder and others (2016) and Zierdt Smith and others (2021).

Data are listed in tables as averages but will be discussed in this report with one significant figure due to the large variability inherent in benthic data.

Results

The biomass, grazing rate, and recruitment of the two dominant bivalve species, *C. fluminea* and *P. amurensis*, seasonally varied in samples from 10 monitoring stations sampled monthly during 2019 (fig. 1).

Biomass

Corbicula fluminea Biomass

Corbicula fluminea biomass data were collected from stations C9, D16, D24, D28A, and P8 and are shown in figures 2–6. The lowest *C. fluminea* biomass values were seen in the southern part of the delta (station C9; zero biomass all months except April with ~10 g AFDM/m^2 biomass) and in the San Joaquin River near the bay (station D16; ~1 g AFDM/m^2 for all months). Highest *C. fluminea* biomass was seen in the

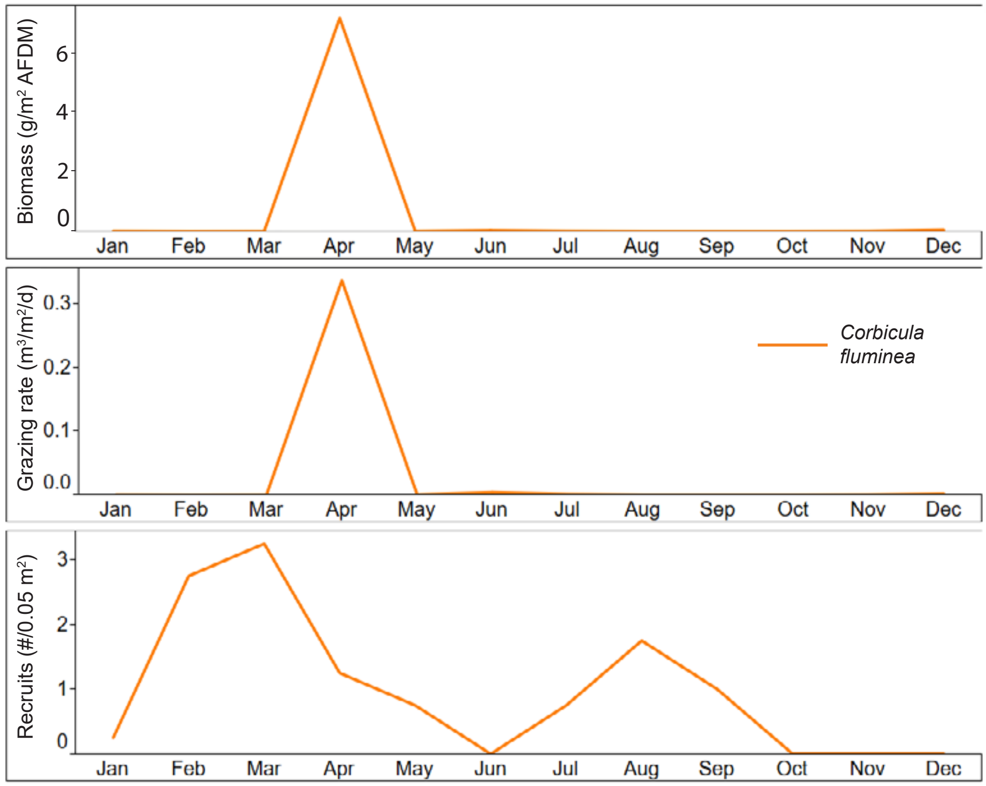

Figure 2. Diagram showing biomass (grams of ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 millimeters) abundance (number of recruits [#]/0.05 m²) values for *Corbicula fluminea* at station C9 (shallow station, ≤ 3 meters). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

