California Fish and Game 97(4):164-189; 2011

Spatial perspective for delta smelt: a summary of contemporary survey data

Joseph E. Merz*, Scott Hamilton, Paul S. Bergman, and Bradley Cavallo

Cramer Fish Sciences, 13300 New Airport Road, Auburn, CA 95602, USA (JM, PB, BC)

Center for California Water Resources Policy and Management, 1017 L Street #474, Sacramento, CA 95814, USA (SH)

**Correspondent: jmerz@fishsciences.net*

We utilized recently available data from the 20-mm Tow-Net and Spring Kodiak Trawl, together with other Interagency Ecological Program and regional monitoring programs, to provide a comprehensive description of the range and temporal and geographic distribution of delta smelt (*Hypomesus transpacificus*) by life stage within the San Francisco Estuary, California. Within 21 sampled regions we identified 289,401 survey events at 624 monitoring stations. Delta smelt were observed at 430 stations (69%) in an area from northern San Francisco Bay in the west, to the confluence of the Sacramento and Feather rivers in the north, and to the disjunction of Old and San Joaquin rivers in the south, an area of approximately 51,800 ha. Delta smelt were observed more frequently and at higher densities (at all life stages) near the center of their range, from Suisun Marsh down through Grizzly Bay and east Suisun Bay through the Confluence to the Lower Sacramento region, and into the Cache Slough region. Delta smelt larvae were observed in the San Francisco Estuary from March through July, sub-juveniles in April through August, juveniles in May through December, sub-adults in September through December, and pre-spawning and spawning adults in January through May. This comprehensive review provides managers and scientists an improved depiction of the spatial and temporal extent of the delta smelt throughout its range and lends itself to future analysis of delta smelt population assessment and restoration planning.

Key words: Delta smelt, distribution, *Hypomesus transpacificus,* spatial analysis, life stage, observed presence, Sacramento River delta, San Francisco estuary, San Joaquin River delta

The delta smelt (*Hypomesus transpacificus*) is a small, euryhaline fish endemic to the San Francisco Estuary of California (Estuary). Once the most abundant fish captured in trawl surveys conducted in the Sacramento-San Joaquin Delta (Stevens and Miller 1983, Moyle and Herbold 1989, Stevens et al. 1990) the species suffered a reduction in numbers sufficient to justify threatened listing in 1993 under both the federal and California Endangered Species Acts (ESA). Similar to other Estuary fish species, delta smelt experienced a further decline beginning in 2000 (Sommer et al. 2007) and was listed as endangered under the California ESA in 2009. As a result, the delta smelt has received considerable attention as one of four pelagic fish species experiencing declines in abundance (see Armor et al. 2005, Baxter et al. 2008, Feyrer et al. 2010, Mac Nally et al. 2010, Thompson et al 2010).

Despite the critical condition of the delta smelt population, a geographical summary of its distribution by life stage has not been clearly defined. Conservation planning under federal and state statutes requires spatial resolution (Tracy et al. 2004, Carroll et al. 2006). Distributional summaries of delta smelt were provided in the formal notice conferring its federal protection (USFWS 1993), subsequent designation of critical habitat (USFWS 1994), and completion of conservation planning documents (see USFWS 1996, 2003; California Resources Agency 2005, 2007). However, these sources lack a spatial depiction of where and when delta smelt have been observed. In a California Department of Fish and Game (CDFG) status review (Sweetnam and Stevens 1993), the historical range for the species was described using life history descriptions from existing literature. The United States Fish and Wildlife Service (USFWS 1996) has also provided delta smelt distribution maps using data from the Fall Midwater Trawl, and the CDFG has created interactive maps using individual surveys for some of its monitoring programs (see http://www.dfg.ca.gov/delta). However, to our knowledge, no effort has been made to map the range of delta smelt using all available sampling data or to summarize distribution of delta smelt by life stage.

The distribution of at-risk species is important information for conservation planning. Nearly all ecological data necessary to develop effective resource management agendas have attributes that can be portrayed spatially. Distributional data in the forms of species range maps, breeding surveys, and biodiversity atlases have become tools used commonly in analyses of species-environment relationships (Brundage and Meadows 1982, Flather et al. 1997, Ferrier 2002, Ceballos and Ehrlich 2006, Hulbert and Jetz 2007, Cabeza et al. 2010) and for conservation and management plans for endangered or threatened species, environmental risk assessment, and for calculating responses of at-risk species under future management scenarios (Dormann et al. 2007). Conservation and monitoring programs designed to assess the effectiveness of those actions frequently are site-specific, and are more likely to be successful when spatial elements of planning are well understood (Tracy et al. 2004, Carroll et al. 2006).

Delta smelt are vulnerable to many environmental stressors (USFWS 1993, Moyle 2002, Baxter et al. 2008, Healey et al. 2008), and the significance of a particular stressor may change in relation to its manifestation or proximity to the species (Tong 2001, Armor et al. 2005). Furthermore, delta smelt are migratory (Bennett et al. 2002, Dege and Brown 2004, Hobbs et al. 2007, Sommer et al. 2011), and habitat requirements differ by life stage. An understanding of where delta smelt are distributed throughout their range at each life stage may provide insight about habitat attributes important for each life stage and, therefore, help inform strategies as managers undertake habitat restoration actions.

The purpose of this paper is to present a geographic summary of publicly available data on the distribution of delta smelt by life stage. With initiation of the 20-mm Tow-Net in 1995 and the inception of the Spring Kodiak Trawl in 2002, the CDFG and other agencies that comprise the Interagency Ecological Program (IEP) provide data on the distribution of delta smelt at various life stages. Using data from these surveys and a variety of publicly available sources, we refined knowledge of the spatial extent and distribution of delta smelt in the Estuary. Specifically, we reviewed all available data on observed presence and density of delta smelt from a spatial perspective in an effort to document (1) the observed geographic extent of delta smelt, and (2) the spatial and temporal distributions for identified life stages.

Methods

Study area.—The Estuary is the largest of its kind along the U.S. Pacific Coast (approximately 1,235 km^2, Rosenfield and Baxter 2007; Figure 1). Formed by the confluence of the Sacramento and San Joaquin watersheds with San Francisco Bay, the Estuary drains an area of approximately 163,000 km^2 (40% of California's surface area; van Geen and Luoma 1999, Sommer et al. 2007) that stretches from the upstream limits of the Sacramento River in the north to the mountain tributary streams of the San Joaquin River in the south (Moyle 2002, Sommer et al. 2007). The Estuary is brackish and tidally influenced through its connection to San Francisco Bay, and is an example of an inverted river delta (whereby the narrow end of the delta emerges on the seafront and the wide end is located further inland), one of only a few existing worldwide. The water bodies east of the Sacramento River confluence with the San Joaquin River are commonly referred to as the Sacramento-San Joaquin Delta (Delta). The Delta is the upstream portion of the Estuary where riverine freshwater tidally washes back and forth within leveed channels, roughly between the cities of Sacramento, Stockton, Tracy, and Antioch. The Delta extends about 37 km east to west and 77 km north to south and includes parts of Sacramento, San Joaquin, Contra Costa, Solano, and Yolo counties (Moyle 2002, Lund et al. 2007).

To facilitate the spatial depiction of delta smelt, we grouped monitoring locations into Estuary regions (Table 1; Figure 1) based on preliminary work by Kimmerer (2009) and physical landmarks (e.g., bays, sloughs) (Figure 1). To distinguish areas with large-scale habitat differences (e.g., watershed drainages, confluences), we subdivided (1) the upper Sacramento River into two regions, differentiating the Ship Channel, Yolo Bypass, and Cache Slough from the rest of the upper Sacramento River; (2) San Pablo Bay into western and eastern regions; and, (3) the South Delta into the South Delta and upper San Joaquin River. We also added a Sacramento Valley region (covering upstream from the confluence of the Sacramento and American rivers), two Napa River regions (split between the lower and upper), and a San Francisco Bay region.

IEP monitoring programs.—The CDFG and USFWS, as members of the IEP, have surveyed fish at a number of stations throughout the Estuary for several decades (Table 2, Figure 1). These monitoring programs include the 20-mm Tow-Net (20-mm), Summer Tow-Net (STN), Fall Midwater Trawl (FMWT), Bay Study Midwater Trawl (BMWT), Spring Kodiak Trawl (Kodiak), and Beach Seine (herein collectively referred to as the IEP monitoring programs). Each IEP monitoring program is conducted during a different season and sampling frequency (monthly or bi-weekly), and at a varying number of stations (30-113; Table 2). By employing different gears during different time periods, each monitoring

