Backe Karen (Orcid ID: 0000-0001-7445-6447)

Title: Effects of sea-level rise and storm enhanced flooding on Pacific harbour seal habitat: a comparison of haul-out changes at the Russian and Eel River Estuaries

Author List: [1]Karen Backe, [1]Ellen Hines, [1]Karina J. Nielsen, [2]Doug George, [3]Elinor Twohy, [4]Mark Lowry

Author Affiliations: [1]Estuary & Ocean Science Center, San Francisco State University, [2]Bodega Marine Lab, University of California Davis, [3]Elinor Twohy, Jenner, California, 95450, [4]Retired, Encinitas, CA 92024

Abstract

1. Patterns and changes in the distribution of coastal marine mammals can serve as indicators of environmental change which fill critical information gaps in coastal and marine environments. Coastal habitats are particularly vulnerable to the effects of near-term sea-level rise.
2. In California, Pacific harbour seals (*Phoca vitulina richardii*) are a natural indicator species of coastal change due to their reliance on terrestrial habitats, abundance, distribution, and site fidelity. Pacific harbour seals are marine top predators that are easily observed while hauled out at terrestrial sites which are essential for resting, pupping, and moulting.

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/aqc.3574

3. While increasing inundation from recent sea-level rise and storm driven flooding has changed the California coastline, little is known about the effect of future sea-level rise and increased storm frequency and strength on harbour seal haulout site availability and quality in California.
4. Harbour seal habitat was modelled at two sand bar-built estuaries under a series of likely sea-level rise and storm scenarios. The model outputs suggest that, over time, habitat at both estuaries decreased with increasing sea level, and storm enhanced water levels contributed significantly to habitat flooding. These changes reflect pressures on coastal habitats that have an impact on human and natural systems.

Keywords

climate change; habitat suitability; harbour seal; indicator species; *sea-level rise; storm surge;* Phoca vitulina

1. Introduction

Increasing inundation from sea-level rise and storm enhanced water levels are projected to change coastal habitats (Grigg et al., 2009; Karl, Melillo & Peterson, 2009; Parris et al., 2012; Funayama et al., 2013). These phenomena are already being observed in coastal areas (Tebaldi, Strauss & Zervas, 2012; Wang et al., 2017). Increases in storm surge and sea level, attributes of global climate change, are having an impact on coastal communities and critical habitat for a myriad of species (Cloern et al., 2016; Griggs et al., 2017), including Pacific harbour seals (*Phoca vitulina richardii*). Rising sea levels combined with increasing frequency and intensity of storm enhanced water levels result in more frequent and greater areas of coastal flooding and inundation (Gallien et al., 2013; Muis et al., 2015; Vitousek et al., 2017). These threats are variable, relative to water elevation, elevation range, the duration of high and low tide events, substrate resistance to erosion, and presence or absence of natural or man-made barriers (Parris et al., 2012; Gallien et al., 2013; Behrens et al., 2013; Griggs et al., 2017; Wang et al., 2017). Understanding these changes is urgent, as pressures stemming from climate change compound other anthropogenic pressures on coastal ecosystems (Mitchell et al., 2015; Yang et al., 2015).

Patterns and changes in the distribution of marine top predators, including Pacific harbour seals and other marine mammals, are indicators of environmental change as they respond to changing features of their environment over long temporal and broad spatial scales (Moore, 2008). The State of California Environmental Protection Agency (EPA) has called for the use of indicators in climate change research (Kadir, Mazur & Milanes, 2013); harbour seals can fulfill that role.

Harbour seals are a natural indicator species due to their abundance, wide distribution, site fidelity, and sensitivity to changes in their habitat (Suryan & Harvey, 1998; Funayama et al., 2013). They are also relatively easily observed on land at terrestrial habitats which are essential for resting, pupping, and molting (Allen, 1991; Jansen et al., 2015). Harbour seals are abundant on the California coast and exhibit these characteristics, making them a good candidate as an indicator species of the effects of coastal climate change (Lowry, 2008; Codde & Allen, 2013; Codde & Allen, 2017).

While their current patterns of habitat use are relatively observable, there are knowledge gaps concerning the effects of climate change on harbour seal haul-out habitat (Funayama et al., 2013). Modelling current habitat use will enable future available habitat to be predicted (McClenachan, Ferretti & Baum, 2012; Pacifici et al., 2015). In their capacity as indicators, observing how harbour seals do or do not persist in using these habitats has the capacity to offer insights into coastal and near-shore climate change drivers, including sea-level rise and storm surge flooding (Funayama et al., 2013). Given the persistence of these haulouts over time, if changes are observed concurrently with dramatic environmental variables, they are likely to be the primary response driver.

Novel techniques are emerging to integrate species observations and environmental data (Guillera-Arroita et al., 2015; Pacifici et al., 2015; Pacifici et al., 2017; Boets et al., 2018). With sufficient temporal and spatial data resolution, these integrations permit fine-scale projections of species responses to climate change (Ehrlen & Morris, 2011; Morelli et al., 2015). Collection of observations necessary to monitor changes at all sensitive locations is not feasible, but concerted efforts of interested local stakeholders and community scientists can make substantial contributions to research efforts by increasing spatial and temporal observation coverage (Theobald et al., 2014; Chandler et al., 2017; McKinley et al., 2017).

This work proposes to model sea-level rise and storm impacts on harbour seal haul-ut habitat and hypothesizes that climate change driven sea-level rise and storm enhanced water levels will decrease harbour seal haulout habitat availability and quality.

1.2 Study Species

Pacific harbour seals are an eastern North Pacific basin subspecies found along the entire coastline of western North America. They faced significant population pressure from hunting in the early 19th century which reduced their numbers to a few hundred individuals in small groups on areas of the coast naturally sheltered from disturbance (Bonnot, 1928). Pacific harbour seals are currently protected by the Marine Mammal Protection Act but are not listed as threatened or endangered under the Endangered Species Act due to their successful population recovery and current abundance (MMPA 2007; Carretta et al., 2015). Aerial surveys conducted by the National Marine Fisheries Service in 2014 estimated the current population of the California stock at 27,348 individuals (Lowry, Carretta & Forney, 2008; NMFS 2015).

Harbour seals haul out on sections of coastline that offer protection from wind and wave action and isolation from human disturbance (e.g. kayakers, hikers, etc.), and have limited access by predators and nearby access to local and abundant prey resources (Allen, 1991; Nordstrom, 2002; Grigg et al., 2009; Jansen et al., 2015). Harbour seals are generally found hauled-out within 10 km of foraging areas that are patchily distributed in nearshore waters along the California coastline (Grigg et al., 2009). Harbour seals are flexible in their choice of prey, which include fish, crustaceans, and cephalopods, and will change prey based on availability and abundance (Suryan & Harvey, 1998; Grigg et al., 2009). Generally, harbour seals exhibit site fidelity to haulout sites (Suryan & Harvey, 1998; London et al., 2012) during the pupping and moulting season (Lowry et al., 2008). Protection is particularly important for pups and moulting individuals (Montgomery, Van Hoef & Boveng, 2007; Grigg et al., 2009). Pups, being less adept swimmers, are less able to weather storm events impacting a haul-out, and are more vulnerable to strong waves which have the potential to separate pups from their mothers. Additionally, storms and strong waves can place additional thermoregulatory demands on moulting seals (Harding et al., 2005; London et al., 2012).

