Prepared in cooperation with California Department of Water Resources

Bivalve Effects on the Food Web Supporting Delta Smelt— A Spatially Intensive Study of Bivalve Recruitment, Biomass, and Grazing Rate Patterns with Varying Freshwater Outflow in 2019

Open-File Report 2022–1102

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

Cover. Photograph of sunrise viewed from research vessel on the San Joaquin River, California. U.S. Geological Survey photograph taken by Emily Zierdt Smith, October 17, 2018.

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Conversion Factors

International System of Units to U.S. customary units

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 °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Datum

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

Recruits are given as the number of bivalves ≤ 2.5 millimeters in length per meter squared (#/m^2 of bivalves ≤ 2.5 mm in length). The low salinity zone (LSZ)—salinities range from 1 to 6 practical salinity units (psu)

Abbreviations

DOD	U.S. Department of Defense
AFDM	ash-free dry mass
AFDW	ash-free dry weight
CF	*Corbicula fluminea*
DWR	California Department of Water Resources
EMP	Environmental Monitoring Program
GR	grazing rate
GRTO	grazing rate turnover rate
IEP	Interagency Ecological Program
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 Spatially Intensive Sampling Study of Bivalve Recruitment, Biomass, and Grazing Rate Patterns with Varying Freshwater Outflow in 2019

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. The decline of phytoplankton biomass is one potential factor in the decline of the protected *Hypomesus transpacificus* (delta smelt) and other pelagic organisms. The bivalves *Corbicula fluminea* and *Potamocorbula amurensis* (hereafter *C. fluminea* and *P. amurensis*, respectively) have been shown to control phytoplankton biomass in several locations throughout the San Francisco Bay and the Sacramento-San Joaquin Delta; therefore, knowledge of their distribution and population dynamics are of great interest.

Here, we describe the distribution and dynamics of bivalve biomass using samples collected by the California Department of Water Resources (DWR) as part of the benthic monitoring program in 2019. One element of DWR's and the Bureau of Reclamation's Environmental Monitoring Program—the Generalized Random Tessellation Stratified (GRTS) program—examines the spatial and temporal extent of *C. fluminea* and *P. amurensis* control on phytoplankton. Historically, the GRTS program sampled 175 benthic stations (50 stations that are monitored every year and 125 randomly selected new stations that are changed yearly) throughout the Sacramento-San Joaquin Delta and northern San Francisco Bay (San Pablo and Suisun Bays) during one week in May and October. In 2019, only the 50 annually replicated stations were sampled.

Corbicula fluminea and *P. amurensis* biomass and grazing rates had similar trends; therefore, the conclusions regarding biomass are applied to grazing rate data as well. *Corbicula fluminea* biomass decreased from May to October, whereas *P. amurensis* average biomass (reported increased from May (1 g ash-free-dry-tissue mass/square meter (g AFDM/m^2) to October (2 g AFDM/m^2). Although *C. fluminea*'s average biomass was lower in October (10 gAFDM/m^2) than in May (20 gAFDM/m^2), the highest single biomass value was also observed in October (300 gAFDM/m^2). In both May and October, most stations that recorded high *C. fluminea* biomass values were located in the deep water (≥3 m of depth between the surface of the water and the surface of the substrate on the bottom) and were sampled in either rivers or sloughs. A relation between depth and biomass was not observed for *P. amurensis*.

Both *C. fluminea* and *P. amurensis* recruitment (recruits are considered animals ≤2.5mm in length in this study and recruitment is the process of recruits successfully settled to the bottom) increased from May to October. The total number of *C. fluminea* recruits more than doubled from May to October, whereas *P. amurensis* total recruitment increased by 8-fold during the same period. Most *P. amurensis* recruits in May can be attributed to one station, whereas the recruits in October were found at 14 stations. A relation between number of recruits and station depth was not evident for either *C. fluminea* or *P. amurensis.*

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 Department of Water Resources (DWR) and Bureau of Reclamation (Reclamation). Water Rights Decisions (D-1379, D1485, 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 of DWR's and Reclamation's Environmental Monitoring Program (EMP)

[1]U.S. Geological Survey.

[2]California Department of Water Resources.

wherein the potential effects of water project operations on the estuary are determined. These effects are determined by changes in benthic fauna presence, abundance and distribution associated with physical factors in the estuary, and the detection of newly introduced species in the estuary. This monitoring program is the foundation of the benthic studies in the San Francisco Bay (San Pablo and Suisun Bays) and Sacramento-San Joaquin Delta that produced data used to examine how the biomass and grazing rate of the bivalves have changed in time and space since 1977 (Crauder and others, 2016). DWR, supported by Reclamation, expanded their benthic monitoring program to include spatially intensive sampling (Generalized Random Tessellation Stratified Sampling Program, hereafter GRTS) in the spring and fall of every year beginning in 2007. Here, we use samples from collected by DWR as part of the GRTS program to estimate biomass and grazing rates of bivalves throughout the northern part of the San Francisco Bay and Sacramento-San Joaquin Delta in 2019.

Large ecological changes that have occurred throughout San Francisco Bay and the Sacramento-San Joaquin Delta over the past several decades have driven the interest in bivalve grazing rates and biomass. Four species of fish, many macro-zooplankton species, and the native *Neomysis mercedis* (mysid shrimp) have shown large population declines in the northern San Francisco Bay over the last 28 years (Sommer and others, 2007; Baxter and others, 2008). Although the reductions in abundance of species 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. Alpine and Cloern, 1992 and MacNally and others, 2010 suggest one of the causes for ecological decline, referred to here as the pelagic organism decline (POD), is the reduction of the phytoplankton in the northern San Francisco estuary coincident with the 1987 introduction of the exotic, filter-feeding bivalve *Potamocorbula amurensis* (hereafter *P. amurensis*). The phytoplankton biomass in the northern San Francisco estuary and western Sacramento-San Joaquin Delta area is now chronically low and is considered a contributor to, if not a major cause of, the POD and the decline of the delta smelt (Baxter and others 2008, Hammock and others, 2015).

If we consider the northern San Francisco Bay and the Sacramento-San Joaquin Delta area as the habitat for POD species, two large nonnative bivalve species inhabit the area—an 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 Bay and Sacramento-San Joaquin Delta (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 freshwater bivalves; Scherwass and others, 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 limit on distribution for both species should be physiological. Other factors that are likely to affect the bivalve's 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 spatial variability of *C. fluminea* and *P. amurensis* in northern San Francisco Bay and the Sacramento-San Joaquin Delta area by examining biomass, grazing rate, and recruitment of bivalves in samples from 50 monitoring stations sampled in May and October 2019. These bivalves are from benthic samples that have been collected as part of the 2019 monitoring program conducted by the California Department of Water Resources Environmental Monitoring Program (https://water.ca.gov/Programs/Integrated-Science-and-Engineering/Biological-Monitoring-and-Assessment).

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 State Water Control Board, 2011) highlights the importance of the biotic habitat as well as the abiotic physical 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 therefore 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 mostly 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 (August through November) in the low salinity zone (LSZ), a favored habitat of the delta smelt. Several components of the LSZ food web, including the wider distribution of bivalves, and increased magnitude of bivalve grazing may be affected by this reduction in salinity variability.

Bivalve grazing effects and recruitment patterns were analyzed at all GRTS stations sampled in May and October 2019 to better understand how increasing freshwater flow can influence the distribution of each species. The data in this Open-File Report are from the 2019 data of the EMP and are available in a data release (Zierdt Smith and others, 2021).

