San Francisco Estuary Invasive *Spartina* Project
2007-2012 Drift Card Study Report

Report to:
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Abstract

Atlantic smooth cordgrass (*Spartina alterniflora*) was introduced to the San Francisco Bay in the mid-1970s and hybridized with native Pacific cordgrass (*S. foliosa*) to produce *S. alterniflora* × *foliosa*. Generations of mixing and backcrossing produced a highly invasive hybrid swarm with characteristics that allow it to outcompete either parental species and other marsh plants, such that infested tidal wetlands become hybrid *Spartina* monocultures with disrupted ecological integrity. The California State Coastal Conservancy created the San Francisco Invasive *Spartina* Project in 2000 to control and eradicate invasive *Spartina* and has achieved a 97.4% reduction in net infested acreage as of December 2022. To help predict potential dispersal patterns of invasive *Spartina*, this study used wooden drift cards to simulate floating *Spartina* propagules. A total of 3,150 drift cards were released from 16 different sites in the San Francisco Bay over three rounds spanning 2007-2012. By May 2016, 901 cards had been found and reported by members of the public. The furthest dispersal distance from each release site (not including cards reported from the outer coast) ranged from 2.6 to 42.2 miles. In general, cards from the North Bay and West Bay release sites dispersed more widely than cards from the East Bay, probably due to prevailing westerly winds blowing East Bay cards back towards shore. If cards made it into stronger offshore currents, they could be transported nearly anywhere within the Estuary or beyond. Cards from 10 sites were found on the outer coast, demonstrating the potential for an uncontrolled hybrid *Spartina* invasion to spread well beyond the San Francisco Estuary.

Introduction

The San Francisco Estuary Invasive *Spartina* Project (ISP) was established in 2000 by the California State Coastal Conservancy (Conservancy) in partnership with the U.*S.* Fish and Wildlife Service (USFWS) in response to the invasion of the tidal marshes and mudflats by non-native cordgrass (*Spartina* spp.). *Spartina alterniflora* (Atlantic smooth cordgrass) was introduced from its native range along the East Coast of the United States to the San Francisco Estuary ('Estuary' or 'Bay' throughout this report) by the U.S. Army Corps of Engineers (ACOE) in the mid-1970s in an experiment in dredge spoils stabilization and tidal marsh restoration. *S. alterniflora*, which is now known to be highly invasive outside of its native range (Stokstad 2023), subsequently hybridized with *S. foliosa* native to the Estuary (Daehler and Strong 1997; Ayres, Strong et al. 2003). Multiple generations of backcrossing between hybrid *S. alterniflora* × *foliosa* and the parental species produced a robust, fertile, and highly invasive "hybrid swarm" that infested habitat throughout the Estuary, degrading the ecological integrity of the existing tidal wetlands and mudflats and threatening the potential success of future restoration efforts (Daehler and Strong 1997; Goals 1999; Ayres, Strong et al. 2003; State Coastal Conservancy 2003; Ayres, Zaremba et al. 2004).

The ISP's Programmatic Environmental Impact Statement/Environmental Impact Report (PEIS/EIR; State Coastal Conservancy 2003) and references therein described many threats posed to the Estuary by non-native *Spartina*. At the time of the formation of the ISP, predicted impacts from non-native *Spartina* were already being realized in the Estuary and were expected to worsen, including the widespread destruction or degradation of endangered species habitat, loss of naturally unvegetated mudflats vital for resident and migratory shorebird foraging on the Pacific Flyway, loss of urban flood control capacity, creation of mosquito-breeding areas through water impoundment, corruption of salt marsh restoration efforts, and the possible eventual extinction of native congener *S. foliosa*. Conversion of mudflats to hybrid *Spartina* meadows was shown to reduce benthic

invertebrate biomass by greater than 70%, and caused a shift from surface feeders available to shorebirds and other consumers to belowground feeders that are not accessible (Levin 2006, Neira 2005, Brusati 2009).

The ISP was formed with the mission to implement a coordinated regional program to control and eventually eliminate the impacts of non-native *Spartina* species throughout the Estuary. Substantial progress towards these goals has been made through a coordinated program of inventory mapping and treatment that is planned and supervised by ISP biologists and implemented at a landscape scale across nine counties by a Bay-wide network of over 300 partners including landowners, resource agencies, contractors, grantees, and stakeholder groups.

After several years of planning, permitting, environmental documentation, and extensive survey and mapping efforts, landscape-scale treatment of the hybrid *Spartina* began in 2005 and ramped up through 2006 to cover at least a portion of all known sites throughout the Estuary. By 2010, the ISP had reduced the infestation by 90%, from 805 net acres at the start of the project to 84 net acres. However, while the invasion of hybrid *Spartina* was detrimental to most native species, the tall, dense stands also provided high tide refugia for the endangered California Ridgway's rail (*Rallus obsoletus obsoletus*) to hide from predators. Consequently, rail numbers increased at some infested sites beyond what they would have been without the hybrid *Spartina* invasion. In response, USFWS set permit requirements in 2011 that prohibited continued treatment at 26 sites distributed widely across the estuary. The ISP was concerned that these many untreated locations would create long-term loci from which hybrid *Spartina* propagules could potentially disburse to new sites or reinfest sites where several years of treatment had made great progress towards local eradication. After the final round of drift card releases was completed in 2012, this study helped inform discussions that resulted in a compromise in which 11 sites, concentrated in four marsh complexes, remained under treatment restrictions. As of the close of the 2022 monitoring and treatment season, the ISP and its partners had reduced hybrid *Spartina* to 20.7 net acres throughout the Estuary, a reduction of 97.4% since 2005.

Spartina alterniflora × *foliosa* spreads primarily through the dispersal of seed, coupled with rhizomatous growth once a plant is established. It is a perennial intertidal plant whose aboveground biomass dies back at the end of the growing season each autumn/early winter, producing new aboveground vegetative growth from its underground rhizome structures the following season. The senescent cordgrass stems eventually break off near the base, often with their inflorescences still attached, and can cluster together to form detrital rafts called 'wrack' that float on the water surface and can be transported long distances by the tide, currents, and surface wind. Elsey-Quirk (2009) found *S. alterniflora* seeds have an average flotation time of 24 days. In another study from Willapa Bay, *Spartina* inflorescences with seeds floated for fewer than 30 days, but stems (which comprise much of the structure of wrack mats) floated for four to eight weeks; approximately 90% of seeds germinated and most were from seeds that remained attached to floating inflorescence branches (Sayce et. al. 1997). *Spartina* seeds not only survive in wet, cold, salty conditions (like those found in Bay or Pacific waters) but actually require these conditions to germinate successfully (Kittelson and Boyd 1997). As sea level rises with climate change and regular tidal exchange begins to intrude on upstream areas that were once brackish in their salinity, these areas may become more susceptible to hybrid *Spartina* invasion. Marsh restoration projects may also become vulnerable as they are opened to tidal flow.

Another exotic cordgrass, Chilean cordgrass (*Spartina densiflora*), has also spread to numerous marshes, primarily in the North Bay, where it has disrupted species compositions and ecological functions. *Spartina densiflora* was originally introduced to the San Francisco Estuary at Creekside Park (renamed Hal Brown Park in

2010) in Kentfield, Marin County, during a restoration effort in the 1970s. It spread throughout the Corte Madera Creek watershed, into the Bay shoreline of eastern Marin County, Point Pinole Regional Shoreline, Mare Island, and Tomales Bay via the outer coast. Another infestation of unknown origin established in San Mateo County. Unlike *S. alterniflora* × *foliosa, Spartina densiflora* is a bunchgrass that maintains its aboveground biomass year-round rather than dying back to its perennial roots each autumn/winter. It does not create substantial wrack that might collect into a mat and transport seed longer distances, although its seeds may hitch a ride on wrack generated by other sources. The ISP is nearing full eradication of *S. densiflora* from the Estuary; only ten seedlings were detected and manually removed from all historic infestation sites in the winter 2023 round of surveys. Despite differences between *S. densiflora* and *S. alterniflora* × *foliosa*, drift cards provide a model of invasion risk for both water-dispersed species.

The marshes of the Estuary are part of an open aquatic system connected by twice-daily tidal exchange capable of dispersing both native and non-native plant seeds and rhizomes (vegetative propagules) within and between marshes. An enormous volume of water flows into San Francisco Bay through the Golden Gate on the flood tide and back out to the Pacific Ocean on the ebb tide. According to the Department of Water Resources' Delta Atlas, average tidal flow through the Golden Gate Bridge is 2,300,000 cubic feet per second (DWR 1995), creating a powerful current and exerting a strong influence on anything floating in the surrounding water column. As the tide floods and ebbs, the water flows around the shorelines within the Bay generating currents and circulation patterns that, in combination with prevailing winds, can transport *Spartina* propagules over long distances. Over a period of a few months, the exchange between ocean water and bay water affects the entire Bay (Smith 1987). Learning more about potential dispersal patterns of hybrid *Spartina* propagules could help inform ISP management actions, guiding biologists' surveys and potentially activate a rapid response with necessary treatment of nascent infestations.

The drift card study reported here was designed to model dispersal patterns of non-native *Spartina* seed and vegetative propagules within the Estuary in order to help predict where to survey for potential new infestations. The drift cards also provide a public outreach tool to demonstrate the interconnectedness of the Estuary, engage stakeholders throughout the project area, and involve them in the tidal marsh and mudflat resource conservation work of the ISP, Coastal Conservancy, USFWS, and other partners.

The ISP modelled this drift card experiment after a similar study conducted by researchers at Portland State University who conducted monthly drift card releases over the course of one year (2004-2005) to study potential ocean dispersal from the large infestations of non-native *Spartina* along the West Coast – in Humboldt and San Francisco Bays in California, and Willapa Bay in Washington State (Morgan and Sytsma 2013). Their paper cites the use of buoyant drift cards or bottles in a range of scientific investigations, including the fate of sewage effluent, the shoreline accumulation of pollutants, the dispersal of nonnative mangroves in Hawaii, and the impact of wind patterns on sea turtle strandings.

Methods

Drift Card Releases

The cards for this study were constructed of mahogany plywood that was purported to degrade in the estuarine environment within a year. The cards were hand-painted with a lead-free primer and oil-based enamel using a

bright yellow color to catch the eye of a passerby. Each 4 in. x 6 in. x 3/32 in. card was then silk-screened on both sides with enamel ink. The ISP posted a Frequently Asked Questions (FAQ) page on their website to assist with outreach to interested project stakeholders and provide them with the broader context for the work of the ISP, while addressing common questions that had been received or were anticipated. Before and during the release of the drift cards, the ISP issued several press releases through the State Coastal Conservancy to spread awareness of the study amongst shoreline user groups, so they would be more likely to report drift card findings.

Each group of cards had the same printed information except for the distinct identifying group code. The letters (A–U) identify the sites and the numbers (1–3) indicate the release batch/date. For example, at Site A (the Alameda Flood Control Channel), there were three separate releases of 50 cards each, so the identifying group code would be A-1 for the first release, A-2 for the second, and A-3 for the third.

Figure 1. Sample drift card for the initial release from the Alameda Flood Control Channel (identifying group code A-1).

The drift cards were released in three rounds over the course of five years from 2007-2012. There were seven release sites in each of the three rounds. Each round was comprised of three releases of 50 cards per site over the course of several weeks, for a total of 150 cards per site per round (1050 total cards per round over all seven sites). At each site, a single release location was used for each of the three releases of 50 cards, with at least two weeks between release dates. Cards were released on an outgoing tide into the open water along the outer shoreline edge of all sites with the intention of maximizing the potential of dispersal from the site and minimizing the number of cards that would remain at the release location. The drift cards were released individually, rather than as a single 50-card package. In an attempt to ensure dispersal from the site, the cards were not released into the interior vegetated portions of the marshes, but rather were flung as far as possible out into the open water from the edge of the marsh. The purpose of the study was to learn about mechanisms of dispersal to other tidal resources within or outside of the Estuary rather than to study intra-marsh dispersal dynamics.

The release sites were chosen primarily to represent large, regionally significant infestations of non-native *Spartina* where monitoring and treatment efforts were already underway. Five sites were chosen as repeat release sites in later rounds of the study due to their representation of various key elements of the project that

demonstrated potential dispersal from important site complexes: Bair Island Ecological Reserve at Steinberger Slough (releases B and O), Colma Creek/San Bruno Marsh (releases E and L), San Leandro Bay at Arrowhead Marsh/MLK New Marsh (releases I and T), Alviso Slough/Coyote Creek (releases K and P), and San Pablo Marsh/Rheem Creek (releases J and S).

Table 1. Release site names, identifying group codes, and release locations for all three rounds of the ISP drift card study.

Code	Release Site	Location	Release Point Within Site
Round One			
A	Alameda Flood Control Channel	Fremont, Alameda Co.	Mouth of the channel (north side)
B	Bair Island Ecological Reserve	Redwood City, San Mateo Co.	Mouth of Steinberger Slough (west side)
C	Elsie Roemer Bird Sanctuary	Alameda, Alameda Co.	Jetty at the western boundary of the Sanctuary
D	San Lorenzo Creek Mouth	San Leandro, Alameda Co.	Pedestrian bridge over the creek mouth
E	Colma Creek/San Bruno Marsh	South San Francisco, San Mateo Co.	Pedestrian bridge at mouth of Colma Creek
F	Cogswell Marsh	Hayward, Alameda Co.	Northern pedestrian bridge
G	Creekside Park/Hal Brown Park	Kentfield, Marin Co.	Outlet of Creekside Park into Corte Madera Creek
Round Two			
H	Stevens Creek Tidal Marsh	Mountain View, Santa Clara Co.	Mouth of channel into Stevens Creek
I	MLK New Marsh/Arrowhead Marsh	Oakland, Alameda Co.	Pedestrian bridge at mouth of San Leandro Creek
J	San Pablo Marsh/Rheem Creek	Richmond, Contra Costa Co.	Point of the jetty
K	Alviso Slough at Coyote Creek	Santa Clara County	Confluence of Alviso Slough and Coyote Creek
L	Colma Creek/San Bruno Marsh	South San Francisco, San Mateo Co.	Pedestrian bridge over Colma Creek
M	San Leandro Marina	San Leandro, Alameda Co.	Point of the jetty
N	Napa River	Vallejo, Solano Co.	Sears Point Bridge
Round Three			
O	Bair Island Ecological Reserve	Redwood City, San Mateo Co.	Mouth of Steinberger Slough
P	Alviso Slough at Coyote Creek	Santa Clara County	Confluence of Alviso Slough and Coyote Creek
Q	Cooley Landing	East Palo Alto, San Mateo Co.	Cooley Landing Education Center
R	Corte Madera Creek Mouth	Larkspur, Marin Co.	Larkspur Ferry Terminal
S	San Pablo Marsh/Rheem Creek	Richmond, Contra Costa Co.	Point of the jetty
T	MLK New Marsh/Arrowhead Marsh	Oakland, Alameda Co.	Pedestrian bridge at mouth of San Leandro Creek
U	North Marsh	San Leandro, Alameda Co.	Mouth of main channel connecting to Bay

The three releases of Round 1 were conducted March 16, 2007 through August 3, 2007. Round 2 was conducted December 19, 2007 through December 13, 2008, and Round 3 was conducted from November 23, 2011 through March 2, 2012.

The third round of releases was added to the study in 2011 as the ISP and Coastal Conservancy worked with USFWS to balance hybrid *Spartina* removal with short-term impacts to the endangered Ridgway's rail. Sites were selected for the third round of drift cards to demonstrate the potential impacts of distributing these restricted sites widely around the estuary, and to inform discussions with regulators about consolidating the restricted sites down to a few clustered locations to limit the damage from continued widespread *Spartina* propagule dispersal.

Drift Card Reports and Analyses

When a drift card was found along the shoreline, the person who found it could report the location through a dedicated page on the ISP website or via phone. Reporting fields included the date, time, and location of the find, and any additional notes desired by the community member. The database from the website was

downloaded periodically and evaluated as part of quality control. Where contact information was provided, submitters were contacted for clarification or additional information, if needed. Data points were marked for omission in cases where the location of the find could not be reasonably inferred from the report. Each found card was recorded with a separate report, even if multiple cards were found at the same time and location.

Occasional card reports were still being received up to four years after the last release, until the portal was closed. Beginning in May 2016, data from the online portal for each report was manually entered into an ESRI ArcMap geodatabase as a georeferenced point (Geographic Coordinate System: GCS_North_American_1983; Datum: D_North_American_1983.) The location of each collection point was determined using multiple sources ranging from georeferenced data to descriptions of the locations. Consequently, some of the drift cards could only be mapped with an accuracy provided by municipal jurisdiction boundaries down to the city/town level. Other reports were much more specific, some providing latitude/longitude coordinates. This GIS geodatabase allowed for further analyses and generation of drift card dispersal maps for each release site (**Figures 2 through 18** in Results).