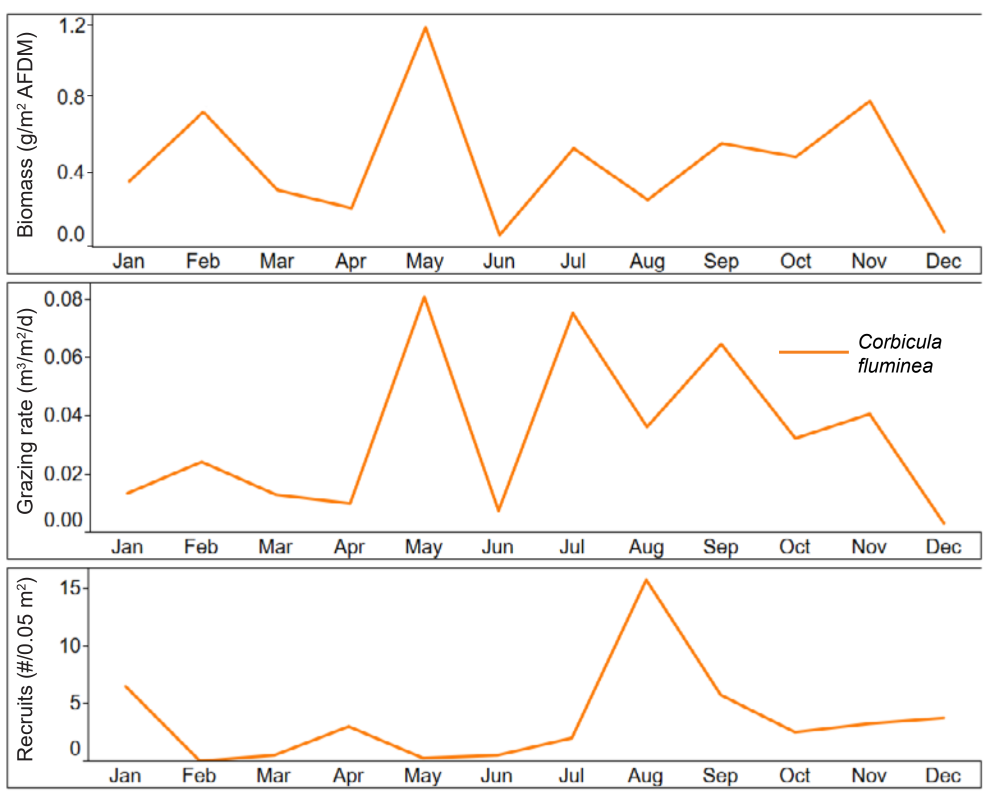

Figure 3. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m²) values for *Corbicula fluminea* at station D16 (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

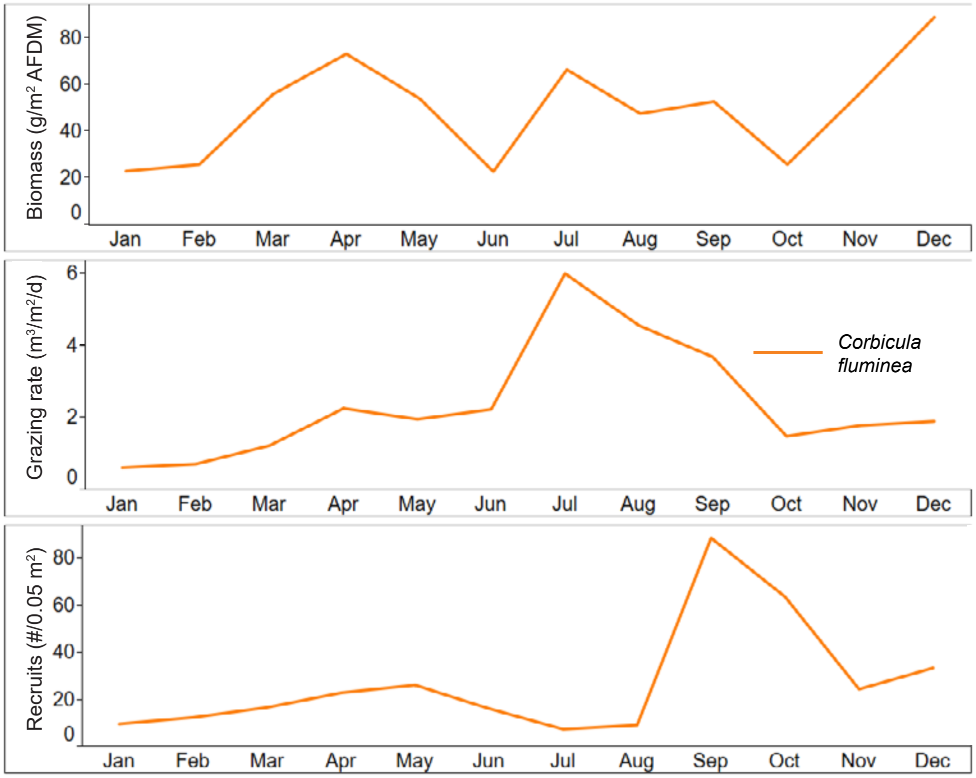

Figure 4. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m²) values for *Corbicula fluminea* at station D24 (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

