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ARTICLE

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Sea otters in a California estuary: Detecting temporal and spatial dynamics with volunteer monitoring

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Abstract

Volunteer monitoring can support conservation of imperiled wildlife, by providing higher resolution data in space and time than those available from professional scientists. However, concerns have been raised that data collected by amateurs are inaccurate or inconsistent and thus do not allow for robust detection of spatial or temporal trends. We evaluated the rigor and value of volunteer monitoring data for one iconic wildlife species, the southern sea otter (*Enhydra lutris nereis*), in Elkhorn Slough estuary in central California, USA, and explored whether volunteer monitoring could provide added value to complement limited professional surveys. First, we compiled and analyzed sea otter counts taken on daily ecotourist boat trips along the estuary, and then compared temporal patterns to data collected by professional scientists tasked with monitoring this federally listed species. Second, we analyzed data on sea otter abundance, habitat use, and behavior collected by a team of trained volunteers, the Elkhorn Slough Reserve Otter Monitoring Program. Overall, we demonstrated the ability to detect important ecological patterns relevant to sea otter conservation and wetland habitat management using volunteer-derived datasets. Long-term trends and inter-annual variability were similar between professional agency monitoring data and volunteer datasets. Moreover, the much higher frequency of volunteer observations allowed for seasonal and tidal dynamics to be detected that could not be revealed by less frequent professional monitoring. We found higher sea otter abundance in the estuary in spring–summer, indicating seasonality in use of the estuary. We detected differences in habitat use of the estuary between higher and lower tides, and greater frequency of foraging at low tide and in certain areas. Volunteer observations revealed fine-scale differences in habitat use: eelgrass beds were used much more heavily than adjacent areas only a few meters away. Volunteer data can thus provide critical information about coastal habitat use and behavior that can improve conservation strategies for threatened wildlife species.

KEYWORDS
citizen science, estuary, marine mammal, monitoring, sea otter, seagrass

INTRODUCTION

> *Citizen science can contribute to a paradigm shift taking place in science, wherein scientists and the public work together to investigate and address emergent environmental issues.*
> (Kobori et al., 2016)

Many wildlife species are imperiled around the globe (Bowyer et al., 2019; Ceballos et al., 2017). Conservation and adaptive management of the species and their habitats is most effective if informed by monitoring data that can be used to track their further decline or recovery, and to determine how distribution and behavior vary among habitats (Lindenmayer & Likens, 2010). Monitoring is an intensive activity, however, and many threatened wildlife species are not adequately monitored due to lack of sufficient resources and personnel (Witmer, 2005).

Volunteer monitoring represents a potentially powerful tool for expanding knowledge about charismatic species of concern (Pimm et al., 2014). Monitoring by amateurs has often been termed "citizen science," but this term can inadvertently imply that noncitizen immigrants are not welcome to participate, so we refer to this activity as "community science" or "volunteer monitoring." Community science has been used to provide information on rare animals and their habitat use (Parsons et al., 2018). While community science holds promise, the quality of results can be quite variable and depend on the design of the program (Brown & Williams, 2019).

One iconic wildlife species well suited to volunteer observations is the southern sea otter (*Enhydra lutris nereis*). Sea otters suffered near extinction in California due to the fur trade, with only a few dozen animals remaining in remote locations by the early 1900s (Kenyon, 1969). Over the past century, southern sea otters have slowly recovered, and are now regularly found from about Santa Barbara to Pigeon Point along 500 km of the California coastline (Hatfield et al., 2019a; Tinker et al., 2008). Recovery of the southern sea otter, which is listed as threatened under the US Endangered Species Act, is slow because only a very narrow band of shallow coastal habitat is occupied, and expansion is hampered to the north and south by shark predation (Tinker et al., 2016, 2021).

Estuaries provide valuable foraging and resting habitat for sea otters (Hughes et al., 2019) (Figure 1). Only one estuary has been extensively recolonized by the recovering southern sea otter population—Elkhorn Slough in central California—and the numbers of sea otters supported there have increased more rapidly than elsewhere on the coast, in part due to releases of captive-reared orphaned pups (Mayer et al., 2021). The San Francisco Bay estuary lies about 70 km north of the current range of the southern sea otter. If fully occupied, this immense estuary could contribute significantly to population growth (Hughes et al., 2019; Tinker et al., 2021), making observations from Elkhorn Slough valuable for understanding future habitat use. Estuaries in California were highly altered and extensive habitat restoration is underway (Haskins et al., 2021; Thorne et al., 2019). A better understanding of how sea otters use estuarine habitats, and how this use varies across seasons and tidal cycles, can inform habitat restoration design. In the calm waters of estuaries, sea otters may be easier to observe from a distance in shore-based observations by volunteers, than along the high-energy open coast, where waves and choppiness obscure viewing (Figure 2). If volunteer data are reliable, they can be used to inform sea otter conservation strategies and estuarine restoration planning.

The goal of this investigation was to determine whether volunteer observations can provide robust, relevant information on southern sea otter abundance and habitat use. We examined two sources of community science. First, we compiled and analyzed sea otter counts taken on daily ecotourist boat trips along the estuary. Second, we analyzed data on sea otter abundance, habitat use, and behavior collected by the Elkhorn Slough Reserve Otter Monitoring Program (ROMP), a team of highly coordinated and trained volunteers. We explored whether these separate volunteer datasets, from untrained tourists and trained local volunteers, could be used to elucidate temporal and spatial dynamics of southern sea otters in Elkhorn Slough, and provide data relevant to sea otter conservation and wetland habitat management.

METHODS

We first provide an overview of the different monitoring programs conducted by both volunteers and experts for sea otters in Elkhorn Slough. Then, after introducing the three data sources, we explain in more detail which subsets of data were used to answer particular questions.

FIGURE 1 Sea otters in Elkhorn Slough. Estuarine habitats, including eelgrass beds shown here, provide valuable foraging and resting habitat for southern sea otters (photo credit: Yohn Gideon).

All data used for analyses are publicly available (https://doi.org/10.7291/D1FX0Z).

Overview of sea otter monitoring approaches in Elkhorn Slough

Ecotourism: Counts by Elkhorn Slough Safari

The Elkhorn Slough Safari, which offers ecotourist boat excursions in the lower Elkhorn Slough estuary, began collecting sea otter and harbor seal counts on each excursion beginning in 1994. These counts were collected by a single-volunteer tourist passenger using a handheld clicker until 2017, when the captain began doing the counts instead. The raised elevation of the pontoon boat allowed excellent vantage points for even distant sea otters. Because hundreds of excursions were taken each year, these counts represent the highest frequency monitoring of sea otter abundance in the estuary. Counts were necessarily limited to the areas visible from the boat's tour track through Moss Landing Harbor and the lower main channel of Elkhorn Slough (specifically Areas 1, 2, 3, 5, 6, 8, 10, and 13 in Figure 3), and were only taken on the outbound journey to avoid double counts on the return journey. The boat's tour track was specifically designed to maximize sea otter observations, since these are the primary draw for tourist passengers.