Dispersal distances were derived in GIS as the shortest linear path between the point of release (estimated within 10 meters) and the reported point of collection, manually adjusted to forbid "impossible paths" across land. The resulting linear feature represents the shortest possible distance traveled by a drift card; if a card took a meandering route between the two endpoints, it may have traveled a much greater distance than the linear path used to represent it. Permitted paths could include travel over the surface of the Bay, along sloughs, channels and other tidal bodies of water, and across mudflats that were submerged during high tides. Water, mudflat, and land were represented with BAARI Baylands polygon features (San Francisco Estuary Institute and Aquatic Science Center, 2015), and ESRI World Imagery was also referenced.

The Furthest Dispersal Distance (FDD) was calculated for each release site as the greatest distance traveled by any card from the site. Because this study was concerned with dispersal patterns *within* the San Francisco Bay, distances traveled by cards found along the Pacific coast outside the Golden Gate were truncated at the middle of the Golden Gate Bridge. For cards that left the Bay, the reported FDD *within the Bay* includes only the distance from the release point to the midpoint of the bridge, if that was the longest intra-Bay distance traveled by any card from that release point.

Results

Over the course of the three rounds of drift card releases from March 2007 through March 2012, 3,150 cards were released from 16 locations with the San Francisco Estuary. With seven sites in each round, 150 cards were released per site per round (five sites were repeated in multiple rounds of the study, see Methods). No cards were ever reported found for three sites from the third release event of the third round of the study. These were Cooley Landing (Q-3), Arrowhead Marsh/MLK New Marsh (T-3), and North Marsh (U-3). It is suspected that the scheduled third round of card releases at these sites did not actually take place, since these sites are not located in remote parts of the Estuary and all 60 other releases had at least one card reported by a member of the community. Omitting these three releases from the study reduces the total number of cards released to 3000. Fortunately, for two of these three missing releases, dispersal data from other releases is likely comparable to expectations from the lost data. Arrowhead Marsh/MLK New Marsh (site T) was a site repeated

from an earlier round of releases (site I), so there is still data from five releases at the site after dropping the one missed release. North Marsh (site U) is in the same Roberts Landing complex as San Lorenzo Creek mouth (site D) and San Leandro Marina (site M), all of which showed similar dispersal patterns.

By May 2016, 901 cards were reported either through the ISP website or over the phone, resulting in a final retrieval rate of 30%. Twelve cards could not be mapped in GIS due to missing or ambiguous location information from the reporter. Card retrieval per release round ranged from a low of 21 cards reported from Napa River (site N) to a high of 92 cards from Elsie Roemer (site C). Releases at a few East Bay sites were impacted by wind due to the long fetch across the surface of the Bay. The wind pushed the floating drift cards back to shore as the tide receded and some washed back to near the release points; see Discussion.

The average Furthest Dispersal Distances (FDD) for the study was 23.6 miles (38.0 km) traveled within the Bay, ranging from the greatest FDD of 42.2 miles (67.9 km) measured from the Napa River site, release 1, to the lowest FDD of 2.6 miles (4.3 km) for San Lorenzo Creek mouth site, release 2 **(Table 2)**.

Cards from 10 of 16 release sites (63%) left the Golden Gate and traveled as far north as Goat Rock Beach in Sonoma County and as far south as Bean Hollow State Beach in San Mateo County. This suggests propagules from numerous infestation locations could travel out of San Francisco Bay to the Pacific Ocean, potentially spreading hybrid *Spartina* to outer coast marshes. Cards were collected and reported from several environmentally sensitive locations on the outer coast, such as Point Reyes National Seashore and Golden Gate National Recreation Area. Cards from all North Bay release sites and many Central Bay sites left the Golden Gate, but even sites as far south as Bair Island and Alviso Slough had some cards leave the Bay. Outer coast retrievals are shown in **Figure 2** and summarized in the Discussion for each release site.

Table 2. Results by site, including number of cards retrieved and Furthest Dispersal Distance (FDD) within the Bay.

Code	Release Site	Cards Retrieved (* = 2 rounds)	Furthest Dispersal Distance within Bay		Cards Left the Golden Gate
			(km)	(miles)	
A	Alameda Flood Control Channel	56	7.4	4.6	No
B/O	Bair Island Ecological Reserve	50*	40.5	25.2	Yes
C	Elsie Roemer Bird Sanctuary	92	31.5	19.6	No
D	San Lorenzo Creek Mouth	27	4.3	2.6	No
E/L	Colma Creek/San Bruno Marsh	112*	44.0	27.3	Yes
F	Cogswell Marsh	33	36.1	22.5	Yes
G	Creekside Park/Hal Brown Park	86	53.3	33.1	Yes
H	Stevens Creek Tidal Marsh	61	60.1	37.3	No
I/T	Arrowhead Marsh/MLK New Marsh	56*	25.4	15.8	Yes
J/S	San Pablo Marsh/Rheem Creek	95*	37.0	23.0	Yes
K/P	Alviso Slough at Coyote Creek	45*	58.5	36.3	Yes
M	San Leandro Marina	46	38.5	23.9	Yes
N	Napa River	21	67.9	42.2	Yes
G	Cooley Landing	30	41.6	25.9	No
R	Corte Madera Creek mouth	45	41.1	25.5	Yes
U	North Marsh	34	21.6	13.4	No

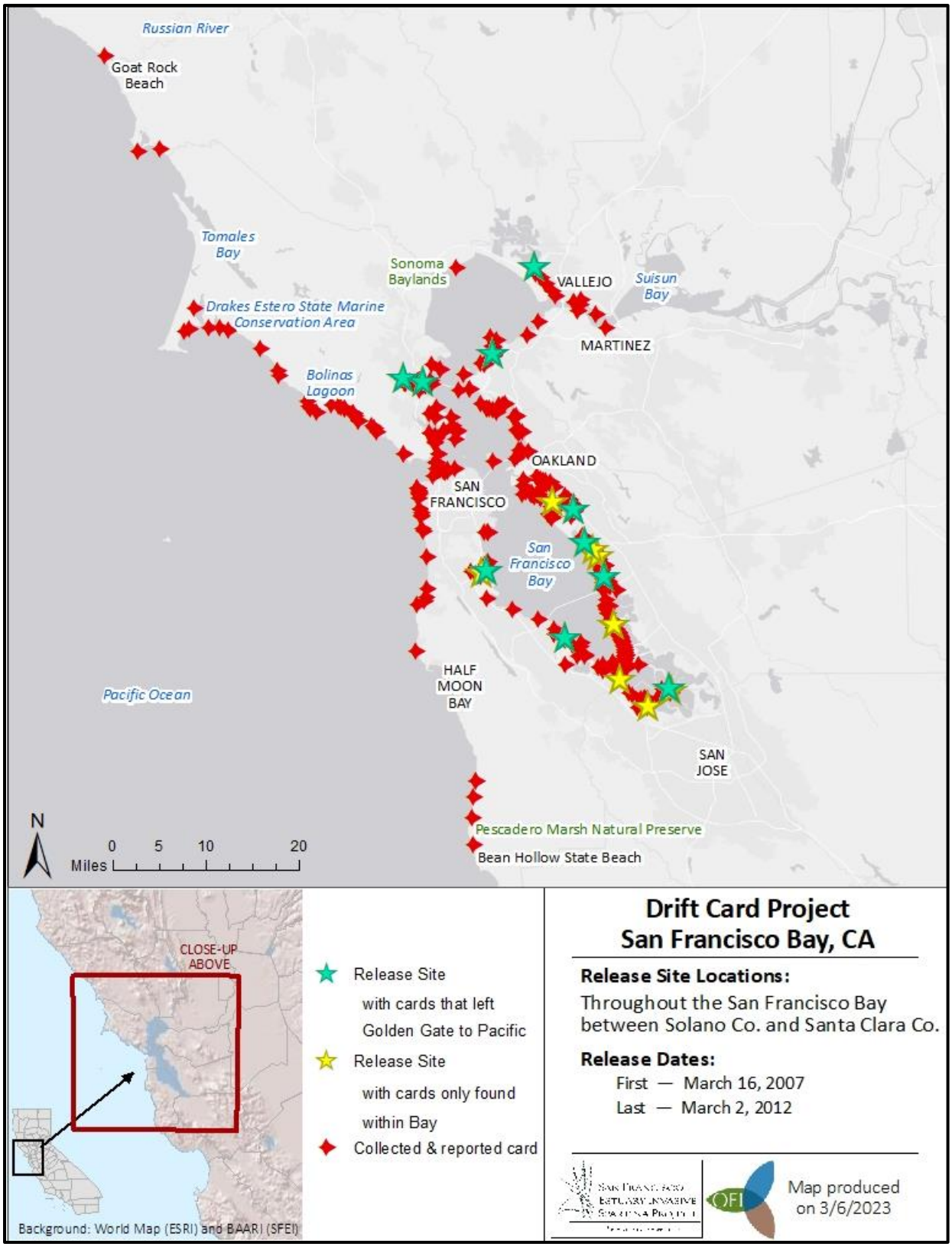

Figure 2. Map with all drift card reporting locations over the course of the study, including outer coast and within the Estuary.

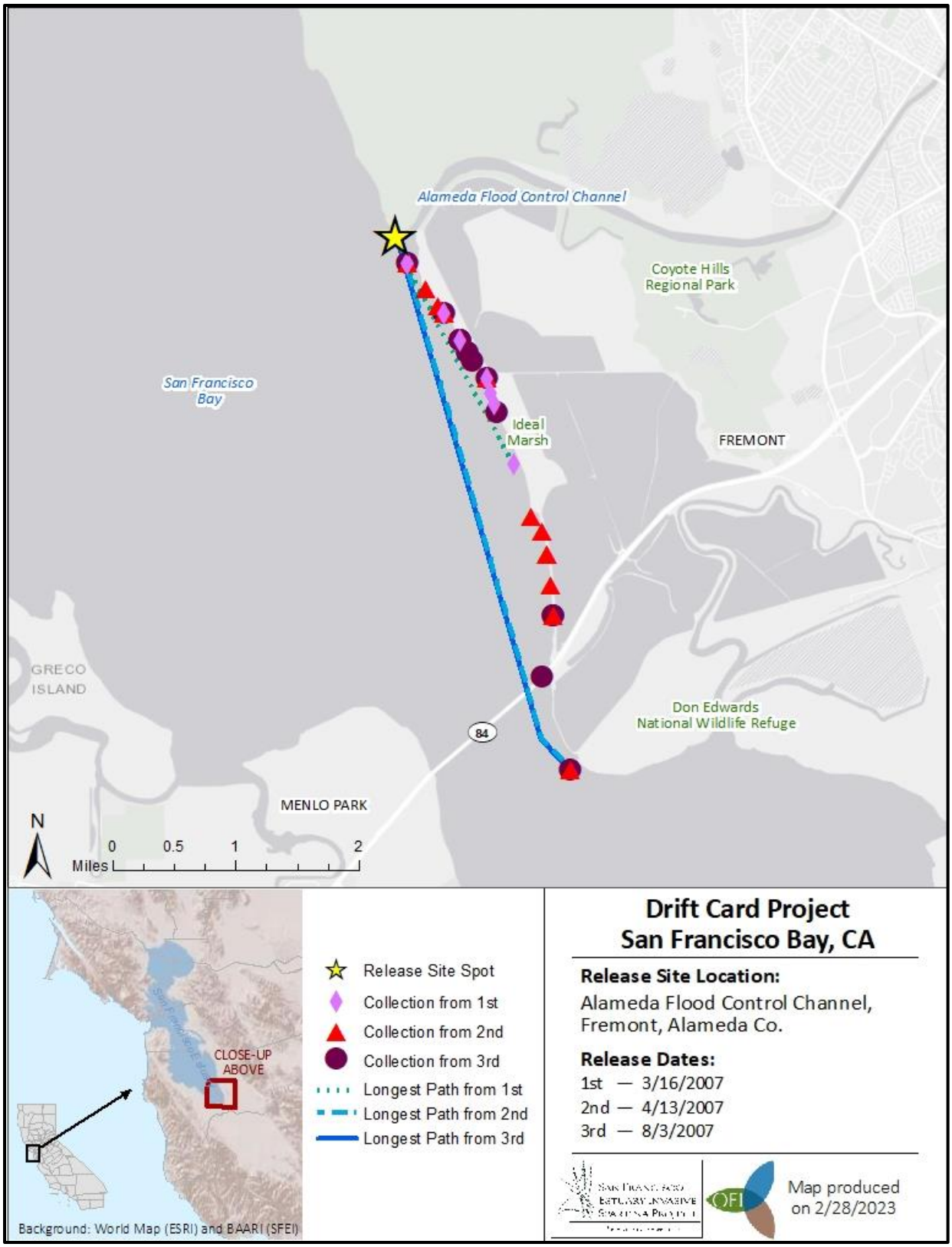

Figure 3. Map of reports from within the Estuary for the Alameda Flood Control Channel release site (Site A).

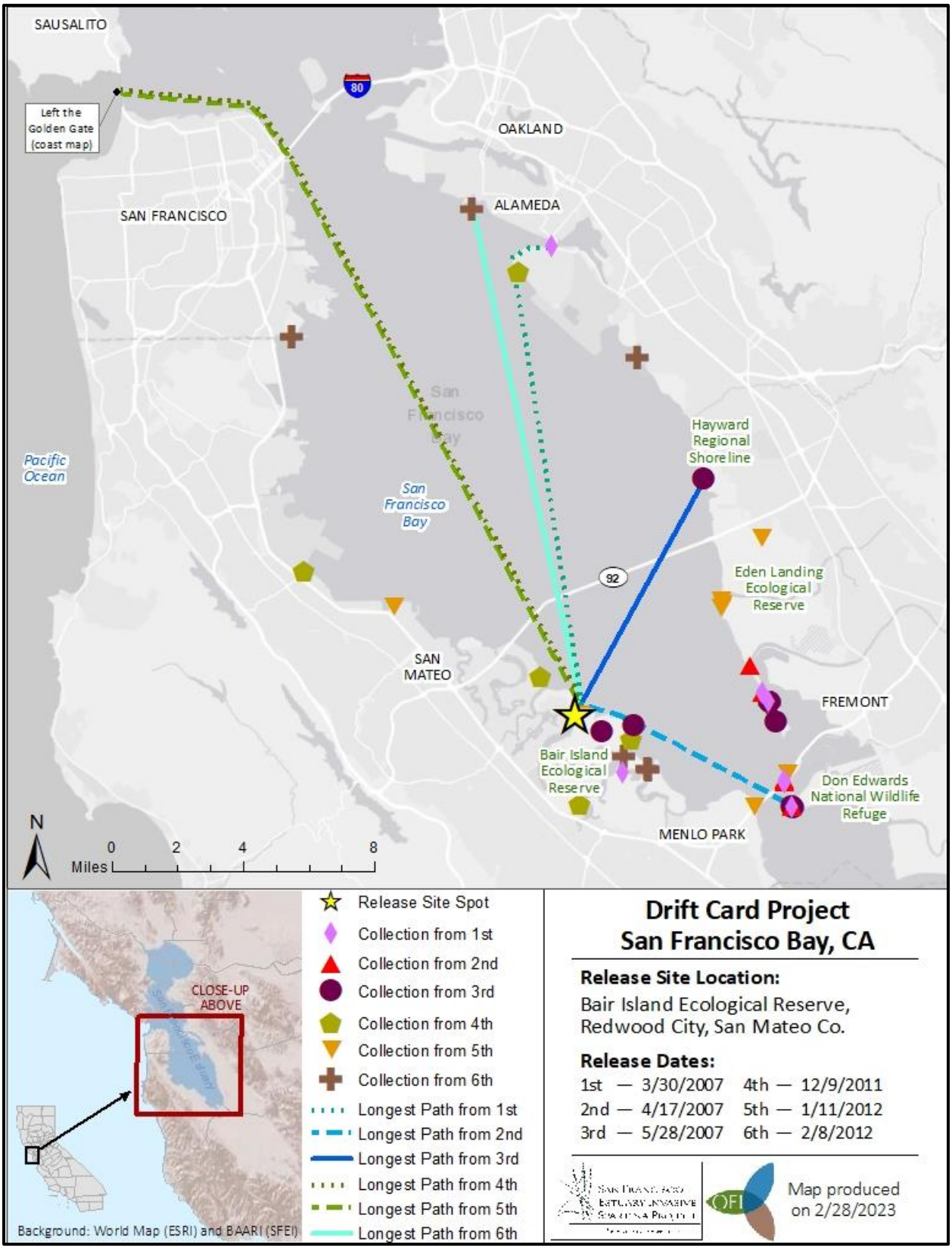

Figure 4. Map of reports from within the Estuary for the Bair Island Ecological Reserve release site (Site B).

