

## ***Effects of sea-level rise on northern elephant seal breeding habitat at Point Reyes Peninsula, California***

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### ABSTRACT

1. Northern elephant seals (*Mirounga angustirostris*) historically experienced a significant population decrease to the brink of extinction owing to human exploitation, but have since recovered and recolonized former breeding/haul-out sites. Point Reyes Peninsula, California, is one location where population increase has resulted in colony expansion.

2. Initial models identified suitable breeding haul-outs and suggested that human disturbance, geomorphology, mean wave height, and slope were important explanatory variables. Three sea-level rise (SLR) scenarios were run, which indicated that most current and potential haul-out sites would largely be inundated by 2050. Because the Point Reyes coast has limited suitable habitat for the seals to colonize, conservation measures may guide management responses to SLR.

3. The resulting analyses can be used to better understand local-scale seal responses to SLR and contribute to effective management of pinnipeds within Point Reyes National Seashore and elsewhere.

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### INTRODUCTION

Physical changes associated with global warming (e.g. sea ice retreat, sea-level rise, and ocean acidification) can significantly affect marine and coastal environments, thus challenging marine mammals that might not be capable of adapting to such rapid changes (Simmonds and Isaac, 2007; Moore, 2008). Greater concerns about marine species and coastal environments are resulting in an increasing volume of research about marine mammals in relation to climate change (Whitehead *et al.*, 2008). However, current scientific knowledge

lacks specifics in how climate changes could affect marine mammals and their habitats, as well as the extent to which marine mammals can adapt to these changes (Simmonds and Isaac, 2007).

Many marine mammal species are predicted to be highly susceptible to the impacts of climate change (Simmonds and Isaac, 2007). Harwood (2001) has argued that climate change would affect marine mammals indirectly through their critical breeding and foraging habitats. The effects of climate change on the magnitude and distribution of oceanographic features as well as on the reduction of sea ice would be habitat loss and degradation both in the short

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and long terms (Harwood, 2001). In addition, human impacts make marine mammal populations more susceptible to these changes by reducing their abundance through a variety of activities, such as exploitation, commercial and international trades, increased market demands for seafood, harmful algal blooms, and improved fishing technology (O'Shea and Odell, 2008).

It is also important to consider the effects of climate change on marine mammals because they often function as keystone species in marine and coastal communities (Harwood, 2001; Moore, 2008). Impacts on marine mammal populations may have significant consequences for these ecosystems, as they are top-trophic predators (Harwood, 2001; Proffitt *et al.*, 2007). Moore (2008) further describes marine mammals as natural indicators of marine ecosystem variability and degradation as they are fully adapted and dependent on marine environments.

Recent literature on marine mammals has shifted from species-focused studies to those that encompass surrounding climatic and oceanic characteristics, as linkages between these animals and their environment become increasingly important to investigate (Moore, 2008). Notably, many studies have focused on marine mammals that have critical habitats (breeding, feeding, or hauling out) on ice or around polar regions, or have evaluated influences on those species through changes in prey availability and abundance (Harwood, 2001; Heide-Jorgensen and Laidre, 2004; Le Boeuf and Crocker, 2005; Proffitt *et al.*, 2007; Simmonds and Isaac, 2007; Moore, 2008). Some studies have also examined climate change impacts on distributions of marine mammals at a coarser scale (Moore, 2008; Whitehead *et al.*, 2008). Although Harwood (2001) recognized that many otariid seals that rely on local areas for both feeding and breeding would be affected if suitable foraging areas move further from terrestrial breeding habitats, relatively little research has been done on climate change and its associated effects on terrestrial habitats for phocid pinnipeds. This research focuses on terrestrial breeding habitats and investigates possible sea-level rise effects on northern elephant seals (*Mirounga angustirostris*) at Point Reyes National Seashore, California.

### Northern elephant seals

The breeding range of northern elephant seals is limited to the Pacific coast of the North American continent from Baja California to the Farallon Islands and Point Reyes Peninsula in central

California (Le Boeuf and Laws, 1994; Hindell, 2002) (Figure 1). The seals occupy beaches and coves with a variety of substrates from fine sand to cobble, but prefer sandy beaches (Le Boeuf and Laws, 1994; Pettee, 1999). The seals demonstrate site fidelity and females often return to the same rookeries to reproduce (Gavette, 1992; Pettee, 1999). Moreover, they seem to show clear colonization patterns as they expand their colonies to nearby unoccupied sites. Le Boeuf *et al.* (1974), for example, observed that young adult females at Año Nuevo Island initiated new colonies at previously unoccupied sites in a density-dependent fashion, when the established island colony had limited space and was overcrowded. McGinnis and Schusterman (1981) also recorded that young adults utilized nearby sites for haul-outs, leading to further colonization. At Point Reyes, seals spread out to beaches nearby or adjacent to established breeding sites as they became overcrowded (Pettee, 1999). Reduction of human disturbance there also seems to have contributed to the population growth and expansion of the colony (Adams *et al.*, 2007). Some females also used sites protected from high energy surf instead of those exposed to waves and extreme weather events (Pettee, 1999).