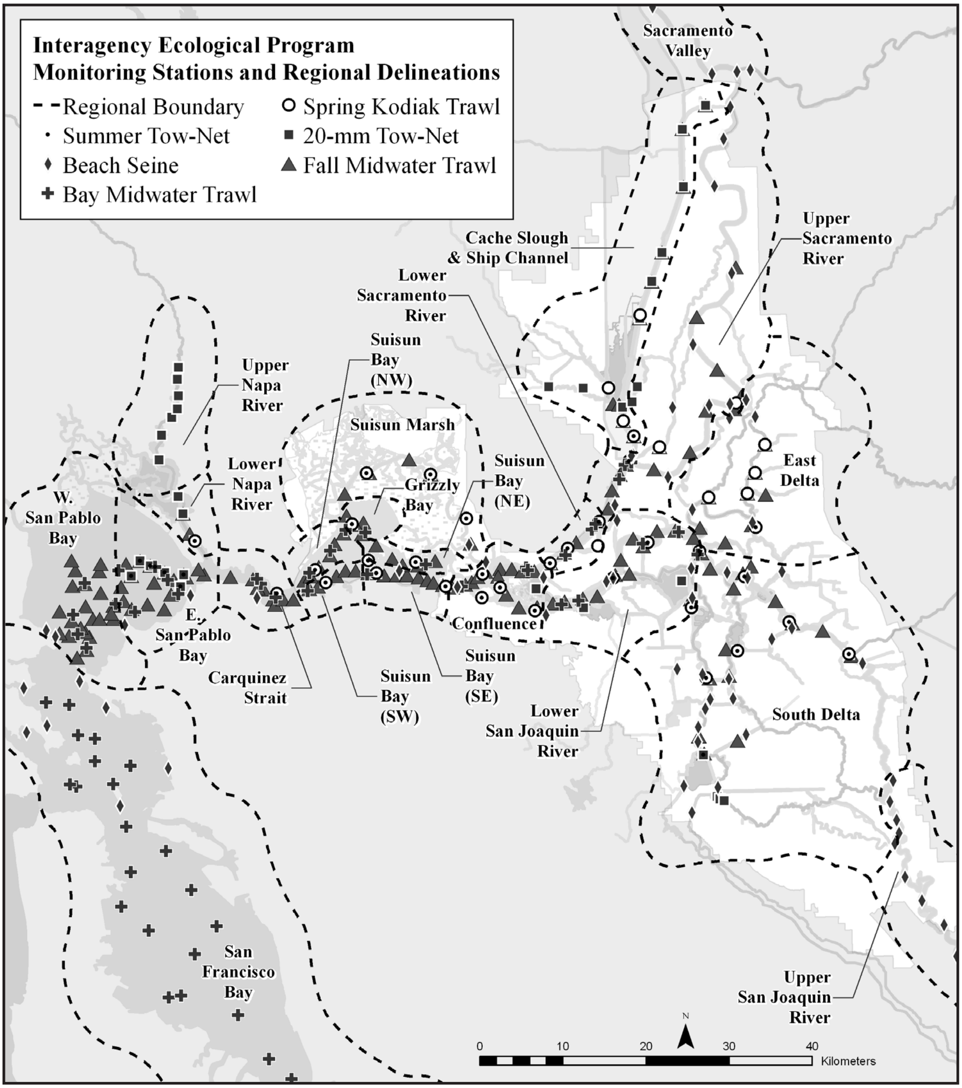

FIGURE 1.—Monitoring stations of Interagency Ecological Program surveys conducted in the San Francisco Estuary by the California Department of Fish and Game (Summer Tow-Net, Fall Mid-Water Trawl, Bay Mid-Water Trawl, Spring Kodiak Trawl, and 20-mm Tow Net) and the United States Fish and Wildlife Service (Beach Seine). Dashed lines indicate regional boundaries. The white area represents the legal Delta as set forth in the Delta Protection Act of 1959.

Table 1.—San Francisco Estuary sampling regions and associated stations by sample method. IEP monitoring programs are described in Table 2 and regional monitoring programs are described in Table 3. NS = not sampled and NI = no regional sampling identified.

	IEP Monitoring Programs						
Region	20-mm Tow-Net	Summer Tow-Net	Fall Midwater Trawl	Spring Kodiak Trawl	Bay Midwater Trawl	Beach Seine	Regional Monitoring
San Francisco Bay	NS	NS	NS	NS	20	7	NI
West San Pablo Bay	NS	NS	12	NS	5	3	NI
East San Pablo Bay	7	7	19	NS	5	2	NI
Lower Napa River	3	1	2	2	NS	NS	NI
Upper Napa River	7	NS	NS	4	NS	NS	NI
Carquinez Straight	1	1	7	1	2	NS	1
Suisun Bay Southwest	1	1	5	1	1	NS	1
Suisun Bay Northwest	1	1	5	1	2	NS	1
Suisun Bay Southeast	2	3	8	2	1	NS	2
Suisun Bay Northeast	2	1	5	2	1	NS	2
Grizzly Bay	1	1	4	1	2	NS	1
Suisun Marsh	3	3	5	5	NS	1	73
Confluence	5	4	10	4	2	1	8
Lower Sacramento River	4	3	4	4	3	NS	4
Upper Sacramento River	1	2	16	4	3	12	3
Cache Slough and Ship Channel	13	NS	3	5	NS	10	43
Lower San Joaquin River	6	4	12	6	5	4	6
East Delta	1	1	8	5	NS	5	29
South Delta	9	6	11	6	NS	18	12
Upper San Joaquin River	NS	NS	NS	NS	NS	16	NI
Sacramento Valley	NS	NS	NS	NS	NS	18	1
Total	67	39	136	53	52	97	187
Percent of Regions Represented	81%	71%	81%	76%	62%	57%	71%

Table 2.—Interagency Ecological Program monitoring programs that sample delta smelt: years and months surveyed, number of survey stations, and size of delta smelt captured for each monitoring program.

Monitoring Program (Agency)	Years	Sampling Period (Frequency)	No. of Stations	Captured Delta Smelt Lengths (mm)
Fall Midwater Trawl (CDFG)	1967-present	Sep-Dec[a] (Monthly)	53-113	> 30
Summer Tow-Net (CDFG)	1959-present[b]	Jun-Aug (Bi-Weekly)	~30	15 - 65
20-mm Tow-Net (CDFG)	1995-present	Mar-July (Bi-weekly)	41-49	5 - 60
Spring Kodiak Trawl (CDFG)	2002-present	Jan-May (~Bi-weekly)	30-40	> 50
Bay Midwater Trawl (CDFG)	1980-present[c]	All Year (Monthly)	52	> 30
Beach Seine (USFWS)	1977-present	All Year[d] (~Bi-weekly)	~40	> 30

[a]Survey continued through March during 1991-2001.
[b]Delta smelt were not measured or consistently enumerated until 1973.
[c]Delta stations added in 1991 and 1994.
[d]Since 1994. Before 1994 only January-March were consistently sampled each year.

program is selective for different sizes of delta smelt, and therefore different life stages (Table 2). The methods for the IEP monitoring programs have been described previously (Moyle et al. 1992, USFWS 2003, Bennett 2005), as have the merits of several resulting abundance indices (Bennett 2005).

Regional monitoring programs.—In addition to the IEP monitoring programs, numerous other monitoring programs are carried out by various governmental and non-governmental entities, and for a variety of purposes (Table 3). These programs utilize an assortment of gears including seining, electrofishing, and tow-nets. Some of these programs have been carried out for a decade or more. Collectively, they are referred to as regional monitoring programs throughout the remainder of this paper.

Table 3.—Regional monitoring programs sampling delta smelt: survey location, survey gear, project, study period, and data source.

Location	Survey Gear Used	Project	Study Period	Source
Cosumnes River	seine, electrofishing	Floodplain Monitoring	1998-2005	Moyle et al. 2007
Cosumnes River	light trap	Floodplain Monitoring	1999-2001	Crain et al. 2004
Cosumnes River	seine	Stream Evaluation	1990s-2000s	R. Titus[a]
Lower American River	rotary screw trap	Stream Flow and Habitat Evaluation Program	1990s-2000s	R. Titus[a] Snider and Titus 2000 Snider et al. 1998
Yolo Bypass	rotary screw trap, fyke net/trap, beach seine, purse seine	Yolo Bypass Study	1998-2005	CDWR[b]
Yolo Bypass	rotary screw trap, and egg and larval nets	Yolo Bypass Floodplain	1999-2002	Sommer et al. 2004
Sacramento Deep Water Shipping Channel	tow nets and trawl	20 mm, STN, FMWT	2009	Samii-Adib 2010
Suisun Marsh	beach seine, larval sled, midwater trawl, otter trawl	Suisun Marsh Fisheries Monitoring	1979-2005	UCD[c]
Lower Mokelumne River	seining, backpack electrofishing surveys, boat electrofishing surveys	East Fish Community Survey	1997-2004	Merz and Saldate 2005
Lower Mokelumne River	rotary screw trap	Mokelumne River Salmon and Steelhead Monitoring	1990-2009	EBMUD[d]
Lower Calaveras River	beach seine	Calaveras River Barrier Removal program	2010	T. Kennedy[e]
West Delta	beach seine	West Delta Survey	2005-2006	T. Kennedy[e]
North Delta	plankton net	North Bay Aqueduct Survey	1994-2004	CDFG
Upper San Francisco Estuary	plankton net	Smelt Larval Survey	2009 -2010	CDFG
South Delta	louvers	Central Valley Project	1955-present	CDFG
South Delta	louvers	State Water Project	1972-present	CDFG
Chipps Island	boat trawling	Chipps Island Midwater Trawl	1976-2008	USFWS
South-east Suisun Bay, Confluence of Sacramento & San Joaquin Rivers	sieve net	Mirant Power Plants	2006	IEP
South Delta	sieve net	Contra Costa Water District Intake Facility	1995-present	CDFG

[a]CDFG, personal communication
[b]California Department of Water Resources
[c]University of California, Davis
[d]East Bay Municipal District
[e]Fishery Foundation of California, personal communication

Observed geographic extent.—To identify the geographic extent of delta smelt, we utilized records taken from IEP and regional monitoring programs. We present all years of available data for each monitoring program (Tables 2 and 3). If delta smelt were detected at least once at any given monitoring location, they were designated as present at that site; otherwise they were designated as not observed. Because the detection probability for each type of survey gear is not available and each monitoring program is conducted at different sampling frequencies and levels of effort, we did not consider delta smelt to be absent from locations where the species was not observed (Pearce and Boyce 2006). Since our objective was to identify the range of delta smelt presence, and not to examine where delta smelt are absent, we did not further assess the likelihood of falsely identifying delta smelt as being absent at a given location.

We developed a boundary for the observed geographic extent of delta smelt by using a 1-km buffer around sites where delta smelt were observed, including all open water between points within the boundary (Graham and Hijmans 2006 for discussion of buffer size). We then calculated the surface area of all waters within the boundary.

We also examined the geographic distribution of sampling stations and sampling effort among the IEP and regional monitoring programs. We enumerated how many stations were sampled by each of the IEP monitoring programs and all the regional monitoring programs combined within each of the 21 identified regions, and calculated the percentage of regions sampled by each monitoring program.

Distribution by life stage.**—**Extending from the life history discussions of Moyle (2002) and Bennett (2005), we differentiated five separate delta smelt life stages: larvae,

TABLE 4.—Delineation of delta smelt life stages by the Interagency Ecological Program, fish size or reproductive stage, time periods, and years of available samples. 20-mm = 20-mm Tow-Net, STN = Summer Tow-Net,

Life Stage	Monitoring Program	Life Stage Distinction	Time Period	Years of Data Used
Larvae	20-mm	<15 mm	Apr-Jun	1995-2009
Sub-juveniles	20-mm, STN	≥15,<30 mm	20-mm: Apr-Jul STN: Jun-Aug	1995-2009
Juveniles	20-mm, STN, FMWT	30-55 mm	20-mm: May-Jul STN: Jun-Aug FMWT: Sep-Dec	1995-2009
Sub-adults	FMWT	>55 mm	Sep-Dec	1995-2009
Mature Adults	Beach Seine, BMWT	>55 mm	Beach Seine: Dec-May BMWT: Jan-May	Beach Seine: 1995-2009 BMWT: 1995-2006
Mature Adults: Pre-spawning	Kodiak	Reproductive stages[a]: females 1-3; males 1-4	Jan-Apr	2002-2009
Mature Adults: Spawning	Kodiak	Reproductive stages[a]: females 4; males 5	Jan-May	2002-2009

[a]Gonadal stages of male and female delta smelt found in Spring Kodiak Trawl database were classified by California Department of Fish and Game following Mager (1986). Descriptions of these reproductive stages are available at: http://www.dfg.ca.gov/delta/data/skt/eggstages.asp

sub-juveniles, juveniles, sub-adults, and mature adults (Table 4). We chose a 15-mm total length as the cut-off between larvae and sub-juveniles because when delta smelt reach 16-18 mm their fins are more developed and their swim bladder is filled with gas, making them more mobile within the water column (Moyle 2002). We used 30 mm as the cut-off between sub-juveniles and juveniles because this size is associated with a change in feeding regime (Moyle 2002). We chose 55 mm as the cut-off between juveniles and sub-adult and mature adults because growth slows between 55 and 70 mm (with most of the available energy diverted to gonadal development [Radtke 1966, Erkkila et al. 1950]). Because maturation rate of captured delta smelt was reported for the Spring Kodiak Trawl, we used reproductive stage to further subdivide mature adults into pre-spawners and spawners. Reproductive stages 1 to 3 for females, and 1 to 4 for males, were classified as pre-spawning. Reproductive stages 4 in females, and 5 in males, were classified as spawning (J. Adib-Samii, CDFG, personal communication; additional information is available at: http://www.dfg.ca.gov/delta/data/skt/eggstages.asp).