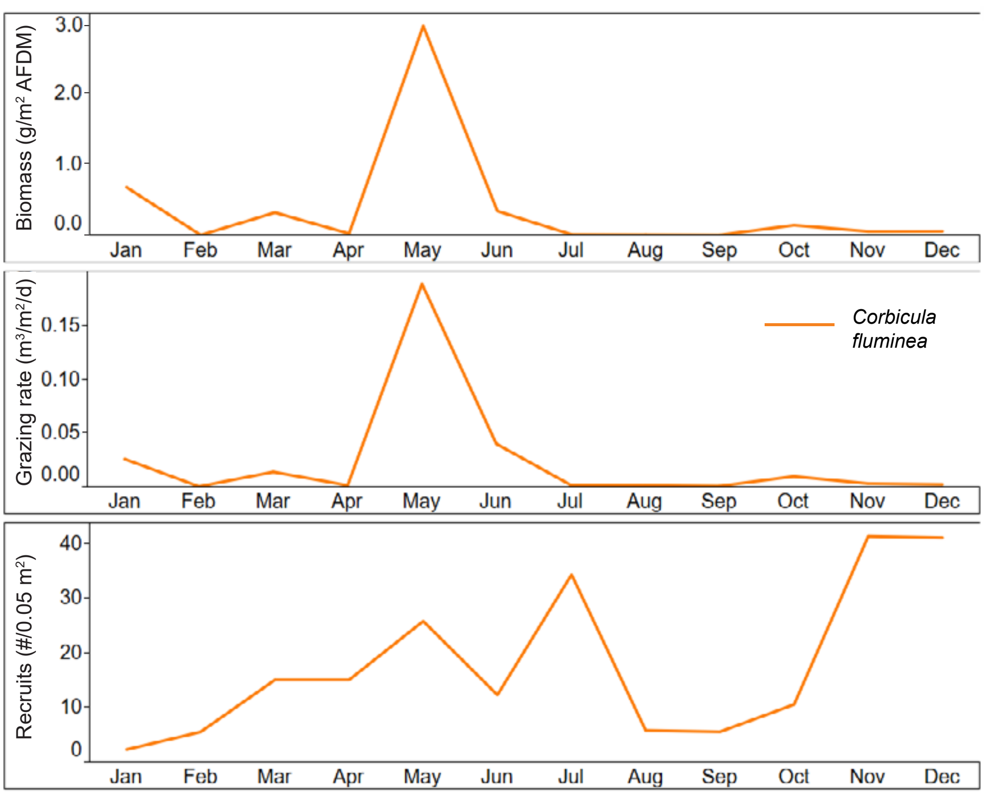

Figure 5. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m²) values for *Corbicula fluminea* at station D28A (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

