



# Increases in Sea Level Associated with a Marine Heatwave Drive Tidal Marsh Habitat Shifts

Kellie A. Uyeda<sup>1,2</sup> · Kathryn M. Beheshti<sup>3</sup> · Jeffrey A. Crooks<sup>1</sup> · Charlie Endris<sup>4</sup> · John Haskins<sup>4</sup> · Russell Johnston<sup>3</sup> · Henry M. Page<sup>3</sup> · Rachel S. Smith<sup>3</sup> · Kerstin Wasson<sup>4</sup>

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## Abstract

Extreme climate events provide an opportunity to understand how habitats will respond to future long-term climate change. Starting in late 2013, an exceptionally strong marine heatwave, or the “Blob”, which was followed by El Niño in 2015–2016, resulted in an anomalous temporary rise in sea level on the Pacific US coast. We examined the response of tidal marsh plant communities in three California estuaries spanning over 600 km to these elevated water levels. We focused on the seaward ecotone of *Salicornia pacifica*, the succulent marsh dominant in the region. *S. pacifica* cover declined rapidly and sharply at all three estuaries in response to increased tidal inundation. In areas with *Spartina foliosa* (Tijuana River Estuary), this low marsh dominant colonized areas of *S. pacifica* dieback. In the absence of *S. foliosa* (Carpinteria Salt Marsh and Elkhorn Slough), areas of low *S. pacifica* marsh converted to mudflat. We demonstrate the rapid response of these systems to transient sea level changes, and emphasize the value of consistent long-term monitoring using field surveys and remote sensing for detecting tidal marsh responses to sea level rise. These case studies can be used to test model predictions, as we provide empirical evidence of vegetative response to ~15 cm of sea-level rise. They also offer concrete examples of marsh habitat loss or type conversion resulting from climate change, and thereby build support for climate adaptation strategies.

**Keywords** Salt marsh · Vegetation · ENSO · Elevation · Marine heatwave · Long-term monitoring

## Introduction

Climate is predicted to affect the global distribution of habitats, with valuable tidal marshes at the frontlines of potential sea level rise (SLR) impacts (Barbier et al., 2011; Donnelly & Bertness, 2001; Fagherazzi et al., 2020). Models are typically used to predict responses to accelerated SLR with climate change (Wiberg et al., 2020), and locations or time periods that match predicted future conditions are important

tests of climate models. Such models also provide concrete examples of habitat conversion useful for outreach to stakeholders interested in climate responses and responding to the need for climate change mitigation (Thorne et al., 2018). For tidal marshes, extreme climate or oceanographic events can build our understanding of how these systems may respond to accelerated SLR.

The Pacific coast of the USA has not yet experienced much acceleration in SLR (Bromirski et al., 2011), but the pace appears to be quickening (Sweet et al., 2022). In this region, marine heatwaves can act as surrogates for understanding the impacts of climate change and future SLR on tidal marshes (Goodman et al., 2018). Specifically, starting in late 2013, the northeast Pacific experienced an unusual marine heatwave, called the “Blob” (Di Lorenzo & Mantua, 2016; Sen Gupta et al., 2020). This was followed by the 2015–2016 El Niño, which appears to be linked to the Blob event (Tseng et al., 2017) and was one of the strongest ever recorded, causing marked coastal erosion and flooding (Barnard et al., 2017). El Niño events can cause elevated sea levels due to changes in large-scale atmospheric forcing,

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✉ Kellie A. Uyeda  
kuyeda@ucsd.edu

<sup>1</sup> Tijuana River National Estuarine Research Reserve, Imperial Beach, CA 91932, USA

<sup>2</sup> University of California San Diego, San Diego, CA, USA

<sup>3</sup> Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA, USA

<sup>4</sup> Elkhorn Slough National Estuarine Research Reserve, 1700 Elkhorn Rd, Watsonville, CA 95076, USA