We used data from the IEP monitoring programs to elicit information on the temporal and spatial distribution of life stages. For each life stage, we delineated a period of several months when delta smelt of that life stage often were observed. We excluded months when delta smelt were caught in very low numbers (<3% of the total for that life stage) because those data would have biased frequency of observation and observed density results downward. Where possible, we used data from multiple monitoring programs that sampled the same life stage at different months during the year (Table 4).

Although data are available for juveniles and adults back to 1967 (FMWT), we present only results from 1995 onward to compare life stage distributions during similar time periods; 20-mm Tow-Net surveys were first conducted in 1995, and provided data for larvae, sub-juveniles, and juveniles. Data from two monitoring programs were not available for the full period from 1995 to 2009: the Kodiak (2002-2009), and the BMWT (1995-2006), which after 2006 was adjusted to avoid high levels of delta smelt take (R. Baxter, CDFG, personal communication). We excluded supplemental samplings because such surveys were conducted for special purposes and were not always consistent with the protocol for the program (R. Baxter, CDFG, personal communication). To avoid introducing anomalies caused by the addition of new stations, we included only sampling stations that were sampled consistently (i.e., stations that were sampled ≥ 90% of the years).

We calculated the average annual frequency of delta smelt observation at consistently surveyed stations for each life stage in each region for all years as

$$P_{lrpy} = (S_{lrpy} / N_{rpy})(100) \quad (1)$$

where: P_{lrpy} is the percent of sampling events (i.e., a sample at a station) when delta smelt of life stage l were caught in region r during time period p and year y, S_{lrpy} is the number of sampling events in region r when delta smelt of life stage l were caught during time period p and year y, and N_{rpy} is the total number of sampling events in region r during time period p and year y. Next, the average annual frequency of delta smelt observation for each life stage and region was calculated as a simple average over all years.

We calculated the yearly observed density (Density; i.e. relative measure of abundance) of delta smelt for each life stage and region for all years by dividing the summed catches C of delta smelt for each life stage l, region r, time period p, and year y by the volume of water in cubic meters V that was sampled for each region and year, then multiplying by

10,000 to determine the catch per 10,000 m^3 of water for each life stage, region, and year as

$$Density_{lry} = (\Sigma C_{lry} / \Sigma V_{ry})\,(10000) \qquad (2)$$

Next, the average annual observed density for each life stage and region was calculated as a simple average over all years. To standardize these data, the average observed density for each life stage and region was then divided by the highest average annual observed density for that life stage and multiplied by 100.

While recognizing that the gear employed to sample Estuary fishes varies in catch efficiency, and that catch efficiency varies both between monitoring programs and within samples of each monitoring program depending on a variety of factors including the size of individual fish, we did not attempt to adjust the results reported here for catch efficiency. As a result, we did not attempt to draw conclusions regarding differences in densities between monitoring programs, or between life stages within a given monitoring program.

Our treatment of catch data was limited to frequency of observation and average observed density, rather than population estimates. The latter would have required estimates of the volume of the body of water and reliance on the assumption that samples are representative of the density of smelt in the targeted water body. The validity of such an assumption may be questionable in a variety of circumstances, particularly when using Beach Seine data since the demarcation between "beach habitat" and "open-water habitat" is difficult to specify.

To describe the temporal extent of the presence of each life stage across all years, we calculated the frequency of observation and observed density by month for each life stage. In so doing, we built upon the conceptual and analytical work of Bennett (2005), who provided a model of delta smelt life history that included the approximate months during which each life stage exists. The percentage of delta smelt caught in any individual month was calculated as the total number of smelt of that life stage caught in that month since 1995, divided by the total number of smelt of that life stage caught since 1995. Because we did not attempt to compare catch between monitoring programs, we reported this result separately for each monitoring program. We also reported the frequency with which each life stage was observed in each month in each monitoring program.

Results

Within the 21 identified regions of the San Francisco Estuary, we identified 289,401 survey events (a sampling event at a given location and time) at 624 monitoring stations. Of these, 444 (71%) were from IEP and 180 (29%) were from regional monitoring programs. The program with the single greatest number of monitoring stations was FMWT (136), followed by the Beach Seine (97), 20-mm (67), Kodiak (53), BMWT (52), and STN (39) (Table 1). Delta smelt were observed at 347 of the 444 (78%) IEP monitoring stations and at 83 of the 180 (46%) regional monitoring stations identified in this study.

Observed geographic extent.—Delta smelt were observed in all of the 21 regions covering an area of about 51,800 ha (Figure 2). Observations occurred as far west as Berkeley in San Francisco Bay, north on the Sacramento River to its confluence with the Feather River, and the San Joaquin River south of Stockton. Tributary observations included the Napa River, Cache Slough, the American River to the north, and the Mokelumne and

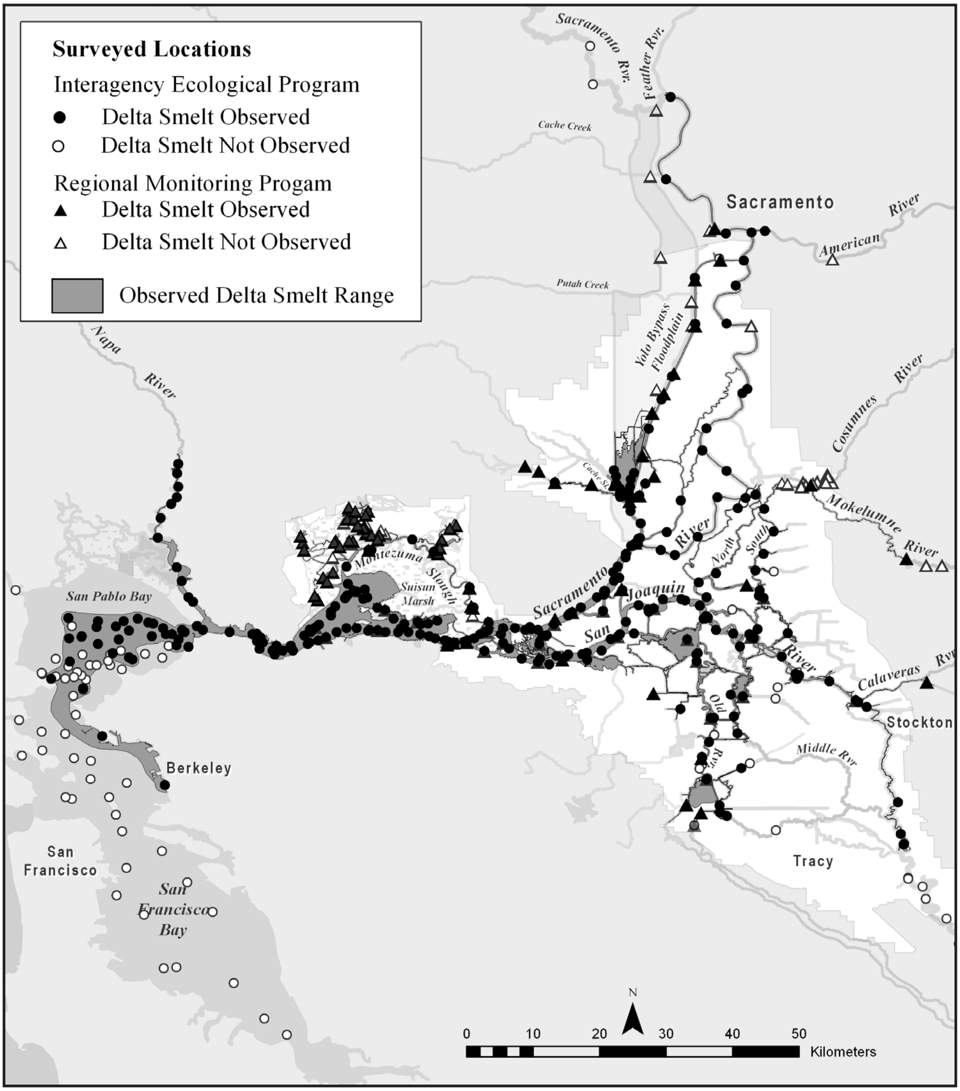

FIGURE 2.—Observations of delta smelt at monitoring stations of Interagency Ecological Program and Regional surveys. Circles indicate Interagency Ecological Program stations where delta smelt were observed (closed) or not observed (open). Triangles indicate Regional survey stations where delta smelt were observed (closed) or not observed (open). The outlined area represents the observed delta smelt range.

Calaveras rivers to the east. Delta smelt were also observed in seasonally-inundated habitat of the Yolo Bypass and the Cosumnes River at its confluence with the Mokelumne River.

No single IEP monitoring program sampled all of the 21 regions (Table 1) that make up the observed extent of range (Figures 3 to 5). The 20-mm and the FMWT had the highest coverage (80% of regions each). The STN covered 71% of the regions, while coverage among the other IEP surveys ranged from 57 to 76%.