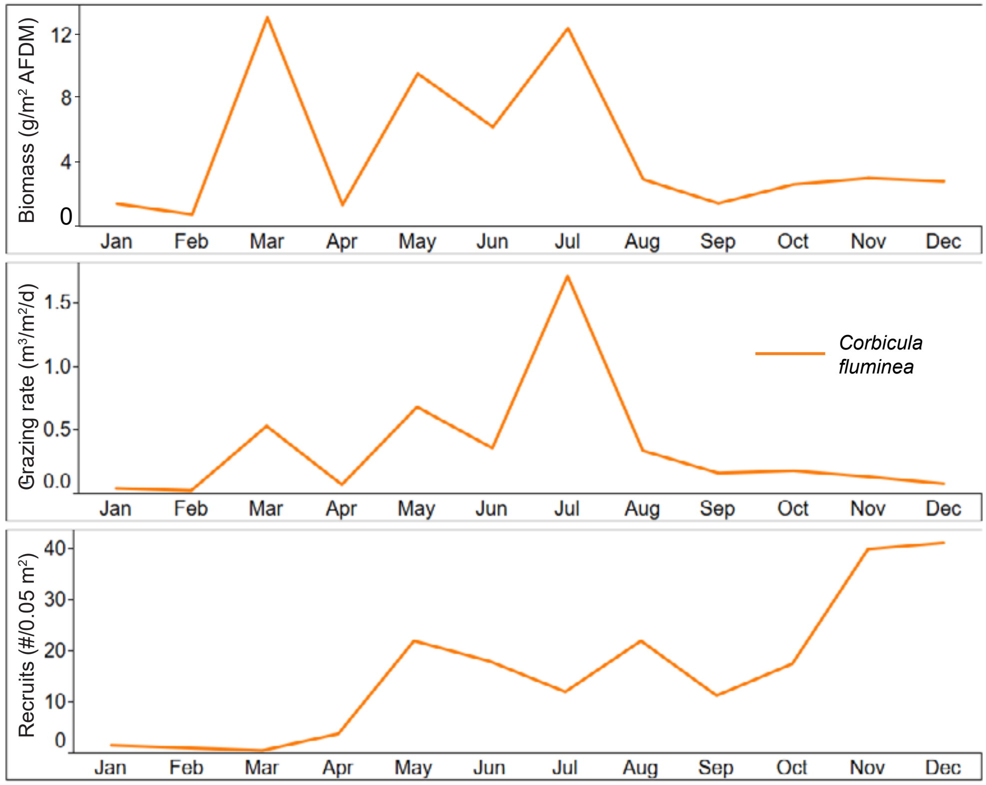

Figure 6. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m^2]), grazing rate (cubic meters of water filtered per square meter per day [m^3/m^2/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m^2) values for *Corbicula fluminea* at station P8 (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

Sacramento River station (station D24) where biomass values in all months were >20 g AFDM/m^2, with three months (April, July, December) having values in the 70–90 g AFDM/m^2 range. *Corbicula fluminea* biomass on the western side of the delta (station D28A) had very little biomass (~1 g AFDM/m^2 for all months**)** whereas the eastern station (P8) had biomass values in the 5–10 g AFDM/m^2 range in March and May–July and ~1 g AFDM/m^2 for the remaining months of the year.

Potamocorbula amurensis Biomass

Potamocorbula amurensis biomass data were collected from stations D6, D7, D41, and D41A and are shown in figures 7–10. *Potamocorbula amurensis* biomass values were <10 g AFDM/m^2 January through May and ~10–30 g AFDM/m^2 June through December in Suisun Bay (station D6). Biomass values in the adjacent shoal at Grizzly Bay (station D7) were ~1 g AFDM/m^2 January through July and ~10 g AFDM/m^2 August through December. Biomass values in the channel in San Pablo Bay (station D41) were zero except in May through October when they increased to 10–50 AFDM/m^2. As seen in Suisun Bay, the biomass of *P. amurensis* in the San Pablo Bay shoal (station D41A) was much less than in the channel with biomass peaking at ~10 g AFDM/m^2 June through December and falling to near zero the remaining months.

Biomass Where Species Co-occur

Corbicula fluminea and *P. amurensis* occurred together at only one station. At station D4L, at the confluence of the Sacramento and San Joaquin Rivers, *C. fluminea* biomass was low (<5 g AFDM/ m^2) January through May but increased to ~10–20 g AFDM/m^2 in June through December (fig. 11). In an opposite pattern, *P. amurensis* biomass values were low (<1 g AFDM/ m^2) until December when biomass increased slightly to ~1 g AFDM/m^2.

Biomass Summary

Corbicula fluminea biomass was high, relative to other values at a location, in April or May at all stations. The upstream Sacramento River station (D24) and a downstream San Joaquin River station (P8) continued to have elevated biomass into July. These two stations were also the only stations to show a strong seasonal pattern with *C. fluminea* biomass being lowest in January or February.

Potamocorbula amurensis biomass was variable everywhere and lower (<20 g AFDM/m^2) in the shallow, shoal stations (D7 and D41A) than in the channel stations. The Carquinez Strait (D6) biomass fluctuated between 2 and 20 g AFDM/m^2 and the San Pablo Bay channel (D41) biomass fluctuated between 0 and 50 g AFDM/m^2.