Methods

Generalized Random Tessellation Stratified Sampling Program Collection Method

The California Department of Water Resources Environmental Monitoring Program (https://water.ca.gov/Programs/Integrated-Science-and-Engineering/Biological-Monitoring-and-Assessment) selected sampling locations (fig. 1) using a GRTS design (Stevens and Olsen, 2004). Locations were selected to include varying strata (see table 1) and include as much of the Sacramento-San Joaquin Delta as possible. The probabilistic sampling design allows for the estimation of regional and system-wide means of benthos population densities and grazing rates. A major benefit of a GRTS sampling design over other random sampling methods is that it is spatially balanced. The original population of possible sampling locations included all navigable, subtidal habitats in the northern San Francisco Bay (throughout the legal Sacramento-San Joaquin Delta, Suisun Bay, Suisun Marsh, and San Pablo Bay) that were accessible by EMP research vessels. Fifty of the GRTS sites are fixed sites that are sampled each year (fig. 1 and table 1) to allow for a temporal aspect to be included in the study. The remaining 125 sites are

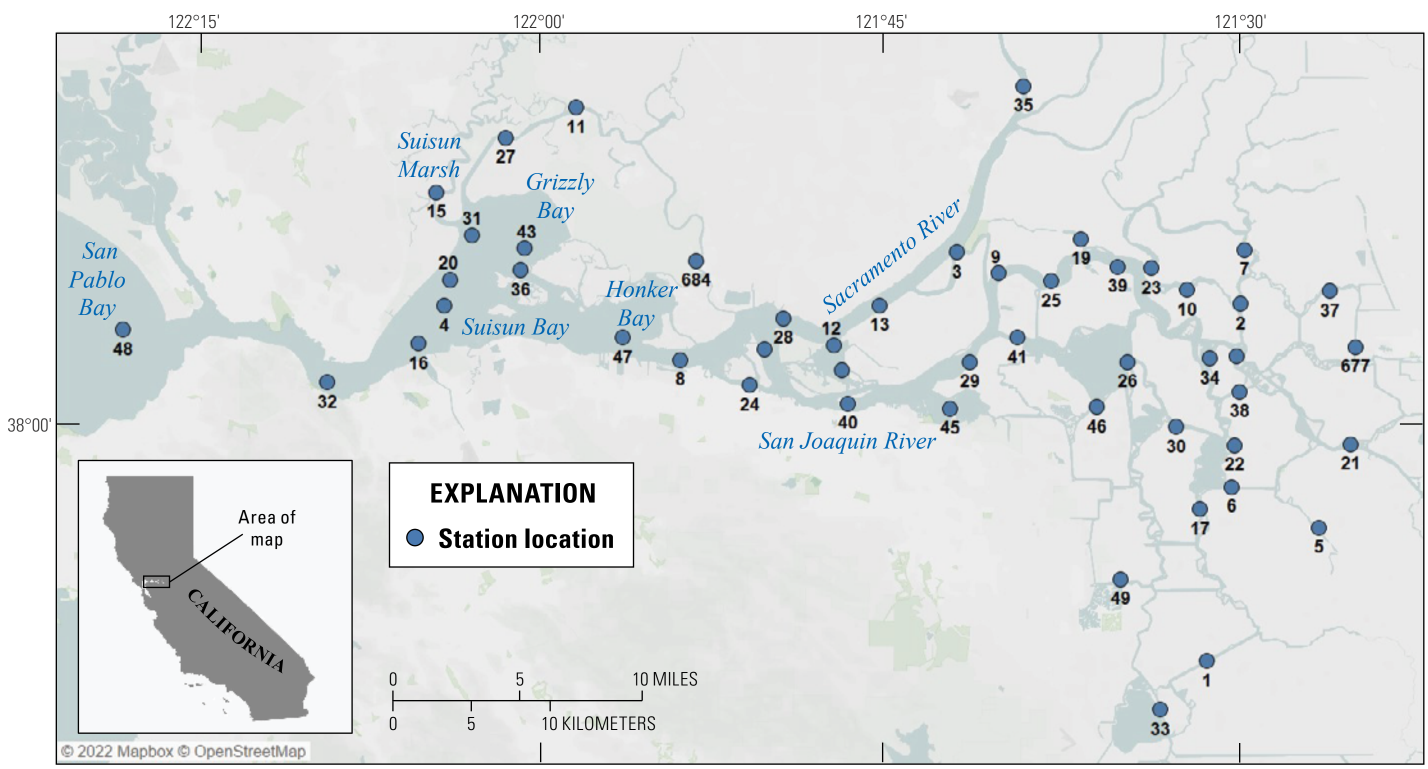

Figure 1. Map of Generalized Random Tessellation Stratified program station locations for benthic samples, Sacramento–San Joaquin River Delta, California, 2019. Labels on round dots are station numbers. Station names andlocations were determined by the California Department of Water Resources for the Generalized Random Tessellation Stratified program. See inset map of California for regional context.

Table 1. The 2019 Generalized Random Tessellation Stratified program stations, their coordinates, geographic area, and waterbody type of California Department of Water Resources and Bureau of Reclamation's Environmental Monitoring Program.

[Samples from each station were collected and sorted for the bivalves *Potamocorbula amurensis* and *Corbicula fluminea*. NE; northeastern]

Station no.	Latitude	Longitude	Geographic area	Waterbody type
1	37.87321	−121.5256418	Middle River	River
2	38.07603	−121.5016658	East Slough	Slough
3	38.10519	−121.7056152	Sacramento River	Large River
4	38.07493	−122.0752165	Honker Bay	Bay
5	37.94923	−121.4454081	San Joaquin River	Slough
6	37.97227	−121.5081304	Mildreds Island	Slough
7	38.10654	−121.4990456	NE Sloughs	Slough
8	38.04418	−121.9049592	Suisun Bay	Bay
9	38.09364	−121.6757006	San Joaquin River	Large River
10	38.08389	−121.5405267	NE Sloughs	Slough
11	38.18738	−121.9799724	Suisun Marsh	Slough
12	38.05262	−121.7941528	Confluence	Lake
13	38.07513	−121.7618192	Sacramento River	Large River
15	38.13926	−122.0806783	Suisun Marsh	Slough
16	38.05346	−122.0935171	Suisun Bay	Bay
17	37.95944	−121.5309691	Middle River	River
18	38.04651	−121.5045414	San Joaquin River	River
19	38.11291	−121.6166457	San Joaquin River	Slough
20	38.08982	−122.0712632	Honker Bay	Bay
21	37.99655	−121.4224475	San Joaquin River	River
22	37.99578	−121.5060827	Mildreds Island	Slough
23	38.09614	−121.566257	NE Sloughs	River
24	38.03006	−121.8551682	Confluence	Slough
25	38.08884	−121.6380112	San Joaquin River	Large River
26	38.04315	−121.5829928	Franks Tract	River
27	38.17014	−122.0307802	Suisun Marsh	Slough
28	38.06798	−121.8312752	Confluence	Large River
29	38.04321	−121.6969818	San Joaquin River	Large River
30	38.00619	−121.5479355	San Joaquin River	Slough
31	38.11519	−122.0553825	Grizzly Bay	Bay
32	38.03159	−122.1593116	Suisun Bay	Large Bay
33	37.84568	−121.5595999	Middle River	River
34	38.0451	−121.5235446	San Joaquin River	River
35	38.19936	−121.658223	Sacramento River	Slough
36	38.0952	−122.0202613	Honker Bay	Bay
37	38.08325	−121.4376125	East Slough	Slough
38	38.02636	−121.5022652	San Joaquin River	Slough
39	38.09721	−121.5898778	San Joaquin River	Large River
40	38.01947	−121.7843427	Confluence	Large River
41	38.05697	−121.6627016	Franks Tract	River
43	38.10775	−122.0174624	Grizzly Bay	Bay
44	38.05043	−121.8445307	Confluence	Large River
45	38.01661	−121.711121	San Joaquin River	Lake
46	38.01763	−121.6054396	Franks Tract	Slough
47	38.05695	−121.9468429	Suisun Bay	Bay
48	38.06141	−122.3068364	San Pablo Bay	Large Bay
49	37.91995	−121.588025	Old River	Slough
677	38.05162	−121.4186028	East Slough	River
684	38.1006	−121.8937056	Suisun Marsh	Slough
696	38.03862	−121.7889593	Confluence	Lake

sampled in both the spring and the fall but change each year, which allowed for an increased distribution of samples among geographically and physically diverse locations of the northern part of the San Francisco Bay and the Sacramento-San Joaquin Delta. Unlike previous years, sampling in 2019 only included the 50 fixed stations. Sites were classified by DWR into waterbody types: bay-large, bay, river-large, river, slough, and lake (flooded island; fig. 2). Figure 3 shows the geographic area for each station for the 2019 sampling period.