Distribution by life stage.—Delta smelt larvae were observed in the Estuary from March through July, sub-juveniles during April through August, juveniles during May

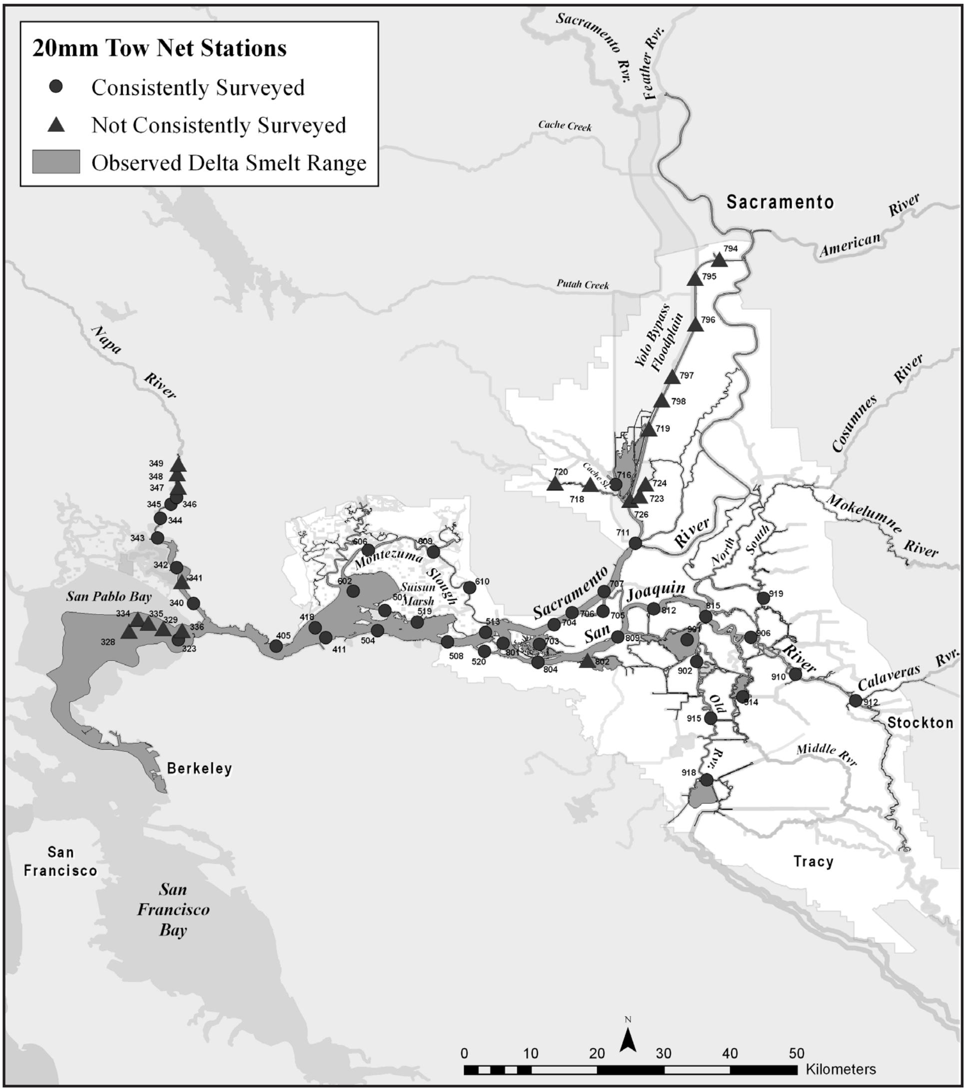

Figure 3.—Location of 20-mm Tow-Net survey stations in relation to the observed delta smelt range (outlined area). Circles represent stations consistently surveyed across all years (1995-2009). Triangles represent stations not consistently surveyed.

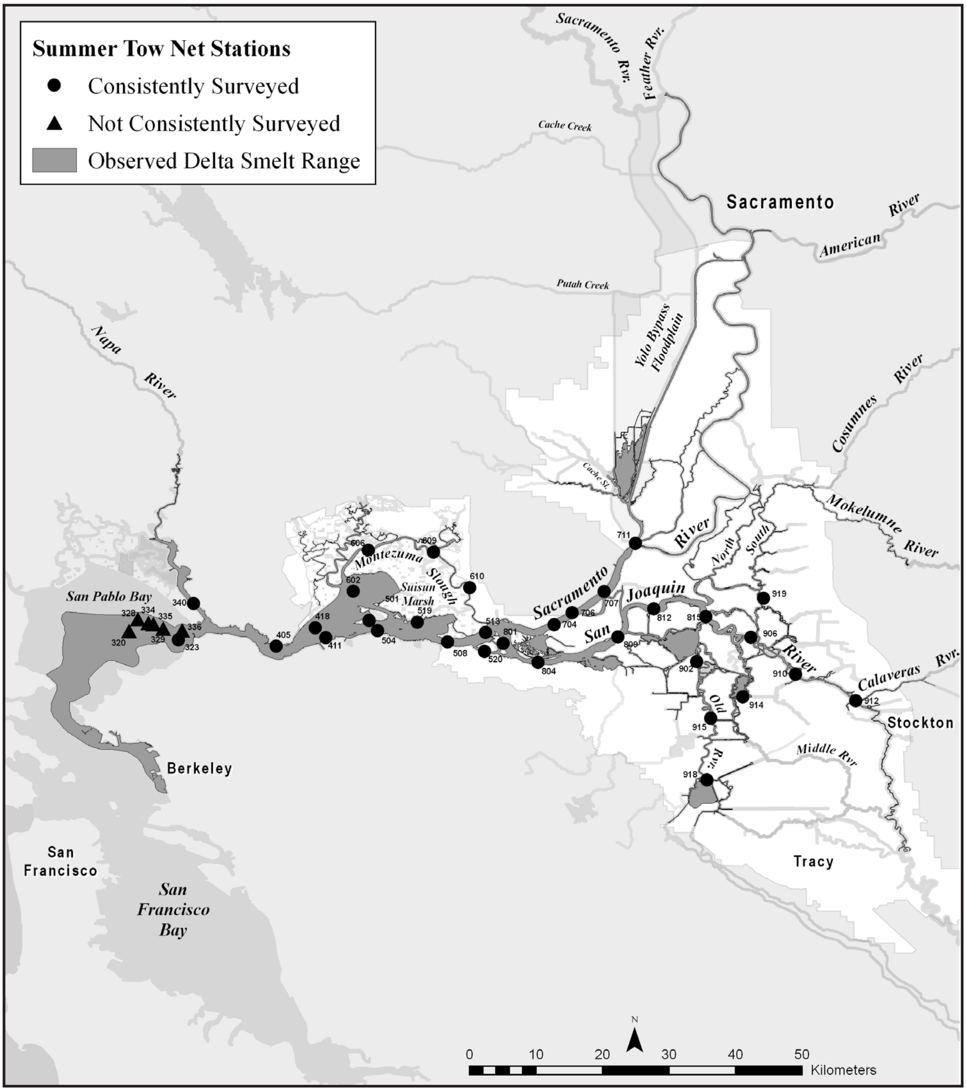

FIGURE 4.—Location of Summer Tow Net survey stations in relation to the observed delta smelt range (outlined area). Circles represent stations consistently surveyed across all years (1995-2009). Triangles represent stations not consistently surveyed.

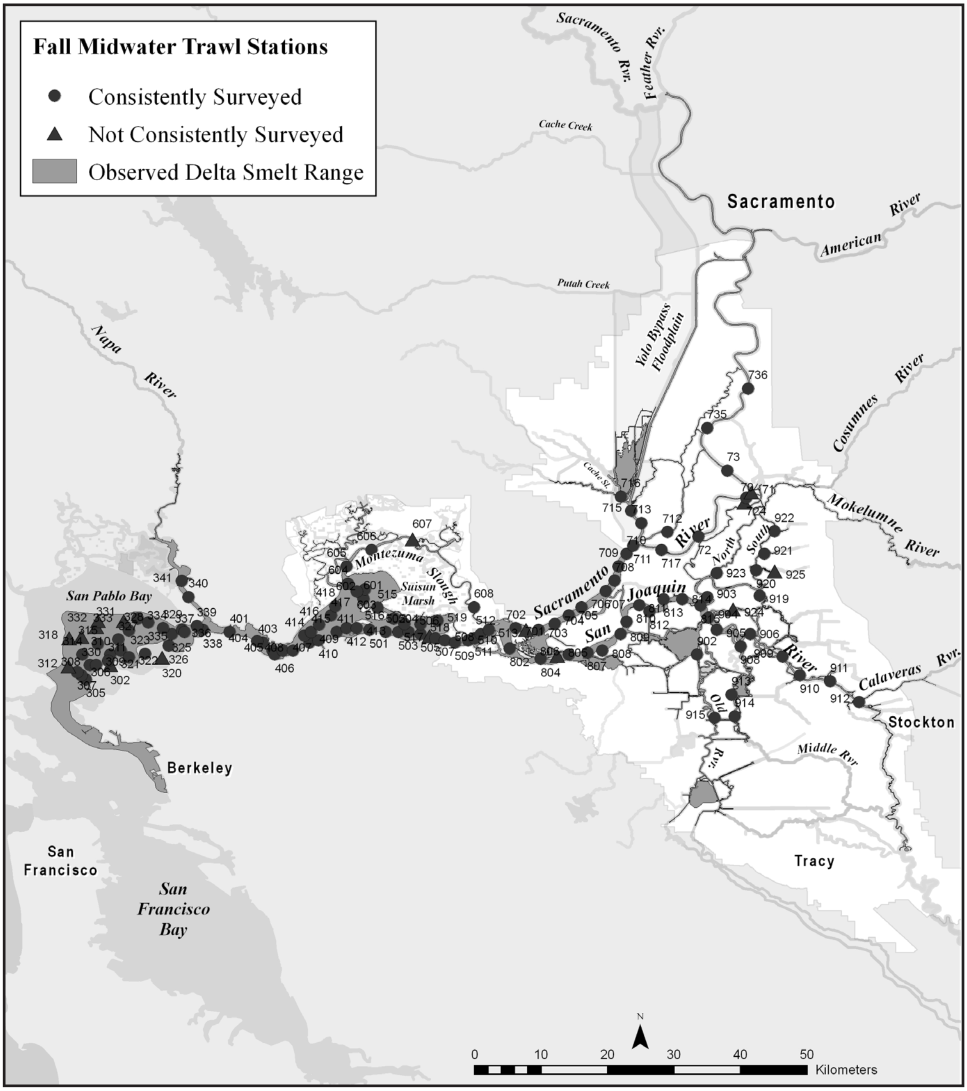

FIGURE 5.—Location of Fall Mid-Water Trawl survey stations in relation to the observed delta smelt range (outlined area). Circles represent stations consistently surveyed across all years (1995-2009). Triangles represent stations not consistently surveyed.

through December, sub-adults during September through December, and pre-spawning and spawning adults during January through May (Tables 5 and 6). For most life stages, delta smelt were observed most frequently near the center of their range — from Suisun Marsh down through Grizzly Bay and east Suisun Bay through the Confluence to the Lower

Table 5.—Percent of years delta smelt were observed in each month in at least one location in the Estuary by life stage and monitoring program (1995-2009). 20-mm = 20-mm Tow-Net, STN = Summer Tow-Net, FMWT = Fall Midwater Trawl, BS = Beach Seine, BMWT = Bay Midwater Trawl, and SKT = Spring Kodiak Trawl.