Community volunteers: Monitoring by Elkhorn Slough ROMP

The ROMP was conducted by trained volunteers from the Elkhorn Slough National Estuarine Research Reserve (ESNERR). The program began in 2010 with only a few areas and volunteers, and was expanded over the subsequent decade. The primary objective of ROMP was to monitor the number, locations, and activities of sea otters in Elkhorn Slough, so changes could be tracked over time. A critical aspect of this monitoring is that exactly the same study area boundaries were used for each visit, and observation methods were standardized each time, so that comparisons could be made among areas or over time. Sampling occurred simultaneously across the

FIGURE 2 Volunteer monitoring for sea otters. (a) Elkhorn Slough Safari boat trip and (b) captain pointing to raft of sea otters (photo credit: Elkhorn Slough Safari); (c) Reserve Otter Monitoring Program (ROMP) observer overlooking Yampah Creek (photo credit: Kerstin Wasson); (d) ROMP observer cruising Main Channel (photo credit: JoEllen Arnold); (e) ROMP observer using tablet to collect data at Seal Bend (photo credit: Ron Eby); (f) ROMP observer at North Harbor (photo credit: Heather Hayashi).

estuary to allow comparisons among areas and to allow totals to be tallied across areas for an estuary-wide estimate, and occurred at both low and high tides each month to include both tidal and seasonal dynamics. Volunteers conducted simultaneous shore-based surveys of 4 harbor areas and of 12 areas within the Elkhorn Slough estuary (Figure 3).

ROMP team members recorded counts and instantaneous observations of behavior of each individual within area boundaries every 30 min for 2 h on each

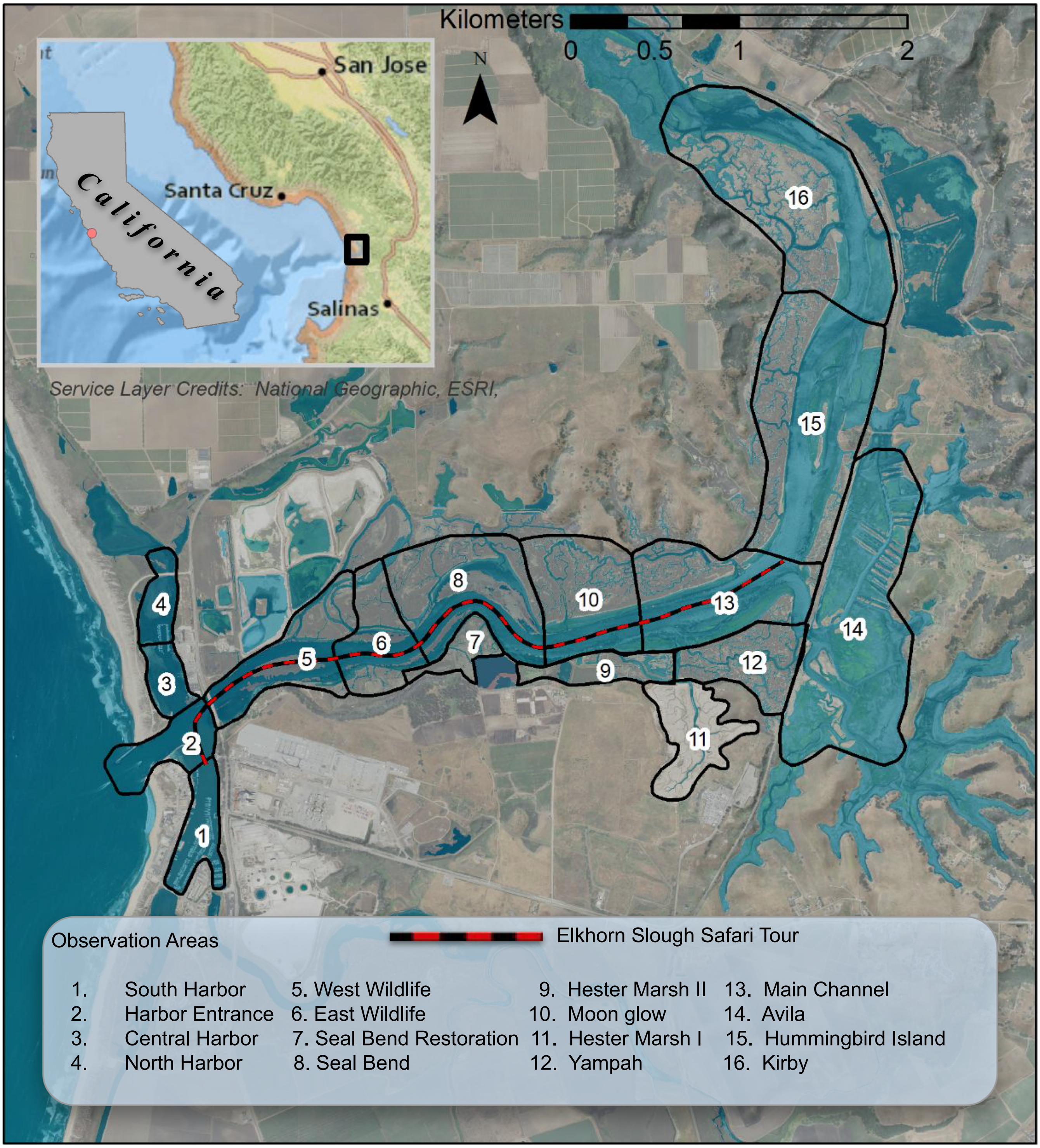

FIGURE 3 Elkhorn Slough sea otter monitoring locations. The numbered areas are observed simultaneously by Reserve Otter Monitoring Program teams. The red line shows the route of the Elkhorn Slough Safari. Background imagery, elevation data, and state of California outline are public domain the National Agriculture Imagery Program (NAIP), United States Geological Survey ⅓ arcsec digital elevation model, and CA.gov open data portal.

monitoring day. For the following analyses, we used only data collected at 11:00 AM to avoid pseudoreplication and the potential double counting of animals that move between areas. At 11:00 AM, volunteers also marked a map indicating the location of each otter. A ROMP team member later used Google Earth to assign coordinates for each marked location. See Appendix S1 for details on ROMP procedures.

Expert surveys: Counts coordinated by United States Geological Survey

The Western Ecological Research Center of the United States Geological Survey (USGS) has coordinated a standardized range-wide census of the entire southern sea otter population annually (spring) or semiannually (spring and fall) since 1982 (Hatfield et al., 2019b; Tinker et al., 2021). Trained staff from USGS and collaborating partner organizations recorded the locations of individuals and groups of sea otters using a combination of aerial and shore-based survey methods. Individual locations recorded on high-resolution coastal maps were later digitized into GIS.