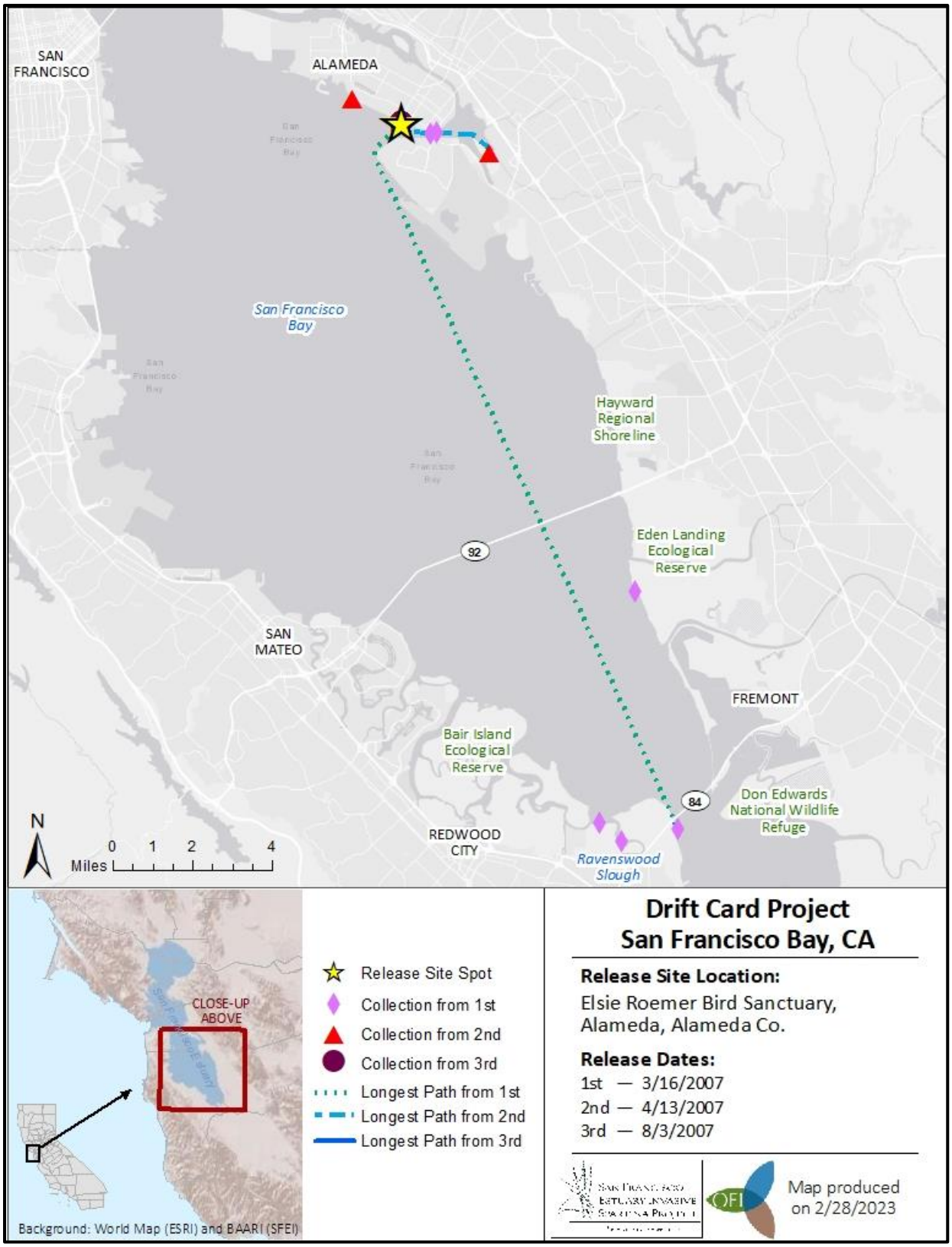

Figure 5. Map of reports from within the Estuary for the Elsie Roemer Bird Sanctuary release site (Site C).

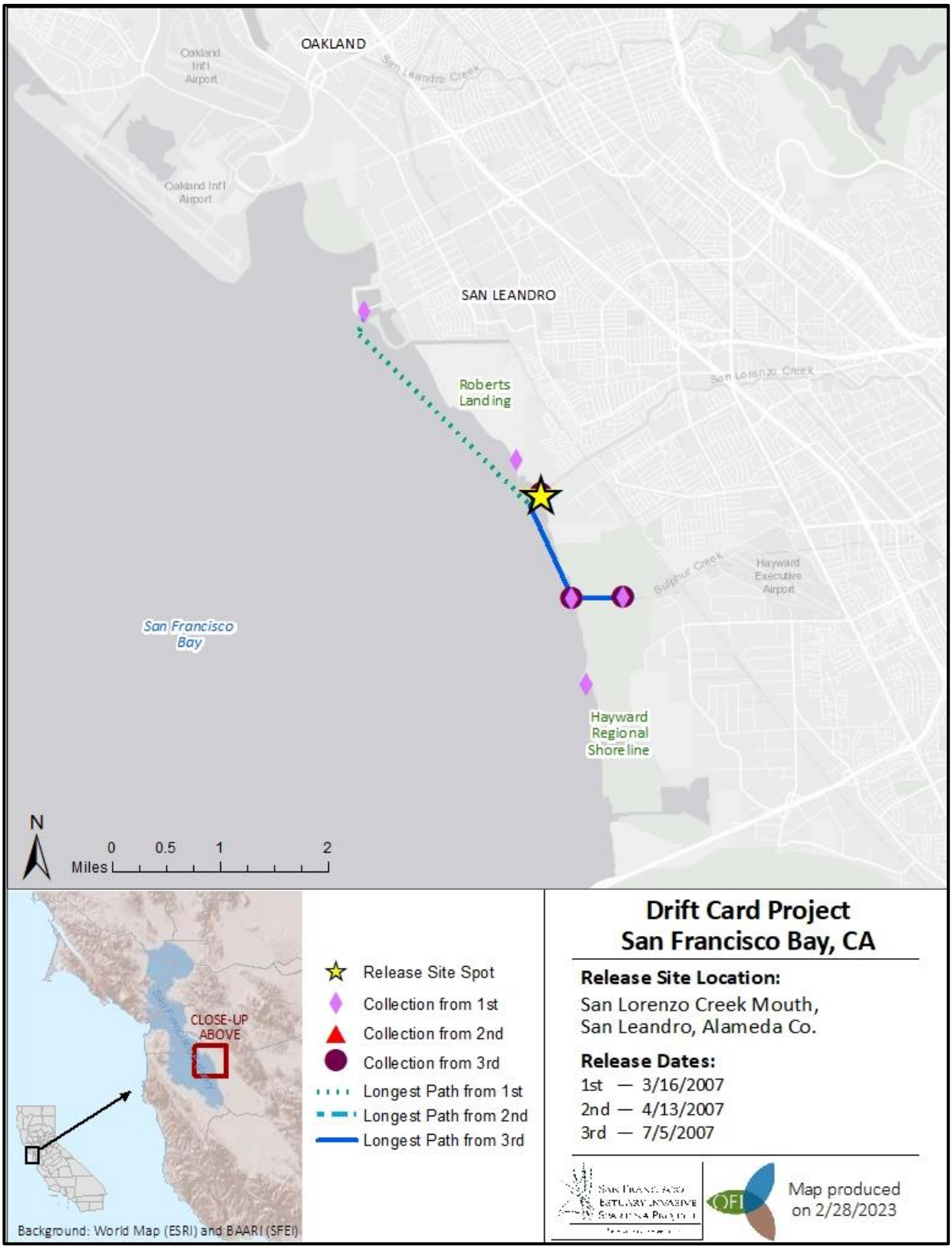

Figure 6. Map of reports from within the Estuary for the San Lorenzo Creek Mouth release site (Site D).

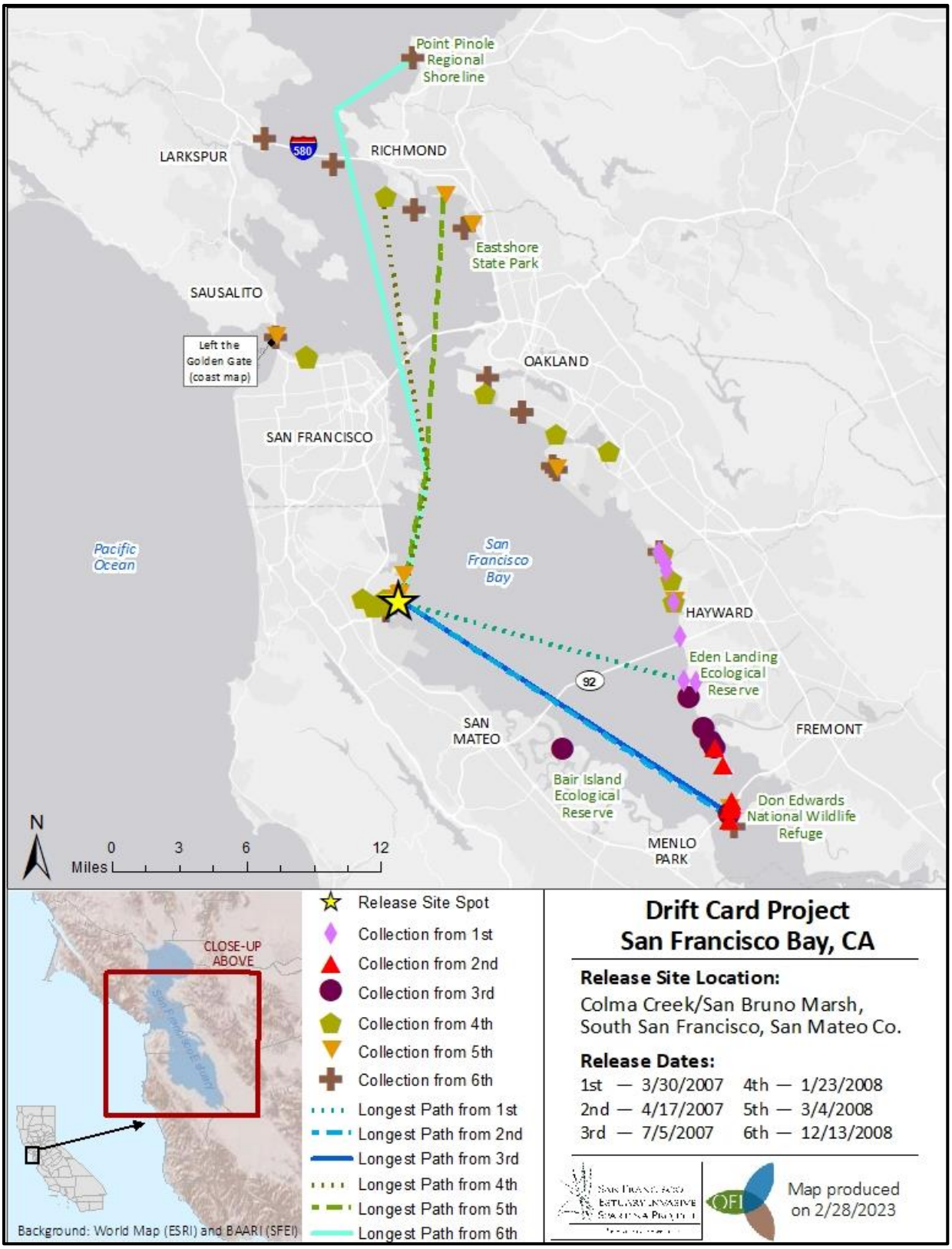

Figure 7. Map of reports from within the Estuary for the Colma Creek/San Bruno Marsh release site (Sites E & L).

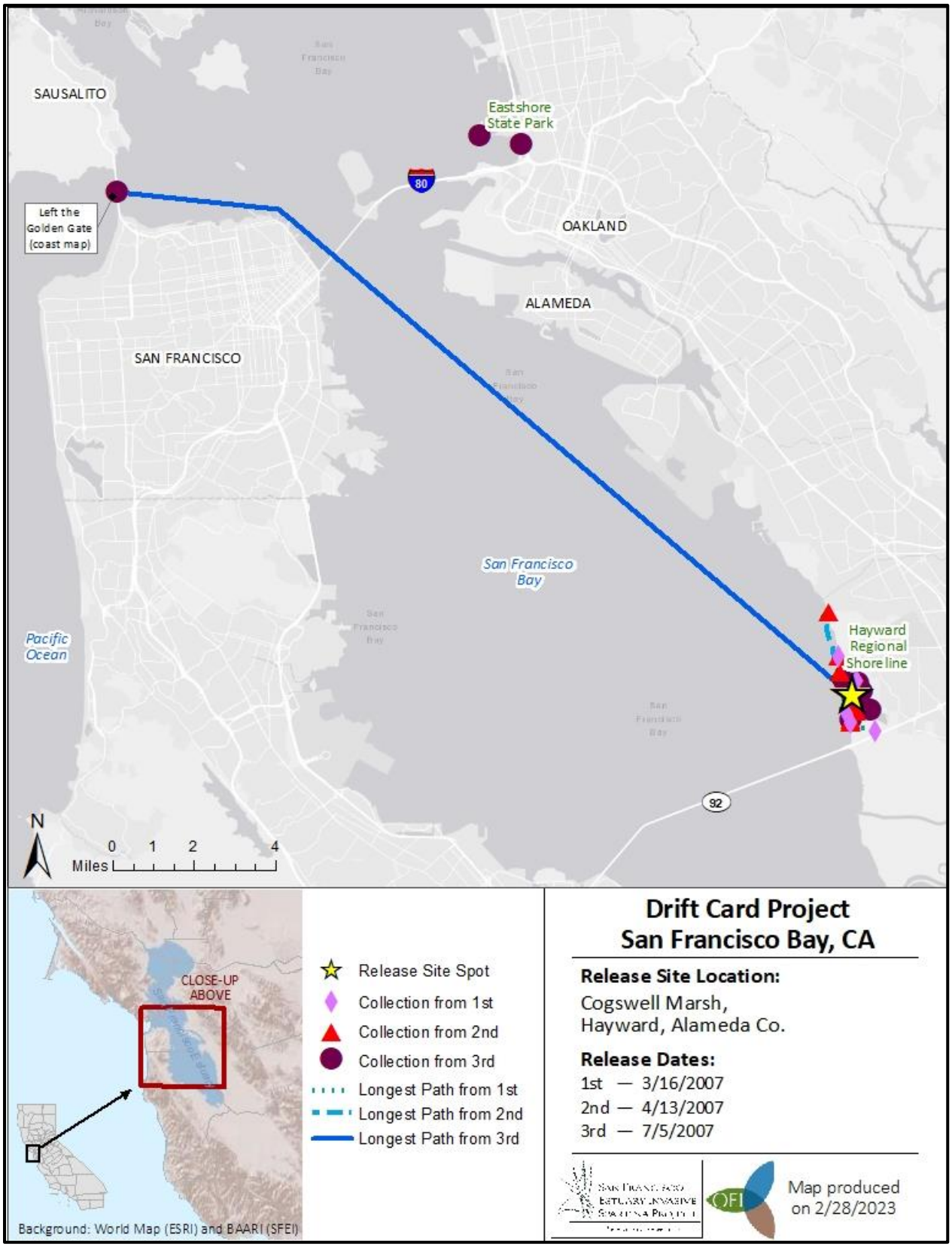

Figure 8. Map of reports from within the Estuary for the Cogswell Marsh release site (Site F).