Life Stage	Monitoring Program	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Larvae	20-mm			64%	100%	100%	100%	43%	0%				
Sub-juvenile	20-mm			0%	93%	100%	100%	93%	50%				
Sub-juvenile	STN						100%	93%	58%				
Juvenile	20-mm			0%	7%	93%	100%	93%	50%				
Juvenile	STN						100%	100%	100%				
Juvenile	FMWT									87%	80%	73%	53%
Sub-adults	FMWT									100%	93%	93%	100%
Mature Adults	BS	69%	81%	94%	94%	93%						38%	56%
Mature Adults	BMWT	89%	80%	89%	92%	75%	58%	75%	100%	75%	8%	0%	18%
Pre-spawning	SKT	100%	100%	100%	100%	100%							
Spawning	SKT	43%	75%	100%	100%	50%							

Table 6.—Percent of total delta smelt catch occurring in each month by lifestage and monitoring program (1995-2009). 20-mm = 20-mm Tow-Net, STN = Summer Tow-Net, FMWT = Fall Midwater Trawl, BS = Beach Seine, BMWT = Bay Midwater Trawl, and SKT = Spring Kodiak Trawl.

Life Stage	Monitoring Program	Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Larvae	20-mm	1995-2009			2%	59%	29%	9%	1%					
Sub-juvenile	20-mm	1995-2009			0.0%	5%	43%	43%	9%	0.3%				
Sub-juvenile	STN	1995-2009						34%	56%	11%				
Juvenile	20-mm	1995-2009			0.0%	0.0%	5%	55%	38%	3%				
Juvenile	STN	1995-2009						18%	56%	26%				
Juvenile	FMWT	1995-2009									40%	37%	14%	9%
Sub-adults	FMWT	1995-2009									16%	34%	28%	22%
Mature Adults	BS	1995-2009	9%	10%	31%	21%	17%						2%	10%
Mature Adults	BMWT	1995-2006	20%	12%	17%	23%	7%	3%	9%	5%	3%	0.2%	0.0%	
Pre-spawning	SKT	2002-2009	45%	34%	16%	4%	1%							
Spawning	SKT	2002-2009	4%	23%	53%	17%	4%							

Sacramento River region, but also in the region of Cache Slough (Figure 6). Regions where delta smelt were observed most frequently (regions in the upper quartile of each column in Table 7) for any life stage were northeast Suisun Bay, Grizzly Bay, Suisun Marsh, Confluence, Lower Sacramento River, Upper Sacramento River, Cache Slough and Ship Channel, and

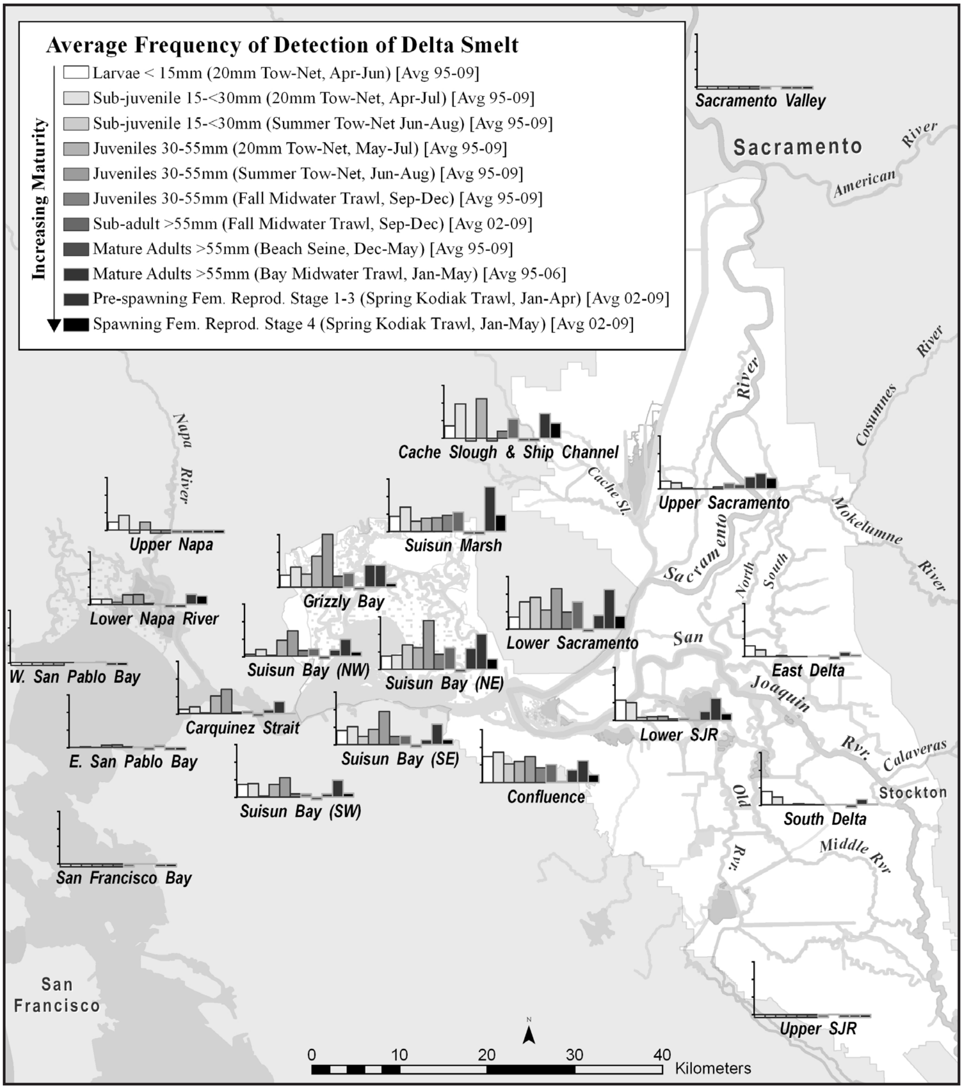

FIGURE 6.—Average annual frequency of delta smelt observation (percentage of sampling events where delta smelt were observed) by life stage and Region for Interagency Ecological Program surveys. Regions where the average frequency of detection for a given life stage was zero are indicated by no data column being present. Regions that were not sampled for a given life stage are indicated by a data column suspended slightly below the x-axis. Y-axis ticks indicate frequencies of 0, 25, 50, 75, and 100 percent.

Table 7.—Average annual frequency of delta smelt occurrence by life stage, IEP monitoring program, and region. 20-mm = 20-mm Tow-Net, STN = Summer Tow-Net, FMWT = Fall Midwater Trawl, BS = Beach Seine, BMWT = Bay Midwater Trawl, and SKT = Spring Kodiak Trawl. NS indicates no survey conducted in the given life-stage and region.

	Life-stage										
	Larvae	Sub-juvenile		Juvenile			Sub-adult	Mature Adults		Pre-spawning	Spawning
Monitoring Program	20-mm	20-mm	STN	20-mm	STN	FMWT	FMWT	Beach Seine	BMWT	Kodiak Trawl	Kodiak Trawl
Years of data used	95-09	95-09	95-09	95-09	95-09	95-09	95-09	95-09	95-06	02-09	02-09
Time period	Apr-Jun	Apr-Jul	Jun-Aug	May-Jul	Jun-Aug	Sep-Dec	Sep-Dec	Dec-May	Jan-May	Jan-Apr	Jan-May
San Francisco Bay	NS	NS	NS	NS	NS	NS	NS	0.0%	0.0%	NS	NS
West San Pablo Bay	NS	NS	NS	NS	NS	0.2%	0.0%	0.0%	1.2%	NS	NS
East San Pablo Bay	0.0%	1.0%	0.0%	2.8%	3.6%	0.7%	0.6%	NS	2.7%	NS	NS
Lower Napa River	7.3%	7.7%	3.3%	13.3%	14.0%	1.7%	0.8%	NS	NS	14.3%	11.8%
Upper Napa River	11.6%	21.2%	NS	12.0%	NS	NS	NS	NS	NS	NS	NS
Carquinez Strait	5.7%	9.3%	1.1%	24.4%	33.7%	1.9%	3.3%	NS	5.4%	16.7%	0.0%
Suisun Bay (SW)	17.8%	18.3%	1.3%	17.5%	26.9%	4.3%	4.3%	NS	4.3%	23.3%	5.6%
Suisun Bay (NW)	2.2%	8.9%	1.1%	21.7%	34.8%	7.3%	10.0%	NS	8.7%	23.3%	5.6%
Suisun Bay (SE)	19.5%	24.9%	11.0%	20.9%	45.7%	11.0%	12.1%	NS	6.5%	28.3%	6.9%
Suisun Bay (NE)	17.8%	19.2%	33.6%	29.7%	66.7%	20.3%	29.3%	NS	28.3%	48.3%	13.9%
Grizzly Bay	16.3%	27.6%	17.9%	42.9%	72.8%	15.0%	19.6%	NS	30.4%	30.0%	5.6%
Suisun Marsh	21.4%	33.6%	14.2%	18.5%	19.2%	22.8%	27.2%	NS	NS	62.0%	23.1%
Confluence	35.7%	41.6%	25.7%	29.2%	36.1%	20.2%	24.5%	1.8%	17.4%	30.0%	10.4%
Lower Sacramento River	16.5%	37.0%	43.3%	26.2%	55.5%	22.9%	37.1%	NS	18.8%	54.4%	17.8%
Upper Sacramento River	10.8%	8.2%	1.3%	0.0%	0.0%	2.7%	8.0%	5.8%	16.7%	21.7%	15.3%
Cache Slough & Ship Channel	17.2%	47.3%	NS	54.3%	NS	9.8%	26.7%	NS	NS	33.9%	21.1%
Lower San Joaquin River	28.0%	24.5%	4.1%	5.1%	5.6%	2.6%	3.5%	0.9%	12.6%	30.6%	9.7%
East Delta	14.6%	8.8%	0.0%	1.2%	0.0%	0.0%	0.0%	1.6%	NS	5.7%	2.3%
South Delta	18.4%	10.8%	0.0%	1.4%	0.3%	0.0%	0.0%	0.3%	NS	7.1%	1.1%
Upper San Joaquin River	NS	NS	NS	NS	NS	NS	NS	0.2%	NS	NS	NS
Sacramento Valley	NS	NS	NS	NS	NS	NS	NS	0.2%	NS	NS	NS

Lower San Joaquin River. Westward of Suisun Bay, the frequency of observation tended to decrease as the distance from Suisun Bay increased. San Pablo Bay typically had the lowest observed frequencies west of Suisun Bay. The East and South Delta regions generally had low observed frequencies relative to other regions for the same life stage. The exception was for larval delta smelt where these regions (with observed frequencies of 15% and 18%, respectively) were close to the median observed frequency of 16%.