Sea otters were first observed in Elkhorn Slough in 1984, when males seasonally foraged in the harbor area (Kvitek et al., 1988), and surveys conducted by USGS for the estuary began in 1985. Due to issues related to topography, tidal effects, and limited accessibility in some areas for shore-based observers, census methods in the harbor and estuary were adapted to employ a combination of boat- and shore-based observations. Multiple teams of two shore-based observers counted sea otters in back-channel salt marsh habitats (Areas 8, 10, 12, 14, and 16 in Figure 3), while a separate team of two boat-based observers concurrently counted sea otters in the main slough channel between Moss Landing Harbor and Hudson Landing (north of Area 16 in Figure 3). For this study, Elkhorn Slough sea otter counts and GPS coordinates were obtained for the years 1985–2019 (courtesy of USGS).

Long-term trends in lower estuary abundance

To compare the information provided by three independent monitoring approaches (ecotourist boat trips, community volunteers, and professional agency staff), we examined data provided by each group on long-term trends in sea otter abundance in the estuary. We focused on the lower estuary, which was the only portion of the estuary covered by the ecotourist voyages. We used only ROMP and USGS data from the lower estuary areas corresponding to the boat pathway (Areas 1, 2, 3, 5, 6, 8 10, and 13 in Figure 3). We used ROMP data from 2015 to 2021; earlier years (2010–2014) did not contain surveys of all parts of the lower estuary. We compiled survey data and calculated the number of surveys over time for each approach, using all data available until December 2021. No data were collected by USGS in 2020 due to the COVID pandemic, and 2021 data were not yet publicly available, so these years are not included for this data source.

We analyzed trends in sea otter counts from each monitoring approach by fitting generalized additive models (GAMs) to represent nonlinear changes in the time series (Rigby & Stasinopoulos, 2005), using negative binomial distributions and a log link function. We evaluated three candidate models representing different hypotheses: (1) no differences among monitoring approaches; (2) additive effects, where one approach counts consistently more otters than another; and (3) interaction effects, where one approach has a different trend from another. We selected the model with the greatest weight of evidence based on highest Akaike likelihood weight (Burnham & Anderson, 2002), and we regarded the effects to be statistically significant when their p values were less than 0.05. We also graphically examined the long-term temporal trends in sea otter abundance and how these varied by data source. We conducted all analyses using R statistical software (R Core Team, 2022).

Seasonal dynamics sea otter abundance

To determine whether ecotourist data could effectively detect differences in sea otter abundance across seasons, we used the complete Elkhorn Slough Safari dataset (1994–2021) and divided each calendar year into quarters. As with the comparison of monitoring approaches for the long-term trend analysis, we used GAMs and Akaike weights to evaluate temporal patterns in sea otter counts, except we compared three season-based hypotheses: (1) no differences among seasons; (2) additive differences, where a season has consistently higher counts than another; and (3) interaction effects, where a season has a different trend from another. We complemented this assessment using ROMP data by examining seasonal and spatial dynamics between 2016 and 2020 in four main Slough regions: Wildlife (Areas 5 and 6 in Figure 3), Seal Bend (8), Main Channel (10, 13), and Yampah (12). Anecdotal observations indicated shifts in habitat use in the estuary over this period, particularly during summer, and so a goal of this analysis was to determine whether this was evident in the ROMP dataset. We used GAMs and Akaike weights to analyze quarterly trends while comparing three area-based hypotheses: (1) no differences among regions; (2) additive differences, where a region has consistently higher counts than another; and (3) interaction effects, where a region has a different trend from another.

Tidal effects on habitat use and behavior

To evaluate whether volunteer observations can be used to detect tidal effects on sea otter habitat use and behavior, we focused on ROMP observations. To examine spatial patterns of abundance as a function of tides, we conducted a geospatial analysis using ESRI ArcMap 10.8.1. We used ROMP observations from all areas between November 2018 and December 2020 (the first period when geospatial data were collected), and selected data from high tides (above 1.22 m NAVD88) and low tides (below 0.35 m) for comparison. These tidal extremes each represented approximately 20% of the total observations (40% combined). We visualized differences in abundance by area using a kernel density analysis. This tool uses a nonparametric function to smooth observation data into a density estimation raster grid. The planar search method, grid size of 20 m, and search radius of 160 m were adopted from a previous study (Lindsey, 2016) because they were found to effectively visualize sea otter distribution. A kernel density analysis for each tidal extreme dataset was calculated. This nonparametric tool provided an expected count of sea otters in a certain area based on the input of point observations. The rasters generated with observations during the highest tides were subtracted from those during the lowest tides. This generated a distribution map of areas with large differences in sea otter densities between high and low tides.

We complemented this analysis of the entire estuary with a closer examination of two contrasting estuary areas, Seal Bend along the main channel of the estuary and Yampah, a narrow tidal creek running through a salt marsh adjacent to the main channel (Areas 8 and 12 respectively in Figure 3). For this analysis, we used ROMP observations from 2016 to 2020, the first period where these areas were regularly observed. All observations were either categorized as occurring at high tide (≥0.95 m NAVD88) or low tide (<0.95 m)—this allowed all data to be used, rather than just the extreme high and lows as in the geospatial comparison. The elevation used to distinguish high from low tide corresponded to the mean tide level in the estuary (Van Dyke, 2012).

We analyzed differences in sea otter counts and foraging activity between tide levels, areas, and their interaction effects by using generalized linear models (GLMs) to estimate these effects while allowing non-normal distributions characteristic of count and proportion data, that is, nonnegative values and nonconstant variances (McCullagh & Nelder, 1989). Specifically, we used GLMs with over-dispersed Poisson distributions and log link function to compare numbers of sea otters counted at low versus high tide in these two areas, and over-dispersed binomial distributions and logit link function to compare the percentage of otters foraging in them. We used Akaike weights to compare three hypotheses about sea otter use and foraging: (1) no differences between tide levels for the two areas; (2) additive effects, where tide level affects sea otters consistently in both areas; and (3) interaction effects, where tide level affects sea otters differently between areas.

Fine-scale spatial dynamics

To explore whether volunteer estimates of geographic locations were accurate enough to detect fine-scale spatial dynamics of sea otters, we focused on the use of eelgrass beds (located in Area 8, Figure 3) as revealed by ROMP data. Sea otters in Elkhorn Slough are known to frequent eelgrass (Hughes et al., 2013). We used the locations of the 4609 sea otter observations in this area between November 2018 and December 2020 to conduct a geospatial analysis of sea otter abundance inside and outside of eelgrass beds. Sea otter observations were spatially joined with the Elkhorn Slough Enhanced Lifeform habitat layers showing eelgrass beds in NAD 83 UTM 10. The enhanced lifeform and tidal wetland alliance level map (https://noaa.maps.arcgis.com/apps/webappviewer/index.html?id=e8b462c4817745b58542c1f9654783d0) is in the public domain. It was completed by Kass Green & Associates and Tukman Geospatial using 15-cm-resolution NAIP imagery, which is a 33-class land use and land cover map of Elkhorn Slough Watershed reflecting the state of the watershed in summer 2018. Separately in 2018, Charlie Endris, at the ESNERR, used Google Earth imagery and heads-up digitizing at a scale of approximately 1:500 to map the eelgrass beds in the main channel; the eelgrass layer was later incorporated into the final lifeform map. For this project, we focused on two habitat types, eelgrass versus adjacent open water. We visualized kernel densities for sea otters and used a paired *t* test with date as a replicate to compare densities in the two habitat types.