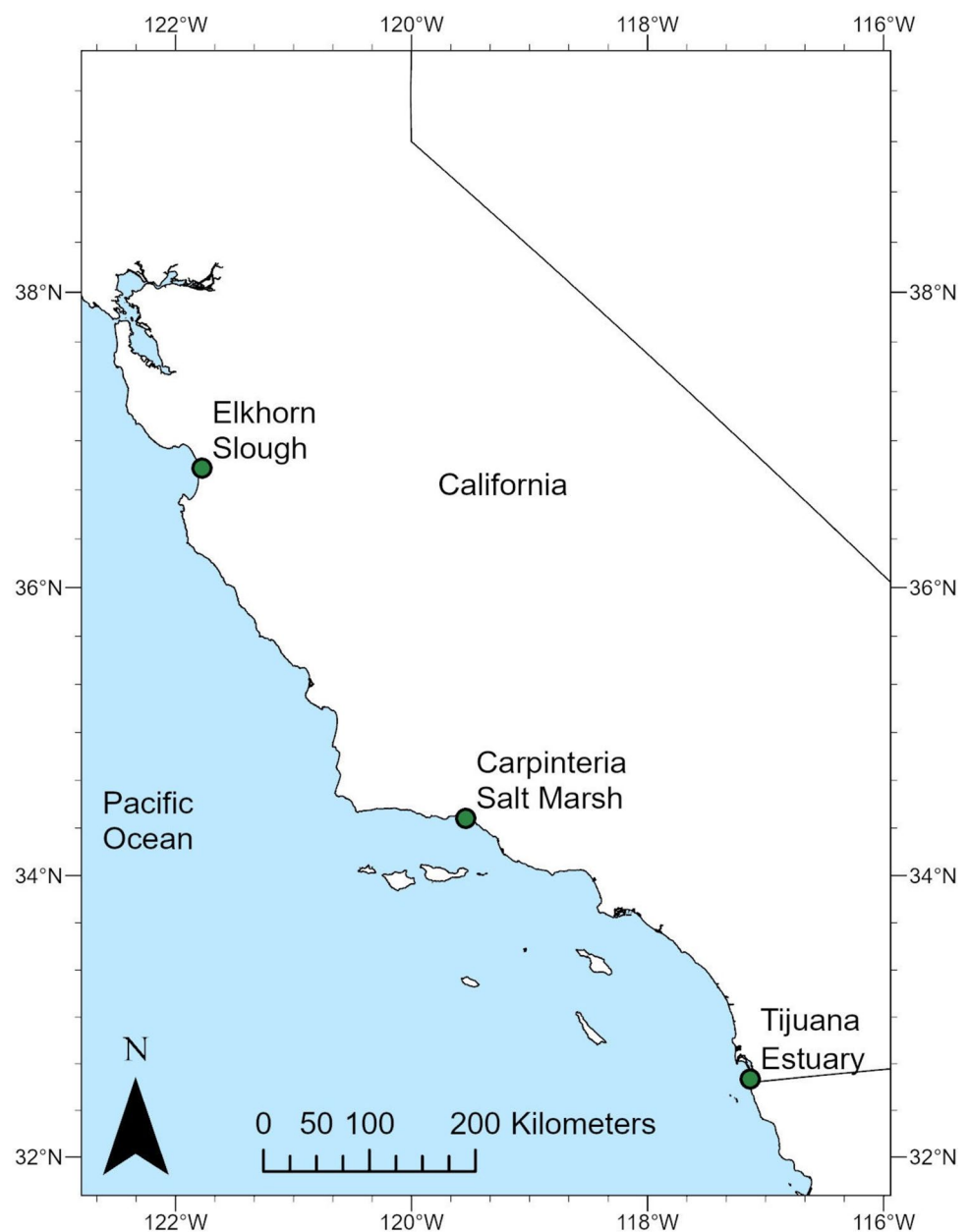
oceanic circulation patterns, storm surge, and wave climate (Harvey et al., 2020; Holbrook et al., 2020). In estuaries along the Pacific coast, high tide anomalies peaked between December 2015 and March 2016 (Goodman et al., 2018). Water levels remained elevated from 2015 to 2016 in a series of southern California estuaries (Harvey et al., 2020). This increase in tidal inundation was suggested as a potential stressor on tidal wetlands (Goodman et al., 2018), but no negative consequences had been demonstrated empirically.

Our teams working independently at three California estuaries (Tijuana Estuary, Carpinteria Salt Marsh, Elkhorn Slough, Fig. 1) noticed tidal marsh responses to the 2015–2016 El Niño. Drawing on long-term monitoring

conducted at each estuary, we examined the signatures of tidal marsh response to this El Niño. All three estuaries have extensive tidal marshes dominated by the succulent perennial pickleweed *Salicornia pacifica* (also known as *Sarcocornia pacifica*). Succulent-dominated marshes are typical of low latitudes and areas prone to drought; understanding the response of this marsh type to climate change is a research gap, since most studies have focused on marsh grasses more typical of higher latitudes (Osland et al., 2019).