Delta smelt were observed at higher densities near the center of their range — the same area where they were observed most frequently: from Suisun Marsh down through Grizzly Bay and east Suisun Bay through the Confluence to the Lower Sacramento River region, but also in the Cache Slough region (Figure 7). The regions where delta smelt were

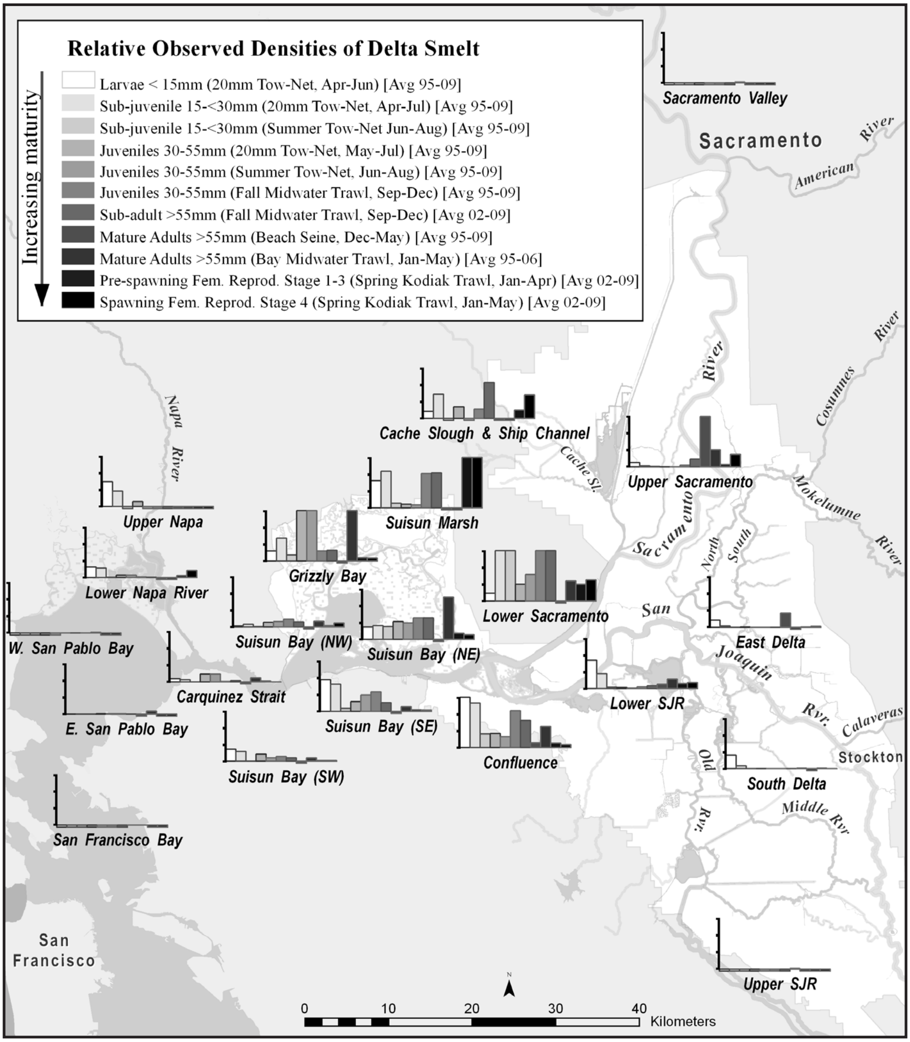

FIGURE 7.—Relative observed densities (average density for each life stage and region divided by highest average annual density observed for that life stage multiplied by 100) of delta smelt by life stage and region for Estuary-wide surveys. Regions where the relative observed density for a given life stage was zero are indicated by no data column being present. Regions that were not sampled for a given life stage are indicated by a data column suspended slightly below the x-axis. Y-axis ticks indicate 0, 25, 50, 75, and 100 percent of highest observed density.

observed in the greatest densities were the Confluence for larvae in the 20-mm; Lower Sacramento River for sub-juveniles in both the 20-mm and STN; Grizzly Bay for juveniles in the 20-mm and STN, but Lower Sacramento River for juveniles later in the year in the FMWT; Lower Sacramento River for sub-adults in the FMWT; Upper Sacramento River for mature adults in the Beach Seine; Grizzly Bay for mature adults in the BMWT; and Suisun Marsh for both pre-spawning and spawning adults in the Kodiak (Table 8). Regions with the highest average observed densities (regions in the upper quartile of each column in Table 8) for any life stage were northeast Suisun Bay, Grizzly Bay, Suisun Marsh, Confluence, Lower Sacramento River, and Upper Sacramento River. Delta smelt observed densities (for all but the earliest life stages) were low in the western Suisun Bay and regions further to the west, and in the east and south Delta, relative to other areas.

Discussion

Observed geographic extent.—Extent of habitat is a critical piece of information for assessing the conservation status of a species (e.g., Millsap et al. 1990, IUCN 1994, Lunney et al. 1996, Burgman and Fox 2003). The historical range of delta smelt was provided by Sweetnam and Stevens (1993) who described the species as existing as far upstream in the Sacramento River as the Feather River mouth (citing Wang 1991) and Mossdale on the San Joaquin River (citing Moyle et al. 1992), and downstream to western Suisun Bay.

We utilized recently available data from the 20-mm (since 1995) and Kodiak (since 2002), together with other IEP and regional monitoring programs (since 1995) to provide information on areas of the Estuary where identified delta smelt life stages have been observed. Though our study included additional portions of San Pablo Bay not detailed by Sweetnam and Stevens (1993), we identified essentially the same distribution of delta smelt on the Napa River, Cache Slough, Suisun Marsh tributaries, and San Joaquin River inferred by the earlier study.

Observations at the most upstream sampling stations in the Napa River, Cache Slough, and Sacramento and Calaveras rivers indicate that the extent of delta smelt distribution in these locations remains unknown. Recently, Cache Slough and its tributaries have been identified as key habitat for delta smelt across all life stages (DSC 2010). However, available survey data suggest the full distributional range of delta smelt in the Cache Slough drainage has not been identified by current sampling efforts. These observations suggest sampling locations beyond those covered by current IEP monitoring could yield further insights into distribution and habitat requirements of this endangered fish.

Distribution by life stage.—While numerous factors affect the distribution of delta smelt (EET 1997, Meng and Matern 2001, Bennett et al. 2002, Kimmerer 2002, Baskerville-Bridges et al. 2004, Dege and Brown 2004, Feyrer 2004, Grimaldo et al. 2004, Sommer et al. 2004, Bennett 2005, Feyrer et al. 2007, Baxter et al. 2008, Nobriga 2008), it was beyond the scope of this paper to relate distribution to causal factors. Nevertheless, important information can be gleaned from this review, which may inform conservation planning and lead to research into factors driving delta smelt distribution. For example, high frequency of observation and observed density of mature adults and early life stages are indicators of areas that could be spawning regions (Sommer et al. 2011). Spawning occurring upstream in freshwater has been supported elsewhere through high catches of larval delta smelt along the edges of rivers and in adjoining sloughs in the western Delta (Moyle et al. 1992). The newer IEP monitoring programs provide potentially important information regarding general spawning locations. The relatively higher presence of spawning adults in Suisun Marsh, Cache Slough, and the Lower Sacramento River indicate possible proximity to spawning areas, a suggestion also supported by high relative observed densities of larval smelt in downstream areas. The Upper Napa River has relatively high observed densities of larvae, suggesting that this may also be an important area for spawning; considering their poor swimming ability, it is unlikely that larvae would have migrated up the Napa River from other locations. The Napa River, which at one time was considered to be a population sink for delta smelt, is now considered a contributor to the adult population (Hobbs et al. 2007).

An important rearing area appears to be the stretch of water between the Lower Sacramento River and Grizzly Bay, with Grizzly Bay supporting an increasing proportion of young delta smelt as they mature. The highest relative observed densities of juveniles in STN (with surveys from June to August) were found in Grizzly Bay. This is corroborated by data from the 20-mm, which also showed Grizzly Bay to have the highest relative observed densities of juveniles (May to July). By fall, the FMWT data indicate the highest relative observed juvenile densities usually are found further to the east in the Confluence and Lower Sacramento River regions — an area where sub-adults were also found in relatively high observed densities.

Spawning in the upstream regions of Napa River, Suisun Marsh, the Upper Sacramento River and Cache Slough, and maturing downstream in waters from Grizzly Bay upstream to the Lower Sacramento River is consistent with the well-noted migration of delta smelt (Grimaldo et al. 2009, Sommer et al. 2011). The data also suggest year-round populations in the central regions (Lower Sacramento River downstream to Suisun Marsh) and in the Cache Slough and Ship Channel region. Collectively, these observations, along with the report of Hobbs et al. (2007), are an indication of variability in the migratory patterns observed by Sommer et al. (2011).

Outside of the central regions, the Cache Slough and Ship Channel was the only region that yielded high catches of delta smelt relative to other regions across multiple life stages for years 1995-2009. Recent monitoring efforts have shown that delta smelt are utilizing the near-shore habitats of the Cache Slough and Ship Channel region (a restored tidal marsh) not only during the spawning season, but also on a year-round basis (DSC 2010). Many IEP studies are underway to understand the environmental mechanisms in Cache Slough that help create critical habitat for delta smelt.

A number of observations can be taken from these distributional data that could contribute to more effective conservation planning for delta smelt. First, some of the highest observed densities of delta smelt are found close to shore (Table 8), suggesting that some necessary or desired habitat conditions exist along the shoreline, possibly related to migration (Sommer et al. 2011) or spawning. Second, it could be inferred from subregional delta smelt observed densities that, under contemporary conditions, the fish seem to be exhibiting higher densities in areas that are most similar to historic habitat — deep channels that occur proximate to more extensive areas of shallow water (Whipple 2010), which may to some degree be insulated from the influences of anthropogenic environmental stressors. Third, it appears that the monitoring programs may be missing useful information at some life stages in areas potentially important for delta smelt (e.g., areas upstream of existing consistently monitored stations in the Napa River, around Cache Slough and the adjacent ship channel, and several other tributaries to the Sacramento River).