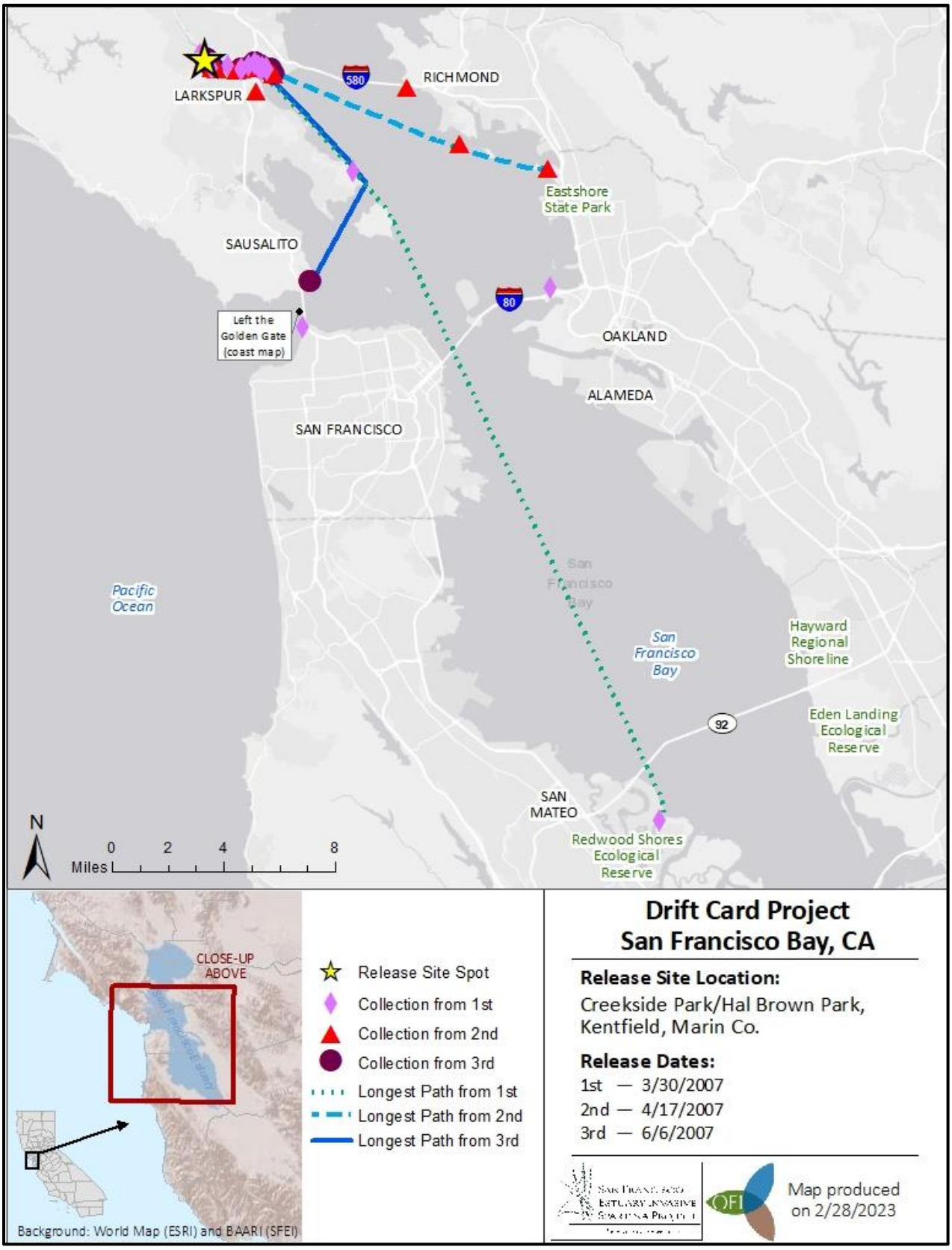

Figure 9. Map of reports from within the Estuary for the Creekside Park/Hal Brown Park release site (Site G).

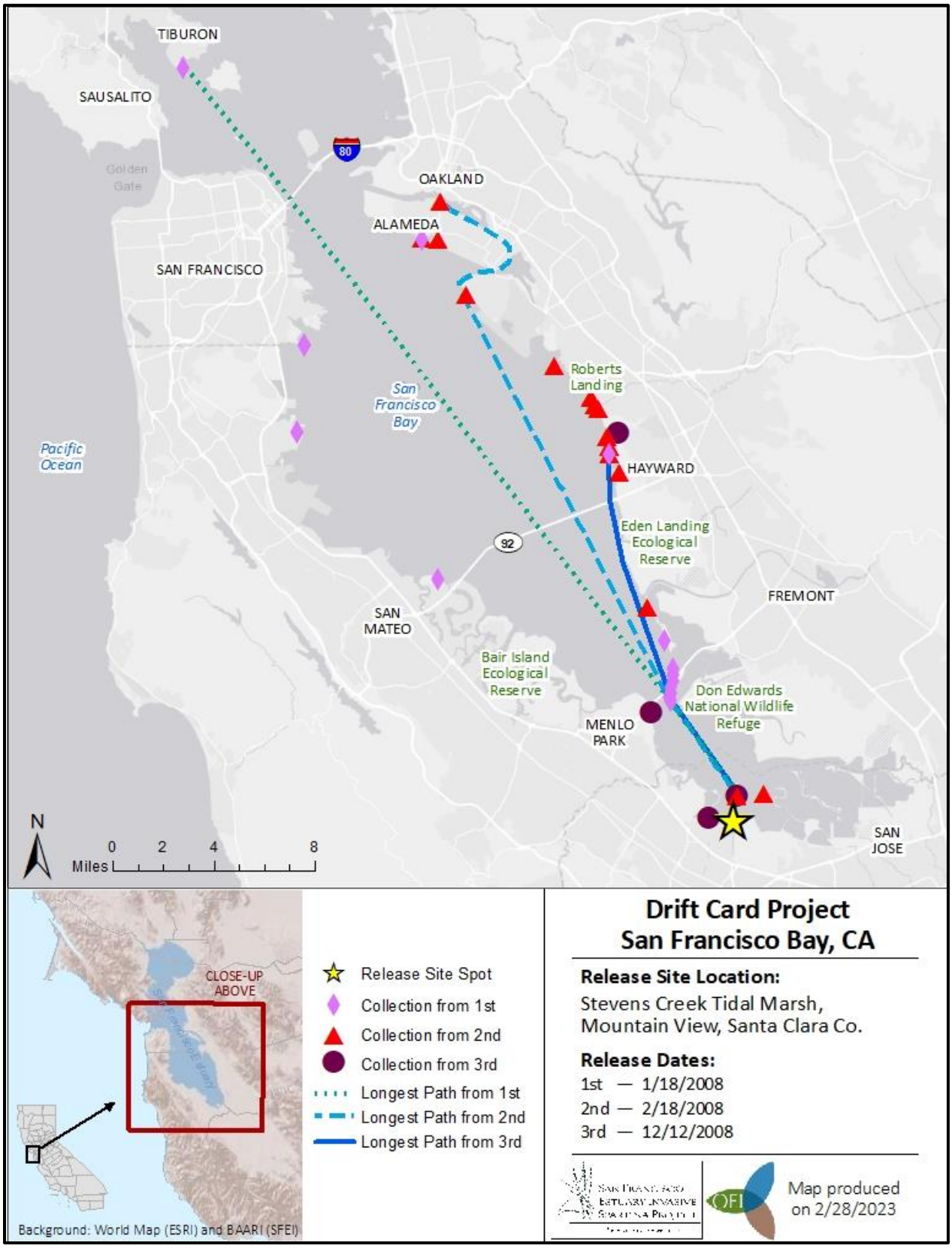

Figure 10. Map of reports from within the Estuary for the Stevens Creek Tidal Marsh release site (Site H).

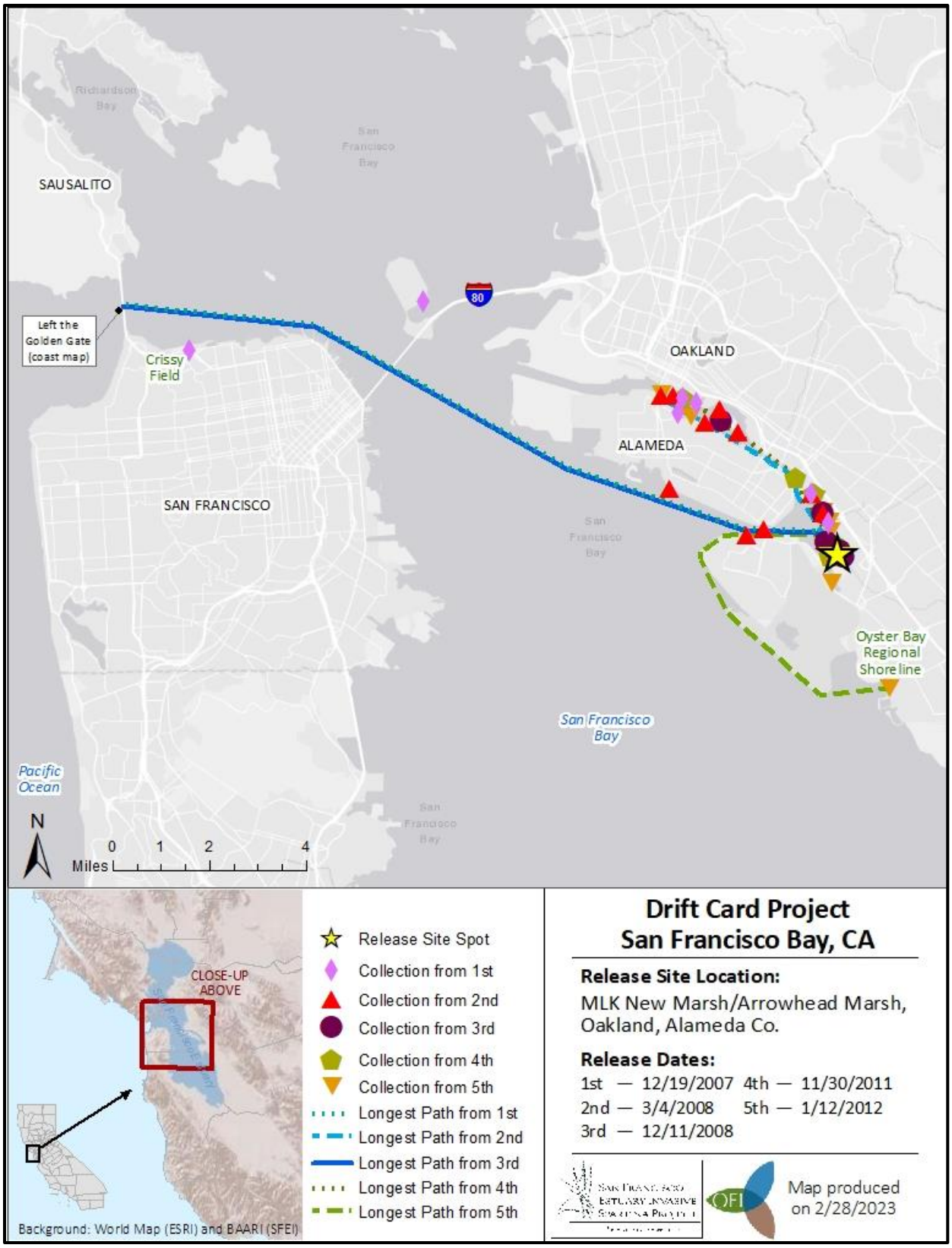

Figure 11. Map of reports from within the Estuary for the MLK New Marsh/Arrowhead Marsh release site (Sites I & T).

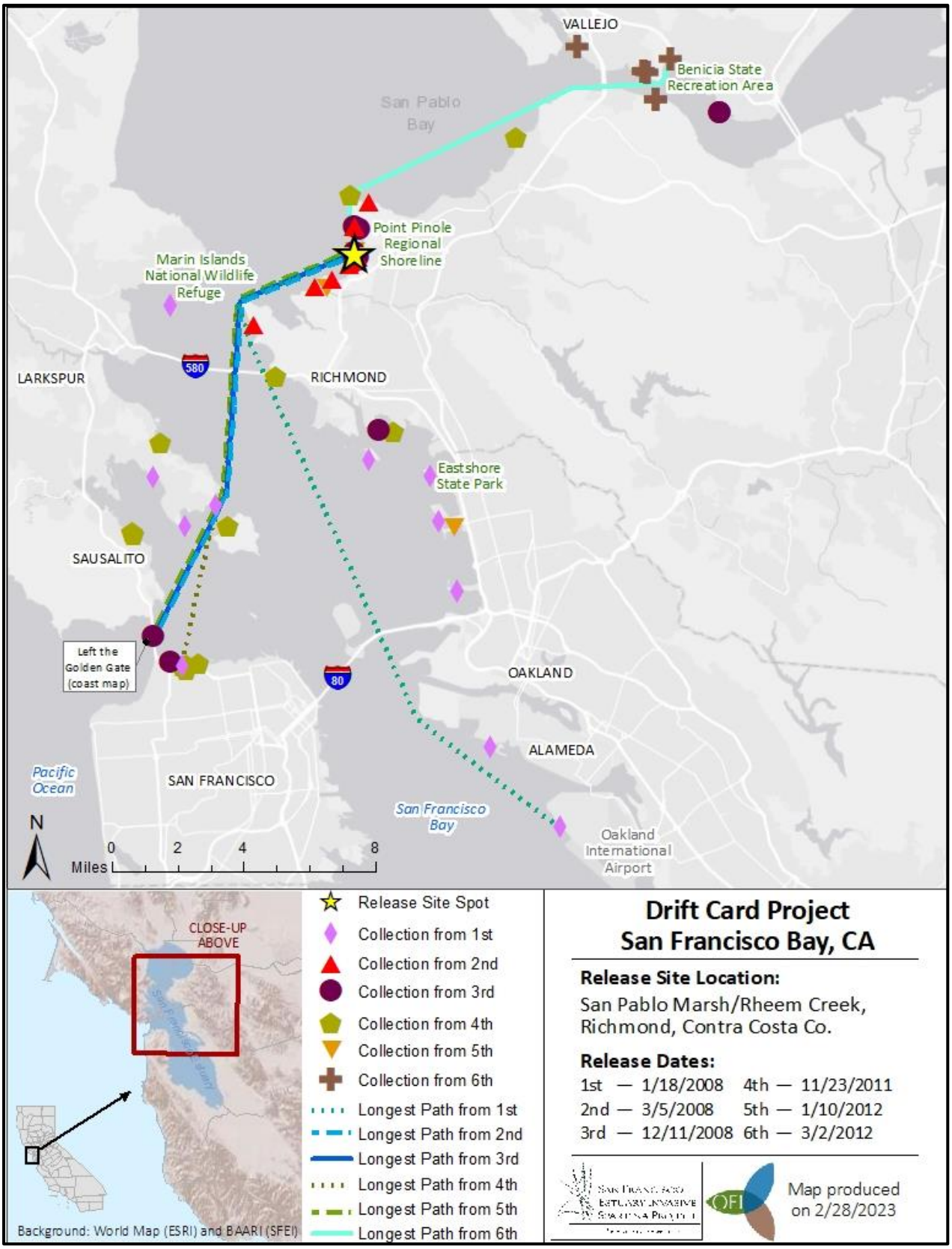

Figure 12. Map of reports from within the Estuary for the San Pablo Marsh/Rheem Creek release site (Sites J & S).

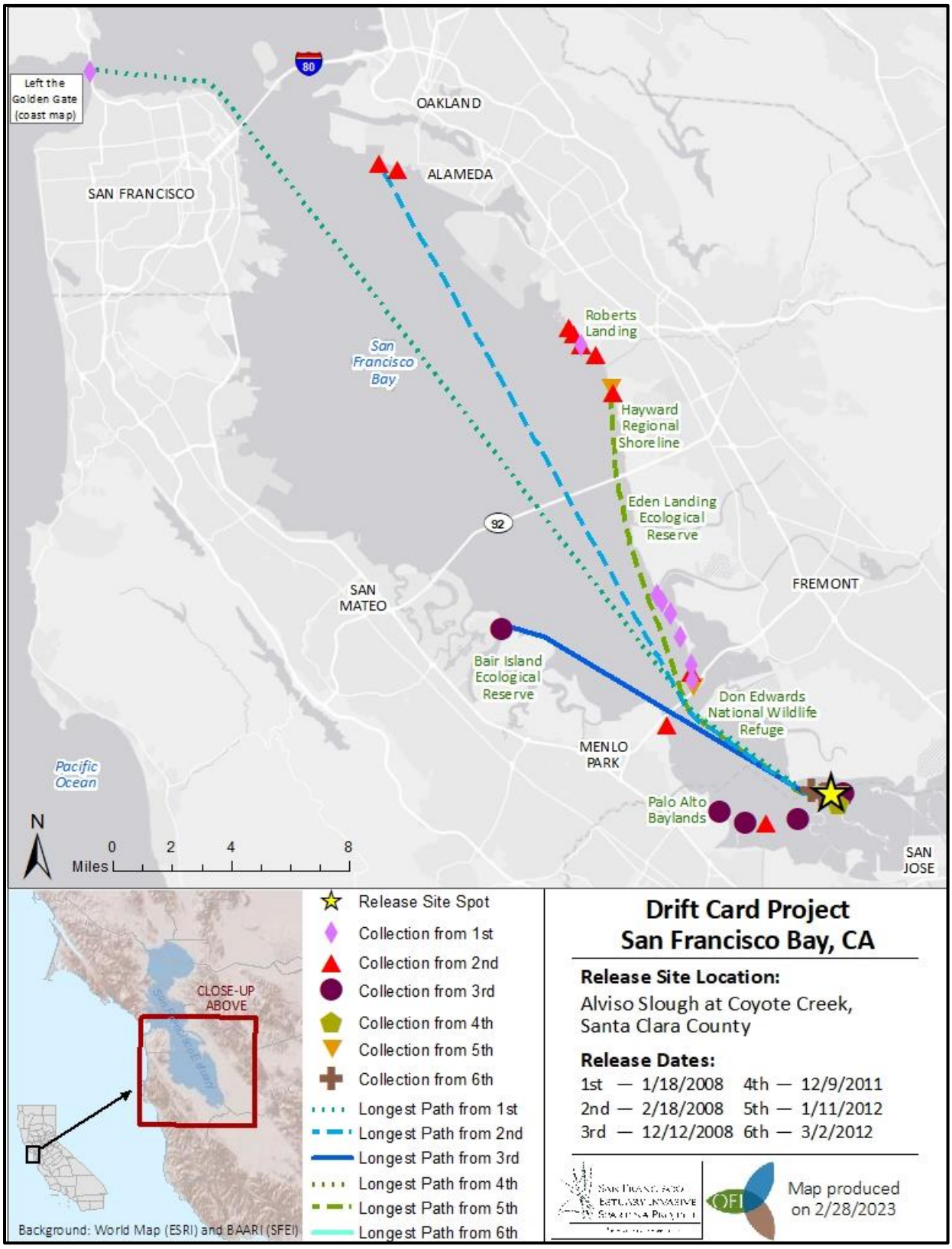

Figure 13. Map of reports from within the Estuary for the Alviso Slough at Coyote Creek release site (Sites K & P).