2. Methods

2.1. Study Sites

Seals haul out on intertidal sand bars, beaches, tidal mud flats, rocky reefs, and estuaries (Lowry et al., 2008; Jansen, 2015). Estuaries are threatened by sea-level rise and increased storm wave energy (George, Gelfenbaum & Stevens, 2012; Luisetti et al., 2014; Thorne et al., 2015). Estuaries are ecologically productive, offer protected habitat, and are heavily affected by local anthropogenic pressures (Merrifield et al., 2011; Janousek et al., 2016). In northern California, estuarine haulouts offer model locations to study the effects of sea-level rise and storm events on harbour seal habitats.

The Russian and Eel Rivers form sand bar-built estuaries at the river mouths. Bar-built estuaries are dynamic systems, due to natural and managed patterns of opening and closure of the estuary mouth and lagoon water levels. These patterns are seasonal, weather-dependent, sediment load dependent, and frequently heavily managed (NMFS, 2008; Pecharich & Martini-lamb, 2014; Quinones et al., 2015). Situated on the northern California coast, the Russian and Eel River estuaries are subjected to similar primary wind and wave phenomena (Behrens et al., 2009; Rubel & Kottek, 2010). These estuaries consequently share predominant physical characteristics and environmental pressures (Merrifield et al., 2011) and provide consistent harbour seal haulout habitat (Figure 1). To capture a range of resting sites likely to be used by seals from each estuary, habitat was analysed within a 30 km buffer around each estuary mouth, based on the ranges found in radio-tagging studies (Suryan & Harvey, 1998; Sharples, Mackenzie & Hammond, 2009; Wilson et al., 2014).

Russian River Estuary

The Russian River estuary is located on the western coastline of Sonoma County (Figure 1). This is a typical bar-built estuary (Behrens et al., 2009), managed to balance salmonid habitat needs with flood protection for low-lying properties along the lower Russian River. Natural conditions are maintained unless flood risk to low-lying homes reaches unacceptable levels, in which case the county breaches the sandbar (NMFS, 2008; Pecharich & Martini-Lamb, 2014).

Eel River Estuary

The Eel River estuary is located on the western coastline of Humboldt County just north of Cape Mendocino (Figure 1). River management includes two dams constructed prior to a protected Wild and Scenic River designation, a federal environmental protection classification, but no future dams will be constructed (National Wild and Scenic Rivers System, 2016). Like the Russian River, the Eel River is both ecologically and economically valued for providing salmonid habitat (Yoshiyama & Moyle, 2010; Quinones et al., 2015).

2.2 Modelling Overview

Modelling habitat under climate change scenarios has been done for a variety of species, including other phocids (Funayama et al., 2013; Pacifici, 2015; Boets et al., 2018). Climate change impacts on harbour seal haulouts were projected by developing a habitat suitability model (HSA) under current conditions and calculating change with different baseline scenarios of sea level and storm events. The HSA is a geographic information systems (GIS) model developed in ArcGIS 10.5 (ESRI, 2017) which identifies haulout habitat given present conditions. Sea-level rise (SLR) and storm effects at these estuaries were then modelled to analyse the additional impact of climate change. Using the HSA model to calculate habitat given a variety of sea-level rise scenarios and storm conditions provided a series of spatial habitat projections for analysing changes to available habitat.

2.3 Harbour Seal Habitat Suitability Analysis

The harbour seal habitat suitability analysis is a rules-based model. Based on expert knowledge and previous literature, we were able to create rules to spatially define potential haulout habitat (Briscoe et al., 2014). The primary features of this rules-based model were, for each raster cell of the digital elevation model (DEM), slope, Euclidean distance to the water, and protection from wind and wave action which was described by aspect of the landscape (Nordstrom,2002;

Funayama et al., 2013; Allen pers. com., 2016). Each cell of the DEM was tested for these features and assigned a numerical score. The composite numerical score resulted in a GIS layer where every cell was ranked relative to its potential habitat quality. The HSA only included areas of the DEM that met physical slope and distance restrictions as habitat. Within potential habitat area, areas better protected from wind and wave action, determined by the compass-degree aspect of the landscape relative to the prevailing wind direction, were ranked as higher quality habitat (Table 2).

Coastal Data Information Program (CDIP) buoys indicate that California coastal wave action mostly comes from the north west (Garcia-Reyes & Largier, 2010; CDIP 2017). At the buoys nearest to each study site, Fort Bragg (Buoy 235) and Humboldt Bay (168), wave direction was 295 degrees, relative to true north (SD ± 23). As the response to the wind and wave direction were classified by the same rules at both sites, the response of an individual 1 m cell of the raster gave the same result at both sites. However, the predominant response may be expected to vary between sites, given the general direction of the shoreline relative to the direction of the wind and wave action.

2.4 Data Assembly

The model is based on elevation data, water level data including tide and storm surge height, storm projections, and both ground and aerial seal observations. Elevation data were a 1 m horizontal resolution continuous topographic-bathymetric DEM (Dewberry & Davis, 2013). Water data were composite NOAA tidal data (VDatum 2017), and storm projections were 20-

year storm projections from the United States Geological Survey (USGS) Coastal Storm Monitoring System (CoSMoS) projections (CoSMoS, 2017). The ground-based seal observations were daily harbour seal counts collected at the Russian River estuary by Mrs. Elinor Twohy (1990 – 2016). The Twohy dataset is three decades of fine-scale observations collected at the mouth of the Russian River. Mrs. Twohy, a community scientist and local activist, worked with scientists from the Bodega Marine Laboratory of University of California, Davis, and Dr. Sarah Allen, a pinniped expert from the National Park Service, to standardize data collection (pers. comm. Twohy 2016). Daily count data from 1990 to 2016 were used to validate the habitat suitability model. Aerial seal observations were from National Marine Fisheries Service (NMFS) aerial survey data at the Russian and Eel River estuaries from the years 2002, 2004, 2009, and 2012 (Lowry & Carretta, 2003; Lowry et al., 2005; NMFS unpublished data).

The NMFS monitors harbour seal populations along the California coast with aerial photographic counts made from surveys conducted during the moult period when the highest number of individuals are most likely be to be on land (Lowry & Carretta, 2003; Lowry, Carretta & Forney, 2005; NMFS unpublished data; Lowry, Carretta & Forney, 2008; Lowry unpub. data). There is latitudinal variation in phenology, with the pupping and moulting seasons beginning earlier further south (Tempte, Bigg & Wiig, 1991). In northern California, the pupping and breeding season spans March through May, continuing into the moulting period from July through early August (Caretta et al., 2014). These aerial surveys produced photographs from a high-resolution camera mounted on board a small airplane in late May to July of 2002, 2004, 2009, and 2012 (Lowry, Carretta & Forney, 2008).

2.5 Habitat Suitability Model Validation

The HSA model was validated by separately fitting the results to two datasets of seal observations: the ground counts at haulouts in the Twohy dataset and corresponding NMFS aerial photo survey counts. The model was fitted by sampling the seals found in habitat ranks resulting from the DEM. This was done by overlaying the localized habitat value, determined using a focal statistic analysis, with a kernel density analysis of the aerial seal counts. The focal statistic analysis produces a raster layer of the habitat values, which is a way to test for spatial clustering of habitat features (Kitron et al., 2006; De Jager & Fox, 2013). The kernel density layer produced a raster layer of the seals observed, where more individuals produced a larger target around the seal point observations (Seaman & Powell, 1996; De Solla, Bonduriansky & Brooks, 1999). Overlaying these two rasters and sampling where the seals are found showed density of habitat use. The HSA was fitted by incrementally adjusting the weighting of habitat variables until the fitting tests indicated that a majority of seal observations were captured in areas that ranked as the highest quality habitat.