*Salicornia* is much less tolerant of inundation than marsh grasses such as *Spartina* spp., and so *Salicornia*-dominated marshes are found higher in the tidal frame (Raposa et al., 2016). We were particularly interested in the

**Fig. 1** Locations of the three study sites along the central and southern California coast



ecotone between *Salicornia* and what lies below it—California cordgrass, *Spartina foliosa* (syn. *Sporobolus foliosus*) at some California marshes, or mudflat at those estuaries where *S. foliosa* is absent. Ecotones are particularly sensitive to environmental change (Risser, 1995), and although the landward ecotone of California marshes had been shown to respond to increased inundation (Wasson et al., 2013), shifting boundaries have not been demonstrated for the seaward ecotone. The seaward ecotone should be even more vulnerable, because *S. pacifica* is living near its tolerance limit for inundation. *S. pacifica* biomass is greatest when it is inundated 0–10% of the time, and declines nonlinearly with increased submergence (Janousek et al., 2016).

All three of these California estuaries experienced elevated sea levels during the Blob and subsequent El Niño (Fig. 2). Our objective was to examine responses of *Salicornia* seaward ecotones to this temporary increase in tidal inundation, as a proxy for understanding responses to future long-term accelerated SLR.

We used existing long-term data collected at each estuary to characterize the signature of the 2015 El Niño. Because different organizations conducted the monitoring, approaches varied across the estuaries. Remote sensing imagery is presented for all three estuaries and field data is shown for two (Elkhorn Slough and Tijuana Estuary). The estuaries span 4° of latitude and 600 km of coastline, yet have some geographic similarities: all experience

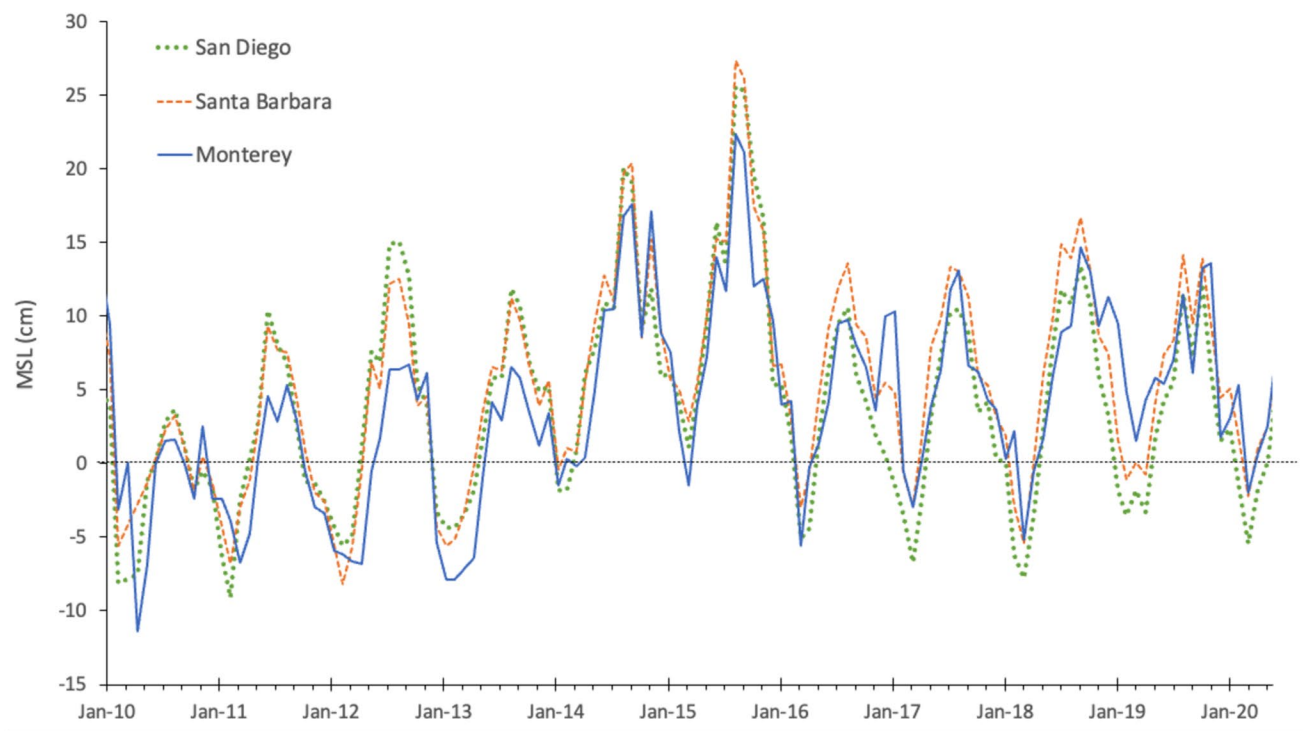
a Mediterranean climate, with limited rainfall that occurs largely from Nov–May; all three have limited freshwater inputs and are primarily inundated by semi-diurnal tides. Nevertheless, the estuaries also differ. For example, the Tijuana Estuary faces threats from excessive sedimentation (Endris et al., 2024; Zedler et al., 1992), whereas Elkhorn Slough is stressed by sediment starvation and erosion (Endris et al., 2024; Van Dyke & Wasson, 2005).