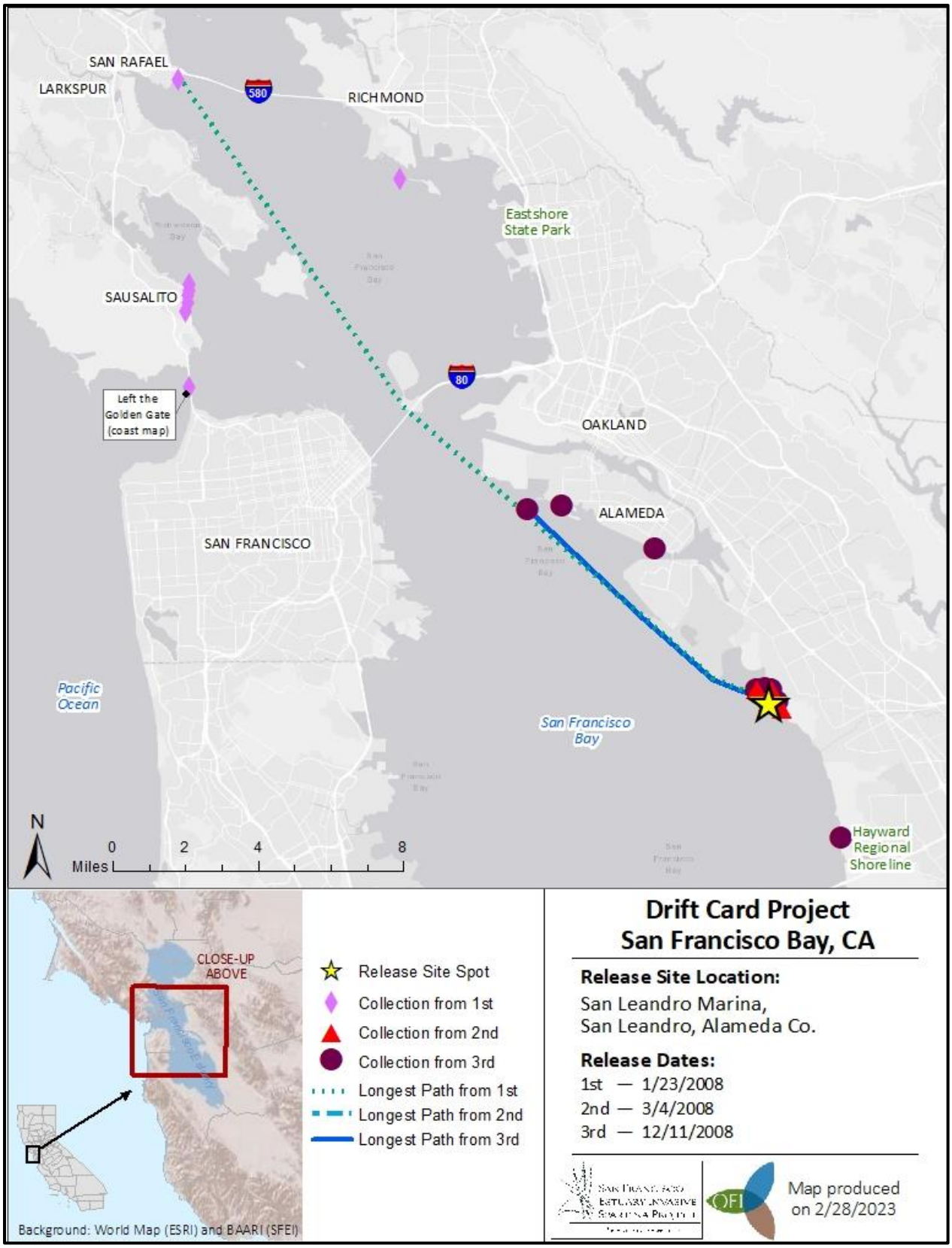

Figure 14. Map of reports from within the Estuary for the San Leandro Marina release site (Site M).

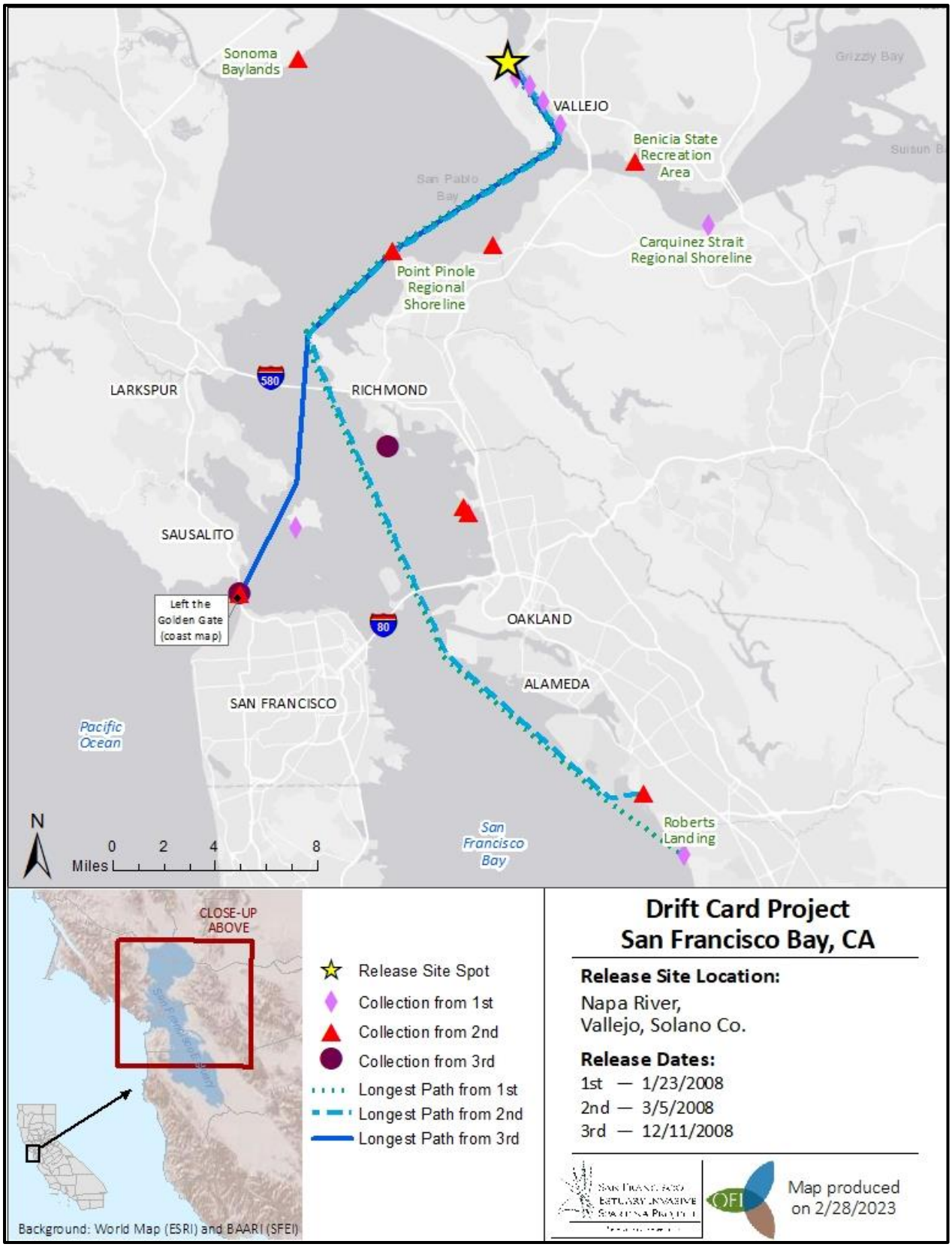

Figure 15. Map of reports from within the Estuary for the Napa River release site (Site N).

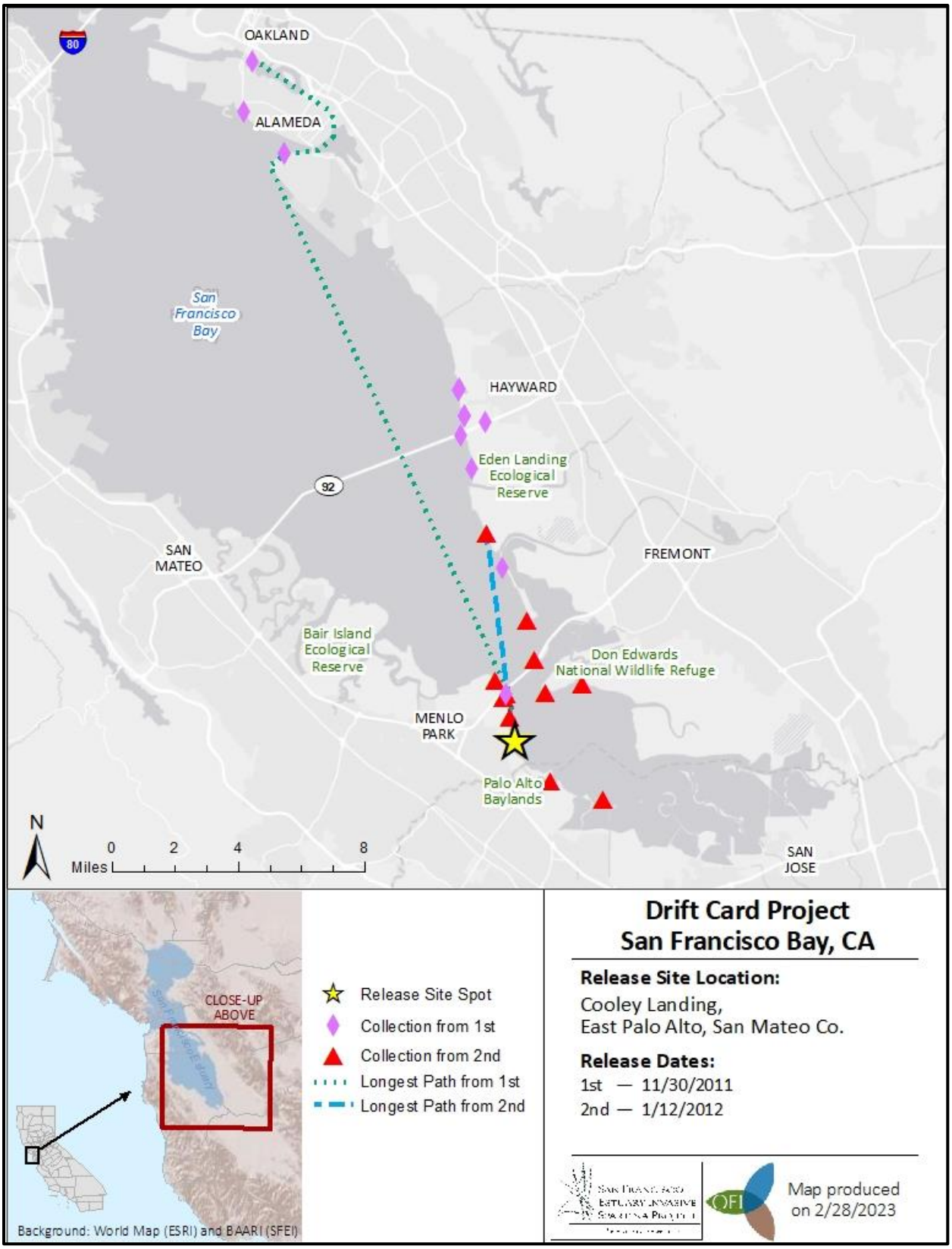

Figure 16. Map of reports from within the Estuary for the Cooley Landing release site (Site Q).

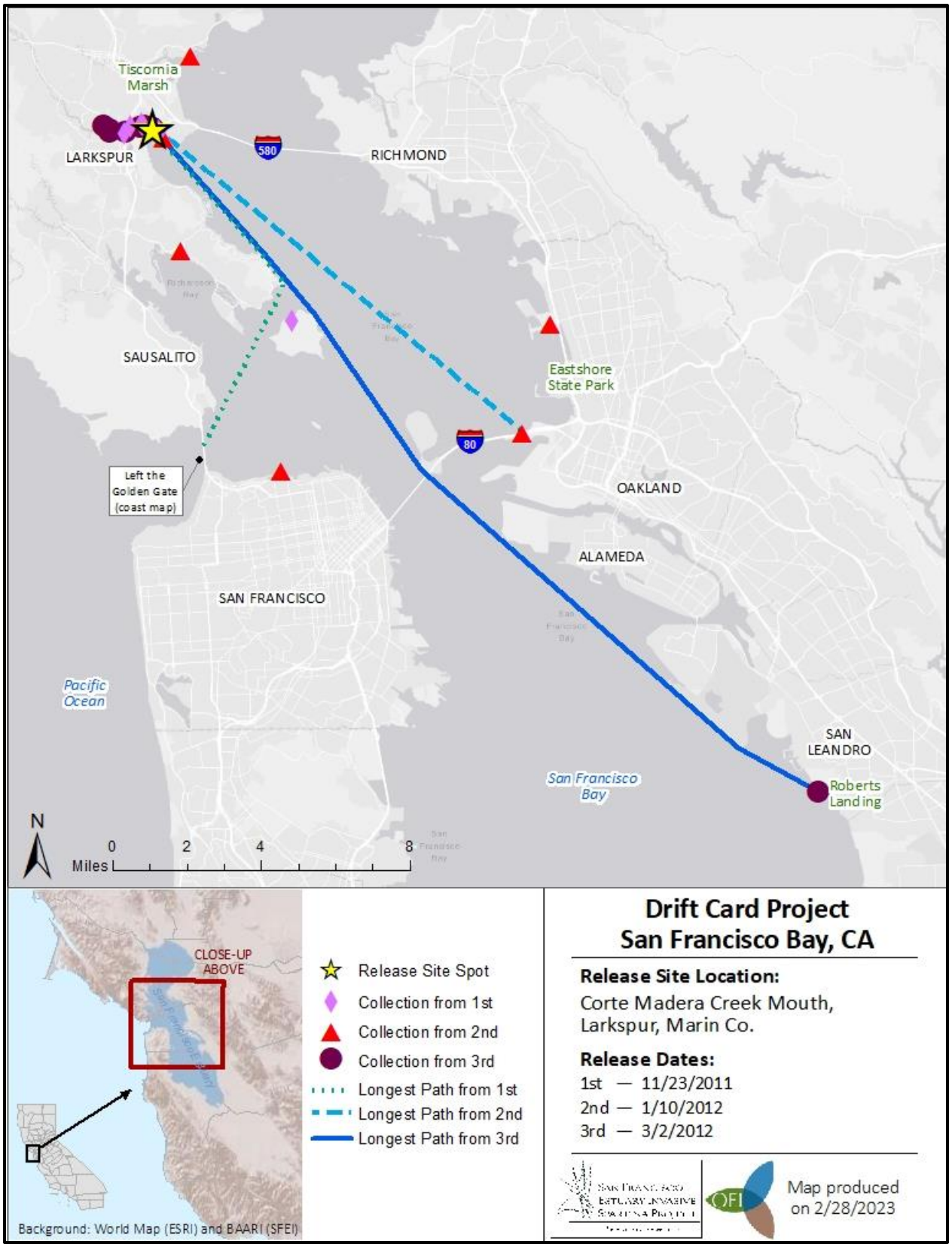

Figure 17. Map of reports from within the Estuary for the Corte Madera Creek Mouth release site (Site R).