RESULTS

Long-term trends in lower estuary abundance

The numbers of surveys conducted by the three monitoring approaches differed dramatically (Figure 4). Since 2000, the ecotourist Elkhorn Slough Safari generated over 300 sea otter counts in the lower estuary per year. ROMP surveys typically occurred 20–30 days per year. USGS conducted up to two counts per year as part of a range-wide census, but this was limited to a single annual count after 2009.

All GAMs strongly supported annual patterns ($p < 0.005$), and there were no statistical differences found among monitoring approaches for years when they co-occurred (1994–2021). The null model with only year effects and no differences among monitoring approaches had the majority of the weight of evidence (Akaike weight 68.6%) and was three times as likely as the next supported model (additive effect of data source; Akaike weight 22.6%) where no significant differences were found among data sources ($p > 0.2$). Overall, sea otter abundance in the lower estuary increased dramatically from the late 1980s, when only a few animals were present, to the 2000s, when over 60 animals were typically present in this region (Figure 5). The counts taken by the ecotourist Slough Safari boat documented the same peaks in 1998 and 2008, and a drop around 2003, as surveyed by USGS. Likewise, the volunteer ROMP counts, Slough

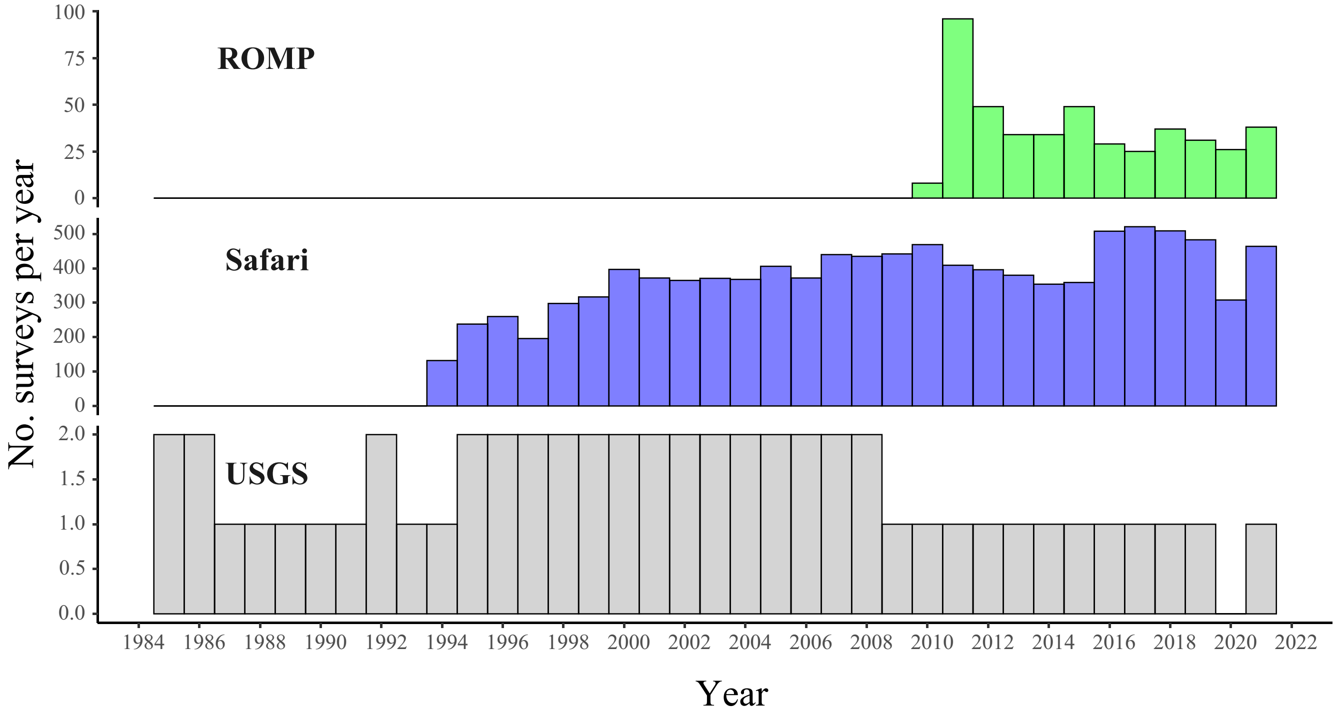

FIGURE 4 Numbers of sea otter counts over time. Histograms contrasting the frequency of surveys by three different monitoring approaches. Note that *y*-axis scale varies among datasets. ROMP, Reserve Otter Monitoring Program; USGS, United States Geological Survey.

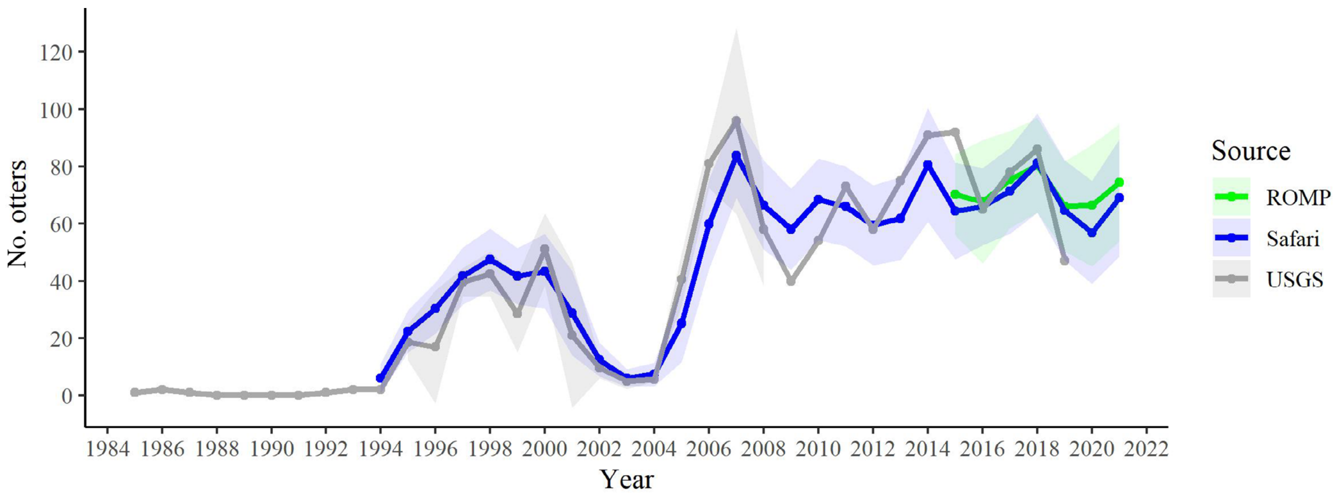

FIGURE 5 Trends of sea otter abundance in Elkhorn Slough estuary. Data from three sources are shown for all years where they were available: Safari = Elkhorn Slough Safari, ecotourist trips; ROMP = Elkhorn Slough Reserve Otter Monitoring Program, volunteer observations; USGS = survey by professional scientists coordinated by the United States Geological Survey. Standard deviations are shown with shading to illustrate variations in counts.