Field Collection Methods

The California Department of Water Resources Environmental Monitoring Program uses a 0.052 m^2 Ponar dredge to sample the bottom sediment to a depth that varies with the type of sediment and the ability of the dredge to penetrate it. Under the current program, a single sample is collected at each sampling station. At some stations, an extra sample is collected to determine the length to weight (ash free dry mass [AFDM]) relation of each bivalve species. Each sample is sieved through a U.S. Standard No. 30 stainless steel mesh screen (0.595 millimeter [mm] openings) to remove sediment and detritus that was <0.595 mm. The remaining sample (>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.

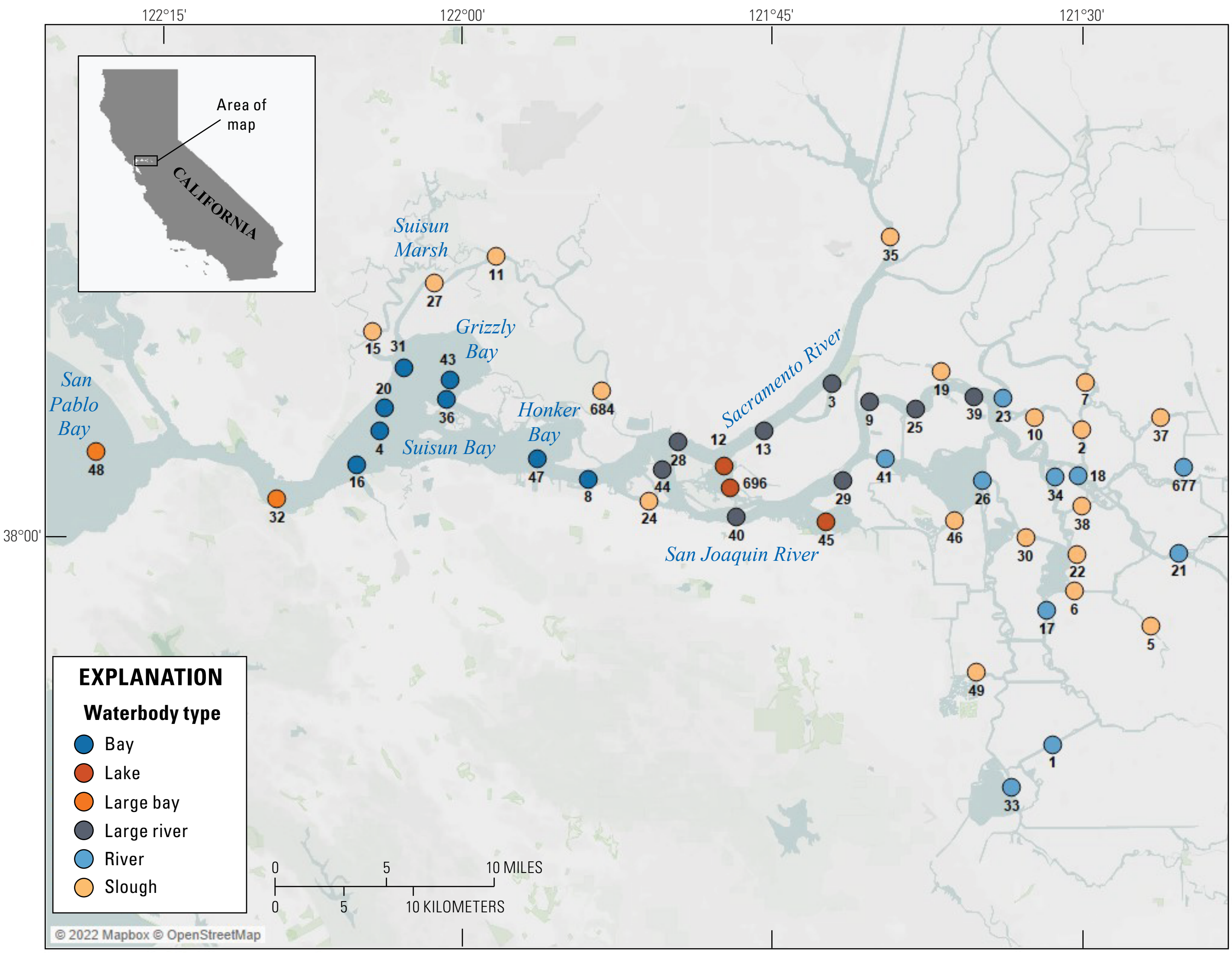

Figure 2. Map of Generalized Random Tessellation Stratified program station locations for benthic samples organized by waterbody type, Sacramento–San Joaquin River Delta, California, 2019. Labels on round dots are station numbers and locations supplied by the California Department of Water Resources for the Generalized Random Tessellation Stratified design study.