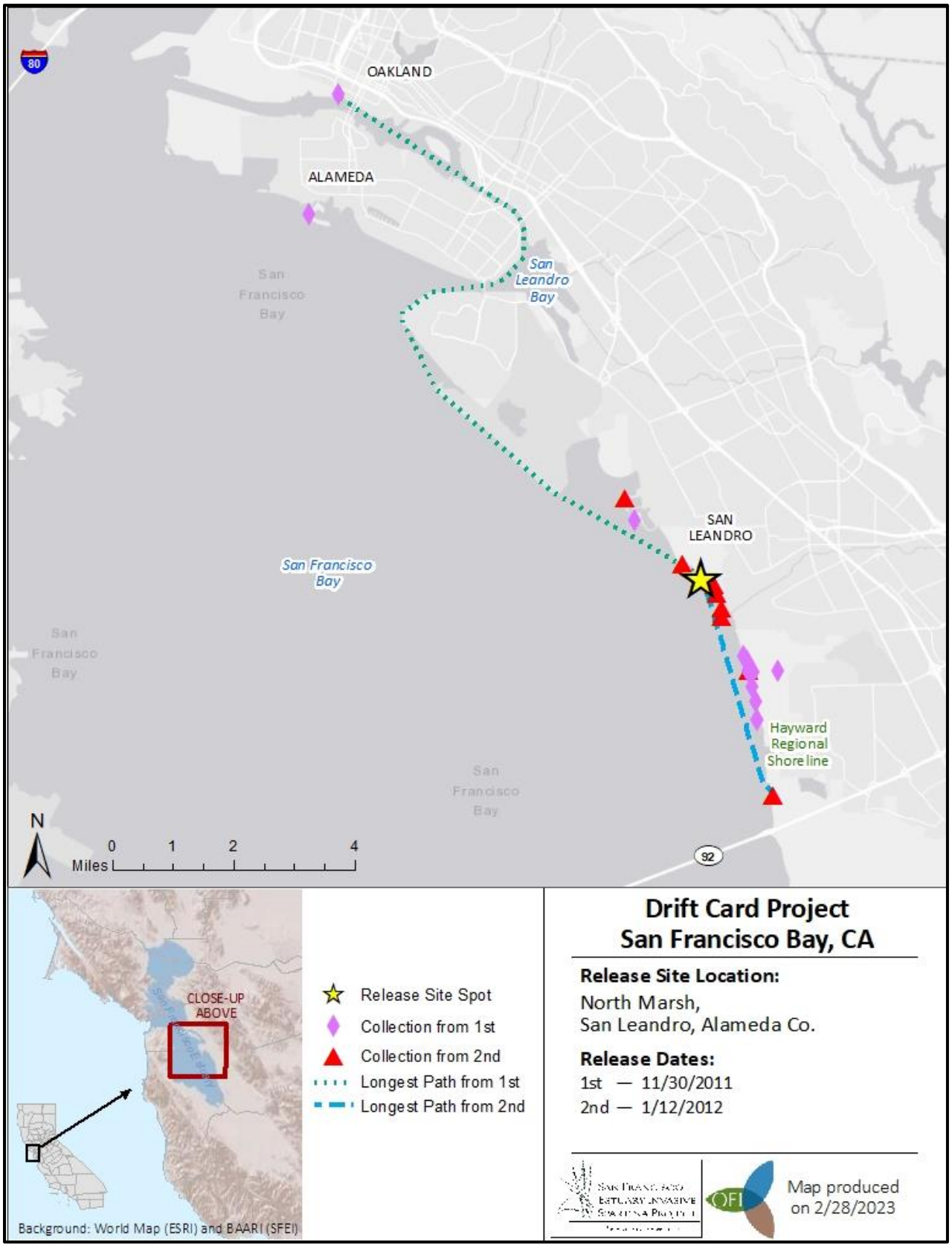
80
OAKLAND
ALAMEDA
San Francisco Bay
San Leandro Bay
SAN LEANDRO
San Francisco Bay
San Francisco Bay
San Francisco Bay
Hayward Regional Shoreline
92
N
0 1 2 4
Miles
CLOSE-UP ABOVE
Release Site Spot
Collection from 1st
Collection from 2nd
Longest Path from 1st
Longest Path from 2nd
Drift Card Project
San Francisco Bay, CA
Release Site Location:
North Marsh,
San Leandro, Alameda Co.
Release Dates:
1st — 11/30/2011
2nd — 1/12/2012
Map produced on 2/28/2023
Background: World Map (ESRI) and BAARI (SFEI)

Figure 18. Map of reports from within the Estuary for the North Marsh release site (Site U).

Discussion

The retrieval rate of 30% for this study is similar to Morgan and Sytsma's (2013) reported retrieval rate of 37% across all sites in their drift card study along the outer coast of Washington, Oregon, and California, despite differences in study designs and environments.

While most of the drift cards from this study were found and/or reported too long after their release to be useful for estimating potential dispersal speeds, some were found at distances far enough from the release site and close enough to the release date to show that they may travel rather quickly. One card from the San Pablo Marsh/Rheem Creek site, retrieved at Crissy Field restoration marsh four days later (Figure 19), traveled at least 6.0 km per day.

When stems from large stands of *Spartina* are senescent in the autumn, they break off at the base of the plant and can form large rafts of wrack that can disperse by floating for several weeks, carrying viable seeds with them (Elsey-Quirk 2009; Sayce et. al. 1997). Considering both the dispersal velocity demonstrated by the drift cards and the long period of viability of floating *Spartina* seeds and wrack, invasive *Spartina* likely has an extensive dispersal range within the Estuary, and potentially an even greater range along the outer coast. Pfauth (2007) found that long distance ocean transport of *Spartina* from California estuaries to Oregon and Washington is possible, especially during El Niño years. In the 1997-98 El Niño event, the current speeds recorded along the west coast could have allowed *Spartina* seeds to travel from Humboldt Bay, California, to Coos Bay, Oregon in 5-8 days.

The reflection of the tide wave in the South Bay causes slack water (zero current) to occur near the high or low tide extremes, whereas in San Pablo Bay slack water occurs one to two hours after the extremes, resulting in the South Bay beginning to flood while San Pablo Bay is still ebbing (Disney and Overshiner, 1925). This may explain why cards released from several northern sites drifted to the South Bay even though they were released on an outgoing tide that could have pulled them through the Golden Gate. Although the actual path between the release and discovery points cannot be known, a drift card may even have been deposited on the shoreline mid-journey and then resuspended by the tide at a later date, to be carried farther to the shoreline where it was discovered and subsequently reported. This may also explain dispersal from San Pablo Bay inland through the Carquinez Strait, if a card released on an ebb tide settled on the shore and was later picked up by a strong flood tide and carried deeper into the Estuary.

Figure 19. Drift card found at Crissy Field restoration marsh by a volunteer during Coastal Cleanup Day.

While releases were conducted on outgoing tides, biologists often conducted several releases in a given day. Not all cards were released right at the moment when the tide transitioned from slack to ebb, which could theoretically enable the longest dispersal as the full volume of water for that tide cycle drained away from the release site. Some cards were released a couple of hours into the ebb cycle, which, along with other factors such as the strength and direction of the wind, may have impacted where they were retrieved. If cards were released late enough in the ebb cycle and didn't move far before the incoming tide began to flood, their dispersal would be mainly driven by flow back into the Bay rather than towards the Golden Gate.

Details by Release Site

Release Site A: Alameda Flood Control Channel (Figure 3)

The restoration marsh Pond 3/Ecology Marsh on the north side of the Alameda Flood Control Channel (AFCC) was the original introduction site for *Spartina alterniflora* in the mid-1970s. Since this drift card release site is at the mouth of one of the major sloughs of the South Bay, we might expect that the large volume of water flowing out with the tide would carry the cards far out into the main currents of the Bay, and therefore that the cards

would travel long distances. However, the cards from AFCC had the second shortest FDD of any release site in the study, just 4.6 miles, and all retrieved cards had travelled south, the opposite direction from the prevailing currents. Almost all reported cards were found in Ideal Marsh, immediately south of the AFCC release site. Cards from two releases reached Audubon Marsh just south of the Dumbarton Bridge, the furthest dispersal recorded from this site. Audubon Marsh, a part of the USFWS Don Edwards National Wildlife Refuge (DENWR), contains high quality habitat for the endangered Ridgway's rail and salt marsh harvest mouse but is also moderately infested with hybrid *Spartina*.

Release Site B (and O): Bair Island Ecological Reserve (Figure 4)

The Bair Island Ecological Reserve includes numerous tidal marshes of widely varying character, from older marshes restored to tidal action after agricultural use in the 1960s, to others that have been restored within the past 7-15 years. Hundreds of acres of some of the highest quality tidal marsh habitat remaining in the Estuary can be found at Bair Island, with hundreds more recently restored acres quickly developing into habitat. Some of the reserve's marshes still contain entrenched infestations of hybrid *Spartina*, and one site (B2 North Quadrant East [2c.1b]) was one of the sites restricted from treatment from 2011-2018. The Bair Island release site was used in two rounds of this study and therefore had six total release events, with a FDD of 25.2 miles traveled within the Bay.

The drift card retrievals for this site show the potential for a single infestation of invasive *Spartina* to disperse propagules to many different locations. Bair Island drift cards were reported from locations throughout much of the region between the San Mateo and Dumbarton bridges, on both the western and eastern shores. North of the San Mateo Bridge, most cards were reported along the eastern shoreline, although a few were found along the western shoreline near San Francisco International Airport (SFO) and Candlestick Point State Recreation Area. Bair Island cards that dispersed along the outer coast were found at Stinson Beach to the north, and at Pescadero Marsh Natural Preserve, 40.6 miles south of the Golden Gate, a journey of at least 65 total miles from the release point and the second furthest southern outer coast dispersal in the study.

One card was found 3.6 km up Mt. Eden Creek at Eden Landing Ecological Reserve in Hayward, just outside some newly breached tidal marsh restoration sites that had little established vegetation at the time, and therefore minimal biotic resistance to an invasive ecosystem engineer like hybrid *Spartina*. This finding again demonstrates the importance of controlling invasive *Spartina* and preventing its dispersal into new restoration marshes, where it could wreak havoc on the restoration project.

Release Site C: Elsie Roemer Bird Sanctuary (Figure 5)

The Elsie Roemer Bird Sanctuary is a narrow strip marsh located on the southwestern shoreline of Alameda Island. It was one of the original introduction sites of the parent species *S. alterniflora,* likely transplanted from AFCC before the hybridization with native *S. foliosa* occurred. The site became heavily infested with hybrid *Spartina* before the start of the ISP but the invasion has now been controlled and is nearly eradicated. Mudflat habitat, important for shorebird foraging, has been reclaimed by successful treatment of the hybrid, and ISP restoration planting has established an expanding band of native *S. foliosa* at the appropriate tidal elevation.

Strong westerly winds were blowing during two of the three release events at Elsie Roemer, preventing numerous cards from dispersing from the site. This public shoreline is heavily visited throughout the year, and the release site had one of the highest card retrieval rates of any site in the study.

Few cards from Elsie Roemer traveled more than a short distance, and no cards were reported from the outer coast. However, several cards from the first release traveled to the far south bay, with a FDD of 19.6 miles. Two cards washed ashore on the shoreline at the mouth of Ravenswood Slough, while another actually floated upstream approximately 1,000 meters into the heart of the slough. It was rare for a card from any site to be reported from an upstream location within a tidal slough as opposed to being found on the Bay shoreline, but this one card demonstrates that even the marsh interior is vulnerable to new hybrid *Spartina* invasions. Ravenswood Slough is the location of substantial Phase II work for the South Bay Salt Ponds Restoration Project, a major investment in restoring tidal wetlands to the Estuary.

Release Site D: San Lorenzo Creek Mouth (Figure 6)

San Lorenzo Creek begins in Castro Valley and drains a highly urbanized watershed, flowing through Hayward and emptying into San Francisco Bay at the southern end of the Roberts Landing tidal marsh complex. Roberts Landing contains multiple tidal marshes that were restored by the mid-1990s, just as hybrid *Spartina* was rapidly establishing and beginning to be recognized as a threat by land managers around the Estuary. Since it would be another decade before the ISP began treatment throughout the Estuary, much of Roberts Landing became heavily infested with hybrid *Spartina*.

Drift cards released at the mouth of San Lorenzo Creek did not travel far in general. This site had the shortest FDD of any in the study, just 2.6 miles, with none leaving the Golden Gate. Some traveled south and were retrieved along Sulphur Creek, at neighboring Oro Loma Marsh, or along other portions of the EBRPD Hayward Regional Shoreline. Fewer cards were reported from points to the north, along the Roberts Landing shoreline and the adjacent San Leandro Marina.

Release Site E (and L): Colma Creek/San Bruno Marsh (Figure 7)

The Colma Creek and San Bruno Marsh complex is located in South San Francisco, immediately north of SFO airport. Prior to the invasion of hybrid *Spartina*, the tidal plant habitat in the complex was limited to a narrow strip marsh along the Bay shoreline and the vegetated banks of Colma and San Bruno Creeks, two engineered channels that flow through light industrial and commercial development. In an illustration of its capacity as an ecosystem engineer, colonization by hybrid *Spartina* led to the establishment of a meadow of tall, invasive cordgrass on the mudflats and subsequent rapid sediment accretion, much as it did at Elsie Roemer (discussed above). Treatment by the ISP eliminated these monocultures of the invasive plant along the channels and shoreline, and all eight sub-areas in this site complex were at Zero Detection status in 2022. The ISP has reintroduced native *S. foliosa* to the site and a continuous band is getting established along the fringe of San Bruno Marsh at the appropriate elevation, while the adjacent mudflats have been restored to their natural unvegetated state that provides shorebird foraging habitat.

Colma Creek/San Bruno Marsh was a release site for two rounds of the study and had the most cards reported (112) of any site, dispersed over a large area of the Estuary, with an FDD of 27.3 miles. Within the Bay, cards were found as far as south and east as DENWR below the Dumbarton Bridge, and as far north as Point Pinole

Regional Shoreline beyond the Richmond-San Rafael Bridge. Only one card was reported from the western shoreline south of the release site, at Belmont Slough mouth in Redwood Shores Ecological Reserve. By contrast, reports were fairly evenly distributed along the eastern shore, from Audubon Marsh to Roberts Landing, Oakland International Airport, and Alameda Island.

Cards from this site dispersed remarkably far into the North Bay. Overall, relatively few cards released in the South Bay were found north of the Golden Gate. Of those, most were found outside the Golden Gate or in that general vicinity. But cards from Colma/San Bruno dispersed further north to Eastshore State Park in Albany and Richmond on multiple releases, and even as far as San Rafael on the Marin shoreline and Giant Marsh in Point Pinole. One card was retrieved from the restoration site at Crissy Field in San Francisco. Two cards travelled up Colma Creek from the release site, and one was found west of Hwy 101, which is near the upper limit of the historic infestation of hybrid *Spartina* in this channel.

Multiple cards from Colma/San Bruno were found north of the Golden Gate at Rodeo Lagoon in Golden Gate National Recreation Area (GGNRA), Stinson Beach, Bolinas, and several retrievals in Point Reyes National Seashore, including the mouth of Drakes Estero. Others were found south of the Golden Gate, including the furthest dispersal in this direction for the entire study, 42.6 miles (68.6 km) from the Golden Gate to Bean Hollow State Beach along the San Mateo coast.

Release Site F: Cogswell Marsh (Figure 8)

Cogswell Marsh is located within the EBRPD Hayward Regional Shoreline and contains an older restoration marsh that was breached in the 1980s. This marsh had not developed much biotic resistance to hybrid *Spartina* invasion by the time it was spreading vigorously in the 1990s, so it became heavily infested. The invasion created a monoculture that excluded the desired native plant assemblage. Notably absent was marsh gumplant (*Grindelia stricta*), an important habitat feature that provides cover for Ridgway's rail and other wildlife. As invasive *Spartina* was brought under control, the ISP began active restoration planting that has since established extensive stands of gumplant along marsh channels. There have been various levels of treatment restrictions at Cogswell Marsh since 2011, and restoration with *S. foliosa* plantings has not begun.

Strong prevailing onshore winds likely skewed the results for this site towards short-distance dispersal. The majority of cards were reported from locations along the East Bay shoreline very close to the release site. A few cards traveled farther, including several to Eastshore State Park at Emeryville Crescent, and even to the outer coast at Ocean Beach south of the Golden Gate.