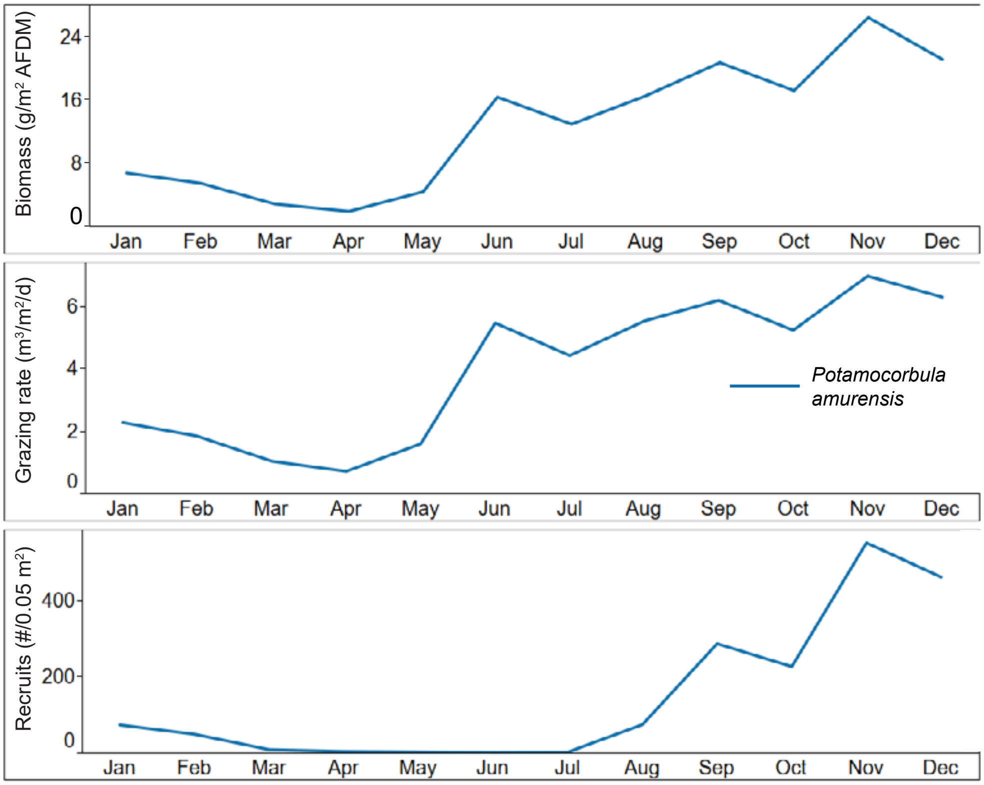

Figure 7. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits/0.05 m²) values for *Potamocorbula amurensis* at station D6 (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

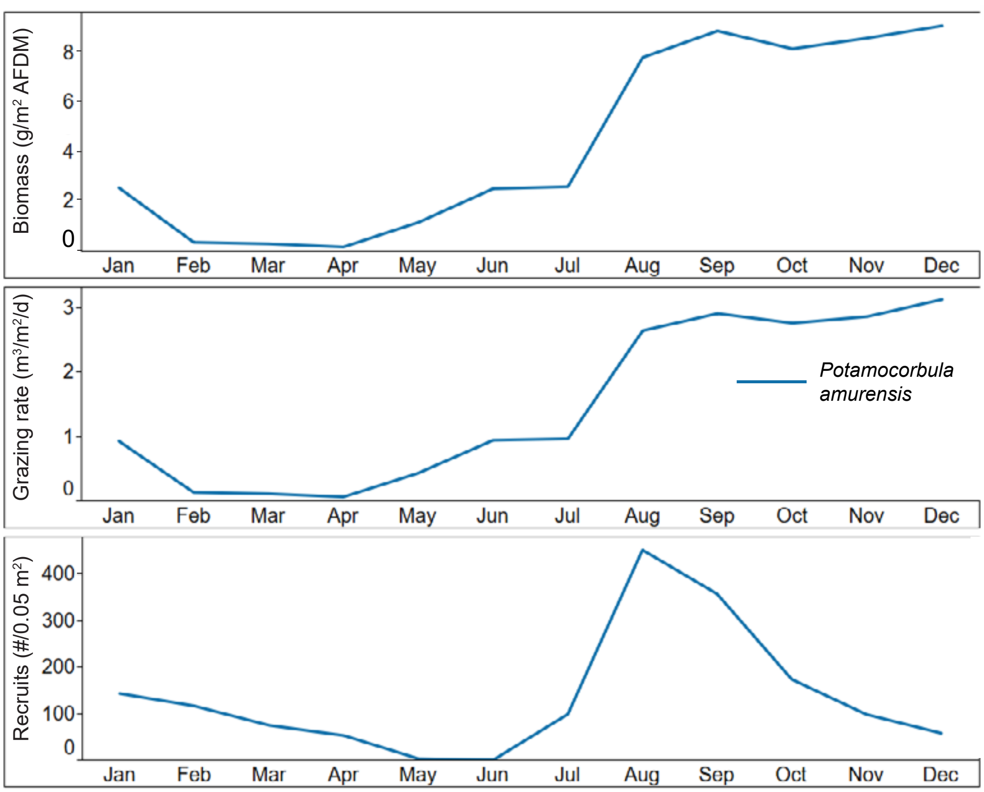

Figure 8. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m²) values for *Potamocorbula amurensis* at station D7 (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