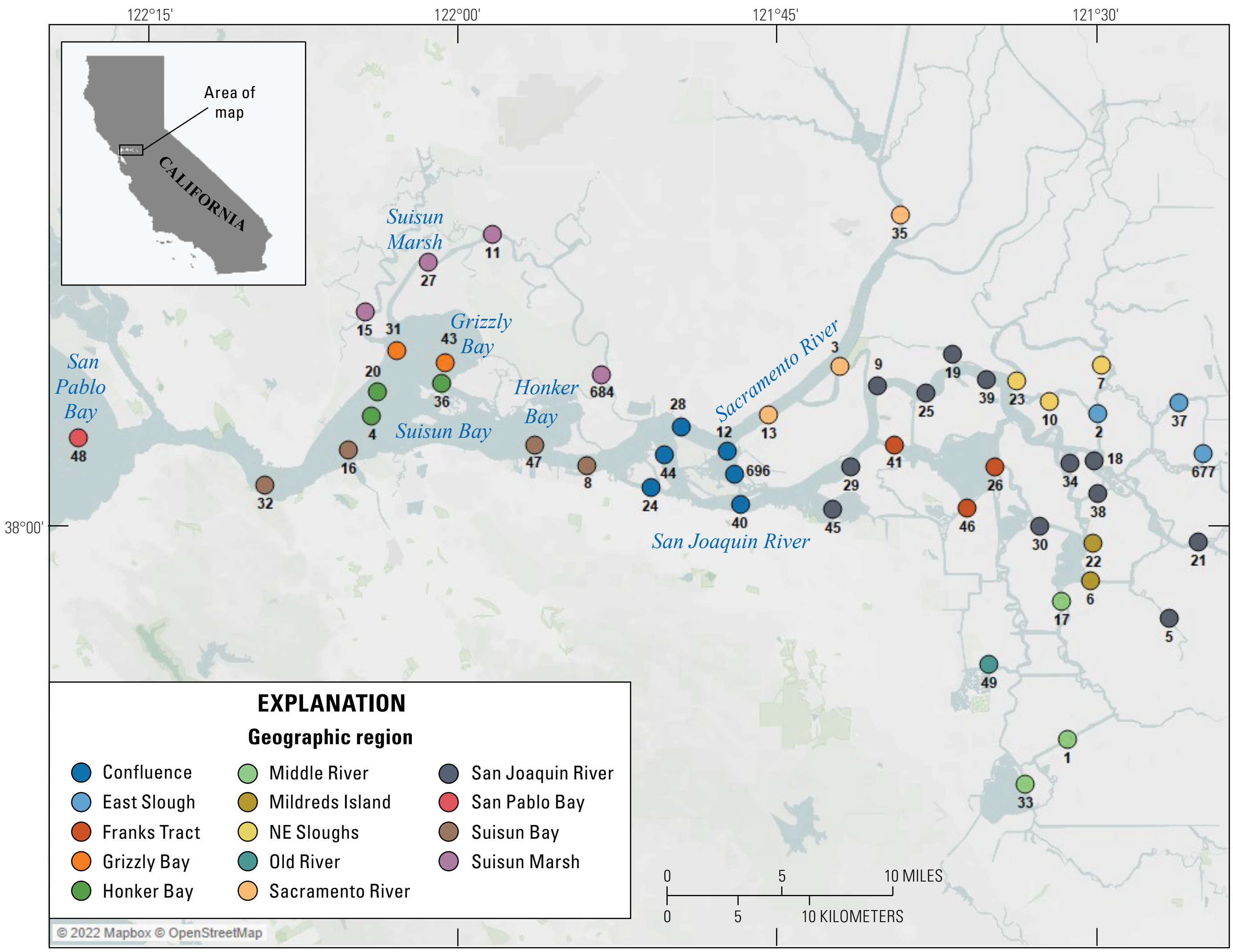

Figure 3. Map of Generalized Random Tessellation Stratified program station locations for benthic samples organized by geographic region, Sacramento–San Joaquin River Delta, California, 2019. Labels on round dots are station numbers and locations supplied by the California Department of Water Resources for the Generalized Random Tessellation Stratified design study.

Analytical Methods

Measuring Bivalves

The U.S. Geological Survey (USGS) Benthic Lab measured the bivalves to the nearest millimeter using handheld calipers and a microscope micrometer. Bivalves were then returned to DWR for archiving. Biomass estimates were based on the date appropriate relation between shell length and dry tissue weight that was calculated by DWR and the USGS during each field sampling using the standard techniques described in Thompson and others (2008).

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 rate (PR), a laboratory measure of a bivalve's rate for passing water over its gills was adjusted for temperature and was estimated as a conservative rate (assuming the development of a concentration boundary layer). Species pumping rates were based on published relations: *P. amurensis* pumping rates (400 liters per gram AFDM/day) 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 O'Riordan's (1995, figure 7b) refiltration relation:

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

where

- GR is grazing rate;
- PR is pumping rate;
- n_{max} is the maximum refiltration proportion—the proportion of water previously filtered by one square meter of bivalves;
- s is the distance between siphon pairs—a measure of animal density;
- d_o is the average diameter of the excurrent siphon of the animals collected at each site—a measure of animal size.

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 the sampling, assuming equidistant spacing within the 0.052 m^2 sample area. Benthic grazing rates calculated in this manner represent the minimum grazing rates, because 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 ash-free dry mass per hour) was derived from data published by Foe and Knight (1986) for *C. fluminea* from the Sacramento-San Joaquin Delta:

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

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:

$$\mathrm{PR} = \mathrm{PR_{wt}} \quad (3)$$

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 bivalve (*Venerupis philippinarum*, with a similar pumping rate (about 8 milliliters per milligram per hour [ml mg^{-1} hr^{-1}]) as *C. fluminea*.

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

where

- n_{max} is the maximum refiltration proportion
- s is a measure of animal density
- d_o is a measure of animal size

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 ≤2.5mm in length in our 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. Therefore, initial recruitment is likely to be at least a month earlier than is observed using this size range.

Data Analysis

Biomass, recruitment, and grazing rate, once calculated, were graphed using a visual analysis software package Tableau 2022.1 (http://www.tableau.com/). Data are shown in graphs (figs. 2–9). Only one sample collected per station and no averaging was necessary. When averages are discussed one significant figure is shown which is appropriate for the variability in the data.

Results

The biomass, grazing rate, and recruitment of the two dominant bivalves, *P. amurensis* and *C. fluminea*, varied seasonally and spatially in 2019. For our purposes, in San Francisco Bay and the Sacramento-San Joaquin Delta, we define any biomass ≥ 5 grams AFDM per square meter (g/m²) AFDM to be high. Grazing rates ≥ 1 cubic meter of water filtered per square meter of bivalves per day ($m^3/m^2/d$) are considered high because grazing rates of 1 $m^3/m^2/d$ are enough to limit the phytoplankton biomass at shallow depths in San Francisco Bay and the Sacramento-San Joaquin Delta. Recruitment was defined as any bivalve ≤ 2.5 mm in length. Stations that are ≤ 3 m deep were considered shallow and stations ≥ 3 m deep were considered deep. We examined the effects of depth and strata (waterbody type) on *P. amurensis* and *C. fluminea* grazing rate, biomass, and recruitment. Here, the temporal variability of *C. fluminea* and *P. amurensis* in San Francisco Bay and the Sacramento-San Joaquin Delta is discussed by examining biomass, grazing rate, and recruit density of bivalves in samples from 50 GRTS monitoring stations collected in May and October 2019 (fig. 1).

Biomass

Corbicula fluminea Biomass

Average *C. fluminea* biomass decreased from May (20 g AFDM/m^2) to October (10 g AFDM/m^2). The number of stations where *C. fluminea* was present also decreased during this period. In May, 20 stations had a biomass value ≥ 5 g/m² AFDM, whereas 6 stations had a biomass value ≥ 40 g/m² AFDM. The highest grazing rate value in May was 200 g/m² AFDW. In October, 15 stations had a biomass value ≥ 5 g/m² AFDM and 4 stations had a biomass value ≥ 40 g/m² AFDM. The highest grazing rate value in October was 300 g/m² AFDM. During both months, most stations with high biomass values were deep stations (≥ 3 m).

In May, the three stations with the highest biomass values were (from least to greatest) station 17 in the "Middle River," station 18 in the San Joaquin River (easternmost station), and station 2 in the "East Slough" on figure 3. In October, the three stations with the highest biomass values were (from least to greatest value) station 23 in the "NE Sloughs," station 46 in Franks Tract, and station 18 in the San Joaquin River (easternmost station) on figure 3. The stations with the highest biomass values were in rivers and sloughs.

In May, the distribution of *C. fluminea* biomass was farther west and overlapped with the distribution of *P. amurensis* biomass in Suisun Marsh (figure 3). By October, *C. fluminea* was no longer present in Suisun Marsh and its distribution did not reach farther west than the confluence of the Sacramento and San Joaquin Rivers. During each sampling month, the distribution of *C. fluminea* biomass was most concentrated in the eastern stations of the Sacramento-San Joaquin Delta (figs. 4 and 5).

Potamocorbula amurensis Biomass

Average *P. amurensis* biomass increased from May (1g AFDM/m²) to October (2g AFDM/m²). There were 16 stations where *P. amurensis* was present in both May and October. In May, 3 stations (11, 15, 36) had a biomass value ≥ 5 g/m² AFDW, whereas in October, 6 stations (4, 11, 15, 20, 31, 48) had a biomass value ≥ 5 g/m² AFDW. *Potamocorbula amurensis* was primarily found in deep water stations. The two highest biomass values observed during the study, both 18 g AFDM /m² occurred in October.