Several cards dispersed a short distance southward to HARD Marsh, located immediately north of the San Mateo Bridge. HARD Marsh has been a *S. foliosa* re-introduction site for the ISP after virtually eradicating hybrid from the site. However, despite the circuitous route propagules must take a to get into HARD Marsh, it was always suspected that untreated stands of hybrid *Spartina* in neighboring Cogswell were exporting propagules that were re-infesting this restoration site and corrupting meadows of native *S. foliosa*. The drift cards demonstrated this dispersal could certainly have occurred, and future restoration work planned for Hayward Marsh will need to be carefully monitored to prevent further re-infestation of HARD Marsh until hybrid *Spartina* is fully eradicated from Cogswell Marsh.

Release Site G: Creekside Park/Hal Brown Park (Figure 9)

Creekside Park (renamed Hal Brown Park in 2010) is located in Kentfield approximately 3.8 km (2.4 miles) upstream from the mouth of Corte Madera Creek. It is the site of the original introduction of invasive *Spartina densiflora* (Chilean cordgrass) in the 1970s, from where it spread throughout the Corte Madera Creek watershed, reaching shorelines of Solano and Contra Costa Counties, and Tomales Bay, 50 miles north of the Golden Gate. A smaller infestation established in San Mateo County at Sanchez Marsh and Burlingame Lagoon, but, due to its distance from Corte Madera Creek and other North Bay infestations, it was often assumed to be an independent introduction.

Most drift cards from Creekside Park washed ashore along the banks of the creek channel in the lower watershed or into Corte Madera Ecological Reserve marsh, adjacent to the creek mouth. However, some cards from all three releases also traveled much further, across to the East Bay, landing at sites like Eastshore State Park (site of a small *S. densiflora* infestation, now eradicated) and Brooks Island Regional Preserve. Numerous cards were found on the outer coast south of the Golden Gate, on Baker Beach and as far as Fort Funston and Mussel Rock.

The FDD from this release site (33.1 miles) was to the mouth of Belmont Slough in Redwood Shores Ecological Reserve, south of the San Mateo Bridge. Interestingly, this is seven miles south of the infestation at Sanchez Marsh/Burlingame Lagoon, demonstrating the possibility of a North Bay source for that invasion.

However, drift cards more closely mimic a small floating raft of detritus than individual seeds, and *Spartina densiflora* does not create large rafts of wrack to transport seeds longer distances. It is odd that, if the Sanchez/Burlingame infestation was established by seeds from Creekside Park, no other “stepping stone” infestations of *S. densiflora* were found in the South Bay between these sites. On the other hand, no other drift cards from Creekside Park were reported between the North Bay and Sanchez Marsh, either. Such long-distance dispersal to the South Bay may be a rare occurrence.

Release Site H: Stevens Creek Tidal Marsh (Figure 10)

Stevens Creek Tidal Marsh is a small, 28-acre brackish marsh located approximately one mile upstream from the mouth of Stevens Creek in Mountain View, adjacent to the Shoreline Amphitheatre. Very few cards were reported from close to this release site; one got caught in a flood tide and pushed far upstream along the adjacent Permanente Creek, another traveled east towards Guadalupe Slough. But most caught the ebb tide and traveled much further north along the eastern shoreline, with only a handful skirting along the western side. Numerous cards were reported from the shoreline of DENWR, a constriction point at the Dumbarton Bridge that can act as a strainer, catching floating objects as they drift by. Most cards were found on the Hayward or Roberts Landing shorelines in the East Bay. One long-distance traveler from the second release drifted into Oakland Inner Harbor, probably on a circuitous route over the course of many tide cycles to float around the northern or southern end of Alameda Island.

While this site had one of the longest FDD of any in the study (37.3 miles), no cards were reported leaving the Golden Gate. The one card that was reported from north of the Bay Bridge was found on the tip of the Tiburon Peninsula in Marin.

Release Site I (and T): MLK New Marsh/Arrowhead Marsh (Figure 11)

MLK New Marsh and Arrowhead Marsh are two adjacent tidal marsh sites within San Leandro Bay in Oakland. They are fragmented from other tidal marsh habitat of the Estuary, surrounded by hardscape and commercial development. MLK New Marsh was a mitigation site for Port of Oakland airport construction that was opened to tidal exchange in 1998, and quickly became dominated by hybrid *Spartina* from propagules spreading from neighboring heavy infestations such as Arrowhead Marsh and Elsie Roemer.

Despite being included in two rounds of this study and therefore getting six releases, very few cards traveled far from the site. This may be because the release point was in the channel along the eastern flank of Arrowhead's triangular marsh that juts out in San Leandro Bay. The majority of cards therefore skirted along the eastern edge of Arrowhead and drifted up into Oakland Inner Harbor rather than exiting San Leandro Bay via the channel between Bay Farm Island and Alameda. Oakland Inner Harbor is heavily developed and hardscaped, with numerous edges that could catch a drift card.

Some cards managed to reach the outer coast, highlighting the potential for hybrid *Spartina* to spread from the several sites in San Leandro Bay that are restricted from treatment. Cards from Arrowhead/MLK New Marsh were found at Muir Beach in Golden Gate National Recreation Area (GGNRA), Stinson Beach by Bolinas Lagoon, Land's End just outside the Golden Gate, and at the Crissy Field restoration marsh on the San Francisco shoreline.

The card that traveled the longest distance from the fifth release took an unlikely route of drifting south and east into Oyster Bay Regional Shoreline, another EBRPD marsh where hybrid *Spartina* has been virtually eradicated by the ISP partners. These longer-distance drift cards demonstrate the potential for untreated infestations in San Leandro Bay to be sources of invasive *Spartina* that can reach new sites and re-infest sites that are open for treatment by the ISP.

Release Site J (and S): San Pablo Marsh/Rheem Creek (Figure 12)

San Pablo Marsh and the fringe marsh along the shoreline at the mouth of Rheem Creek are located just south of Point Pinole Regional Shoreline in Richmond. These marshes are tucked behind the Point San Pablo peninsula, protected from the full wind and wave action of neighboring Point Pinole. By the time the ISP began fully surveying and mapping this area several years into the project, the mudflats of the cove adjacent to the marsh already harbored a dense meadow of hybrid *Spartina*, with many large circular clones expanding out onto the mudflats and starting to coalesce into meadows, while the mouths of all the tidal channels of San Pablo Marsh were stuffed with invasive cordgrass.

Drift card reports from this site on the eastern shoreline illustrate the "stepping stone" model of dispersal, when the invasive plant colonizes and disperses from new locations further and further from the original introduction site at the leading edge of the infestation. Drift cards show this site's potential for dispersing propagules farther upstream into the Estuary. Multiple cards were eventually caught by an incoming flood tide and pushed northeast, through the Carquinez Strait towards the Delta. Some cards were retrieved from the Benicia State Recreation Area (BSRA), where the ISP has been working with California State Parks to eradicate the historic infestation of hybrid *Spartina* at Southampton Marsh. These reports demonstrate one potential pathway of introduction to this remote location.

Many other cards were caught by the outgoing tide and traveled in the expected direction towards the Golden Gate. While several cards drifted south of the Bay Bridge into the Central Bay, most were reported from the eastern or western shoreline of the North Bay, or from numerous locations on the outer coast. Within the Bay, cards were found on the Marin Island National Wildlife Refuge, Angel Island, and in the area of the Crissy Field restoration. Outside the Golden Gate, some cards ended up to the south, on Ocean Beach in San Francisco and Shelter Cove Beach near Pacifica. Cards that traveled north were reported from some very high quality tidal marsh resources, including Stinson Beach adjacent to Bolinas Lagoon, Limantour Estero and Duxbury Reef within Point Reyes National Seashore, and Bodega Bay. Some of these sites are sheltered tidal systems that are extremely vulnerable to invasion from hybrid *Spartina,* and could be completely transformed from shallow mudflats that are essential habitat for shorebirds and harbor seals into vegetated monocultures of cordgrass.

A card from San Pablo Marsh/Rheem Creek had the furthest northern outer coast dispersal of the entire study, 64.7 miles (104.1 km) to Goat Rock Beach at the mouth of the Russian River near the town of Jenner, just under 80 miles from the release site.

Release Site K (and P): Alviso Slough at Coyote Creek (Figure 13)

The release site at the confluence of Alviso Slough and Coyote Creek was used in two rounds of this study, totaling six releases. The site was selected as a truck-accessible proxy for nearby Calaveras Marsh, the largest hybrid *Spartina* infestation in the far south bay at the time but also a remote site that is best accessed by airboat. The release point was on the northern shoreline of Knapp Tract, which has since been breached to tidal exchange and is no longer accessible by truck. Several other large restoration marshes in this area, including the Island Ponds (A19-A21), have since been opened to tidal exchange, and thus the threat of hybrid *Spartina* infestation, as part of the South Bay Salt Pond restoration project. These sites are quickly maturing into high quality tidal marsh habitat, with A21 already supporting Ridgway's rail ahead of the predicted timeline.

Despite this release site being in the far South Bay and the farthest from the Golden Gate, giving the cards ample opportunity to be influenced by the currents that flow generally northwest, almost no cards were reported from the western shoreline. Virtually all of the cards remained near the eastern shoreline of the bay as they drifted northward. Multiple cards were reported from the DENWR area and up to AFCC, another cluster of cards were retrieved along the Roberts Landing shoreline, and some were caught by Alameda Island where it juts out into the Bay. Only a couple of cards were reported from the western shoreline, at Ravenswood Open Space by the Dumbarton Bridge and Steinberger Slough by Bair Island Ecological Reserve. The FDD for the site was 36.3 miles, and cards did leave the Golden Gate, including a report from Pacifica State Beach that required the card to travel an estimated additional 15 miles (24.0 km) south once reaching the Pacific Ocean. Besides the cards that reached the outer coast, no cards were reported north of the Bay Bridge.

Release Site M: San Leandro Marina (Figure 14)

San Leandro Marina is located at the north end of the Roberts Landing tidal marsh complex that also contains San Lorenzo Creek mouth. Despite being released from the end of the protective jetty that stretches into the Bay, most cards from the second and third releases were found on shorelines close to the marina, probably due to onshore windy conditions on those days. Cards from the first release told a much different story, with many cards traveling north of the Bay Bridge to be found on the Marin and Richmond shorelines. The FDD was 23.9 miles to the western landfall of the Richmond-San Rafael Bridge.

Numerous cards from San Leandro Marina were reported from areas of the outer coast with high ecological value and regional significance. Cards were reported from Muir Beach in Golden Gate National Recreation Area (GGNRA), Stinson Beach, and even the interior of the highly vulnerable Bolinas Lagoon 13.3 miles (21.5 km) outside the Golden Gate. The ISP and its partner Marin County Parks & Open Space were able to react quickly to several nascent hybrid detections within Bolinas Lagoon over the years, and it has not been detected for four years in the northern infestation zone and 10 years in the historical southern zone. Farther north, one card from San Leandro Marina was found deep in the northern reaches of Drakes Estero in Point Reyes National Seashore, 31.7 miles from the Golden Gate and a total of 50.3 miles from the release.

Cards also traveled to some of the most distant points south of the Golden Gate. Two cards were reported from San Gregorio State Beach and Pomponio State Beach (37.6 and 39.4 miles from the Golden Gate, respectively), both at the mouths of major creeks along the San Mateo coast. The Pomponio card traveled at least 58 miles from its release.

Release Site N: Napa River (Figure 15)

One of the important early accomplishments of the ISP is that its conservation work arrested the invasion in the northern portion of San Pablo Bay. No major infestations established in that region, and the small populations that had started to develop by the inception of the ISP were eradicated or reduced to very low levels, eliminating them as potentially major sources for seed dispersal.

This site received the fewest reports of found cards (21), however, drift card reports from the Napa River release site suggest that its position in the Estuary would likely have resulted in substantial invasion pressure on Suisun Bay if the ISP had not quickly controlled the nascent infestations there. Multiple cards were reported from Benicia State Recreation Area and Carquinez Strait Regional Shoreline; if infested, both locations could have become seed sources for the expansion of the invasion into Suisun Bay under a stepping-stone model. Cards also drifted west into San Pablo Bay, including one found at Sonoma Baylands near Tolay Creek. This is the location of a restoration site where the ISP treated and eradicated a nascent infestation of hybrid *Spartina*, and none has been detected at this site in 12 years despite regular surveys. Other reports to the south include Point Pinole Regional Shoreline and Angel Island State Park.

Cards from the Napa River reached well into the South Bay, probably due to tidal cycle dynamics in which flood tides begin in the South Bay while San Pablo Bay is still ebbing. The greatest in-Bay FDD of the study, 42.2 miles, was recorded for a card that traveled from Napa River to Roberts Landing. Several cards left the Golden Gate, as well, and were found as far north as Duxbury Reef in Point Reyes National Seashore, and Ocean Beach to the south. Cards also reached Oyster Bay Regional Shoreline near Oakland International Airport, a location that was also reached by cards from MLK/Arrowhead, showing that sites can be colonized by propagules from both nearby and distant populations.

Release Site Q: Cooley Landing (Figure 16)

Cooley Landing is a former salt production evaporator pond that was opened to tidal exchange in 2000, before the inception of the ISP and years before the project had started to gain control of hybrid *Spartina* infestations in that area. Cooley Landing had little established native vegetation and low biotic resistance to a powerful

ecosystem engineer like invasive *Spartina*. Consequently, the infestation at Cooley Landing became one of the largest in this area of the Estuary.

A few cards from the second release drifted south to locations like Palo Alto Baylands and the shoreline between Charleston Slough and Stevens Creek, and very few cards were reported from the western shoreline north of the release. Most cards traveled east across the Bay and were reported from DENWR, Eden Landing Ecological Reserve, Cogswell Marsh along the Hayward Regional Shoreline, and at neighboring HARD Marsh, which has been a site of ISP reintroduction of native *S. foliosa*.

The longest FDD for the site was 25.3 miles into Oakland Inner Harbor from the first release, and it would have to have taken a circuitous path, either drifting into San Leandro Bay and around south end of Alameda Island, or around the more distant north end of Alameda Island. A drift card from the nearby Stevens Creek Tidal Marsh release was also discovered in Oakland Inner Harbor, suggesting an unexpected connectedness between two distant regions of the Bay. These two release sites also share the result that no cards were reported from the outer coast.

Release Site R: Corte Madera Creek Mouth (Figure 17)

Cards were released from the north bank at the mouth of Corte Madera Creek across from the Larkspur Ferry Terminal at the north end of the Corte Madera Ecological Reserve, a marsh complex that contains some of the highest quality tidal habitat remaining in eastern Marin County. The introduction site for *S. densiflora*, Creekside/Hal Brown Park, is within the Corte Madera Creek watershed, and the creek became the primary locus of dispersal in the Estuary. While there have also been hybrid *Spartina alterniflora* × *foliosa* infestations throughout the lower watershed, the efforts of the ISP and its local partner Friends of Corte Madera Creek Watershed did not allow the hybrid to become widespread or produce significant impacts to the tidal marsh and mudflat resources.

Possibly influenced by the typical onshore winds, most cards were reported from upstream in Corte Madera Creek, despite being released on the ebb tide. One card that reached the Bay drifted north to Tiscornia Marsh at the mouth of the San Rafael Canal, but all other reported cards that reached the Bay were transported south. Some washed ashore on the Albany and Emeryville stretches of Eastshore State Park, others on the west side of the Tiburon Peninsula, and on Angel Island State Park. One card from the third release somehow avoided going out to sea and traveled south to Roberts Landing (resulting in the FDD for the site at 25.5 miles).

In addition, many cards from Corte Madera Creek mouth were transported to the Pacific and floated up the shoreline north of the Golden Gate. A card was found at Rodeo Lagoon in Golden Gate National Recreation Area. Several cards reached Point Reyes National Seashore, including Limantour Estero and deep into Drakes Estero. One card from this release was transported even farther north past the Point Reyes peninsula, traveling at least 57 miles from the Golden Gate (over 68 miles from Corte Madera Creek mouth) to Bodega Bay.

Numerous other cards drifted south after passing through the Golden Gate, with several reported from Land's End and Ocean Beach. One card was found along the shoreline near Sharp Park, and a second by Rockaway Beach near Pacifica. Others traveled as far as Moss Beach at the north end of Fitzgerald Marine Reserve north of Half Moon Bay.

The results from this and other North Bay release sites demonstrate the threat to outer coast marshes that uncontrolled invasive *Spartina* in this part of the Estuary could pose, even to remote locations many miles outside the Golden Gate.

Release Site U: North Marsh (Figure 18)

North Marsh is the third release site in this study associated with Roberts Landing, located north of San Lorenzo Creek mouth (site D) and south of San Leandro Marina (site M). It was included as a site in the third round of the study to demonstrate the potential for propagule dispersal from this substantial infestation after it was restricted from treatment in 2011. This site has not been treated by the ISP since 2010. The 91-acre North Marsh contains the largest hybrid *Spartina* infestation remaining in the Estuary in 2023, a 59.9-acre monoculture that has excluded virtually all other native marsh vegetation and corrupted its unvegetated panne features. This represents 41% of the total remaining hybrid *Spartina* infestation in the Estuary in 2023.