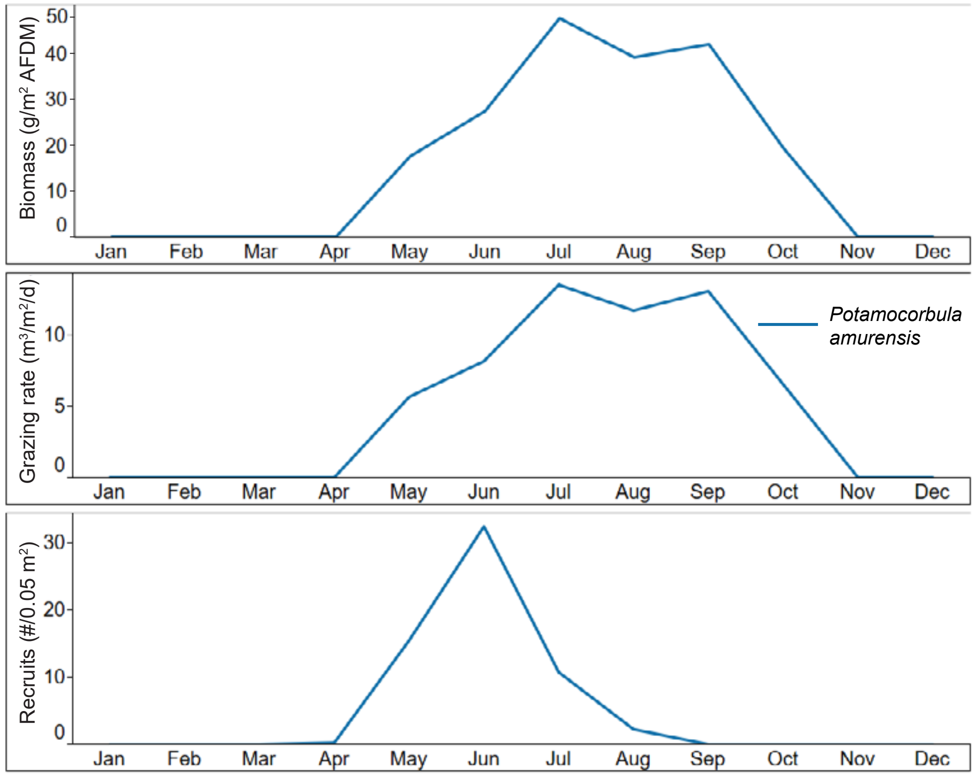

Figure 9. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m²) values for *Potamocorbula amurensis* at station D41 (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

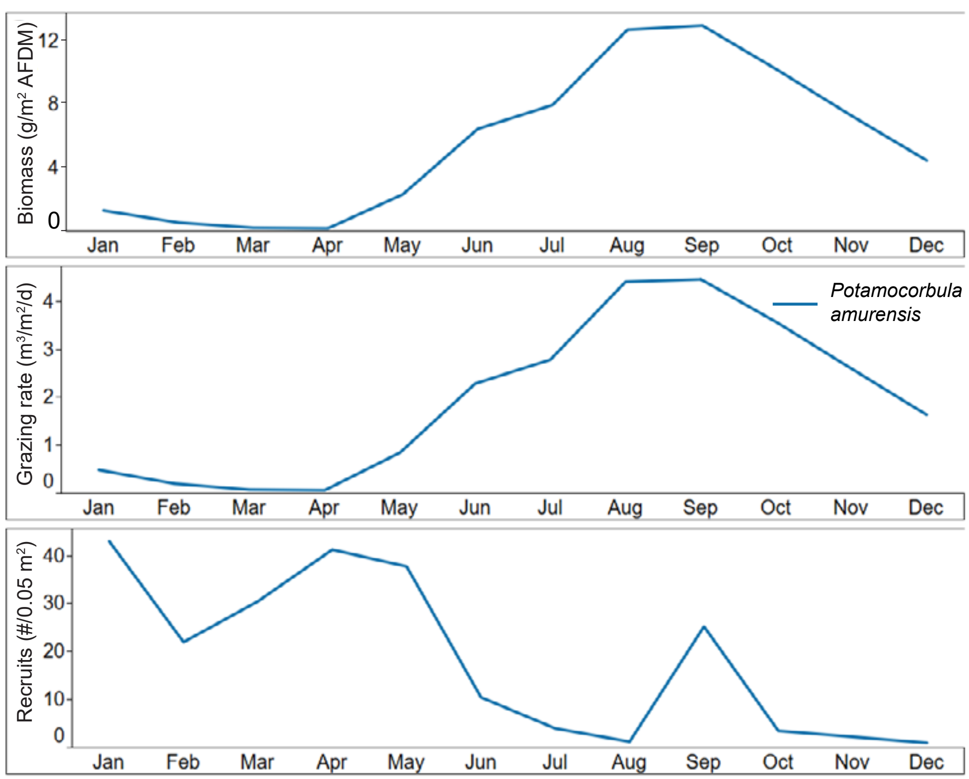

Figure 10. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m²) values for *Potamocorbula amurensis* at station D41A (shallow station, ≤ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