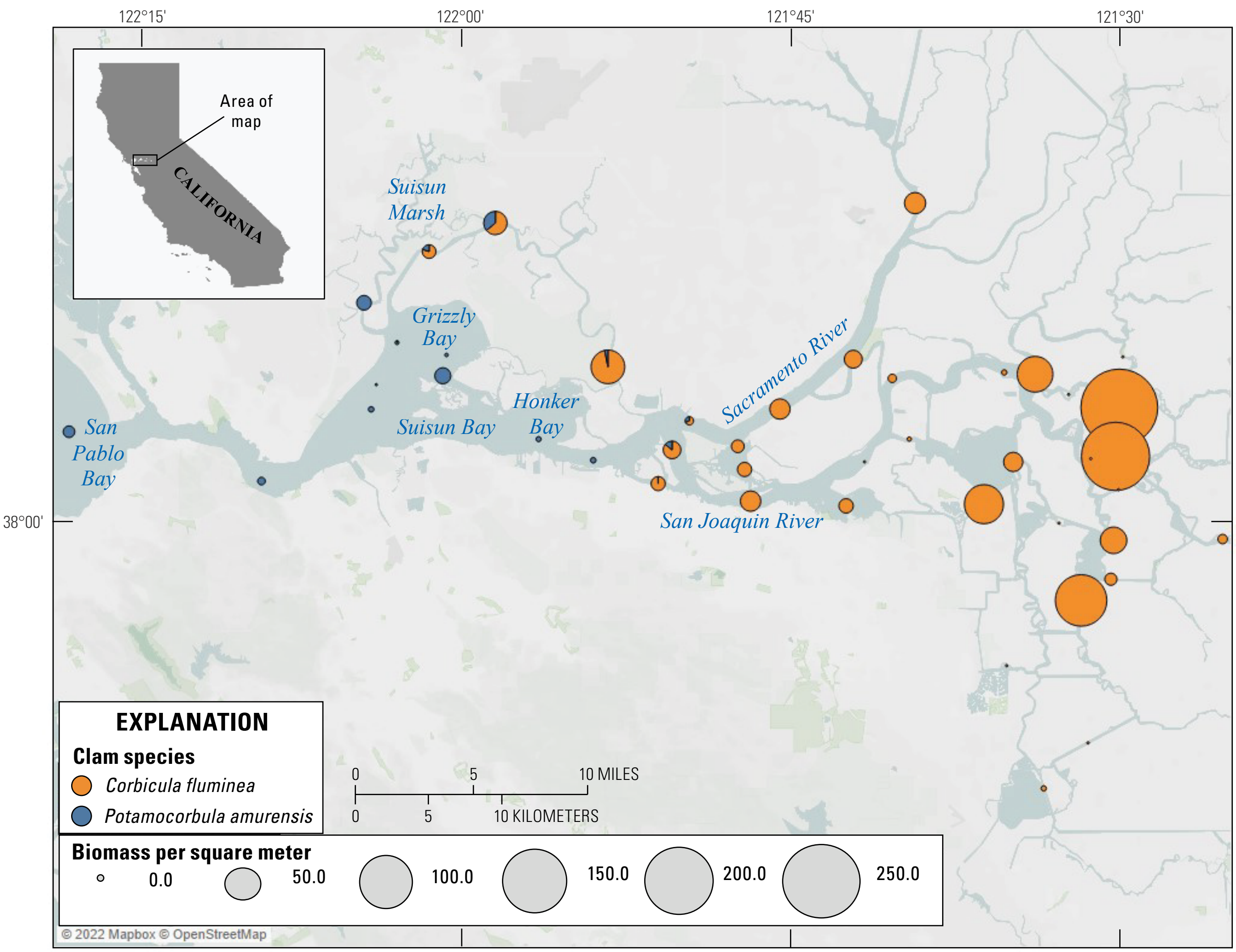

Figure 4. Map of Generalized Random Tessellation Stratified design study stations shown as pie diagrams of biomass (grams ash-free-dry-weight per square meter) for *Potamocorbula amurensis* and *Corbicula fluminea* (hereafter *P. amurensis* and *C. fluminea*, respectively) in May, 2019. Areas where *P. amurensis* (shown in blue) and *C. fluminea* (shown in orange) overlap result in a pie diagram representing both species with the total diameter representing the total biomass.

In May, 2 stations in Suisun Marsh and 1 station in Honker Bay had the highest biomass values. In October, 2 stations in Honker Bay and 1 station in San Pablo Bay had the highest biomass values.

Grazing Rate

Corbicula fluminea Grazing Rate

Average *C. fluminea* grazing rate was similar in May (0.5 $m^3/m^2/d$) and October (0.6 $m^3/m^2/d$). The number of stations where *C. fluminea* was present decreased from 35 to 30 respectively from May to October. A grazing rate value ≥ 1 $m^3/m^2/d$ was observed at 10 stations in May and at 6 stations in October. In both months, the stations with the highest grazing rates were deep water stations.

In May, the three stations with the highest grazing rate values were (from least to greatest) station 17 in the "Middle River," station 18 in the San Joaquin River (easternmost station), and station 2 in the "East Slough" on figure 3. In October, the three stations with the highest grazing rate values were (from least to greatest value) station 23 in the "NE Sloughs," station 46 in Franks Tract, and station 18 in the San Joaquin River (easternmost station) on figure 3. In both months, the stations with the highest grazing rate values were sampled in river or slough waterbody types.

In May, grazing rates were high across the sampling area, but in October, high grazing rate value were concentrated in the eastern stations (fig. 3). In contrast, *C. fluminea* was spread farther west, overlapping with *P. amurensis* in Suisun Marsh (as shown in figure 3) in May, but by October, *C. fluminea* was no longer present in Suisun Marsh and did not reach farther west than the confluence of the Sacramento and San Joaquin Rivers (figs. 6 and 7).