Figure 1. Major rookeries of the northern elephant seal in the western USA and Baja California.

## Elephant seals on Point Reyes Peninsula

Although Point Reyes Peninsula was historically a haul-out site, northern elephant seals were absent starting in the 1920s as a result of hunting (Scammon, 1968; Allen *et al.*, 1989; Evens, 2008). The seals reappeared in the 1970s, and small numbers of individuals were observed on beaches with increasing frequency, eventually leading to a colony at Point Reyes Headland, California in 1981 (Allen *et al.*, 1989). Since then, the population has steadily increased and the colony has expanded, with immigration from other breeding colonies, such as Año Nuevo, Channel Islands and the south-east Farallon Islands (Allen *et al.*, 1989, 2012; Sydeman and Allen, 1999). In 2009, the annual total population at Point Reyes was estimated to be approximately 2500 (Allen *et al.*, 2012). The main causes for the expansion of population and breeding habitats are considered to be limited predation, reduced human disturbance, and immigration from nearby saturated habitats (Allen *et al.*, 1989, 2012; Adams *et al.*, 2007). Although the population growth rate has slowed since 1997, the spatial extent of breeding habitat continues to expand (Petree, 1999; Sydeman and Allen, 1999; Allen *et al.*, 2012). At Point Reyes Peninsula, northern elephant seals are currently present year-round, as different age and sex groups come ashore at different times of the year to breed and moult (Sydeman and Allen, 1999).

This research examines impacts of sea-level rise (SLR) on the spatial distribution of breeding habitats of northern elephant seals in Point Reyes Peninsula. First, a model was built to identify the potential suitability of seal habitat along the Point Reyes Peninsula. Sightings data and a set of environmental variables were used to run Maxent, a statistical model, which provides probability of the species' distribution patterns. Habitat changes were then examined spatially and temporally through SLR scenarios. LiDAR data at 3 m resolution were used to model three SLR scenarios of 0.5, 1.0, and 1.4 m in years 2050, 2081, and 2099, respectively. These estimated scenarios were then compared to evaluate impacts on potential habitats.

## METHODS

### Study area

Point Reyes Peninsula is located 48 km north west of San Francisco, CA (Petree, 1999; Sydeman and Allen, 1999) (Figure 2). The surrounding

waters are under the shared jurisdiction of the State of California, Point Reyes National Seashore (PORE), and the Gulf of the Farallones National Marine Sanctuary (Sydeman and Allen, 1999). Sand and gravel beaches, rocky cliffs, paleo-dune cliffs, and pocket beaches make up the coast of the Peninsula, and the coastline provides pinnipeds with breeding and haul-out sites (Sydeman and Allen, 1999; Pendleton *et al.*, 2005; Evens, 2008). Upwelling occurs off the coast of the Peninsula and marine productivity is high, further making the area attractive to pinnipeds (Sydeman and Allen, 1999). The northern elephant seal is among five species of pinnipeds that appear at the Peninsula (Evens, 2008).

There are four dominant breeding sites for northern elephant seals at Point Reyes National Seashore: Point Reyes Headlands (PRH), Chimney Rock Loop (CRL), North Drakes Beach (NDB), and South Beach (SB) (Allen *et al.*, 2012). Within these sites, 16 sub-sites were selected for statistical and spatial analyses (see below) (Figures 2 and 3). PRH is the haul-out where the seals established their first colony. It consists of a series of rocky cliff-backed coves that are isolated and mostly inaccessible to humans. PRH provides haul-out space in years of normal storm activity; however, it becomes inundated and exposed to high swell and waves when major storms occur (Petree, 1999). Since the inception of the colony, this series of coves has become saturated with seals and the colony had spilled over into nearby coves. CRL is the eastern section of the Peninsula and also consists of cliff-backed coves. It is exposed to high wave energy and susceptible to intense erosion (Allen *et al.*, 2012). NDB is a narrow, cliff-backed beach with limited space for breeding. However, it is relatively protected from high swells and intense waves, and sand deposition from landslides may create more space for the seals (Allen *et al.*, 2012). SB is a relatively wide paleo-dune-backed beach at the southern-most section of Point Reyes Beach. While it provides potential fallback areas, SB is the site most susceptible to erosion and to high energy waves, although sand is continuously replenished by the paleo-dunes. During the 1998 El Niño, large swells and intense waves carved away the beach, and the space for seals was very limited by the end of the breeding season (Petree, 1999). Drakes Beach and South Beach, though both remote, are commonly accessed by people hiking on beaches.