Safari counts, and survey by USGS all detected a distinctive peak in sea otter abundance in 2018, with lower numbers before and after 2018.

Seasonal dynamics of sea otter abundance

The Elkhorn Slough Safari dataset revealed significant seasonal dynamics that shifted over time (Figure 6). The GAM with seasonal differences and interaction effects had the entire weight of evidence (Akaike weight 100%), suggesting shifts in seasonal trends across years. In early years, peak sea otter numbers occurred in winter. Since 2010, in contrast, peak numbers of sea otters were counted in spring and summer. In some years such as 2014 and 2018, dramatically higher numbers of sea otters were counted in these seasons than in fall–winter.

Examination of ROMP data for four regions along the main channel (a subset of the Safari route) for recent years (2016–2021) revealed more complex seasonal and spatial dynamics (Figure 7). The GAM with area differences and interaction effects had nearly all of the Akaike weight (99.7%), strongly indicating recent shifts in space use. Sea otters concentrated seasonally during spring to summer in either the Seal Bend or the Wildlife regions, and the region with the highest counts shifted down slough, from Seal Bend (Area 8, Figure 3) between 2016 and 2018 to Wildlife (Areas 5 and 6) after 2018. By contrast, numbers in the Main Channel (Areas 10 and 13) and at Yampah (Area 12) showed no clear seasonal or directional long-term trends.

Tidal effects on habitat use and behavior

The geospatial analyses of the entire estuary revealed strong differences in relative sea otter abundances as a function of tides. The density estimation raster grid was used to visualize areas preferentially used at high or low tide (Figure 8).

Examination of two contrasting estuary areas also showed strong effects of tide on abundance and behavior, but the effects differed strongly between areas as evidenced by the interaction model (Akaike weight 100%). At Seal Bend, sea otter numbers were consistently higher at low tide in all six years, approximately double compared with high tide (95% CI = 76.5%–147% higher), while at Yampah, the reverse pattern occurred with sea otter use consistently higher at high tide, approximately triple compared with low tide (95% CI = 144%–268% higher) (Figure 9). Tide levels also affected foraging as evidenced by the combined Akaike weight of the additive and interaction models (99%; or 52% and 47% respectively). The percentage of sea otters that were foraging was much higher at Seal Bend than at Yampah (odds ratio 9.2; 95% CI = 3.7–22.7), and a significantly greater percentage of otters foraged at high tide, when fewer otters tended to be present (odds ratio 3.3; 95% CI = 1.6–6.6) (Figure 10).

Fine-scale spatial dynamics

We detected differences in sea otter abundances inside versus outside of eelgrass beds in the main channel of

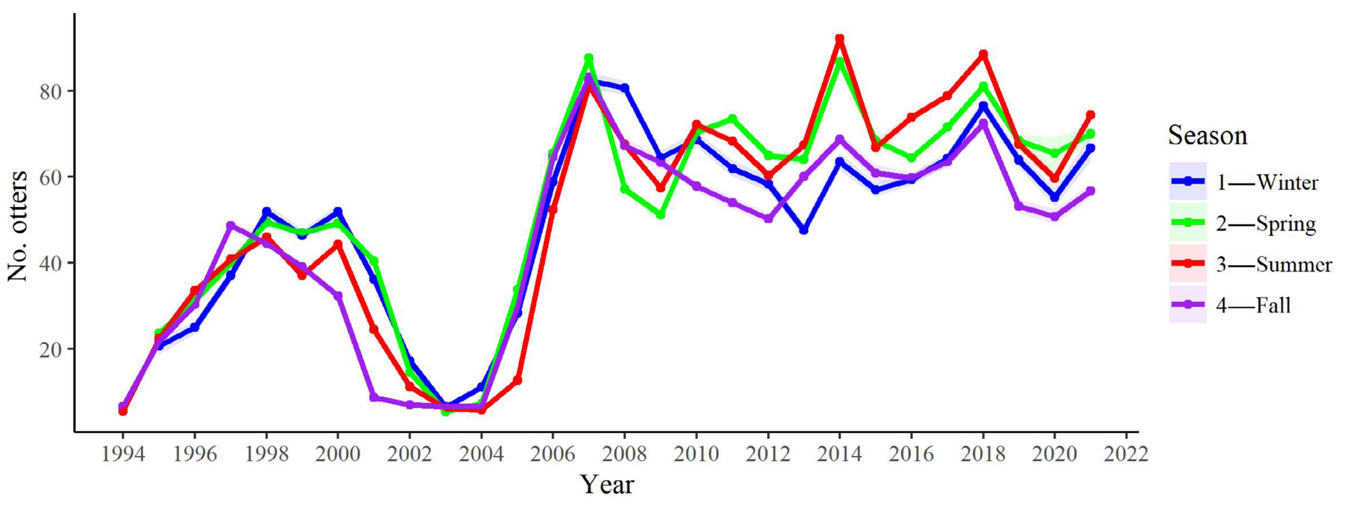

FIGURE 6 Seasonal dynamics of sea otter abundance in the lower estuary. Data are from the ecotourist Elkhorn Slough Safari voyages. Counts have been consistently higher in summer and spring than fall and winter over the past decade. Seasons were divided by calendar quarters: 1—winter = January–March, 2—spring = April–June, 3—summer = July–September, 4—fall = October–December.