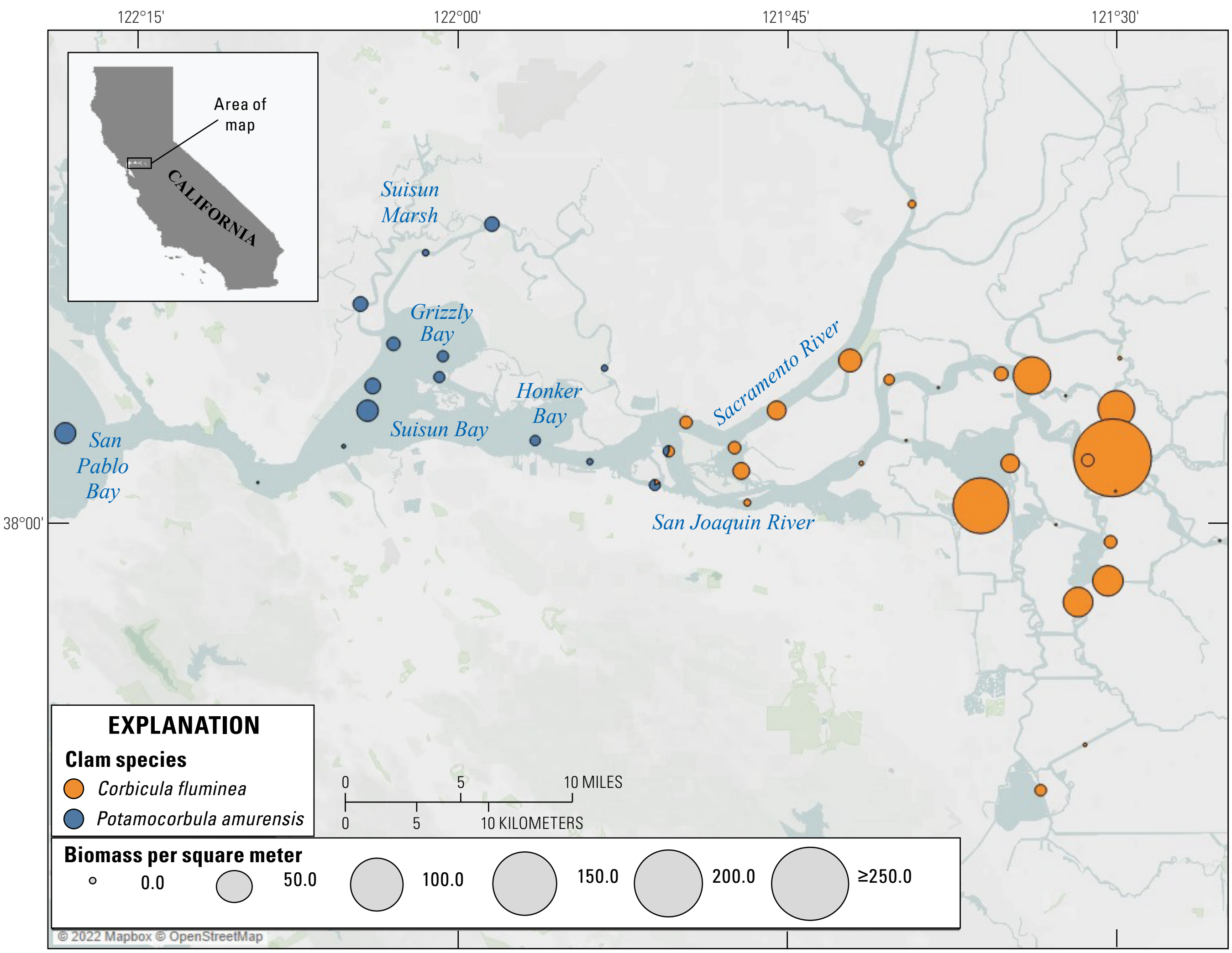

Figure 5. Map of Generalized Random Tessellation Stratified design study stations shown as pie diagrams of biomass (grams ash-free-dry-weight per square meter) for *Potamocorbula amurensis* and *Corbicula fluminea* (hereafter *P. amurensis* and *C. fluminea*, respectively) in October, 2019. Areas where *P. amurensis* (shown in blue) and *C. fluminea* (shown in orange) overlap result in a pie diagram representing both species with the total diameter representing the total biomass.

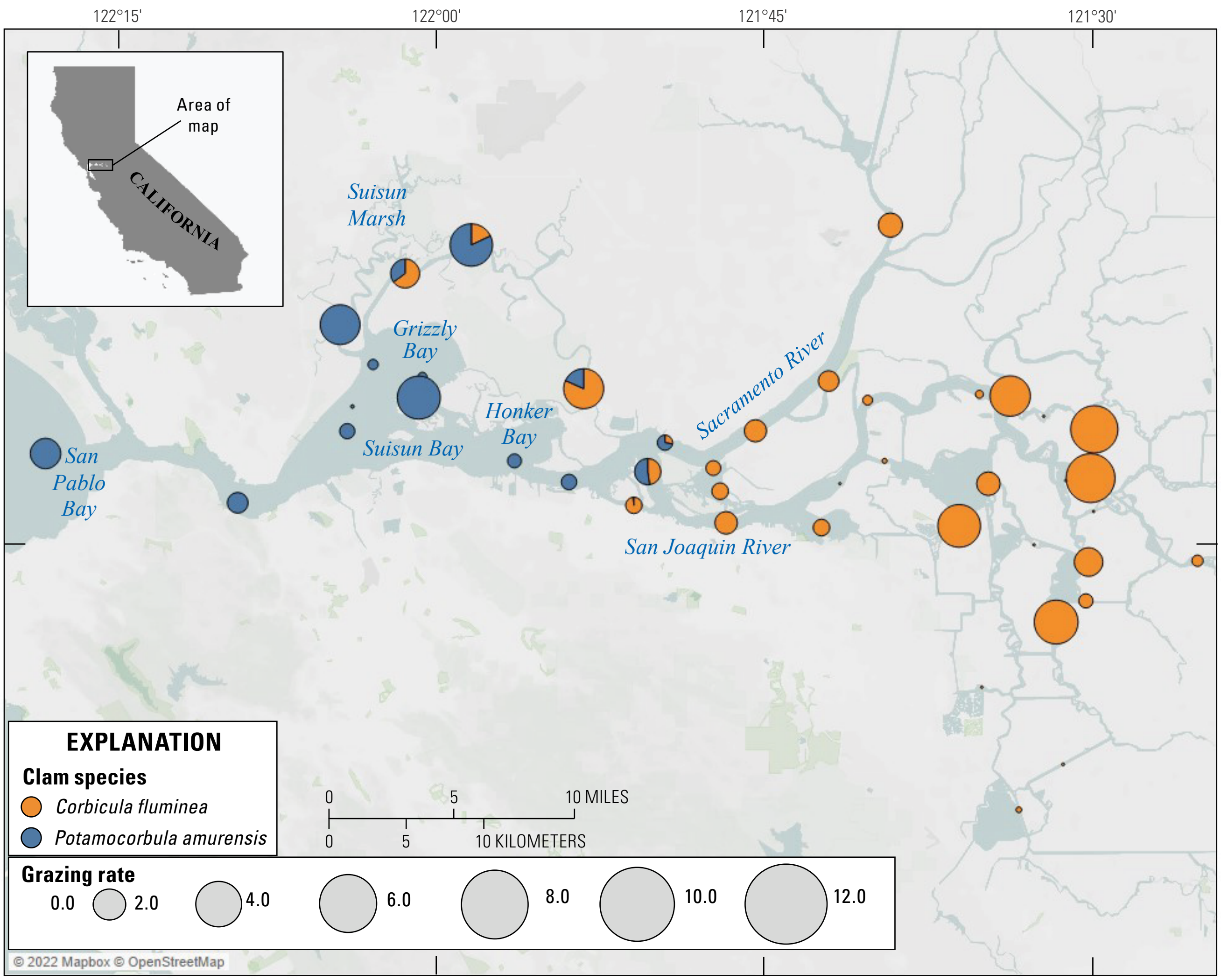

Figure 6. Map of Generalized Random Tessellation Stratified design study stations shown as pie diagrams of grazing rate (volume of water filtered per unit area per day [$m^3/m^2/d$]) for *Potamocorbula amurensis* and *Corbicula fluminea* (hereafter *P. amurensis* and *C. fluminea*, respectively) in May, 2019. Areas where *P. amurensis* (shown in blue) and *C. fluminea* (shown in orange) overlap result in a pie diagram representing both species with the total diameter representing the total grazing rate.

Potamocorbula amurensis Grazing Rate

P. amurensis grazing rate increased from May (0.3 $m^3/m^2/d$) to October (0.6 $m^3/m^2/d$). The number of stations with a grazing rate value ≥ 1 $m^3/m^2/d$ increased from 4 to 10 between May and October. High *P. amurensis* grazing rates were found primarily in deep water stations.

In May, 2 stations in Suisun Marsh and 1 station in Honker Bay had the highest grazing rate values for that date. In October, 2 stations in Honker Bay and 1 station in the San Pablo By had the highest grazing rate values for that date.

Recruitment

Corbicula fluminea Recruitment

Average *C. fluminea* recruitment increased from May (10 recruits/0.05m^2) to October (30 recruits/0.05m^2). The total number of recruits more than doubled from May to October. Recruitment was highest in shallow water stations in May whereas deep water stations were found to have the highest number of recruits in October.