2.6 Sea-level rise Modelling

NOAA’s Vertical Datum Transformation (VDatum) tool and flood modeling method produced water surfaces that accounted for dynamic tidal variability over the last tidal epoch (White et al., 2016; VDatum 2017). These methods are similar to the NOAA Office for Coastal Management

Digital Coast Sea Level Affecting Marshes Model (SLAMM, 2017). The USACE Sea-Level Change Curve Calculator (Version 2017.55) was used to select local sea-level rise projections specific to each study site. Selecting the most probable projections for the years 2030 and 2050 and both the low and extreme SLR projections for the year 2100 provided a range of likely possible outcomes. Adding the local sea-level rise projections for these scenarios to the VDatum tidal surface effectively raised the elevation of the local water surfaces in the GIS model. This inundated additional area of the flood model layers, which allowed for the extraction of likely shorelines reflecting the 2030, 2050, and both 2100 SLR scenarios. These SLR scenario shorelines were the new baseline for each subsequent run of the model, to project haulout habitat at 2030, 2050, 2100 low, and 2100 extreme SLR conditions for each estuary. Throughout, the term flooding is used to refer to storm events, and inundation is used to refer to SLR.

2.7 Storm Enhanced Flooding

To evaluate the impacts of storm enhanced water levels on habitat flooding, CoSMoS projections (currently only available for the Russian River site) were also used as a baseline condition for the HSA model. Consistency was checked between these new SLR flood models and the CoSMoS projections. Inundation results were compared for depth and area of inundation. After determining comparability, CoSMoS storm scenarios were used as a baseline condition for the HSA to calculate area of habitat inundated by storm enhanced flooding.

3. Results

3.1 Harbour seal habitat suitability model results

At the Russian River, total habitat area decreased 9.6% from the baseline by 2030, 8.2% by 2050 (a 1.5% increase over the 2030 scenario), 24.5% from the baseline by the 2100 low scenario, and 26.1% by the 2100 extreme scenario (Figure 3a). At the Eel River, total habitat area increased by 1.3% by 2030, decreased by 4.2% by 2050, decreased 5.9% by the 2100 low scenario (an increase over the 2050 scenario), and decreased 23.3% by the 2100 extreme scenario (Figure 3b).

3.2 Harbour seal habitat suitability validation

At the Russian River, the final HSA model ranked the protected lagoon-facing side of the sandbar as a high-quality haulout siteand ranked the ocean-facing side of the sandbar as poor quality habitat (Figure 2). This result matches the ground and aerial observations of seal habitat use. At the Russian River, 87% of seals congregated on the protected interior part of the estuary mouth sand bar, and 13% were sighted on both the lagoon and exposed ocean side. In less than 1% of sightings, seals were hauled-out exclusively on the ocean side of the sandbar. The HSA model predicted that the protected lagoon region of the sandbar was high quality, and the ocean-facing region of the sandbar was lower quality habitat (Figure 2).

3.3 Sea-level rise & storm enhanced water level impact results

At the Russian River, under both present conditions and a 0.25 m sea-level rise regime, the difference in area flooded as based on the CoSMoS model and the VDatum model was less than 5% (Table 3). Under storm scenarios, regardless of SLR, approximately 65% of habitat became flooded. Under present sea-level conditions, total habitat inundated by storm surge was 65.9%.

Under 0.25m SLR conditions, 64.2% total haul-ut habitat was inundated. Values for each habitat quality rank ranged from 62 to 68% (Table 3). CoSMoS data were not available for the Eel River. Under the sea-level rise scenarios, as inundation changed the shoreline vectors, we noted changes in the complexity and shape of the shoreline in tandem with available habitat.

4. Discussion

4.1 Habitat Suitability

As expected, the SLR and storm analysis predicted higher quality habitat for features sheltered from exposure at both estuary sites. This pattern held up through each of the inundation scenarios. While near-term inundation in some cases increased habitat area, the overall response to inundation resulted in decreased habitat area, with larger decreases associated with increased sea-level rise for the Russian and Eel River estuaries (Figure 3). In other projection scenarios there were larger initial increases in habitat area under initial SLR, but in all tested sea-level rise scenarios, the habitat available declined after the 2050 intermediate projections (Figure 3).

4.2 Sea-Level Rise

Changing complexity in shoreline vectors could be the reason for temporary increases and eventual decreases in habitat area. However, caution is called for in this interpretation. The sandbars forming the mouth of both estuary sites migrate and shift with tidal and storm action (Behrens et al., 2013). This observation may be best explored with higher resolution methods, which have the capacity to capture curviness of features (Guo et al., 2017). Habitat losses with sea-level rise are seen for a variety of species and types of coastal ecosystems (Funayama et al., 2013; Pike, Roznik & Bell, 2015; Cloern et al., 2016). Some ecosystems have the flexibility to migrate if sea-level changes slowly enough and other environmental conditions are met (Thorne et al., 2018). For species without the flexibility to move or where ecosystem migration is restricted, there are significant losses (Cloern et al., 2016). Based on results at these two sites, other haulout sites in California will experience losses and gains, based on current landscape features, landscape response to sea-level rise, and these changes will be dependent on the rate at which sea-level rise occurs.

4.3 Storms enhanced water levels

At the Russian River, where storm models were available, approximately 65% of total habitat was inundated under 20-year storm conditions. Current climate change projections predict an increase in both intensity and severity of storm systems. The frequency and intensity of these events will drive sediment transport and erosion that may affect the shape of these habitats (George & Hill, 2008; Rich & Keller, 2013). For seals using these habitats, the frequency, intensity, as well as the seasonality of storm events will have an influence on the type and severity of impact. Currently in California, storms primarily occur during the winter months, when harbour seals spend less time hauled-out. Storms during the pupping and moulting seasons would have a much greater impact. If these events were to overlap more in the future, due to shifts in storm patterns or phenology, the threat to seals posed by storm events would greatly increase. Using a statistical exploration of the full Twohy dataset, upcoming work will explore the possibility of shifts in timing of peak seal habitat use in response to various local variables, including the intensity of winter storms.

4.4 Model Limitations

The HSA model captured utilized habitat from simple physical parameters. Model results reflected the importance of protection from wind and wave action at a haulout. They also highlighted a fundamental limitation. This model was designed for known seal haulout sites, with the inference that other essential habitat criteria (e.g. distance to prey patches) have been met. If applied to an unknown area of shoreline, this HSA would predict whether seals could haul out, but not the ecological likelihood of this area being utilized as a haulout location. This applies to the future projections of this model even at known haulout areas. Given these restrictions, it is likely that habitat is overpredicted at the baseline and between SLR scenarios, relative to the geomorphology of each site fitting the model.