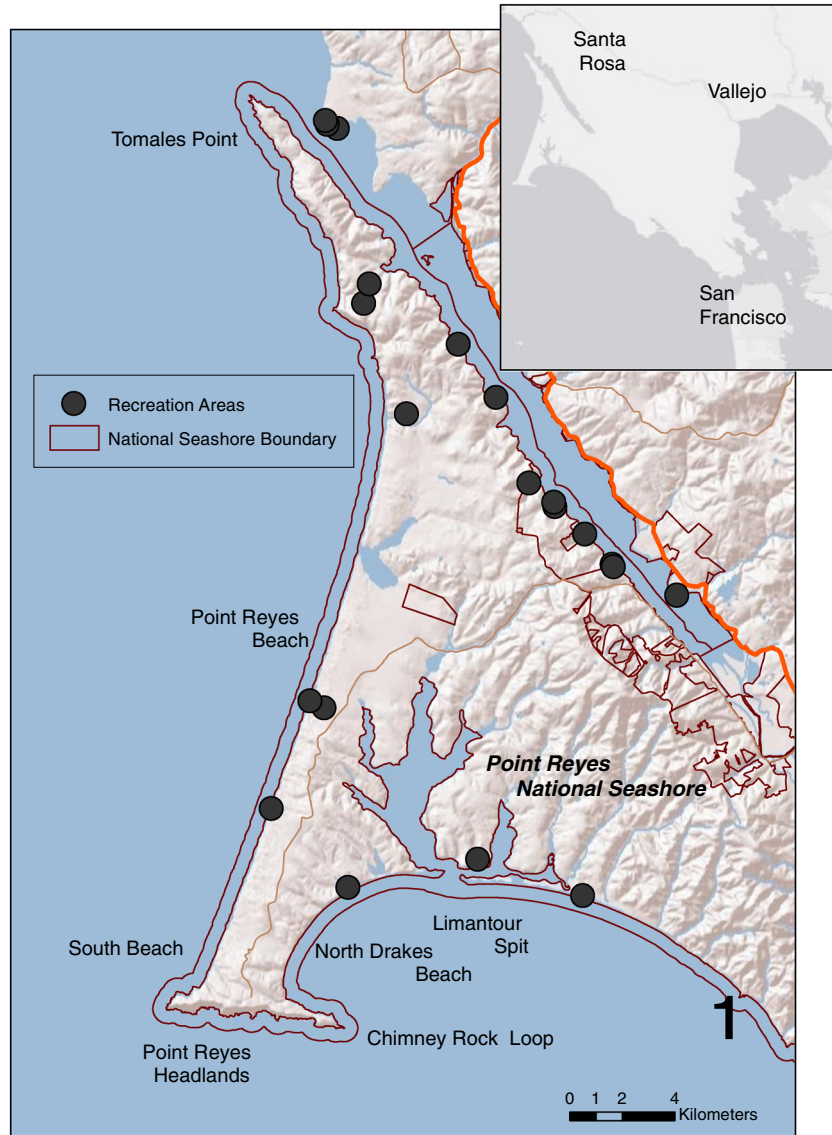


Figure 2. Study area at Point Reyes Peninsula, California.