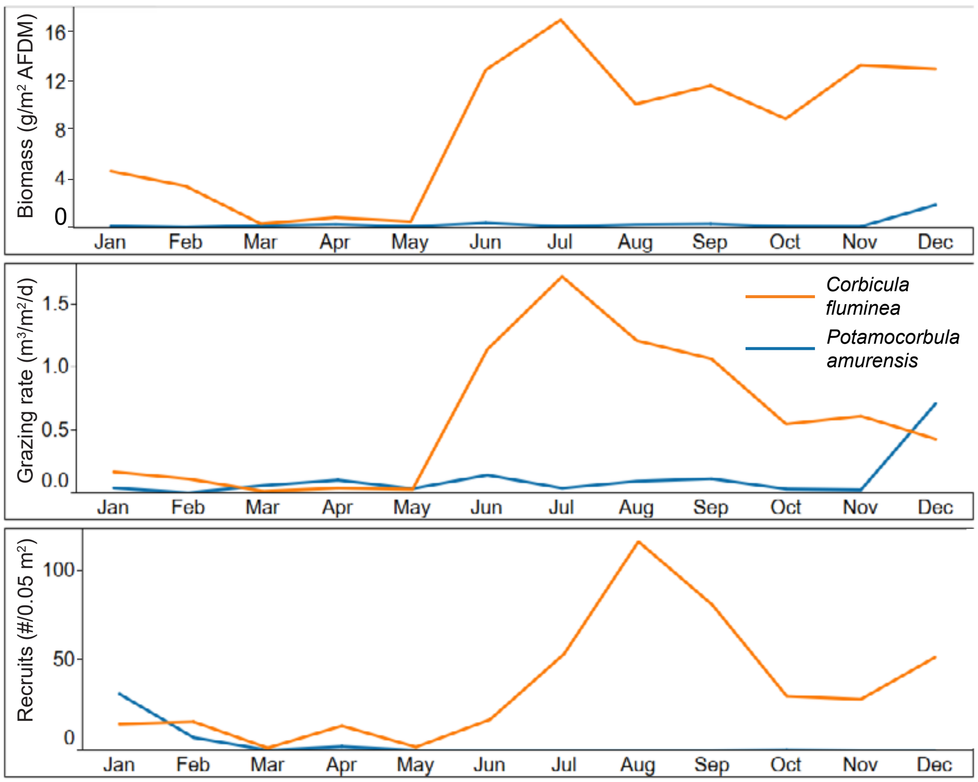

Figure 11. Diagram showing biomass (grams ash-free-dry-mass per square meter [g AFDM/m²]), grazing rate (cubic meters of water filtered per square meter per day [m³/m²/d]), and recruit (bivalves whose length was equal to or less than 2.5 mm) abundance (number of recruits [#]/0.05 m²) values for Corbicula fluminea and *Potamocorbula amurensis* at station D4 (deep station, ≥ 3 m). January through December data from the Sacramento–San Joaquin River Delta, California, 2019. Data from Zierdt Smith and others, 2021.

Grazing Rate

Grazing rate values (figs. 2–11) have the same basic temporal and spatial patterns as biomass values, and the same descriptions and conclusions applied to biomass data can be applied to grazing rate data. However, grazing rate has a nonlinear relation with biomass; high biomass values will have lower grazing rate values than expected owing to the formation of the concentration boundary layer, which increases with increasing bivalve abundance and biomass (O'Riordan and others, 1995). The concentration boundary layer decreases the effectiveness of the bivalves' feeding and reduces grazing rates. In addition, the pumping rate is a function of temperature; therefore, grazing rates tend to be lower in winter months than one would expect if the relation with biomass values was linear. In this case, the lower temperatures slow down the pumping rate, resulting in lower grazing rates.