Below, we provide case studies of tidal marsh responses to the 2013–2016 marine heatwave for each of the three estuaries in turn, provide context on the site, describe the monitoring approach, and summarize findings. These case studies illustrate how sensitive tidal marshes are to sea-level changes, which has direct applications for reevaluating reliability of marsh resilience models, and better understanding vegetation response to climate change (Osland et al., 2019).

## Tijuana Estuary

### Site Description

The Tijuana Estuary is located near Imperial Beach in San Diego County, CA, adjacent to the US–Mexico border (Fig. 1). It is the largest intact salt marsh ecosystem in southern California. The average annual rainfall for the area is approximately 25 cm. *Spartina foliosa* typically



**Fig. 2** Monthly mean sea level at NOAA monitoring stations closest to each study site

dominates the low marsh zone, with *S. pacifica* often dominating the mid-marsh zone. Other species present within the mid-marsh zone include *Batis maritima* (saltwort), *Jaumea carnosa* (marsh jaumea), and *Frankenia salina* (alkali heath) (Zedler et al., 1992).

### Data Collection

To track shifts in salt marsh community composition and location over time, three parallel transects approximately 8 to 15 m apart were established at the Tijuana Estuary in October of 2012 (Fig. 3). Each transect is approximately 20 m long and is made up of eight permanently marked 1-m<sup>2</sup> quadrats. These transects are oriented across the elevation gradient from the upland to the low marsh zone. Field crews visit the transects annually in the autumn, visually estimating the percent cover of vegetation by species within each quadrat. The three quadrats from each transect at the transition zone between *S. pacifica* and *S. foliosa* were examined for this study.

### Results

When the vegetation transects were established in the autumn of 2012, average cover of *S. pacifica* was high (93%) and *S. foliosa* cover was low (2%) (Fig. 4). *S. pacifica* steadily declined starting in 2013, while *S. foliosa* showed a steady increase, with a peak of 48% in autumn 2017. Cover of *S. pacifica* remained low until 2018, when it sharply increased and *S. foliosa* showed a corresponding decline. This process of recovery of the original vegetation composition was slower than the initial species shift in response to the elevated sea levels. Limited cover of *B. maritima* was present in 2012 and 2013, and *F. salina* in 2023, but these species were never dominant and are not shown in Fig. 4.

### Carpinteria Salt Marsh

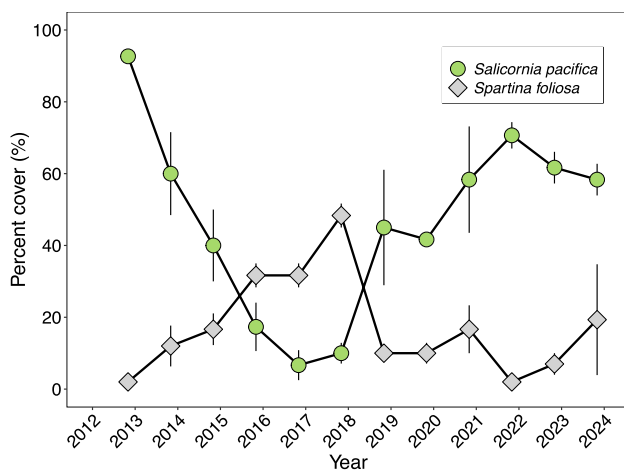
#### Site Description

Carpinteria Salt Marsh is located 12 km east of Santa Barbara, CA (Fig. 1). Tidal waters enter the wetland through an



**Fig. 3** Aerial imagery showing early (2014), immediately after (2017), and post-recovery (2020) time series of low marsh experiencing elevated sea levels at the Tijuana River Estuary. The yellow lines

indicate the position of long-term monitoring transects, with markers showing the location of the specific quadrats examined in this study. Imagery is provided by Nearmap



**Fig. 4** Percent cover of *Salicornia pacifica* and *Spartina foliosa* from autumn 2012 to autumn 2023 at the ecotone between the two species at the Tijuana River Estuary. Error bars represent standard error ( $n=3$ )

inlet at its southern border. The estuary receives freshwater runoff from channelized creeks and other sources that drain the Santa Ynez Mountains and coastal plain. Average annual precipitation is approximately 45 cm. *S. pacifica* dominates the regularly flooded middle tidal marsh. A mix of species, including *Arthrocnemum subterminale*, *J. carnosa*, *Distichlis spicata*, and *F. salina*, comprise the mixed marsh at higher tidal elevations (Ferren, 1985).