Initial inundation of bar-built estuaries may match the SLR modelling results but quickly diverge with erosion. Soft substrates are far less resistant to erosion than harder substrates (Bak, Michalik & Tekielak, 2013; Rich & Keller, 2013). As sandbars shift, habitats shift locally. However, when haul-outs are inundated, or retreat is limited by natural structures (e.g. cliffs) or human infrastructure, habitat may be eliminated, a process referred to as coastal squeeze (Ruckelshaus et al., 2013; Godoy & de Lacerda, 2015; Santora et al., 2020). Patterns of habitat are likely to persist at these sandbar areas under near-term SLR. However, changes in sediment supply and transport are not reflected in these inundation scenarios and are important to include in SLR modelling before planning management action.

4.5 Community Science & Monitoring Research

Community science is an important opportunity to expand coverage of changing environments. The Twohy dataset is an exemplary record making this case, offering longevity and consistency difficult to find in monitoring work supported by traditional research funding programmes, under which it is difficult to maintain long-term monitoring observation. Species observations are ephemeral and cannot be recovered by other means (Chandler et al., 2017). Even in the cases where there are monitoring funds available, the person-hours required to monitor changes at the locations covering the broad spatial scope of the coasts are prohibitive unless invested local stakeholders are engaged.

4.6 Indicator Species

There is much potential for future research concerning the effects of climate change on harbour seals. As ocean conditions change, it is likely that essential habitat features will shift or change in ecologically important ways. In their role as indicators, observing changes in the persistence of seal haulouts under SLR may reflect unobserved ecological changes.

As coastal squeeze impacts coastal habitats, there are limits to the number of seals a given haulout will support (Neumann, 1999). It would be an interesting avenue for future research to examine the minimum habitat density that would support the seals currently present at these habitats. Potential causes of decreases in seals observed at these habitats in the future could indicate an increase in competition for space or indicate changes in other environmental factors. It will be important to rule out density competition before assuming that decreasing seal habitat use is directly correlated with some other factor, such as prey availability or disturbance.

4.7 Conservation Measures

The applications of projecting habitat allow for management actions to preempt a problem, whether it be protecting a place that will be future high quality habitat or setting up barriers to avoid a wildlife – human development conflict. This model also provides a first-warning utility for attendant changes with climate change and sea-level rise; if seals abandon an area that otherwise meets the criteria for good habitat, an unseen change, such as in prey location or availability, may be indicated.

Bar-built estuaries are not necessarily stable systems and are likely to change over time (Behrens et al., 2013). It is reasonable to expect that with significant sea-level rise and storm surge, in the future this area may no longer be optimal habitat. Although harbour seals exhibit site fidelity to stable areas, when habitat criteria change (e.g. haulout and pupping space, foraging proximity, etc.) they will seek other suitable habitat (Cordes & Thompson, 2015). While this may place stress on seals who return to a specific haulout, harbour seals are not currently a threatened species on the California coast. However, in their role as indicators, observing and taking note of changes in site usage may serve as a vital early indicator of other attendant environmental changes. The state of California has recommended monitoring indicator species as one of the methods of maintaining awareness of changes in the environment and communicating these changes to the public (Kadir, Mazur & Milanes, 2013); the Russian River and Eel River haulouts are just such places.

4.8 Future Research

Further analysis of the Russian River estuary dataset is likely to further reveal variables influencing fine-scale harbour seal haulout selection. Normal patterns of seal habitat use in northern California are distinctly visible in the Russian River dataset. This reflection of regional patterns at the Russian River haulout is a useful benchmark for relatability to other similar estuarine environments. Additional understanding of local drivers of fine-scale habitat choice may offer improvements to this type of model.

To expand locally specific SLR modelling efforts at these sites, it would be valuable to include erodibility of inland substrates, barriers to inundation, and the influence of upriver dam management. These features will reshape the shore as rises in sea level and storms batter the coast (Bulleri & Chapman, 2009). Management responses to inundation will certainly be essential to consider. The Russian River estuary is already heavily managed for property flood risks in low lying areas around the lagoon (NMFS, 2008; Pecharich & Martini-lamb, 2014). As sea level rises, management will be required to adapt to these conditions. The simplicity of this base model means it can be applied as a starting point to any region of habitat. Before translating these results to management applications, additional and higher resolution layers are necessary, particularly in cases where the shoreline has high erosion potential, or additional barriers to inundation are in place (Matthews, Lo & Byrne, 2015).

References

Allen, S.G. (1991). Harbor seal habitat restoration at Strawberry Spit, San Francisco Bay. *Report to the Marine Mammal Commission.*

Bak, L., Michalik, A. & Tekielak, T. (2013). The relationship between bank erosion, local aggradation and sediment transport in a small Carpathian stream. *Geomorphology,* 191, 51–63.

Behrens, D.K., Bombardelli, F. A., Largier, J.L.,& Twohy, E. (2009). Characterization of time and spatial scales of a migrating rivermouth. *Geophysical Research Letters*, 36(9), L09402. http://doi.org/10.1029/2008GL037025.

Behrens, D.K., Bombardelli, F.A., Largier, J.L.,& Twohy, E. (2013). Episodic closure of the tidal inlet at the mouth of the Russian River — A small bar-built estuary in California. *Geomorphology,* 189, 66–80.

Blundell, G.M. & Pendleton, G.W. (2015). Factors Affecting Haul-Out Behavior of Harbor Seals (*Phoca vitulina*) in Tidewater Glacier Inlets in Alaska: Can Tourism Vessels and Seals Coexist? *PLoS ONE,* 10(5), e0125486. doi:10.1371/journal.pone.0125486.

Boets, P., Gobeyn, S., Dillen, A., Poelman, E. & Goethals, P.L.M. (2018). Assessing the suitable habitat for reintroduction of brown trout (*Salmo trutta forma fario*) in a lowland river: A modeling approach. *Ecology and Evolution*, 8(10), 5191-5205. doi: 10.1002/ece3.4022.

Bonnot, P. (1928). Report on the Seals and Sea Lions of California. State of California Division of Fish and Game, Fish Bulletin No. 14. *Scripps Institution of Oceanography Library,* http://scilib.ucsd.edu/sio/.

Bulleri, F. & Chapman, M.G. (2010). The introduction of coastal infrastructure as a driver of change in marine environments. *Journal of Applied Ecology,* 47, 26–35. doi: 0.1111/j.1365-2664.2009.01751.

Carretta, J.V., Oleson, E.M., Weller, D.W., Lang, A.R., Forney, K.A., Baker, J. et al. (2015). U.S. Pacific Marine Mammal Stock Assessments: 2014. *U.S. Department of Commerce, NOAA Technical Memorandum*, NOAA-TMNMFS-SWFSC-549. 414 p.

Chandler, M., See L., Copas, K., Bonde, A.M.Z., Claramunt López, B., Danielsen, F. et al. (2017). Contribution of citizen science towards international biodiversity monitoring. *Biological Conservation,* 213, 280–294.

Cloern, J.E., Abreu, P. C., Carstensen, J., Chauvaud, L., Elmgren, R., Grall, J. et al. (2016). Human activities and climate variability drive fast-paced change across the world's estuarine–coastal ecosystems. *Global Change Biology*, 22 (2), 513–529.

Coastal Storm Modeling System: CoSMoS. Northern California (outer coast) 2.0, projected flooding. CoSMoS (2017). *U.S. Department of the Interior, U.S. Geological Survey.* https://walrus.wr.usgs.gov/coastal_processes/cosmos/norcal/.