Recruitment

Corbicula fluminea Recruitment

All stations, except at the southern extreme location (C9; fig. 2), in the delta had at least some *C. fluminea* recruit most months. The San Joaquin station nearest the bay (D16; fig. 3) had too few recruits each month to discern a clear seasonal pattern. The Sacramento River station (D24; fig. 4) had the strongest seasonal pattern: 10–20 recruits/0.05 m² were seen January through August, followed by an increase in recruits in September and October (90 and 60 recruits/0.05 m²) before decreasing to 20–30 recruits/0.05m² in November and December. The stations in the middle of the delta (D28A, P8; figs. 5 and 6) had similar recruitment patterns and abundance. A low abundance at these two stations (<10 recruits/0.05 m²) was seen prior to May; from May to July the recruit abundance increased to 10–20 or 30 recruits/0.05 m². Both stations then saw an increase to 40 recruits/0.05 m² in November and December.

Potamocorbula amurensis Recruitment

The only stations with recruits present most months were in in Suisun Bay (D6; fig. 7), the adjacent shoal in Grizzly Bay (D7; fig. 8), and the shoal in San Pablo Bay (D41A; fig. 10). Largest recruitment numbers were seen in Suisun Bay (500–600 recruits/0.05 m²) and the adjacent shoal (400–500 recruits/0.05 m²) in August through November. The San Pablo Bay channel station (D41; fig. 9) had very few recruits (10–30 recruits/0.05 m²) from May through July and zero recruits the rest of the months. The number of recruits at the San Pablo Bay shoal station was steady from January through May (20–40 recruits/0.05 m²), decreased from June through August (1–10 recruits/0.05 m²), increased in

September (25 recruits/0.05 m^2), and decreased from October through December (1–4 recruits/0.05 m^2).

Overlap Recruitment (Stations Where *C. fluminea* and *P. amurensis* Co-Occur)

Seasonality in *C. fluminea* recruitment in the area where the two bivalves co-occur (station D4L; fig. 11) was similar to what was seen with *C. fluminea* at the Sacramento River station (D24). Recruit abundance was however much lower (100 recruits/0.05 m^2) than at station D24. *Potamcorbula amurensis* recruitment was limited to a small peak in January (30 recruits/0.05 m^2).

Recruitment Summary

Corbicula fluminea recruitment was evident at several locations throughout the year with some seasonal patterns. The Sacramento River (D24; fig. 4) and the mid-delta stations (D28A, P8; figs. 5 and 6) had a reasonably constant presence of recruits from January through August (10–20 recruits/0.05 m^2). The Sacramento River station had a large increase in recruits (60–90 recruits/0.05 m^2) in September through October and the mid-delta stations had a similar but smaller increase in November through December (40 recruits/0.05 m^2).

Potamocorbula amurensis recruitment was more seasonal than that observed for *C. fluminea*, the recruit numbers were higher, and the recruits were smaller than *C. fluminea* recruits. Recruit abundance was similar in season but not magnitude in the Carquinez Strait station in Suisun Bay (D6; fig. 7) and the adjoining shoal station in Grizzly Bay (D7; fig. 8). Both stations had a small recruit period in January and February (50–100 recruits/0.05 m^2). The major recruitment occurred between August and November with the shoal recruit abundance peaking (400 recruits/0.05 m^2) in August, three months before the channel station (500 recruits/0.05 m^2 in November). San Pablo Bay recruitment was limited to May through July in the channel (station D41; fig. 9) with a small abundance of recruits (10–30 recruits/0.05 m^2). The shoal station (D41A; fig. 10) recruitment was similar in abundance (20–40 recruits/0.05 m^2) but occurred much earlier, January through May.

Conclusions

Biomass and grazing rate values for two bivalves in the Sacramento-San Joaquin Delta and San Francisco Bay in California had the same basic patterns in 2019, and the conclusions that we apply to biomass can be applied to grazing rate data. *Corbicula fluminea* biomass and grazing rate values were lowest during January through March and peaked between March and July. *Potamocorbula amurensis* biomass and grazing rate values were generally lowest January through March and peaked in August through December with the increase in salinity.

Corbicula fluminea recruitment was low January through August and peaked sometime in September through December depending on location. *Potamocorbula amurensis* recruited in January through July in the down bay locations (San Pablo Bay) and mostly in August through November at the up-bay locations (Suisun and Grizzly Bays).

Both biomass and recruitment seasonality and distribution of *Potamocorbula amurensis* likely reflects the stress of high freshwater flow in 2019 that both removed previous years bivalves and limited the recruitment period in 2019.

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