## Data Collection

Aerial imagery is collected annually with fixed-wing aircraft (2012–present) in spring-early summer during low tide as part of a long-term mitigation monitoring program for which Carpinteria Salt Marsh serves as a reference (Page et al., 2022). Imagery is acquired at a spatial resolution of 20 cm using a Microsoft UltraCam Falcon digital camera. The images include red green blue (RGB) and near-infrared (NIR) bands. The mosaics are classified using supervised classification techniques based on spectral characteristics and best professional judgment of the cover and species identity to create a thematic raster dataset.

## Results

Wetland-wide, *S. pacifica* habitat declined by 7.8 hectares at Carpinteria Salt Marsh during the El Niño from 2015 to 2018. Much of this decline was due to conversion to mudflat (see inset Fig. 5B), with higher water levels likely drowning *S. pacifica*. Indeed, from 2015 to 2017, mudflat habitat increased by 5 hectares at the wetland (Fig. 6). In other areas of the wetland (Fig. 5C), mixed marsh (largely *J. carnosa*) replaced *S. pacifica*. *S. pacifica*

began to recover immediately following the marine heat-wave and is approaching its pre-marine heatwave long-term average (Fig. 6). Accuracy assessment of the image classifications by using a stratified random sampling of cover classes visually scored (minimum 250 points per image) yielded an accuracy estimate (2012–2024) of  $87.9\% \pm 1.4$  (mean  $\pm$  standard error) with a kappa coefficient of  $83.4\% \pm 2.0$ .