Codde, S. & Allen, S. (2013). Pacific harbor seal (*Phoca vitulina richardii*) monitoring at Point Reyes National Seashore and Golden Gate National Recreation Area: 2013 annual report. *Natural Resource Report* NPS/SFAN/NRR—2015/919. National Park Service, Fort Collins, Colorado.

Codde, S. & Allen, S. (2017). Pacific harbor seal (*Phoca vitulina richardii*) monitoring at Point Reyes National Seashore and Golden Gate National Recreation Area: 2015 annual report. *Natural Resource Report* NPS/SFAN/NRR—2017/1516. National Park Service, Fort Collins, Colorado.

Cordes, L.S. & Thompson, P.M. (2015). Mark-resight estimates of seasonal variation in harbor seal abundance and site fidelity. *Population Ecology*, 57(3), 467–472. http://doi.org/10.1007/s10144-015-0496-z.

De Jager, N.R. & Fox, T.J. (2013). Curve Fit: a pixel-level raster regression tool for mapping spatial patterns. *Methods in Ecology and Evolution*, 4, 789 - 792.

De Solla, S.R., Bonduriansky, R. & Brooks, R.J. (1999). Eliminating autocorrelation reduces biological relevance of home range estimates. *Journal of Animal Ecology,* 68, 221-234.

Denes, S.L., Miksis-Olds, J.L., Mellinger, D.K. & Nystuen, J.A. (2014). Assessing the cross platform performance of marine mammal indicators between two collocated acoustic recorders. *Ecological Informatics,* 21, 74–80.

Ehrlen, J. & Morris, W.F. (2015). Predicting changes in the distribution and abundance of species under environmental change. *Ecology Letters,* 18, 303–314. doi: 10.1111/ele.12410.

Friewald, J., Meyer, R., Caselle, J. E., Blanchette, C.A., Hovel, K., Neilson, D. et al. (2018). Citizen science monitoring of marine protected areas: Case studies and recommendations for integration into monitoring programs. *Marine Ecology*, e12470. doi: 10.1111/maec.12470.

Funayama, K., Hines, E., Davis, J. & Allen, S. (2013). Effects of sea-level rise on northern elephant seal breeding habitat at Point Reyes Peninsula, California. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 23(2), 233–245. http://doi.org/10.1002/aqc.2318.

Gallien, T.W., Barnard, P.L, van Ormondt, M., Foxgrover, A.C. & Sanders, B.F. (2013). A Parcel-Scale Coastal Flood Forecasting Prototype for a Southern California Urbanized Embayment. *Journal of Coastal Research*, 29(3), 642-656. doi: http://dx.doi.org/10.2112/JCOASTRES-D-12-00114.1.

George, D.A. & Hill, P.S. (2008). Wave climate, sediment supply and the depth of the sand–mud transition: A global survey. *Marine Geology,* 254, 121–128. doi:10.1016/j.margeo.2008.05.005.

George, D.A., Gelfenbaum, G. & Stevens, A.W. (2012). Modeling the Hydrodynamic and Morphologic Response of an Estuary Restoration. *Estuaries and Coasts*, 35(6), 1510-1529, doi:10.1007/s12237-012-9541-8

Godoy, M.D.P. & de Lacerda, L.D. (2015). Mangroves Response to Climate Change: A Review of Recent Findings on Mangrove Extension and Distribution. *Anais da Academia Braileira. de Ciências,* 87 (2) Rio de Janeiro Apr./June 2015. http://dx.doi.org/10.1590/0001-3765201520150055.

Grigg E. K., Klimley, A.P., Allen, S.G., Green, D.E., Elliot-Fisk, D.L. & Markowitz, H., E. K. (2009). Spatial and Seasonal Relationship Between Pacific Harbor Seals (*Phoca vitulina richardii*) And Their Prey, At Multiple Scales. *Fishery Bulletin*, 107, 359–372.

Griggs, G., Árvai, J., Cayan, D., DeConto, R., Fox, J., Fricker, H.A. et al. (California Ocean Protection Council Science Advisory Team Working Group). (2017). Rising Seas in California: An Update on Sea-Level Rise Science. *California Ocean Science Trust*, April 2017.

Guillera-Arroita, G., Lahoz-Monfort, J.J., Elith, J., Gordon, A., Kujala, H., Lentini, P.E. et al. (2015). Is my species distribution model fit for purpose? Matching data and models to applications. *Global Ecology and Biogeography*, 24, 276–292

Guo, J., Liu, S., Zhang, P., Wu, L., Zhou, W., & Yu, Y. (2017). Towards semi-automatic rock mass discontinuity orientation and set analysis from 3D point clouds. *Computers & Geosciences,* 103, 164–172.

Harding, K.C., Fujiwara, M., Axberg, Y. & Härkönen, T. (2005). Mass-dependent energetics and survival in Harbour Seal pups. *Functional Ecology,* 19, 129–135.

Holzmueller, E.J., Gaskins, M.D. & Mangun, J.C. 2011. A GIS Approach to Prioritizing Habitat for Restoration Using Neotropical Migrant Songbird Criteria. *Environmental Management,* 48, 150–157. doi 10.1007/s00267-011-9660-1.

Janousek, C.N., Buffington, K.J., Thorne, K.M., Guntenspergen, G.R., Takekawa, J.Y. & Dugger, B.D. (2016). Potential effects of sea-level rise on plant productivity: species-specific responses in northeast Pacific tidal marshes. *Marine Ecology Progress Series*, 548, 111-125. https://doi.org/10.3354/meps11683

Jansen, J.K., Brady, G.M., Ver Hoef, J.M. & Boveng, P.L. (2015). Spatially Estimating Disturbance of Harbor Seals (*Phoca vitulina*). *PLoS ONE*, 10(7), e0129798. http://doi.org/10.1371/journal.pone.0129798.

Kadir T., Mazur L. & Milanes C., R. K. (eds.). (2013). Indicators of Climate Change in California Secretary for Environmental Protection. *California Environmental Protection Agency*, Office of Environmental Health Hazard Assessment.

Karl, T. R., Melillo, J. M. & Peterson, T. C. (eds.) (2009). *Global Climate Change Impacts in the United States*. Cambridge University Press, 2009.

Kitron, U., Clennon, J.A., Cecere, M.C., Gürtler, R.E., King. C.H. & Vazquez-Prokopec, G. (2006). Upscale or downscale: applications of fine scale remotely sensed data to Chagas disease in Argentina and schistosomiasis in Kenya. *Geospatial Health*, 1(1), 49-58.

London, J.M., Ver Hoef, J.M., Jeffries, S.J., Lance, M.M. & Boveng, P.L. (2012). Haul-Out Behavior of Harbor Seals (*Phoca vitulina*) in Hood Canal, Washington. *PLoS ONE,* 7(6), e38180. doi:10.1371/journal.pone.0038180.

Lowry, M.S. & J.V. Carretta. (2003). Pacific harbor seal, *Phoca vitulina richardsi*, census in California during May-July 2002. *NOAA Technical Memorandum* NMFS NOAA-TM-NMFS-SWFSC-353.

Lowry, M.S., Carretta, J.V. & K.A. Forney. (2005). Pacific harbor seal, *Phoca vitulina richardsi*, census in California during May - July 2004. Administrative Report LJ-05-06, available from *Southwest Fisheries Science Center*, 8604 La Jolla Shores Drive, La Jolla, CA 92037. 38 pp.