As was the case with most of the releases from the other Roberts Landing study sites, nearly all the cards from North Marsh were found close to the release site. Numerous cards drifted south to the Hayward Shoreline, including to Oro Loma, an EBRPD marsh that the ISP finds populated annually by countless invasive *Spartina* propagules despite full annual treatment of the site itself. These drift card reports support the hypothesis that Oro Loma is being recolonized by neighboring sites like North Marsh that have been restricted from treatment. Most other cards were reported from neighboring Roberts Landing shorelines that are also likely being re-infested by scores of propagules from North Marsh, increasing the ISP's annual treatment burden.

Similar to reports from Stevens Creek and Cooley Landing, one card took a circuitous path into Oakland Inner Harbor. The pathway through San Leandro Bay around the south end of Alameda Island would be the shortest, but due to abiotic factors (combination of wind and tide), may have been less likely than the longer route around the north end of Alameda Island. No cards from North Marsh were found outside the Golden Gate, nor even north of the Bay Bridge.

Conclusions

In the open aquatic system of the San Francisco Estuary, reproductive propagules from hybrid *Spartina* could, in theory, be carried virtually anywhere on the tides and currents, influenced by wind direction and dispersal timing. Using a drift card model, this study demonstrates that, through the combination of twice-daily tidal cycles and variable winds, a floating object entering the water at one point can indeed be carried to a distant point on the surface of the water, however remote that location may be, and possibly via a very circuitous path. Since these cards are intended to mimic invasive *Spartina* propagules, they also provide a warning of the potentially huge ecological and natural resource management consequences that could result from this wide dispersal.

Many variables acted upon the paths taken by the drift cards released for this study. We can only know the start and end points of each card's journey; we do not know any card's route, nor do we have any information regarding where missing cards went. Even so, the locations where study cards were later retrieved and reported simulate the *potential* for a floating propagule to disperse to that location. However, the combination of a relatively small sample size and natural variation in environmental conditions means that the results do not

represent the *limitations* of dispersal from a particular site. In other words, if cards from a particular site did not happen to travel very far from where they were released, it does not mean that they could not. For example, two release sites that were relatively close to one another had very different results. San Lorenzo Creek mouth cards (**Figure 6**) had the shortest FDD in the study (only 2.6 miles); all reported cards were found close to the release site, and none left the Golden Gate. In contrast, the releases from San Leandro Marina (**Figure 14**), just 3 km to the north, had a much longer FDD of 23.9 miles to San Rafael, with numerous cards reaching the North Bay and multiple others leaving the Golden Gate. Even within-site variability demonstrates this point, since only the first release from San Leandro Marina produced the longer distance travelers, while cards in the second and third rounds stayed much closer to the release point.

Tides and currents dictate the flow of the entire, massive water column during its exchange on each tide cycle, but surface winds may have a greater influence on where floating objects such as drift cards or seeds/rhizomes/wrack rafts are carried. Wind played a key role in determining whether cards dispersed out into the surface currents immediately after their release, and wind partially determined the direction the card would later travel, especially *within* the Estuary. The prevailing winds during most days and seasons are westerly, toward the eastern shoreline of San Francisco Bay, with effects apparent on drift cards released at far South Bay sites, such as Alviso Slough (site K/P) or Cooley Landing (site Q). North of the Dumbarton Bridge, where cards would be exposed to the full fetch of the wind across the Bay, only a single South Bay card was retrieved on the western shoreline, and none were retrieved on that side north of the San Mateo Bridge. In addition, no cards released along the eastern shoreline from Oakland to Fremont were reported moving west across the Bay.

There were many instances where cards didn't leave the release site because the wind pushed them back onshore despite a strong outgoing tidal flow. This happened at all East Bay release sites like Elsie Roemer (site C), Cogswell Marsh (site F), North Marsh (site U), even at sites located at the mouths of major sloughs with strong outflows like AFCC (site A) and San Lorenzo Creek (site D). While the results certainly do not indicate that dispersal from the eastern shoreline of the South Bay is purely limited to short distances (see San Leandro Marina, Figure 14), long distance dispersal seems less likely from the East Bay, and may require calmer wind conditions.

Morgan and Sytsma (2013) found that fall-gathered wrack of hybrid *Spartina* was approximately one-third less dense than the cards used in this study, making the more buoyant plant material subject to greater wind forces than drift cards when floating on the surface. They concluded that *Spartina* wrack could potentially travel farther on the open ocean than drift cards would indicate. Within the San Francisco Estuary, the west wind appears to generally keep propagules from East Bay marshes closer to their source and push propagules from the West Bay eastward, away from shore and into the stronger currents of the Bay. Once there, the combination of currents and wind could carry propagules longer distances in many directions. For example, two of the most widely dispersed releases came from the West Bay sites Colma Creek/San Bruno Marsh (site E/L) and Bair Island (site B/O), with retrieval reports coming from many unique locations in the South Bay, San Pablo Bay, and the outer coast. The majority of cards from both of these sites crossed to the East Bay, but the overall spread of retrieval locations was much wider than for most East Bay releases.

The primary freshwater inputs to the Estuary are from the Sacramento-San Joaquin Delta, the confluence of two major river systems on the western edge of the Central Valley, just east of where they flow into Suisun Bay.

Along with the other streams that feed into San Pablo Bay and central San Francisco Bay, this watershed encompasses 40 percent of the state of California, with an average of 24 million acre feet of freshwater flowing through each year, equivalent to five times the volume of San Francisco Bay (Okamoto and Wong 2011). While there is bi-directional tidal flow through the Carquinez Strait, resulting in lower salinity brackish conditions in Suisun Bay to the east as compared with the saltier San Pablo Bay to the west, the constriction at the strait concentrates the force of this flowing water and acts as a natural impediment to upstream tidal dispersal.

For most of the history of the ISP, and during the entire period of the drift card study, the farthest east/upstream hybrid *Spartina* had been detected within the Estuary was in the Carquinez Strait. A couple of nascent populations – that ISP partners rapidly eliminated – were detected along the southern Carquinez Strait Regional Shoreline, and there was a more established infestation on the northern shore in Southampton Marsh at Benicia State Recreation Area. These very same areas also marked the eastern extent for drift card retrieval reports from this entire study. It may take a rare event for *Spartina* propagules to disperse eastward into Suisun Bay. However, Suisun Bay shorelines and islands have very limited public visitation; the incidence of dispersal may be greater than suggested by the lack of drift card reports and warrants continued periodic surveys of this area for hybrid Spartina.

Indeed, in 2017, the ISP received a report of a hybrid *Spartina* infestation in Suisun Bay at Point Buckler. ISP biologists conducted boat surveys and found a cluster of infestations centered at Snag Island and radiating out to Ryer and Roe Islands to the west and to the eastern shoreline of Honker Bay. These infestations were located 11 miles east/upstream of Southampton Marsh, the nearest known hybrid *Spartina* infestation, and more closely resembled pure *S. alterniflora* than the hybrid forms the ISP had found throughout the Estuary. It was suspected that these Suisun infestations may have been the result of an independent introduction event, possibly a contaminant on a piece of construction equipment. The ISP quickly got these infestations under control through effective treatment, and no other substantial infestations have yet been detected in this area. With no drift cards reported from Suisun Bay, the origin of the population remains unclear and could have been either a rare instance of long-distance dispersal or an independent introduction.

This study highlights the importance of rare events in the spread of invasive species. Reid's paradox of rapid plant migration hypothesizes that rare, long-distance seed dispersal events may explain plant range expansion rates that seem faster than expected based on average seed dispersal distances (Clark et. Al. 1998). Similarly, rare, longer-than-average dispersal events may also play an important role in the spread of invasive plants by quickly advancing the invasion front to distant locations. The successful establishment of one propagule can begin a new infestation and create a new locus for dispersal at the leading edge of an invasion. In this way, a rare dispersal event can have an outsize effect on advancing the invasion process, and the drift cards have helped demonstrate many possible long-distance invasion pathways. Even the hybridization event between the parent non-native *S. alterniflora* and native *S. foliosa* required a somewhat rare phenological overlap of flowering timing for these two species to share pollen (Daehler and Strong 1997), before the formation of the hybrid swarm that made backcrossing much more common.

The original introduction of *S. alterniflora* to the Estuary occurred in the mid-1970s at AFCC, but its hybridization with native *S. foliosa* was not discovered until the mid-1990s (Daehler and Strong 1997). By that time, there were already many burgeoning infestations around the Estuary and numerous populations of *Spartina* behaving

in ways that the wetland community had not seen before in this system, with many mudflats being converted to monocultures of hybrid cordgrass. The results of this drift card study may offer clues as to why it took nearly 20 years for the invasion to raise alarms. Cards released at the original introduction site at AFCC and some of the neighboring sites generally did not travel far. Similarly, the spread of invasive *Spartina* may have been fairly slow initially, until populations were established at sites better situated for wider dispersal.

If the original *S. alterniflora* introduction had been in the North Bay, the progression of the infestation could have been much different. The tidal current out to the Pacific Ocean from San Pablo Bay is strengthened significantly by the riverine inputs from the Sacramento-San Joaquin Delta. While some South Bay drift card releases were retrieved in the North Bay, once they floated up to the Golden Gate/Berkeley area, ebbing tides and the flow of water from the Delta typically combined to constrain the cards to the south or move them towards the outer coast. In contrast, dispersal patterns from the North Bay show that hybrid *Spartina* would still have infested the South Bay, and once established there, it would have circulated throughout that part of the Estuary just as it did from the 1970s AFCC introduction. But it very well could have also spread throughout the North Bay, not only in San Pablo Bay but likely up into Suisun Bay and the Napa-Sonoma Marshes. These northern areas have largely escaped significant impacts from the invasion due in part to the lower likelihood of dispersal of propagules from south to north, and in part to the early and effective management efforts of the ISP.

An earlier and more substantial infestation in the North Bay would also likely have resulted in more dispersal to the outer Pacific Coast. The drift cards demonstrate real risks of hybrid *Spartina* invading the outer coast directly from multiple release sites, particularly from the North Bay. If this had happened before the ISP began control measures, it could have magnified the invasions at Bolinas Lagoon and Point Reyes National Seashore beyond the relatively small infestations that did occur. Dispersal to other vulnerable tidal marshes up and down the outer coast could have established loci of dispersal to advance the invasion front stepwise along much of the North American Pacific coast.

As it was, the invasions by both hybrid *Spartina* and *S. densiflora* did reach the outer coast and required a rapid containment response. The ISP worked with the National Park Service for over seven years to eradicate several hybrid *Spartina* infestations in both Limantour Estero and the Home Bay cove of Drakes Estero (these have now been locally eradicated and Zero Detection for 10 years as of 2022). The ISP and its partners have worked for years to eradicate some small infestations of *S. densiflora* at the north end of Tomales Bay (Tom's Point and Hog Island Oyster Company) that are nearly eradicated but still have a persistent seedbank. While these may have been independent introductions (possibly a contaminant of seed oyster) rather than from *S. densiflora* infestations in the Estuary, the report of a drift card from Corte Madera Creek being found at Bodega Bay argues that it could have been a rare natural dispersal event that brought *S. densiflora* to the North Coast.

The spread of *Spartina densiflora* provides a case study of an invasion that began in the North Bay. Originally introduced at Creekside Park/Hal Brown Park (Site G), it spread throughout the Corte Madera Creek watershed, radiated outward in all directions within the North Bay, and eventually reached distant locations in the South Bay and the Outer Coast, just as the drift cards would predict. While the more distant infestations may have originated from independent, undocumented introductions, the drift cards show that dispersal from Corte

Madera Creek is a defensible hypothesis. The case of *S. densiflora* shows that drift cards may reasonably model the real-world dispersal potential of an invasive plant with floating propagules.

The results of the three rounds of drift card releases, in 2007-2012, showing widespread dispersal from most but not all release sites, informed discussions between the ISP and USFWS on balancing the eradication of hybrid *Spartina* with preserving enough of it at a time to provide adopted habitat for the endangered California Ridgway's rail. By the end of 2012, these discussions resulted in a reduction of restricted sites from 26 scattered widely throughout the Estuary to 11 sites consolidated in four complexes. While still not ideal for the eradication efforts, this was a helpful compromise to reduce the number of hybrid *Spartina* dispersal loci while continuing a careful approach to the removal of habitat that could help ensure healthy Ridgway's rail populations into the future.

Literature Cited

Ayres, D. R., Strong, D. R., & Baye, P. (2003). Spartina Foliosa (*Poaceae*)—A Common Species on the Road to Rarity? *Madroño*, 50(3), 209–213. http://www.jstor.org/stable/41425518

Ayres, D. R., Smith, D. L., Zaremba, K., Klohr, S., & Strong, D. R. (2004). Spread of exotic cordgrasses and hybrids (*Spartina sp.)* in the tidal marshes of San Francisco Bay, California, USA. *Biological Invasions*, 6(2), 221–231. doi:10.1023/b:binv.0000022140.07404.b7

Brusati, E., & Grosholz, E. (2008). Does invasion of hybrid cordgrass change estuarine food webs?. *Biological Invasions*. 11. 917-926. 10.1007/s10530-008-9304-4.

Clark, J. S., Fastie, C., Hurtt, G., Jackson, S. T., Johnson, C., King, G. A., … Wyckoff, P. (1998). Reid's paradox of Rapid Plant Migration. *BioScience*, 48(1), 13–24. doi:10.2307/1313224

Daehler, C. C., & Strong, D. R. (1997). Hybridization between introduced smooth cordgrass (*Spartina alterniflora*) and native California cordgrass (*S. foliosa*) in San Francisco Bay, California, USA. *American Journal of Botany*, 84(5), 607–611. doi:10.2307/2445896

Disney, L.P., & Overshiner, W.H. (1925). Tides and currents in San Francisco Bay: U.S. Coast and Geodetic Survey, Special Publication No. 115

Elsey-Quirk, T., Middleton, B. A., & Proffitt, C. E. (2009). Seed flotation and germination of salt marsh plants: The effects of stratification, salinity, and/or inundation regime. *Aquatic Botany*, 91(1), 40–46. doi:10.1016/j.aquabot.2009.02.001

Kittelson, P. M., & Boyd, M. J. (1997). Mechanisms of expansion for an introduced species of cordgrass, *Spartina densiflora*, in Humboldt Bay, California. *Estuaries*, 20(4), 770–778. doi:10.2307/1352250

Levin, L. A., Neira, C., & Grosholz, E. D. (2006). Invasive cordgrass modifies wetland trophic function. *Ecology*, 87(2), 419–432. doi:10.1890/04-1752

Monroe, M., Olofson, P. R., Collins, J. N., Grossinger, R. M., Haltiner, J., & Wilcox, C. (1999) Baylands Ecosystem Habitat Goals. SFEI Contribution No. 330. U. S. Environmental Protection Agency, 328. San Francisco: Regional Water Quality Control Board

Morgan, V. H., & Sytsma, M. D. (2013). Potential Ocean dispersal of cordgrass (*Spartina spp.*) from core infestations. *Invasive Plant Science and Management*, 6(2), 250–259. doi:10.1614/ipsm-d-12-00042.1

Neira, C., Grosholz, E. D., Levin, L. A., & Blake, R. (2006). Mechanisms generating modification of benthos following tidal flat invasion by a *Spartina* hybrid. *Ecological Applications*, 16(4), 1391–1404. doi:10.1890/1051-0761(2006)016[1391:mgmobf]2.0.co;2

Okamoto, A. R., & Wong, K. M. (2011). In *Natural history of San Francisco Bay* (pp. 22–23). Berkeley, California: University of California Press.

Pfauth, M., Sytsma, M., & D. Isaacson. (2007). Oregon Spartina Response Plan. Oregon: Portland State University.

Sacramento Delta San Joaquin Atlas. (1995, July 1). Sacramento: California Department of Water Resources.

Sayce, K., Dumbauld, B., & Hidy, J. (1997a). Seed dispersal in drift of *Spartina alterniflora*. In *Second International Spartina Conference*. Pullman, Washington: Washington State University-Cooperative Extension.

Smith, L. H. (1987). A review of circulation and mixing studies of San Francisco Bay, California. U.S. Geological Survey Circular 1015.

State Coastal Conservancy. (2003). Final Programmatic Environmental Impact Statement/Environmental Impact Report. Oakland, California: San Francisco Estuary Invasive Spartina Project.

Stokstad, E. (2023). China battles alien weed at unprecedented scale. *Science*, 379(6636), 972–972. doi:10.1126/science.adh4966