## Elkhorn Slough

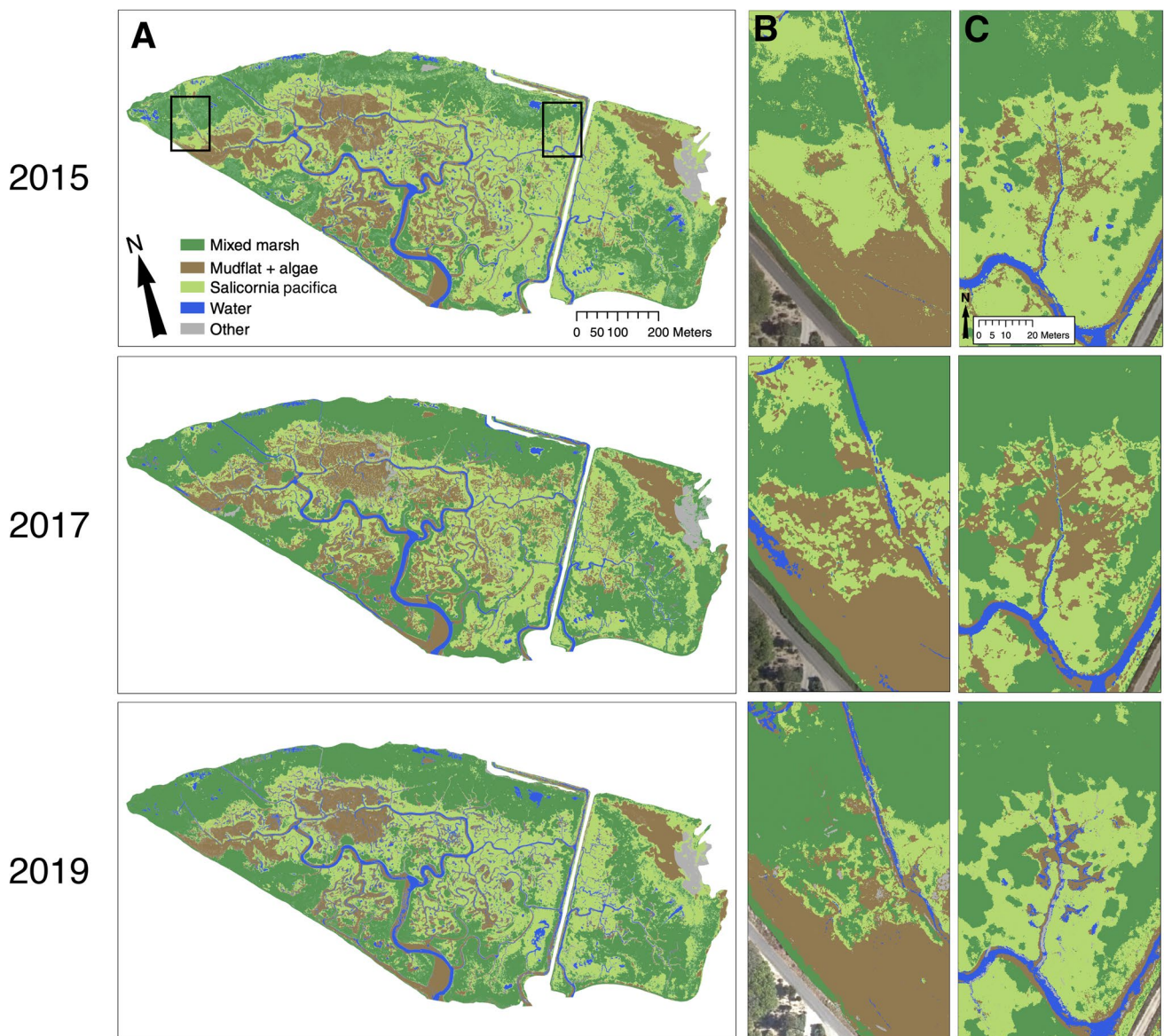
### Site Description

The Elkhorn Slough is an estuary located in the midpoint of Monterey Bay in central California (Fig. 1). It is the largest intact salt marsh ecosystem in California south of San Francisco Bay. The average annual rainfall for the area is approximately 45 cm. The salt marsh is dominated by *S. pacifica* and sits low in the tidal frame; high marsh species are found only close to the marsh-upland boundary (Wasson et al., 2013). Since *S. foliosa* is absent from the estuary, the boundary emphasized by monitoring is the seaward *S. pacifica* boundary, where the transition to mudflat occurs.

### Data Collection

We collected UAV imagery over a portion of Elkhorn Slough's marsh in October 2015 using an E384 fixed-wing drone with a 12-megapixel camera. Two additional flights were flown in February 2017 and April 2019 using a DJI Phantom 4 Pro with a 20-megapixel camera. All imagery was georeferenced to the initial 2015 flight in order to assess temporal change.

For 13 salt pannes within the area of interest, we tracked the position of marsh vegetation over time (2016–2018) to evaluate whether each panne was contracting or expanding over the 2-year period (Beheshti et al., 2022). We resurveyed the same 18 semi-permanent markers within each of the pannes annually and averaged the position of the marsh relative to those semi-permanent markers to characterize and evaluate changes to vegetated marsh extent relative to the panne interior. The elevation of each panne was extracted using 2011 LiDAR, and panne circumference data was collected at the beginning of the study. We visualized changes to two of these pannes using UAV imagery collected in October 2016 and August 2021 using a DJI Phantom 4 drone. Flights were flown at 64 m above ground (3.1 cm resolution) and 50 m above ground (1.3 cm resolution), respectively.



**Fig. 5** Classified aerial imagery of Carpinteria Salt Marsh early (2015), during (2017), and after (2019) the El Niño is shown wetland-wide (A). We highlight two areas (indicated by the two black boxes in panel A) of marked habitat change. Both the western (B) and eastern (C) areas showed a substantial increase in mudflat through the conversion of *Salicornia pacifica* to mudflat during the El Niño

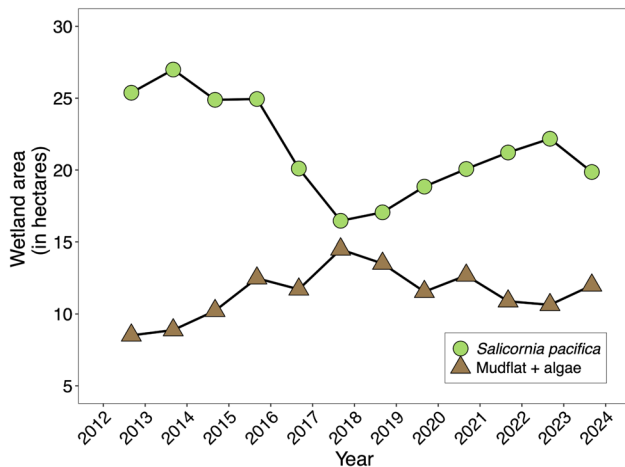
(2017). All maps and figures are color coded with mixed marsh (multiple plants, including *Arthrocnemum subterminale*, *Jaumea carnosa*, *Distichlis spicata*, and *Frankenia salina*) in dark green, *Salicornia pacifica* in lime green, mudflat and algae in brown, water in blue, and other in gray

## Results

The UAV imagery from 2015 shows *S. pacifica* in dark brown surrounded by a lighter brown shade representing intertidal mudflats. By 2017, elevated areas of mudflat were covered by a thin layer of algae (bright green) and showed a noticeable absence of *S. pacifica* in these areas compared with 2015. By 2019, *S. pacifica* (now visible in dark green) had recolonized significant areas of mudflat where it was missing in 2017 (Fig. 7). These results of dieback at the

seaward *S. pacifica* boundary of pannes match observations along channels and creeks during this period (Supplemental Fig. 2).