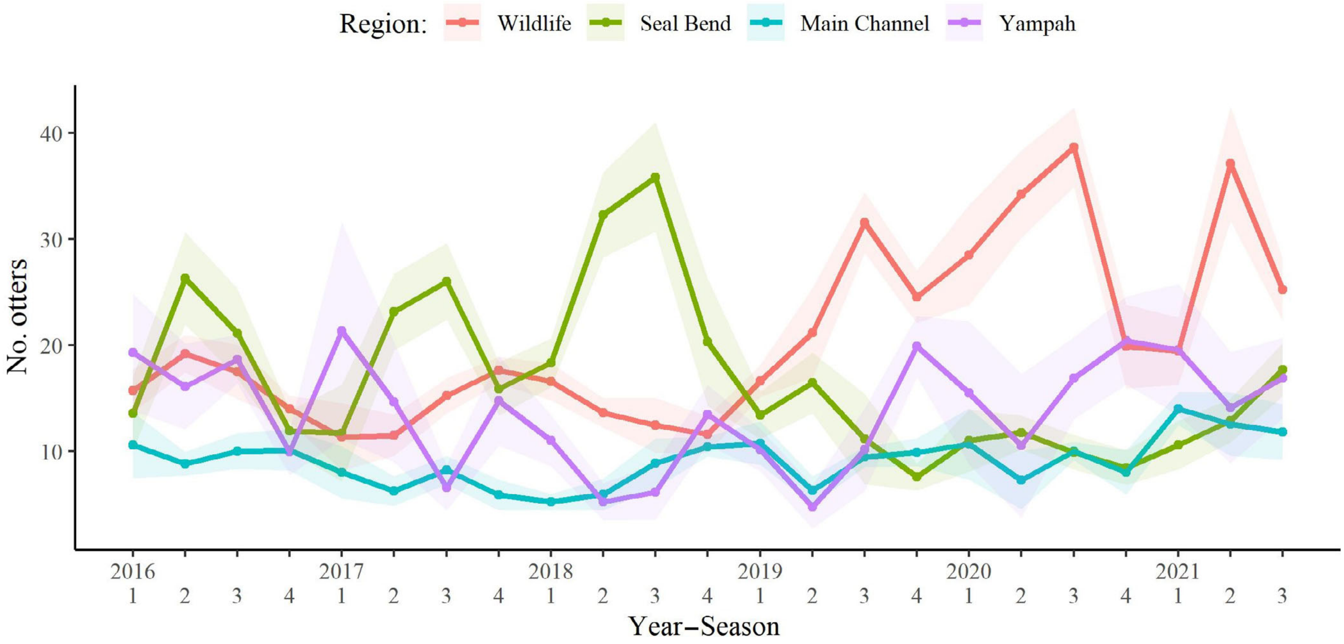

FIGURE 7 Seasonal and spatial dynamics of sea otter abundance in lower estuary. The *x*-axis shows years and seasons (calendar quarters as in Figure 6). Summer peaks in abundance are typical, but have shifted from the Seal Bend to the Wildlife region in recent years. Standard errors are shown with shading.

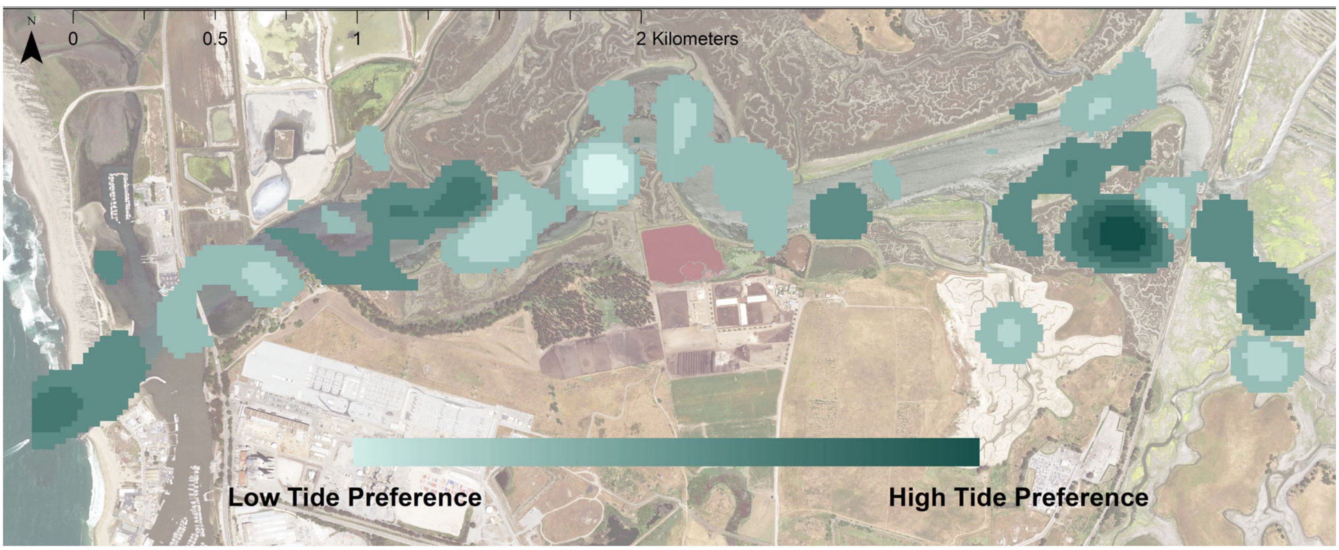

FIGURE 8 Relative abundance differences at high versus low tide. Kernel density plots of sea otter observations were generated for the top and bottom tide quartiles. The background imagery is the National Agriculture Imagery Program (NAIP) (3.75 × 3.75 min tiles 25 October 2016) downloaded from the National Map which is in the public domain.

Elkhorn Slough (Figure 11). Eelgrass beds encompassed 23% of the main channel by area, but accounted for 46% of the total sea otter observations in ROMP surveys from November 2018 to December 2020. The difference in sea otter density between eelgrass and water was highly significant in a paired *t* test, with an average of 0.94 otters/ha in eelgrass versus 0.15 otters/ha in adjacent non-vegetated areas of the main channel.

DISCUSSION

Ecological and conservation relevance of volunteer findings

Overall, we demonstrated the ability to detect important ecological patterns using volunteer data for sea otters in a California estuary. Long-term trends and inter-annual