Lowry, M.S., Carretta, J.V. & Forney, K.A. (2008). Pacific harbor seal census in California during May July 2002 and 2004. *California Fish and Game,* 94(4), 180-193.

Luisetti, T., Turner, R.K., Jickells, T., Andrews, J., Elliott, M., Schaafsma, M. et al. (2014). Coastal Zone Ecosystem Services: From science to values and decision making; a case study. *Science of The Total Environment*, 493, 682–693. http://doi.org/10.1016/j.scitotenv.2014.05.099.

Marine Mammal Protection Act of 1972, as Amended 2007. Compiled and annotated by the *Marine Mammal Commission,* Bethesda MD for NOAA's National Marine Fisheries Service, Silver Spring MD.

Matthews, T., Lo, A.Y. & Byrne, J.A. (2015). Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. *Landscape and Urban Planning,* 138, 155–163.

McClenahan, L., Ferretti, F. & Baum, J.K. (2012). From archives to conservation: why historical data are needed to set baselines for marine animals and ecosystems. *Policy Perspective*, 5(5), 349-359. doi: 10.1111/j.1755-263X.2012.00253.x.

McGregor, H.W., Legge, S., Potts, J., Jones, M.E. & Johnson, C.E. (2015). Density and home range of feral cats in north-western Australia. *Wildlife Research,* 42(3), 223-231. URL: http://www.bioone.org/doi/full/10.1071/WR14180.

McKinley, D.C., Miller-Rushing, A.J., Ballard, H.L., Bonney, R., Brown, H., Cook-Patton, S.C. et al. (2017). Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation,* 208, 15–28.

Merrifield, M.S., Hines, E., Liu, X. & Beck, M.W. (2011). Building Regional Threat-Based Networks for Estuaries in the Western United States. *PLoS ONE,* 6(2), e17407. doi:10.1371/journal.pone.0017407.

Mitchell, S.B., Jennerjahn, T.C., Vizzinid, S. & Zhang, W. (2015). Changes to processes in estuaries and coastal waters due to intense multiple pressures – An introduction and synthesis. *Estuarine, Coastal and Shelf Science,* 156, 1-6. https://doi.org/10.1016/j.ecss.2014.12.027.

Montgomery, R.A., Ver Hoef, J.M. & Boveng, P.L. (2007). Spatial modeling of haul-out site use by harbor seals in Cook Inlet, Alaska Source: *Marine Ecology Progress Series*, 341, 257-264.

Moore, S.E. (2008). Marine mammals as ecosystem sentinels. *Journal of Mammalogy*, 89(3), 534–540. http://doi.org/10.1644/07-MAMM-S-312R1.1.

Muis, S., Verlaan, M., Winsemius, H.C., Aerts, J. C.J.H. & Ward, P.J. (2015). A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, 7, 11969. doi: 10.1038/ncomms11969.

National Marine Fisheries Service (NMFS). (2008). Russian River Biological Opinion. September 24, 2008. Prepared for Sonoma County Water Agency.

National Marine Fisheries Service. (2015). Harbor Seal (*Phoca vitulina richardii*): California Stock. http://www.nmfs.noaa.gov/pr/sars/pdf/stocks/pacific/2014/po2014_harbor_seal-ca.pdf.

National Wild and Scenic Rivers System Publication. (2016). Eel River, California. https://www.rivers.gov/wsr-act.php

Neumann, D. (1999). Agonistic Behavior in Harbor Seals (*Phoca vitulina*) in Relation to the Availability of Haul-Out Space. *Marine Mammal Science*, 15(2), 507–525. http://doi.org/10.1111/j.1748-7692.1999.tb00816.x

Nordstrom, C. (2002). Haul-Out Selection by Pacific Harbor Seals (*Phoca vitulina richardii*): Isolation and Perceived Predation Risk. *Marine Mammal Science*, 18 (1), 194–205. http://doi.org/10.1111/j.1748-7692.2002.tb01028.x

Pacifici, K., Reich, B.J., Miller, D.A. W., Gardner, B., Stauffer, G., Singh, S. et al. (2017). Integrating multiple data sources in species distribution modeling: a framework for data fusion. *Ecology*, 98(3), 840–850.

Pacifici, M., Foden W.B., Visconti, P. Watson, J.E.M., Butchart, S.H.M., Kovacs, K.M. et al. (2015). Assessing species vulnerability to climate change. *Nature Climate Change*, 5, doi: 10.1038/NCLIMATE2448.

Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J. et al. (2012). Global Sea Level Rise Scenarios for the US National Climate Assessment. *NOAA Technical Memoradum* OAR CPO-1. 37 pp.

Pecharich, A. & Martini-lamb, J. (2014). Russian River Estuary Management Project Marine Mammal Protection Act Incidental Harassment Authorization Report of Activities and Monitoring Results, (January). *National Marine Fisheries Service.* Prepared for Office of Protected Resources and Southwest Regional Administrator.

Pike, D. A., Roznik, E. A. & Bell, I. (2015). Nest inundation from sea-level rise threatens sea turtle population viability. *Royal Society Open Science,* 2, 150127. https://doi.org/10.1098/rsos.150127

Quiñones, R.M., Grantham, T.E., Harvey, B.N., Kiernan, J.D., Klasson, M., Wintzer, A.P. et al. (2014). Dam removal and anadromous salmonid (Oncorhynchus spp.) conservation in CA. *Reviews in Fish Biology and Fisheries,* 25,195–215. doi: 10.1007/s11160-014-9359-5.

Rich, A. & Keller, E. A. (2013). A hydrologic and geomorphic model of estuary breaching and closure. *Geomorphology,* 191, 64–74.

Robertson-Rintoul, M.S.E. & Richards, K.S. (1993). Braided-channel pattern and palaeohydrology using an index of total sinuosity. *Geological Society*, London, Special Publications, 75, 113-118, https://doi.org/10.1144/GSL.SP.1993.075.01.06.

Rubel, F. & M. Kottek. (2010). Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift*, 19, 135-141. doi: 10.1127/0941-2948/2010/0430.

Santora, J.A., Mantua, N.J., Schroeder, I.D., Field, J.C., Hazen, E.L., Bograd, S.J. et al. (2020). Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglement. *Nature Communications*, 11, 536. https://doi.org/10.1038/s41467-019-14215-w

Seaman, D.E. & Powell, R.A. (1996). An Evaluation of the Accuracy of Kernel Density Estimators for Home Range Analysis. *Ecology,* 77(7), 2075-2085.

Sharples, R.J., Mackenzie, M.L. & Hammond, P.S. (2009). Estimating seasonal abundance of a central place forager using counts and telemetry data. *Marine Ecology Progress Series*, 378, 289 - 298.

Suryan, R.M. & Harvey, J.T. (1998). Tracking Harbor Seals (*Phoca vitulina richardsi*) to Determine Dive Behavior, Foraging Activity, And Haul-Out Site Use. *Marine Mammal Science*, 14 (2), 361-372.

Tebaldi, C., Strauss, B.H. & Zervas, C.E. (2012). Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters,* 7 (1), 014032.