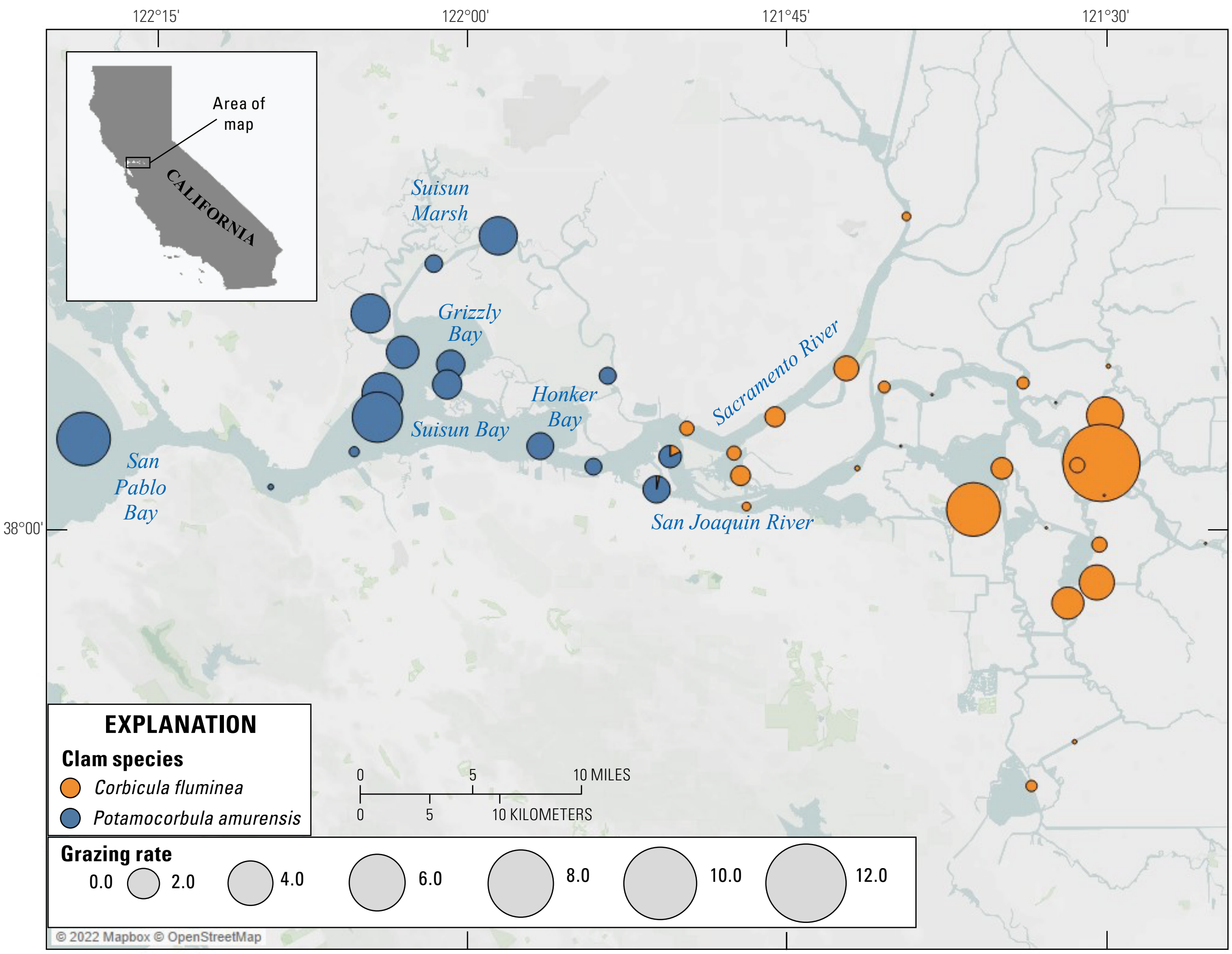

Figure 7. Map of Generalized Random Tessellation Stratified design study stations shown as pie diagrams of grazing rate (volume of water filtered per unit area per day [$m^3/m^2/d$]) for *Potamocorbula amurensis* and *Corbicula fluminea* (hereafter *P. amurensis* and *C. fluminea*, respectively) in October, 2019. Areas where *P. amurensis* (shown in blue) and *C. fluminea* (shown in orange) overlap result in a pie diagram representing both species with the total diameter representing the total grazing rate.

In May, 2 stations in Franks Tract (26, 46) and 1 station in the Sacramento River (station 13) had the highest number of recruits. In October, the 3 stations with the highest number of recruits (from least to greatest) were station 46 in Franks Tract, station 39 in the San Joaquin River, and station 17 in Middle River. Stations (from least to greatest) in river-large, slough, and river waterbody types had the highest number of recruits in May whereas slough, river-large, and river waterbody types had the highest number of recruits in October (figs. 8 and 9 for recruitment values).

Potamocorbula amurensis Recruitment

Potamocorbula amurensis recruitment increased from May (2 recruits/0.05m^2) to October (20 recruits/0.05m^2). Almost all the recruits for May can be attributed to station 48 in San Pablo Bay. In October, the stations with the highest number of recruits were located (from lowest to highest) in Honker Bay (station 4) and Grizzly Bay (stations 43 and 31). The three stations with the highest number of recruits in May were classified as sloughs and large bay. The three stations