Over the 2-year panne study (2016–2018), all 13 pannes contracted and the marsh recovered into the panne area (Fig. 8). Recovery of vegetation along the marsh-panne border ranged from ~10 to 30 cm over the study period. In the years that followed, pannes continued to contract and many of the experimental plots converted from panne to salt marsh habitat by 2023 (Fig. 8). The greatest marsh recovery



**Fig. 6** Hectares of *Salicornia pacifica* decreased and mudflat increased at the wetland-wide scale during the El Niño, from 2015 to 2018 at Carpinteria Salt Marsh. Post 2019 (after the El Niño), *S. pacifica* area rebounded and mudflat area declined



**Fig. 7** UAV imagery of pickleweed marsh in Elkhorn Slough showing a decline of the vegetated marsh from 2015 to 2017 and regrowth by 2019. The change is most pronounced inside the white rectangle

was observed in higher elevation, shallower pannes relative to lower elevation, deeper pannes (Beheshti et al., 2022).

## Discussion

Our three case studies revealed strong, rapid tidal marsh responses to increased sea levels resulting from a marine heatwave starting in late 2013 and extending into 2016. Despite being separated by a linear distance of 600 km, and despite differences in community composition, estuary geomorphology, and climate, the three California estuaries all showed sharp declines in the common mid-marsh dominant, *S. pacifica*, at the ecotone with low marsh or mudflat. The similarity in negative effects of higher sea levels on *S. pacifica* underlines the generality of the finding. Mesocosm studies have demonstrated that *S. pacifica* responds poorly to being submerged more than 10% of the time (Janousek et al., 2016), and our case studies provide empirical evidence of the negative effects of increased submergence in the field.

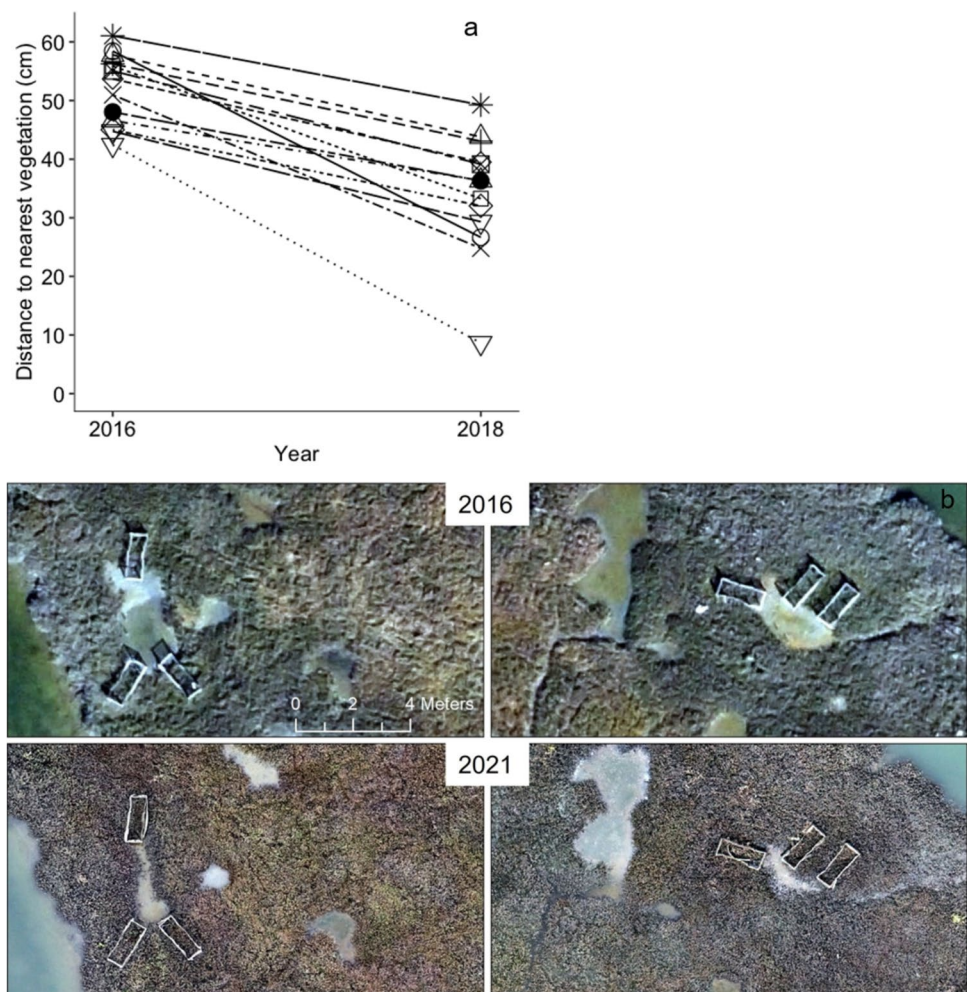
The rapidity of the *S. pacifica* response—effects were evident within a year—to a 15-cm increase in sea level was striking. Transition zones such as this seaward ecotone are most vulnerable to climate change, and are likely to show negative impacts more rapidly than the rest of the habitat. The recovery to temporarily elevated water levels was much slower than the initial response. Although water levels were lower by late 2016 relative to the previous 2 years, there was never a full return to pre-Blob levels (Fig. 2), and *S. pacifica* cover at the seaward ecotone continued to decline in 2017 at all three estuaries (Figs. 4, 6, and 7). Thereafter, it only slowly increased, not entirely regaining original levels by the end of the monitoring period at any of the estuaries. *Salicornia* is a relatively slow-growing, woody perennial, and recovers much more slowly than a fast-growing grass such as *Spartina* (Raposa et al., 2023). Climate adaptation strategies may thus need to differ for drought-tolerant succulent-dominated marshes than for marsh grasses. More generally, efforts to understand temporal change in coastal systems should also consider that longer-term trajectories could be punctuated by shorter-term events that could serve to attenuate or amplify signals of interest, such as the compounding effects of temporary anomalies and warming-induced sea-level rise on coastal processes (e.g., Han et al., 2022; Raposa et al., 2017).