Tempte, J.L., Bigg M.A. & Wiig Ø. (1991). Clines revisited: The timing of pupping in the harbour seal (*Phoca vitulina*). *Journal of Zoology*, 224, 617-632.

Theobald, E.J., Ettinger, A.K., Burgess, H.K., DeBey, L.B., Schmidt, N.R., Froehlich, H.E. et al. (2015). Global change and local solutions: Tapping the unrealized potential of citizen science for biodiversity research. *Biological Conservation* ,181, 236–244.

Thorne, K.M., Buffington, K.J., Elliott-Fisk, D.L., Takekawa, J.Y., Thorne, K.M., Buffington, K.J. et al. (2015). Tidal Marsh Susceptibility to Sea-Level Rise: Importance of Local-Scale Models. *Journal of Fish and Wildlife Management*, 6 (2), 290-304.

Thorne, K.M., MacDonald, G., Guntenspergen, G., Ambrose, R., Buffington, K., Dugger, B. et al. (2018). U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. *Science Advances*, 4, eaao3270. doi: 10.1126/sciadv.aao3270

Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L. & Storlazzi, C.D. (2017). Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, 7, 1399.

Wang, R.Q., Herdman, L.M., Erikson, L., Barnard P., Hummel, M. & Stacey, M.T. (2017). Interactions of Estuarine Shoreline Infrastructure With Multiscale Sea Level Variability. *Journal of Geophysical Research*: *Oceans,* 122, 9962–9979. https://doi.org/10.1002/2017JC012730

Wilson, K., Lance, M., Jeffries, S. & Acevedo-Gutierrez, A. (2014). Fine-Scale Variability in Harbor Seal Foraging Behavior. *PLoS ONE,* 9(4), e92838. doi:10.1371/journal.pone.0092838

White, S.A., Jeong, I., Hess, K.W., Jindong, W.,& Myers, E. (2016). An Assessment of the Revised VDatum for Eastern Florida, Georgia, South Carolina, and North Carolina. *NOAA Technical Memorandum* NOS CS 38.

Yang, Z., Wang, T., Voisin, N. & Copping, A. (2015). Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuarine, Coastal and Shelf Science,* 156, 19-30.

Yoshiyama, R.M. & Moyle, P.B. (2010). Historical Review Of Eel River Anadromous Salmonids, With Emphasis On Chinook Salmon, Coho Salmon And Steelhead. University of California Davis Center for Watershed Sciences Working Paper. *A Report Commissioned By California Trout*, 2010 University Of California, Davis, 1–107.

Data Sources

Dewberry & Davis. (2013). *Coastal California Data Merge Prepared for the National Oceanic and Atmospheric Administration Coastal Services Center*. Contract: EA133C-11-CQ-0007 Task Order: 11 Report Date: 10/31/2013.

Environmental Systems Research Institute (ESRI). (2017). *ArcGIS Release 10.* Redlands, California

NOAA (2017). *Vertical Datum Transformation (VDatum), v3.8*. Available at: https://vdatum.noaa.gov/.

Ocean Engineering Research Group, Integrative Oceanography Division, University of California San Diego Scripps Institution of Oceanography. (2017). *Coastal Data Information Program (CDIP)* Available at: http://cdip.ucsd.edu/data_access/metadata/

United States Geological Survey Coastal Storm Monitoring System. (2017). *CoSMoS 2017.* Available at: https://walrus.wr.usgs.gov/coastal_processes/cosmos/

USACE Sea-Level Rise Grid projections. *Sea-Level Change Curve Calculator (Version 2017.55)* Available at: http://www.corpsclimate.us/ccaceslcurves.cfm, North Spit and Russian River region (38.5_236.5) projections.

Tables

Table 1. Comparison of inundation layer between CoSMoS flood modeling and baseline SLR method.

CoSMoS	Area (km^2)	Baseline SLR Method	Area (km^2)	Difference in Area Flooded (km^2)
No SLR, No Storm	388436	No SLR, No Storm	368883	19553
Storm	391515	--	--	--
0.25 m SLR, No Storm	389092	0.25 m SLR, No Storm	370129	18963
0.25 m SLR, Storm	392014	--	--	--
% Area Flooded Difference: No SLR		5.03		
% Area Flooded Difference: SLR		4.87		

Table 2. Values of slope aspect reclassification, based on orientation relative to wave action, used to rank potential habitat areas. Better protected areas were ranked as better habitat (e.g. most protected areas are classified as 1, least protected areas are classified as 5).

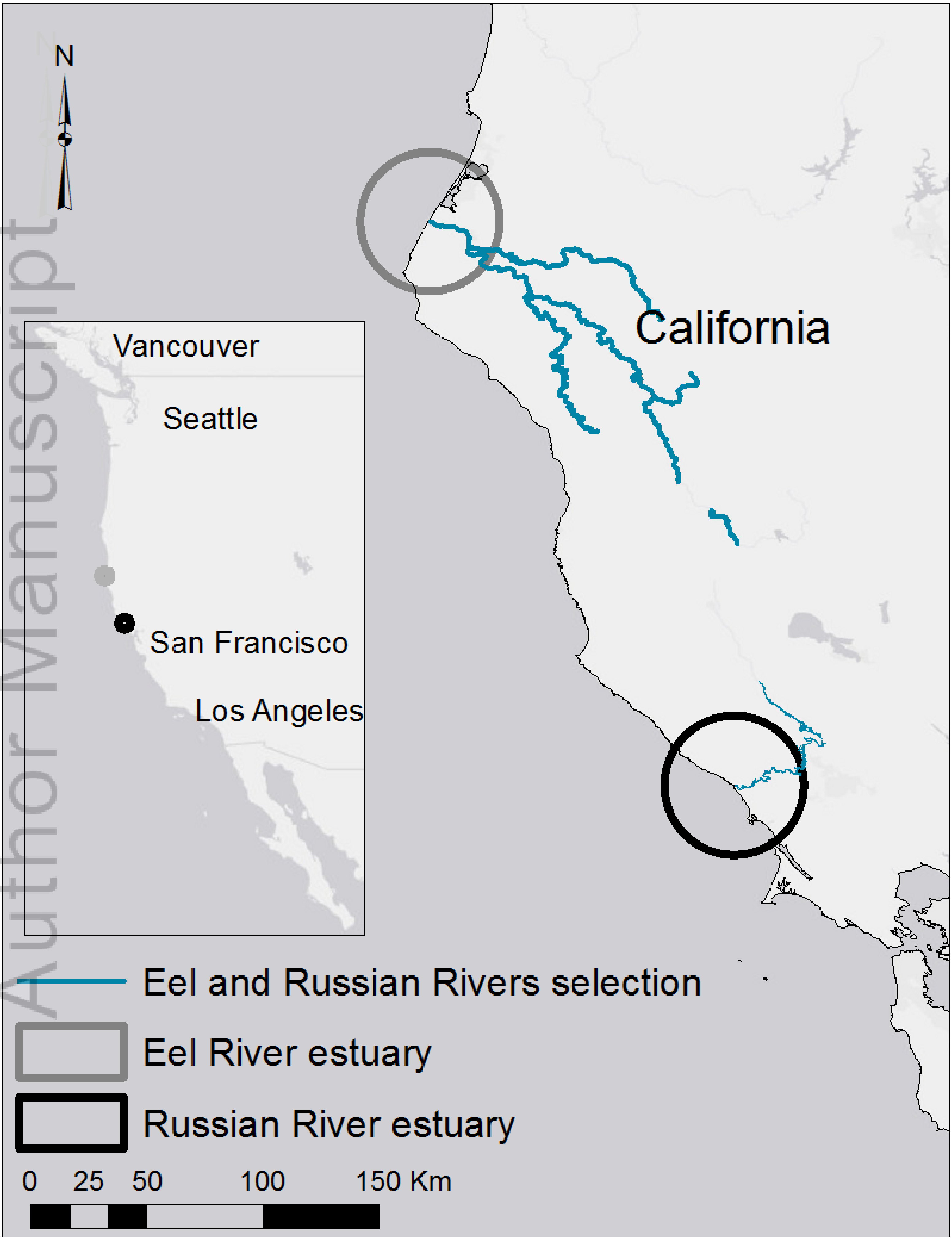
Classification	Degree
1	0 - 90
1	90 - 180
2	180 -220
3	220 - 270
5	270 - 310
4	310 - 360