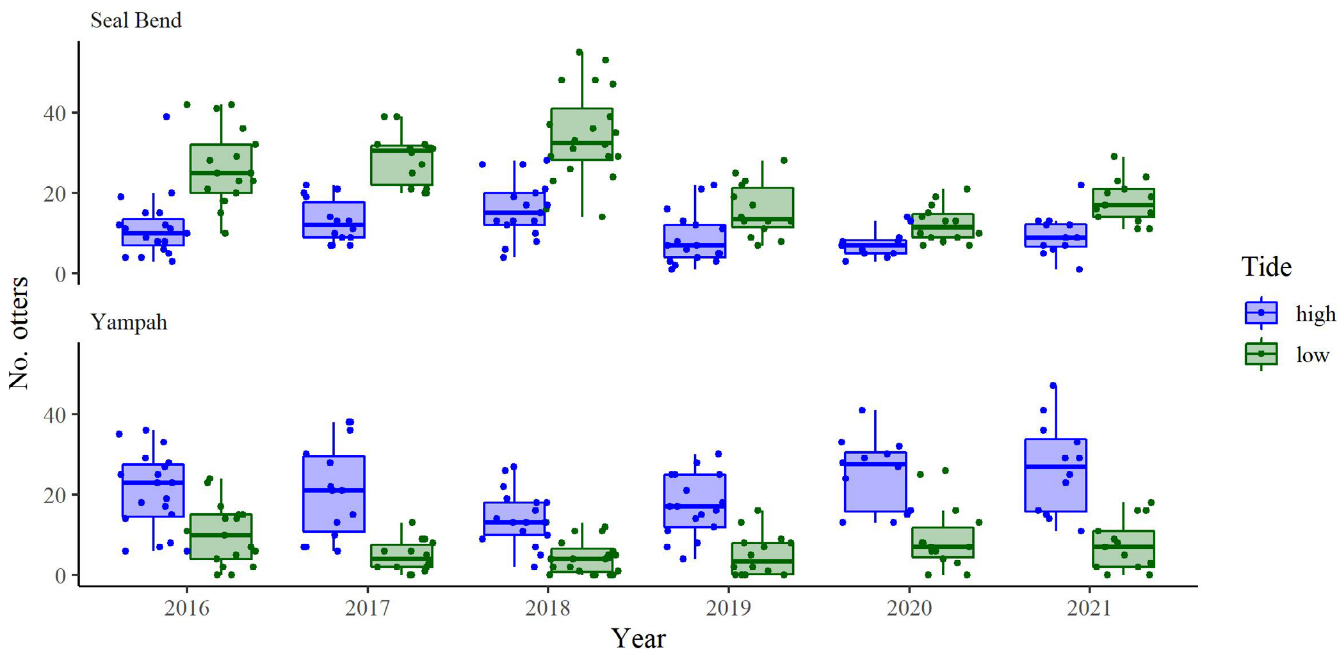

FIGURE 9 Sea otter abundance at high versus low tide in two estuarine areas. Seal Bend (Area 8, Figure 3) abundance is shown in the upper row of plots; Yampah (Area 12) abundance is shown on the lower row of plots. In every year, abundance at Seal Bend was higher at low (green) than high (blue) tide; the reverse was true at Yampah. Box plots show median, 25th and 75th percentile, minimum, maximum, and observed data values.

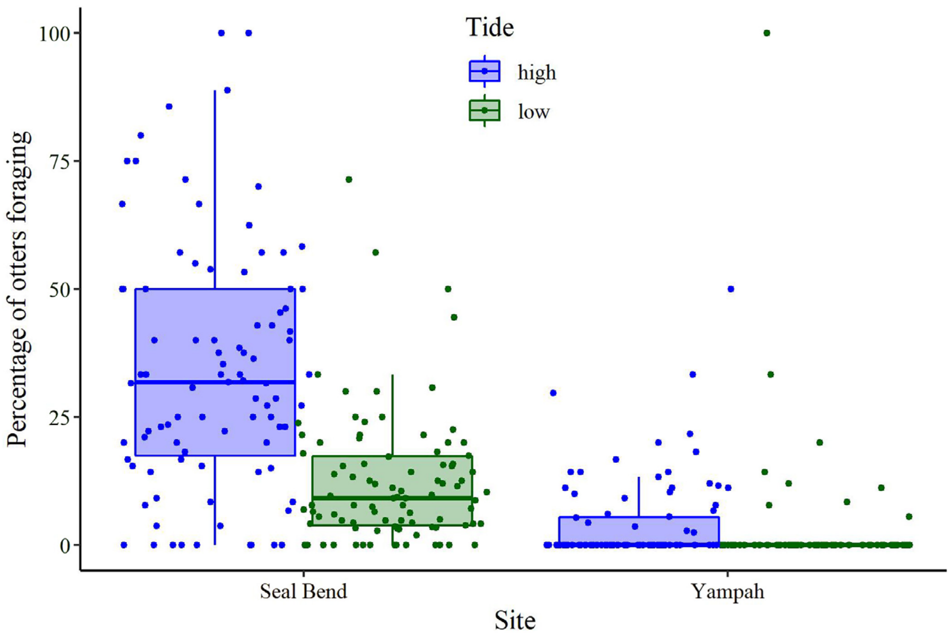

FIGURE 10 Sea otter foraging at high versus low tide in two estuarine areas. Seal Bend is shown on left; Yampah is shown on right. Box plots show median, 25th and 75th percentile, minimum, maximum, and observed data values.

variability were similar between professional agency monitoring data and volunteer datasets. Moreover, the much higher frequency of volunteer observations allowed for seasonal and tidal dynamics to be detected that could not be revealed by less frequent professional monitoring. Volunteer data can thus provide critical information about this and other federally listed species.

The volunteer data highlighted in this study documented very high numbers of sea otters using this estuary. While most southern sea otters dwell on the open coast, estuaries appear to provide especially valuable habitat for foraging and hauling out (Eby et al., 2017; Hughes et al., 2019; Maldini et al., 2012). The 25+ year record of ecotourist observations shows persistent