During marsh dieback resulting from high water events, ecosystem services provided by coastal vegetation may decrease. For instance, accretion rates from sediment trapping may have decreased during the 2015–2016 El Niño (Goodman et al., 2018). At one of the three estuaries in this study, *S. foliosa* was present, and quickly colonized the areas where low *S. pacifica* had died back. At the other two estuaries, these areas were converted to mudflat. Coastal managers

**Fig. 8** Panne recovery following the El Niño in Elkhorn Slough.

**a** Based on semi-permanent markers, the distance to the nearest vegetation relative to the panne interior is shown above for each panne, represented by distinct shape points ( $n = 13$ ). The lines connect individual pannes to show the relative change in the extent of marsh recovery into the panne area. Relatively lower values indicate greater marsh recovery as the distance between the semi-permanent markers and the nearest vegetation narrowed.

**b** Aerial imagery of two of the pannes, soon after the El Niño (upper photos) and 5 years after (lower photos), showing panne recovery. The rectangles are cages that are a part of this study (Beheshti et al., 2022)



could consider a climate adaptation strategy of *S. foliosa* introduction to California estuaries where it is currently absent, so that anticipated sea-level rise results in a shift in marsh species as seen at Tijuana River Estuary, rather than a complete loss of the lowest marsh as seen at Elkhorn Slough and Carpinteria Salt Marsh. This is an example of a nature-based solution that could help marshes continue to persist and provide important flood-control ecosystem services (Stoorvogel et al., 2024).

While marine heatwaves have often been considered in terms of their potential thermal impacts (Jacox et al., 2020; Joyce et al., 2024), they also provide an opportunity to build an understanding of coastal ecosystem responses to changing sea levels. Modeling provides a powerful approach to predicting future habitat scenarios, especially when coupled with empirical observations. Pacific coast tidal marsh models (Byrd et al., 2016; Thorne et al., 2018) could be used to compare biotic responses of modeled vs. observed 15-cm water level increases at these same three study sites, with the understanding that rates of water level change may differ for episodic events and long-term climate change. Similar

approaches have been used for understanding future hazards associated with coastal flooding (Hague et al., 2023; Sweet et al., 2016).

Long-term monitoring is critical in a changing world. We demonstrated that both field and remote sensing data collected consistently over time could detect tidal marsh habitat responses to increased inundation. Although the short-term variation inherent in annual monitoring complicates the analysis of long-term trends, it also provides an opportunity to understand the outcomes of those long-term processes into the future. Ecotone monitoring proved particularly powerful for revealing dramatic and rapid responses to elevated sea levels. Thus, coastal managers should invest in robust, consistent long-term monitoring of tidal marsh habitats, with emphasis on sensitive transition zones, to support understanding of and strategies for coastal marsh resilience.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s12237-025-01530-3>.

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**Author Contribution** All authors contributed to the formal analysis, investigation, visualization, and writing of this study.

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**Data Availability** All datasets are available upon request from the corresponding author.

## Declarations

**Ethics Approval and Consent to Participate** NA.

**Consent for Publication** NA.

**Competing Interests** The authors declare no competing interests.

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