Figures

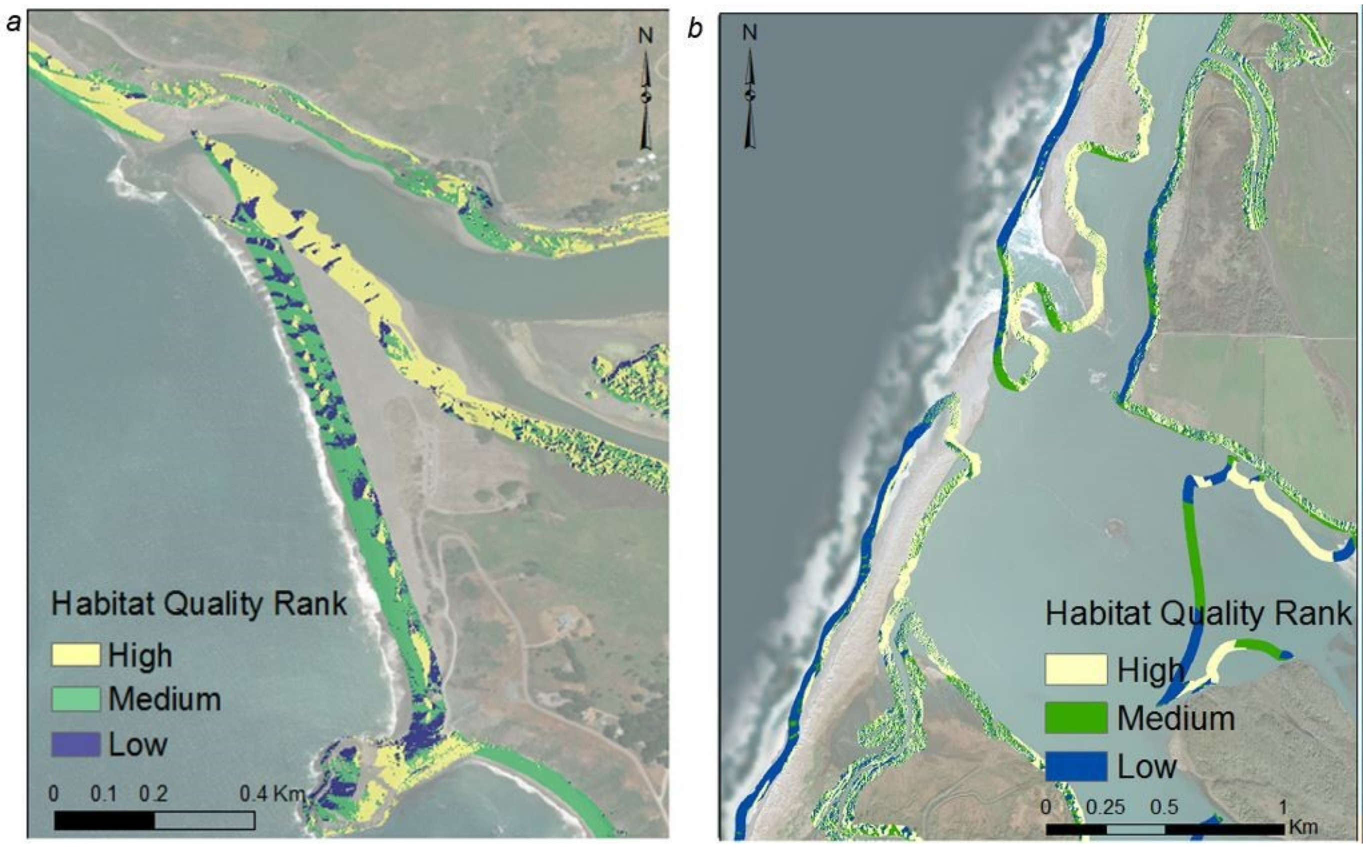
Figure 1. The location of the Russian River and Eel River estuaries in northern California.

Figure 2. Subset of present sea-level haul-out quality at (A) the Russian River and (B) Eel River. Underlying satellite imagery taken at a different season and tide height than the DEM used to generate habitat quality overlays.

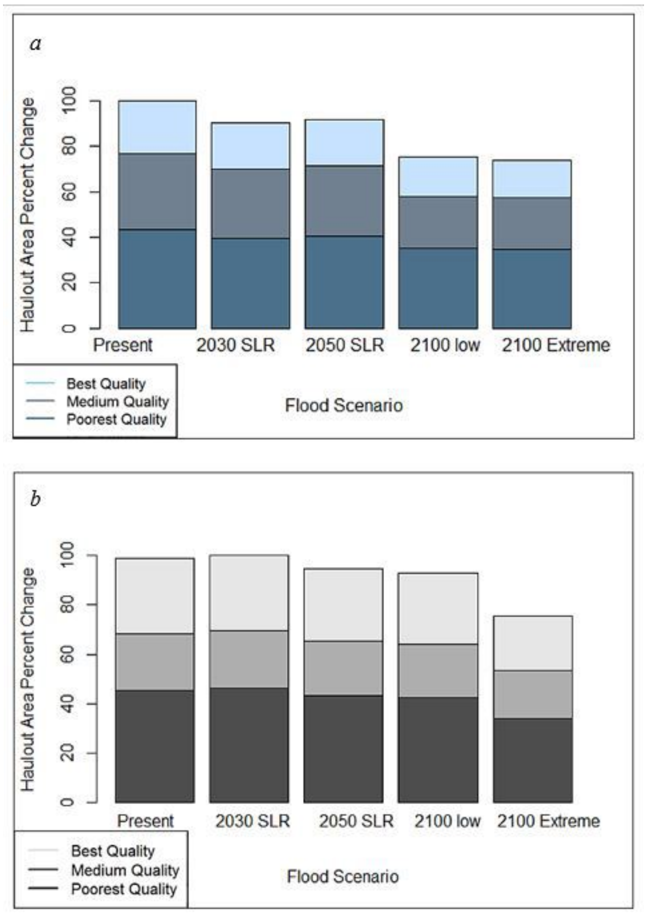
Figure 3. Change in haul-out area available at (A) the Russian River and (B) Eel River with likely sea-level scenarios.



AQC_3574_aqc-20-0066-File002.png



AQC_3574_aqc-20-0066-File003.jpg



AQC_3574_aqc-20-0066-File004.JPG