Table 8.—Average observed densities (number of fish per 10,000 m3) of delta smelt by life stage, Interagency Ecological Program monitoring program, and region. 20-mm = 20-mm Tow-Net, STN = Summer Tow-Net, FMWT = Fall Midwater Trawl, BS = Beach Seine, BMWT = Bay Midwater Trawl, and SKT = Spring Kodiak Trawl. NS indicates no survey conducted in the given life-stage and region.

	Life-stage										
	Larvae	Sub-juvenile		Juvenile			Sub-adult	Mature Adults		Pre-spawning	Spawning
Monitoring Program	20-mm	20-mm	STN	20-mm	STN	FMWT	FMWT	Beach Seine	BMWT	SKT	SKT
Years of Data Used	95-09	95-09	95-09	95-09	95-09	95-09	95-09	95-09	95-06	02-09	02-09
Time Period	Apr-Jun	Apr-Jul	Jun-Aug	May-Jul	Jun-Aug	Sep-Dec	Sep-Dec	Dec-May	Jan-May	Jan-Apr	Jan-May
San Francisco Bay	NS	NS	NS	NS	NS	NS	NS	0.0	0.0	NS	NS
West San Pablo Bay	NS	NS	NS	NS	NS	0.0	0.0	0.0	0.0	NS	NS
East San Pablo Bay	0.0	0.0	0.0	0.1	0.4	0.0	0.0	NS	0.1	NS	NS
Lower Napa River	2.0	3.6	0.2	1.2	3.3	0.1	0.0	NS	NS	1.1	0.4
Upper Napa River	4.6	6.0	NS	2.5	NS	NS	NS	NS	NS	NS	NS
Carquinez Strait	0.5	0.8	0.0	3.9	10.2	0.0	0.1	NS	0.1	0.4	0.0
Suisun Bay (SW)	2.3	3.7	0.1	3.4	4.6	0.4	0.3	NS	0.1	0.3	0.0
Suisun Bay (NW)	0.1	0.9	0.1	2.3	6.8	0.6	0.4	NS	0.1	0.6	0.2
Suisun Bay (SE)	5.9	10.4	0.9	4.8	22.1	1.6	0.7	NS	0.1	0.9	0.1
Suisun Bay (NE)	2.3	5.2	3.7	8.7	21.6	1.8	1.8	NS	1.0	3.0	0.3
Grizzly Bay	1.9	8.7	1.8	24.8	67.1	0.8	0.9	NS	1.2	1.6	0.2
Suisun Marsh	5.0	13.9	1.3	1.7	3.7	2.8	2.9	NS	NS	24.8	3.1
Confluence	9.4	17.0	3.9	7.0	14.8	3.1	2.3	3.9	0.5	2.2	0.2
Lower Sacramento River	1.4	19.3	14.7	8.3	35.1	4.2	4.2	NS	0.5	8.2	1.3
Upper Sacramento River	0.8	0.4	0.1	0.0	0.0	0.1	0.7	39.3	0.4	1.1	0.8
Cache Slough & Ship Channel	1.3	9.2	NS	5.7	NS	0.8	3.0	NS	NS	4.1	1.5
Lower San Joaquin River	5.2	5.6	0.4	0.4	0.4	0.1	0.2	3.4	0.2	2.4	0.4
East Delta	1.3	0.5	0.0	0.1	0.0	0.0	0.0	10.9	NS	0.1	0.0
South Delta	2.5	1.0	0.0	0.1	0.0	0.0	0.0	0.4	NS	0.2	0.0
Upper San Joaquin River	NS	NS	NS	NS	NS	NS	NS	0.4	NS	NS	NS
Sacramento Valley	NS	NS	NS	NS	NS	NS	NS	0.6	NS	NS	NS

According to Feyrer et al. (2007), one factor limiting the utility of delta smelt empirical data is that those data frequently pertain to a particular life stage or time period when sampling was conducted. Thompson et al. (2010) suggested a life history model linking the abundances of each life stage would provide a more continuous picture of the population and would capitalize more fully on available data. Martin et al. (2007) suggested that conservation of migratory species depends largely on understanding links between different periods of life cycles. These suggestions highlight the importance of, and the need for, a clearer understanding of the distribution of the various life stages of delta smelt.

Concepts regarding restoration of native fish habitat and buffering from potential environmental disaster within the San Francisco Estuary have evolved considerably in recent years, particularly the restoration of tidal wetlands and floodplain habitats (Moyle 2008). While significant issues include the management of flow, invasive species responses, and future climatic effects (Brown and May 2006), our review provides important information on the life stage-specific distribution of delta smelt that was made possible by monitoring programs implemented by the IEP and other agencies since 1995.

According to Holl et al. (2003), a common conclusion of many restoration efforts is that success varies substantially among sites. At least in part, varying success results from differences in hydrology, microclimate, and movement of plants, animals, and disturbance regimes. Our review of the spatial distribution of delta smelt highlights general regions that appear important for specific life stages. Such information will be useful when addressing management issues such as anthropogenic stressors, habitat restoration efforts, and testing the success of experimental approaches to achieving habitat objectives for desirable species (Moyle et al. 2010). This comprehensive review of delta smelt distribution within the San Francisco Estuary provides managers and scientists an improved depiction of the spatial and temporal extent of the delta smelt throughout its range, and lends itself to future analysis of population assessment and restoration planning.

Acknowledgments

We gratefully acknowledge the CDFG, USFWS, and IEP, especially R. Baxter, K. Hieb, R. Titus, V. Afentoulis, D. Contreras, B. Fujimara, S. Slater, J. Adib-Samii and J. Speegle for many years of data collection and dissemination. We also thank The Fishery Foundation of California, East Bay Municipal Utility District Fisheries and Wildlife staff, The Moyle Lab (University of California, Davis) and the California Department of Water Resources for sharing data. P. Rueger and J. Melgo provided valuable data and spatial analyses. D. Murphy provided significant input to, and three anonymous reviewers provided valuable insight and guidance on, an earlier draft of this manuscript. Funding for this project was provided by the Center for California Water Resources Policy and Management and the State and Federal Contractors Water Agency.

Literature Cited

Armor, C., R. Baxter, W. Bennett, R. Breuer, M. Chotkowski, P. Coulston, D. Denton, B. Herbold, W. Kimmerer, K. Larsen, M. Nobriga, K. Rose, T. Sommer, and M. Stacey. 2005. Interagency ecological program synthesis of 2005 work to evaluate the pelagic organism decline (POD) in the Upper San Francisco Estuary. Interagency Ecological

Program, Stockton, California, USA. Available at: http://www.science.calwater.ca.gov/pdf/workshops/POD/2007_IEP-POD_synthesis_report_031408.pdf

Baskerville-Bridges, B., J. C. Lindberg, and S. I. Doroshov. 2004. The effect of light intensity, alga concentration, and prey density on the feeding behavior of delta smelt larvae. American Fisheries Society Symposium 39:219-227.

Baxter, R., R. Breuer, L. Brown, M. Chotkowski. F. Feyrer, M. Gingras, B. Herbold, A. Mueller-Solger, M. Nobriga, T. Sommer, and K. Souza. 2008. Pelagic organism decline progress report: 2007 synthesis of results. Available at: http://www.science.calwater.ca.gov/pdf/workshops/ POD/2007_IEP POD_synthesis_report_031408.pdf

Bennett, W. A. 2005. Critical assessment of the delta smelt population in the San Francisco Estuary, California. San Francisco Estuary Watershed Science 3(2). Available at: http://www.escholarship.org/uc/item/0725n5vk

Bennett , W. A., W. J. Kimmerer, and J. R. Burau. 2002. Plasticity in vertical migration by native and exotic estuarine fishes in a dynamic low-salinity zone. Limnology and Oceanography 47:1496-1507.

Brown, L. R, and J. T. May. 2006. Variation in spring nearshore resident fish species composition and life histories in the lower San Joaquin watershed and delta. San Francisco Estuary and Watershed Science 4(2). Available at: http://escholarship.org/uc/item/09j597dn

Brundage, H. M., and R. E. Meadows. 1982. The Atlantic sturgeon: *Acipenser oxyrhynchus*, in the Delaware River and Bay. Fisheries Bulletin 80:337-343.

Burgman, M. A., and J. C. Fox. 2003. Bias in species range estimates from minimum convex polygons: implications for conservation and options for improved planning. Animal Conservation 6:19-28.

Cabeza, M., A. Arponen, L. Jaattela, H. Kujala, A. van Teeffelen, and I. Hanski. 2010. Conservation planning with insects at three different spatial scales. Ecography 33:54-63.

California Resources Agency. 2005. Delta smelt action plan. California Department of Water Resources and California Department of Fish and Game. Sacramento, USA.

California Resources Agency. 2007. Pelagic fish action plan. California Department of Water Resources and California Department of Fish and Game, Sacramento, USA.

Carroll, C., M. K. Phillips, C. A. Lopez-Gonzalez, and N. H. Schumaker. 2006. Defining recovery goals and strategies for endangered species: the wolf as a case study. BioScience 56:25-37.

Ceballos, F., and P. R. Ehrlich. 2006. Global mammal distributions, biodiversity hotspots, and conservation. Proceedings of the National Academy of Sciences of the United States of America 103:19374-19379.

Crain, P. K., K. Whitener, and P. B. Moyle. 2004. Use of a restored central California floodplain by larvae of native and alien fishes. American Fisheries Society Symposium 39:125-140.

Dege, M., and L. R. Brown. 2004. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. American Fisheries Society Symposium 39:49-65.

Dormann. C. F., J. M. McPherson, M. B. Araujo, R. Bivand, J. Bolliger, G. Carl, R. G. Davies, A. Hirzel, W. Jetz, W. D. Kissling, I. Kuhn, R. Ohlemuller, P. R. Peres-Neto, B. Reineking, B. Schroder, F. M. Schurr, and R. Wilson. 2007. Methods to account for spatial autocorrelation in the analysis of species distributional data: a review. Ecography 30:609-628.

DSC (Delta Stewardship Council). 2010. Liberty Island provides insights into Delta ecosystem restoration. Science News, April 2010. Delta Science Program, Sacramento, California, USA. Available at: http://science.calwater.ca.gov/publications/sci_news_0410_liberty.html

Erkkila, L. F., J. W. Moffet, O. B. Cope, B. R. Smith, and R. S. Nelson. 1950. Sacramento-San Joaquin Delta fishery resources: effects of Tracy Pumping Plant and the Delta Cross Channel. United States Fish and Wildlife Service Special Scientific Report 56. Sacramento, California, USA.

EET (Estuarine Ecology Team). 1997. An assessment of the likely mechanisms underlying the "Fish-X2" relationships. Technical Report 52. Interagency Ecological Program for the San Francisco Bay/Delta Estuary. Sacramento, California, USA.