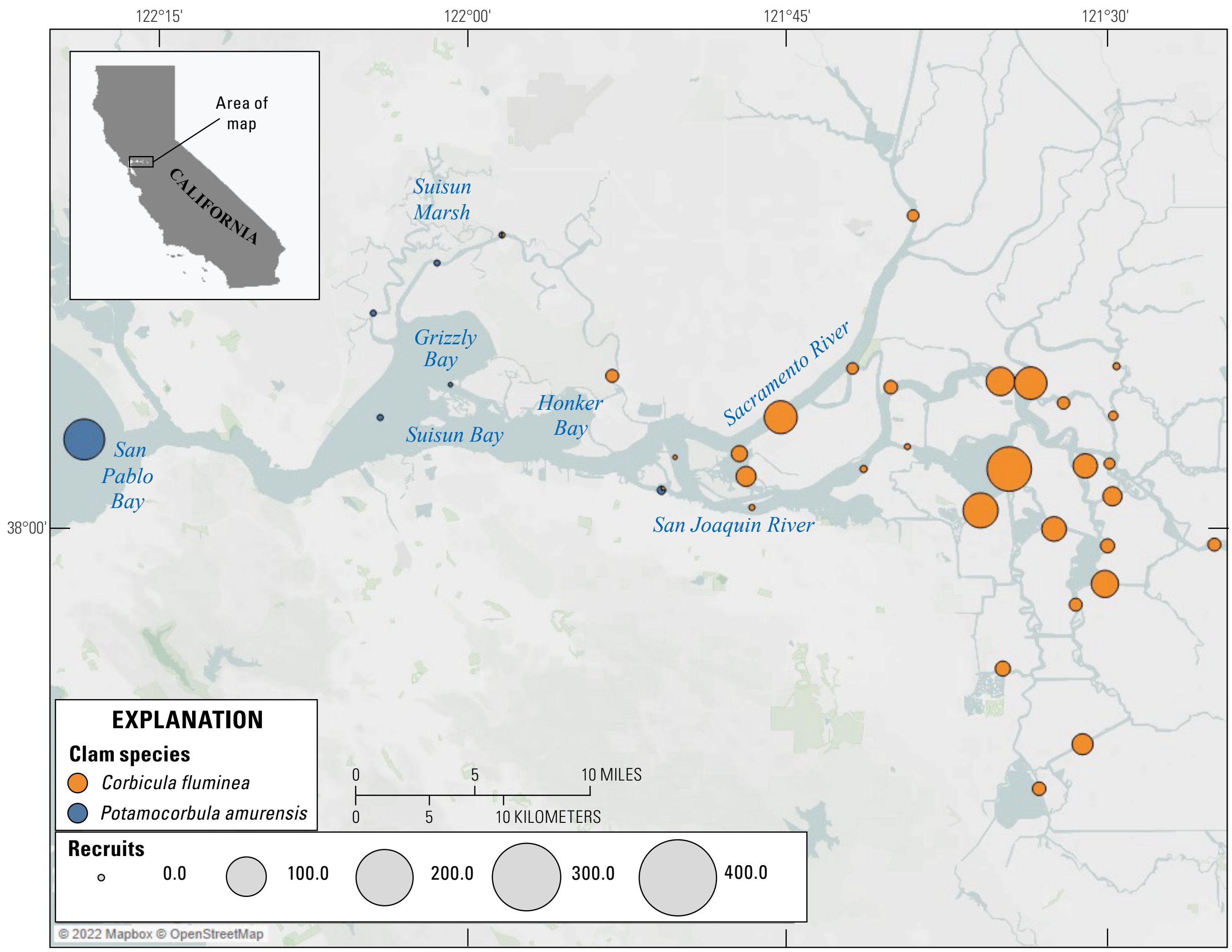

Figure 8. Map of Generalized Random Tessellation Stratified design study stations shown as pie diagrams of recruit (bivalves whose length was equal to or less than 2.5 millimeters) density (number of recruits per 0.05 square meter) for *Potamocorbula amurensis* and *Corbicula fluminea* (hereafter *P. amurensis* and *C. fluminea*, respectively) in May, 2019. Areas where *P. amurensis* (shown in blue) and *C. fluminea* (shown in orange) overlap result in a pie diagram representing both species with the total diameter representing the total recruit density.

with the highest number of recruits in October were all classified as bay (figs 8 and 9 for recruitment values, fig. 2 for waterbody type classification).

Conclusions

Biomass and grazing rate values had similar trends; therefore, the conclusions applied to biomass can also be applied to grazing rate. *Corbicula fluminea* biomass values decreased from May to October, whereas *Potamocorbula amurensis* (hereafter *C. fluminea* and *P. amurensis*, respectively) biomass values increased from May to October. Although average biomass values of *C. fluminea* were lower in October than in May, the highest biomass value measured at a single station was observed in October. For both months, most stations that recorded high *C. fluminea* biomass values were deep water stations (≥ 3 m) and classified as either rivers or sloughs. A relation between depth and biomass was not evident for *P. amurensis*, because shallow stations (≤ 3 m) had low and high biomass values in both May and October. In May, the stations that recorded the highest *P. amurensis* biomass values were sampled in slough or bay settings, whereas stations that recorded the highest *P. amurensis* biomass were sampled in bay or bay-large settings.

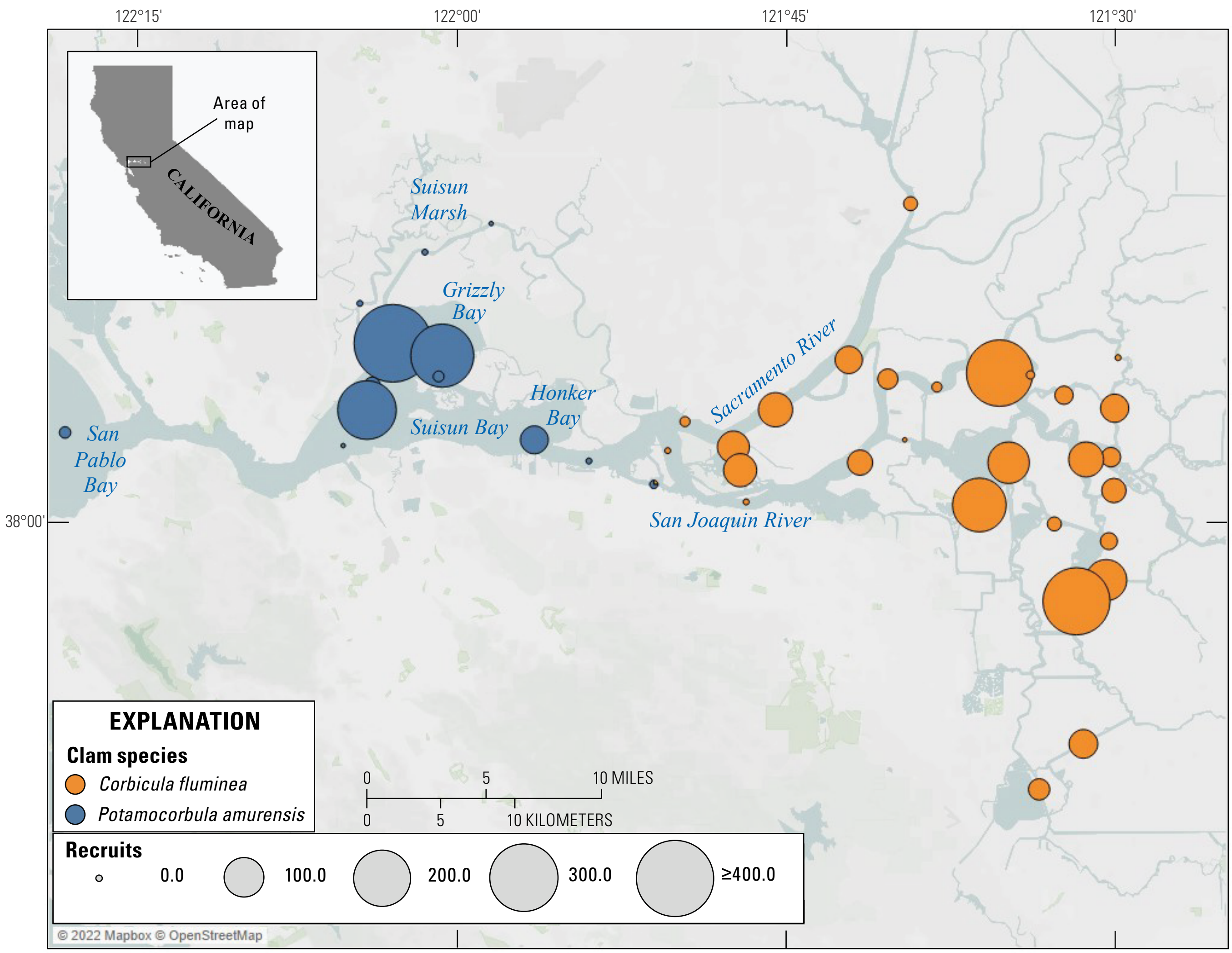

Figure 9. Map of Generalized Random Tessellation Stratified design study stations shown as pie diagrams of recruit (bivalves whose length was equal to or less than 2.5 millimeters) density (number of recruits per 0.05 square meter) for *Potamocorbula amurensis* and *Corbicula fluminea* (hereafter *P. amurensis* and *C. fluminea*, respectively) in October, 2019. Areas where *P. amurensis* (shown in blue) and *C. fluminea* (shown in orange) overlap result in a pie diagram representing both species with the total diameter representing the total recruit density.

Both *C. fluminea* and *P. amurensis* recruitment increased from May to October. The total number of *C. fluminea* recruits more than doubled from May to October. *P. amurensis* total number of recruits collected in October was more than eight times greater than total recruits collected in May. Most of the *P. amurensis* recruits in May can be attributed to one station, A relation between recruitment values for both *C. fluminea* and *P. amurensis* and station depth was not evident. The stations with the greatest number of *C. fluminea* recruits were sampled in the slough, river-large, or river settings. The stations with the greatest number of *P. amurensis* recruits were sampled in the slough, bay-large, or bay settings.

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