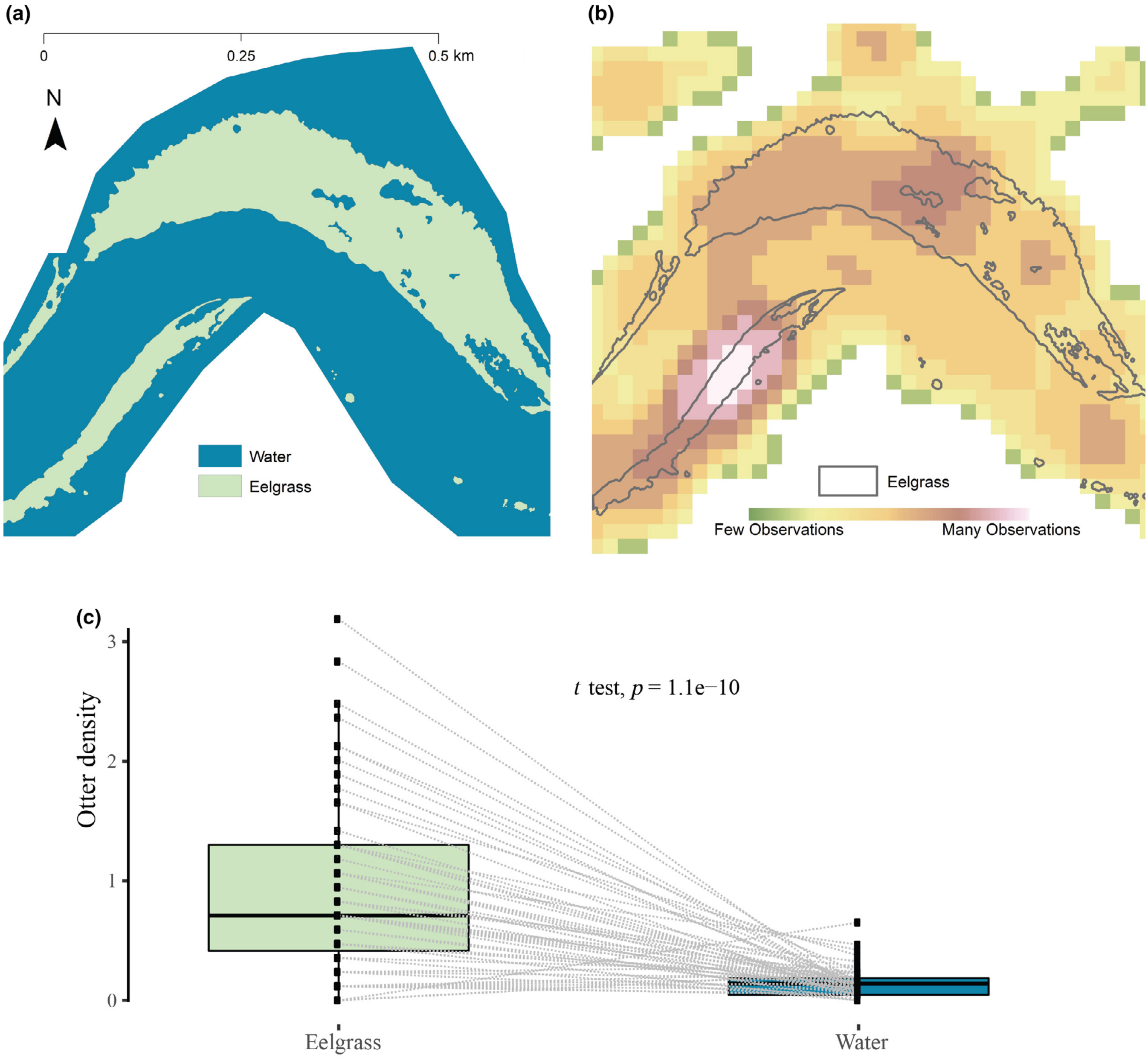

FIGURE 11 Sea otter abundance inside and outside of eelgrass beds. (a) Distribution of eelgrass (green) and open water (blue) in the Seal Bend area (Area 8 in Figure 3). (b) Sea otter kernel density plot of this area, showing that highest otter numbers (dark tan and pink) are found in eelgrass beds. (c) Density of otters (number per hectare) in eelgrass and open water in this area; each point represents a survey date and the dashed lines connect the same dates in the two habitat types, illustrating the way the paired *t* test was calculated.

high numbers in the lower estuary, suggesting sufficient food resources may still be present despite the high foraging rates of these marine mammals. However, the lack of increased population growth may indicate that local carrying capacity has been reached. In years with lower sea otter numbers, such as the marked decrease in 2002–2004 (Figure 5), presumably otters left the estuary and lived somewhere on the adjacent coastline. Dynamics in these early years were driven by immigration and emigration of nonresident males, while after 2004, increases in abundance were due to resident females and their offspring (Mayer et al., 2021). The continued seasonal fluctuations in sea otter numbers detected by the volunteer monitoring data suggest that some nonresidents exit the estuary each fall and return in spring, consistent with movements of males in other parts of the range (Tinker et al., 2017, 2019). Unfortunately, no high temporal resolution monitoring program for otter abundance exists in immediately adjacent areas of open coast. Volunteer monitoring efforts of adjacent stretches of coastline could be initiated to shed light on connectivity and movement patterns between estuary and coast, which would be valuable for informing conservation planning, since such seasonal dynamics of estuary use have not previously been documented.

The volunteer monitoring results highlighted here also showed numbers peaking at certain main channel areas in spring–summer. We suspect that this is due to females with pups using eelgrass beds in this area. Eelgrass beds have expanded in the Wildlife area, in part due to targeted restoration efforts (Beheshti et al., 2021). We hypothesize that the shift of the spring–summer peak from Seal Bend due to Wildlife is linked to eelgrass expansion. The high-resolution spatial data presented here demonstrated dramatically higher use of eelgrass beds than adjacent areas (Figure 11)—otter densities were more than six times higher in eelgrass than nearby unvegetated portions of the estuarine channel. These results highlight the importance of restoration of coastal foundation species to support the recovery of this imperiled mammal species.

The high-frequency volunteer observations were also able to detect tidal dynamics that cannot be studied with the annual surveys conducted by USGS. Volunteer data clearly revealed that spatial patterns of habitat use across the estuary differed at high versus low tide, and the use of particular slough areas differed, as did foraging intensity. Similar patterns had been detected by tracking radio-tagged sea otters in the estuary: more foraging at high than low tide, and more foraging in main channel than creeks (Espinosa, 2018). The ROMP volunteer team has noted that sea otters frequently rest during lower tides in quiet areas such as Yampah, and then as the tide rises move to foraging areas such as Seal Bend. This finding can inform strategic planning by wetland managers. Both types of habitats are critical for sea otters—they need good foraging areas with large clams such as the main estuary channel, as well as good resting areas protected from disturbance by recreational visitors such as the quiet tidal creeks.

Value of ecotourist public observations

Concerns have been raised that the use of untrained volunteers and lack of rigorous protocols generate low-quality data from which strong statistical inferences cannot be made (Brown & Williams, 2019). By contrast, we found observations by untrained ecotourists to yield very similar patterns of long-term trends and inter-annual variability relative to data collected by professional agency scientists (Figure 5). Moreover, since over 300 ecotourist surveys are conducted each year, in contrast to the single-agency survey, this dataset can be used to explore seasonal and other shorter term dynamics. We concur with recent perspectives that community science observations are valuable for spatial ecology and conservation (Kobori et al., 2016). Likewise, eMammal observations and visitor center assessments of camera trap photos yielded valuable mammal data and linked the public to habitat conservation issues (Parsons et al., 2018).

What makes the Elkhorn Slough Safari dataset particularly valuable is that the same route is followed every day—there is high-frequency temporal sampling within consistent spatial boundaries. A comprehensive review of monitoring in Europe suggested that volunteer monitoring can yield excellent assessments of biodiversity, so long as spatial/temporal sampling frequency is high and protocols are robust: high sampling effort can offset any noisiness of data (Schmeller et al., 2009). We suggest that such an approach could be implemented for other ecotourist ventures, where the same route is taken frequently—monitoring can engage visitors and enhance their connection to the iconic species and habitats they are visiting, while generating useful data.

Trained volunteers in coordinated monitoring programs

The ROMP model of experienced, well-organized volunteers proved very effective for detecting novel patterns of spatial habitat use, such as high abundance in eelgrass beds, and complex temporal dynamics, such as shifts in spring–summer peak abundance from one slough area to another, as well as tidally driven differences in spatial distribution and behavior. This model of coordinated community monitoring of sea otters could be implemented in other California estuaries, such as Morro Bay and San Francisco Bay, as they are colonized in the future by the expanding southern sea otter population (Rudebusch et al., 2020). An approach such as that of the ROMP team is also broadly applicable to generating data on other at-risk, understudied wildlife. For example, large and small mammal monitoring in North American woodland showed that volunteers could rapidly be trained to collect accurate information that correlated well with that from professionals, though typically resulted in underestimates (Newman et al., 2003). Community science is increasingly being used to track rare and threatened species, and can powerfully inform conservation science and policy if conducted rigorously over the long term (Fontaine et al., 2022).

Recruitment and retention of volunteers are critical to community monitoring programs. Likewise, the social dimension—team inspiration and enthusiasm—is vital (Bell et al., 2008). For ROMP, regular group meetings, training, and communications and interactions among volunteers, as well as between volunteers and professional scientists, have kept the group energized, resulting in both high recruitment and retention. A large, organized network has also been essential for the accuracy and consistency of ROMP data. Volunteer leaders organize schedules and update and distribute protocols; more experienced volunteers train new team members; all areas are monitored by two people who discuss their observations while monitoring. Such coordination is not trivial, but yields engaged volunteers and high-quality data. ROMP also has recently adopted tablet computers for field data collection, increasing accuracy and consistency of observations. In summary, we concur with others (e.g., Cohn, 2008) who have found that engaging community scientists can yield reliable data and enhance conservation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Wasson & Yee, 2022) are available from Dryad: https://doi.org/10.7291/D1FX0Z.

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SUPPORTING INFORMATION

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

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