Ferrier, S. 2002. Mapping spatial pattern in biodiversity for regional conservation planning: where to from here? Systematic Biology 51:331-363.

Feyrer, F. 2004. Ecological segregation of native and alien larval fish assemblages in the southern Sacramento-San Joaquin Delta. Early life history of fishes in the San Francisco Estuary and Watershed. American Fisheries Society Symposium 39:67-79.

Feyrer, F., K. Newman, M. Nobriga, and T. Sommer. 2010. Modeling the effects of future outflow on the abiotic habitat of an imperiled estuarine fish. Estuaries and Coasts 34:120-128.

Feyrer, F., M. Nobriga, and T. Sommer. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian Journal of Fisheries and Aquatic Sciences 64:723-734.

Flather, C. H., K. R. Wilson, D. J. Dean, and W. C. McComb. 1997. Identifying gaps in conservation networks of indicators and uncertainty in geographic-based analysis. Ecological Applications 7:531-542.

Graham, C. H., and R. J. Hijmans. 2006. A comparison of methods for mapping species ranges and species richness. Global Ecology and Biogeography 15:578–587.

Grimaldo, L. F., R. E. Miller, C. M. Peregrin, and Z. P. Hymanson. 2004. Spatial and temporal distribution of native and alien ichthyoplankton in three habitat types of the Sacramento-San Joaquin Delta. American Fisheries Society Symposium 39:81-96.

Grimaldo, L. F., T. Sommer, N. Van Ark, G. Jones, E. Holland, P. B. Moyle, B. Herbold, and P. Smith. 2009. Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: can fish losses be managed? North American Journal of Fisheries Management 29:1253-1270.

Healey, M. C., M. D. Dettinger, and R. B. Norgaard (editors). 2008. The State of the Bay-Delta Science 2008. CALFED Science Program, Sacramento, California, USA. Available at: http://www.science.calwater.ca.gov/publications/sbds.html

Hobbs, J. A., W. A. Bennett, J. Burton, and M. Gras. 2007. Classification of larval and adult delta smelt to nursery areas by use of trace elemental fingerprinting. Transactions of the American Fisheries Society 136:518-527.

Holl, K. D., E. E. Crone, and C. B. Schultz. 2003. Landscape restoration: moving from generalities to methodologies. BioScience 53:491-502.

Hulbert, A. H., and W. Jetz. 2007. Species richness, hotspots, and the scale dependence of range maps in ecology and conservation. Proceedings of the National Academy of Sciences of the United States of America 104:13384-13389.

IUCN (International Union for the Conservation of Nature). 1994. IUCN red list categories. IUCN Species Survival Commission, Gland, Switzerland.

Kimmerer, W. J. 2009. Individual based model for delta smelt. Presentation to National Center for Ecological Analysis and Synthesis. Pelagic Organism Decline Workshop, 9 September 2009. Santa Barbara, California, USA.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? Marine Ecology Progress Series 243:39-55.

Lund, J., E. Hannak, W. Fleenor, R. Howitt, J. Mount, and P. Moyle. 2007. Envisioning futures for the Sacramento-San Joaquin Delta. Public Policy Institute of California, San Francisco, California, USA.

Lunney, D., A. Curtin, D. Ayers, H. G. Cogger, and C. R. Dickman. 1996. An ecological approach to identifying the endangered fauna of New South Wales. Pacific Conservation Biology 2:212-231.

MacNally, R., J. R. Thomson, W. J. Kimmerer, F. Feyrer, K. B. Newman, A. Sih, W. A. Bennett, L. Brown, E. Fleishman, S. D. Culberson, and G. Castillo. 2010. Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). Ecological Applications 20:1417-1430.

Martin, T. G., I. Chades, P. Arcese, P. P. Marra, H. P. Possingham, and D. R. Norris. 2007. Optimal conservation of migratory species. PLoS ONE 2(8):e751. doi:10.1371/journal.pone.0000751

Meng, L., and S. A. Matern. 2001. Native and introduced fishes of Suisun Marsh, California: the effects of freshwater flow. Transactions of the American Fisheries Society 130:750-765.

Merz, J., and M. Saldate. 2005. Lower Mokelumne River fish community survey: 1 January 1997 through 30 June 2004. Cramer Fish Sciences, Auburn, California, USA.

Millsap, B. A., J. A. Gore, D. E. Runde, and S. I. Cerulean. 1990. Setting the priorities for the conservation of fish and wildlife species in Florida. Wildlife Monographs 111:1-57.

Moyle, P. B. 2008. The future of fish in response to large-scale change in the San Francisco Estuary, California. American Fisheries Society Symposium 64:357-374.

Moyle, P. B. 2002. Delta smelt, *Hypomesus transpacificus* McAllister. Pages 227-232 *in* P. B. Moyle, editor. Inland fishes of California. University of California Press, Berkeley, USA.

Moyle, P. B., P. K. Crain, and K. Whitener. 2007. Patterns in the use of a restored California floodplain by native and alien fishes. San Francisco Estuary and Watershed Science 5(3). Available at: http://escholarship.org/uc/item/6fq2f838

Moyle, P. B., and B. Herbold. 1989. Status of the delta smelt, *Hypomesus transpacificus*. Final Report to U.S. Fish and Wildlife Service. Department of Wildlife and Fisheries Biology, University of California, Davis, USA.

Moyle, P. B., B. Herbold, D. E. Stevens, and L. W. Miller. 1992. Life history and status of delta smelt in the Sacramento-San Joaquin Estuary, California. Transactions of the American Fisheries Society 121:67-77.

Moyle, P. B., J. R. Lund, W. A. Bennett, and W. E. Fleenor, 2010. Habitat variability and complexity in the Upper San Francisco Estuary. San Francisco Estuary and Watershed Science 8(3). Available at: http://escholarship.ucop.edu/uc/item/0kf0d32x

Nobriga, M. L. 2008. Aquatic habitat conceptual model. Delta Regional Ecosystem Restoration Implementation Plan.

Pearce, J. L., and M. S. Boyce. 2006. Modeling distribution and abundance with presence-only data. Journal of Applied Ecology 43:405-412.

Radtke, L. D. 1966. Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento-San Joaquin Delta with observations on food of sturgeon. Fish Bulletin 136:115-129.

Rosenfield, J. A., and R. D. Baxter. 2007. Population dynamics and distribution patterns of longfin smelt in the San Francisco Estuary. Transactions of the American Fisheries Society 136:1577-1592.

Samii-Adib, J. 2010. The presence and relative abundance of delta smelt in the Sacramento Deep Water Shipping Channel. Interagency Ecological Program, 2010 Annual Workshop, May 26, 2010. Sacramento, California, USA. Available at: http://www.water.ca.gov/iep/docs/052510abundance.pdf

Snider, B., and R. G. Titus. 2001. Lower American River emigration survey, October 1997-September 1998. Stream Evaluation Program Technical Report 01-6. California Department of Fish and Game, Sacramento, USA.

Snider, B., and R. G. Titus. 2000. Lower American River emigration survey, October 1996-September 1997. Stream Evaluation Program Technical Report 00-2. California Department of Fish and Game, Sacramento, USA.

Snider B., R. G. Titus, and B. A. Payne. 1998. Lower American River emigration survey, October 1995-September 1996. Stream Evaluation Program Technical Report 98-6. California Department of Fish and Game, Sacramento, USA.

Sommer, T., F. Mejia, M. Nobriga, F. Feyrer, and L. Grimaldo. 2011. The spawning migration of delta smelt in the upper San Francisco Estuary. San Francisco Estuary and Watershed Science 9(2). Available at: http://escholarship.org/uc/item/86m0g5sz

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. Fisheries 32:270-277.

Sommer, T. R., W. C. Harrell, R. Kurth, F. Feyrer, S. C. Zeug, and G. O'Leary. 2004. Ecological patterns of early life stages of fishes in a large river-floodplain of the San Francisco Estuary. American Fisheries Society Symposium 39:111-123.

Stevens, D. E., and L. W. Miller. 1983. Effects of river flow on abundance of young chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin River System. American Journal of Fisheries Management 3:425-437.

Stevens, D. E., L. W. Miller, and B. C. Bolster. 1990. Report to the Fish and Game Commission: a status review of delta smelt (*Hypomesus transpacificus*) in California. Candidate Species Status Report 90-2. California Department of Fish and Game, Sacramento, USA.

Sweetnam, D. A., and D. E. Stevens. 1993. Report to the Fish and Game Commission: a status review of delta smelt (*Hypomesus transpacificus*) in California. Candidate Species Status Report 93-DS. California Department of Fish and Game, Sacramento, USA.

Thomson, J. R., W. J. Kimmerer, L. R. Brown, K. B. Newman, R. MacNally, W. A. Bennett, F. Feyrer, and E. Fleishman. 2010. Bayesian change point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. Ecological Applications 20:1431-1448.

TONG, S. T. 2001. An integrated exploratory approach to examining the relationships of environmental stressors and fish responses. Journal of Aquatic Ecosystem Stress and Recovery 9:1-19.

TRACY, C. R, R. AVERILL-MURRAY, W. I. BOARMAN, D. DELEHANTY, J. HEATON, E. MCCOY, D. MORAFKA, K. NUSSEAR, B. HAGERTY, AND P. MEDICA. 2004. Desert tortoise recovery plan assessment. Report to United States Fish and Wildlife Service. University of Nevada, Reno, USA.

USFWS (UNITED STATES FISH AND WILDLIFE SERVICE). 1993. Determination of threatened status for the delta smelt. Federal Register 58:12854-12864.

USFWS. 1994. Designation of critical habitat for the least Bell's vireo. Federal Register 59:4845–4867

USFWS. 2003. 5-year review of the delta smelt. Federal Register 68:45270-45271.

USFWS. 1996. Sacramento-San Joaquin Delta native fishes recovery plan. U.S. Fish and Wildlife Service, Portland, Oregon.

VAN GEEN, A., AND S. N. LUOMA. 1999. The impact of human activities in sediments of San Francisco Bay, California: an overview. Marine Chemistry 64:1-6.

WANG, J. C. S. 1991. Early life stages and early life history of the delta smelt, *Hypomesus transpacificus*, in the Sacramento-San Joaquin estuary, with comparison of early life stages of the longfin smelt, *Spirinchus thaleichthys*. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary. Technical Report 28. Aug 1991. FS/BIO-IATR/91-28.

WHIPPLE, A. 2010. Historical ecology of the Delta: habitat characteristics of a fluvial-tidal landscape. Interagency Ecological Program 2010 Annual Workshop, 2010 May 25-26. Sacramento, California, USA.

Submitted 20 September 2011
Accepted 27 October 2011
Associate Editor was K. Shaffer