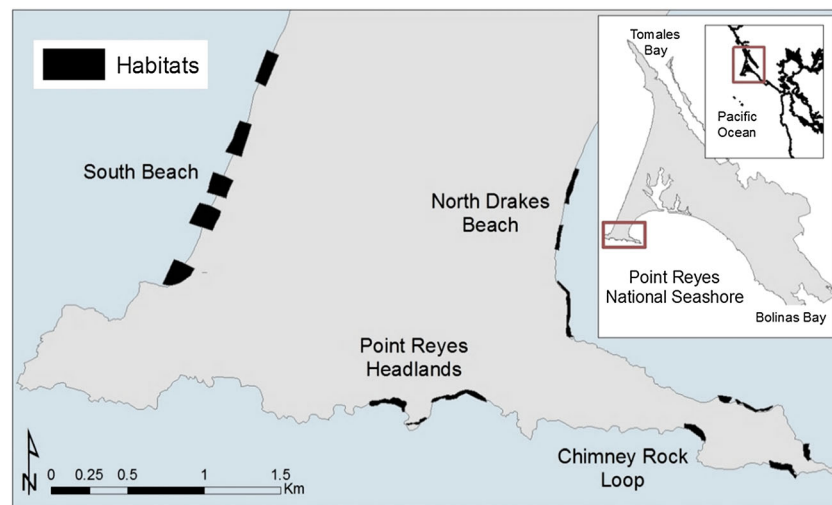


Figure 3. Specific habitat area sub-sites.

## Data

Sightings data were used in this study obtained from reports by PORE (Adams *et al.*, 2007; Allen *et al.*, 2012) and were contained in 16 delineated haul-out areas, which were converted to point locations or occurrences by using centroids for each site to perform statistical analyses. The presence and absence of seals at new and existing haul-out sites was determined annually based on field surveys of suitable habitat.

Eleven environmental variables were considered for influential predictors, based on seal ecology and the availability of data (Table 1, Table 2). Maps of slope, curvature, curvature plan, and curvature profile were created using 3 m resolution LiDAR data, while geology and soil were acquired from the National Park Service (NPS) GIS database (Table 2). Curvature parameters, which emphasize detail in surface complexity, were created using the ArcGIS 9 Curvature tool (Esri Inc., 2009), (Zevenbergen and Thorne, 1987). Geomorphology, RCVI (Relative Coastal Vulnerability Index), and

mean wave height were digitized manually based on the classified data sources listed in Table 2. Distance from nearest public access points was used as a surrogate to account for human disturbance. All data were processed in ArcGIS 9.3.1 (Esri Inc., 2009), and environmental layers were created for spatial and statistical analyses (Figure 4).

## Multicollinearity

Multicollinearity refers to correlations among multiple explanatory variables, and poses a major problem when identifying variables that are more influential for the response variable than others (Graham, 2003; Zuur *et al.*, 2010). Ignoring multicollinearity may cause inaccurate model parameterization, insufficient statistical power or analysis, and exclusion of important variables (Graham, 2003; Zuur *et al.*, 2010). One way to avoid multicollinearity is to perform principal components analysis (PCA) (Zuur *et al.*, 2010). PCA reduces a dataset to a smaller number of uncorrelated components that represent as much

Table 1. Environmental variables

Variables	Comments
Slope	Maximum change in elevation between 1 cell (2 m square) and its neighbours
Curvature	Slope of the slope
Curvature (plan)	Curvature perpendicular to the direction of maximum slope
Curvature (profile)	Curvature in the direction of maximum slope
Geomorphology	Landform types
Relative coastal vulnerability index (RCVI)	Relative vulnerability of the coast to future sea level rise (based on geologic and physical process variables)
Mean wave height	Mean significant wave height in metres
Distance (human disturbance)	Distance in metres from nearest public access points

Table 2. Environmental variables

Variable	Data Type	Year	Source	Reference
Elevation	3m LiDAR	2002	NOAA	NOAA Coastal Services Center: Digital Coast 2002 NASA/USGS Shoreline LIDAR. Available from <a href="http://csc-s-maps-q.csc.noaa.gov/dataviewer/viewer.html">http://csc-s-maps-q.csc.noaa.gov/dataviewer/viewer.html</a>
Slope	Raster	---	Derived	---
Curvature	Raster	---	Derived	---
Curvature (plain)	Raster	---	Derived	---
Curvature (profile)	Raster	---	Derived	---
Geomorphology	Vector	2001, 2005	USGS, NPS	National Park Service Point Reyes Marine Classes (2001). Available from <a href="http://science.nature.nps.gov/nrdata/datastore.cfm?ID=21578">http://science.nature.nps.gov/nrdata/datastore.cfm?ID=21578</a> US Geological Survey (2005) PORE shore. Available from <a href="http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/pore.htm">http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/pore.htm</a>
RCVI	Vector	2005	USGS	US Geological Survey PORE shore. Available from <a href="http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/pore.htm">http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/pore.htm</a> Variables include: geomorphology, shoreline erosion and accretion rate, regional coastal slope, relative sea level change, mean significant wave height and tidal range
MWH	Vector	2005	USGS	US Geological Survey PORE shore. Available from <a href="http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/pore.htm">http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/pore.htm</a>
Distance	Vector		Derived	---

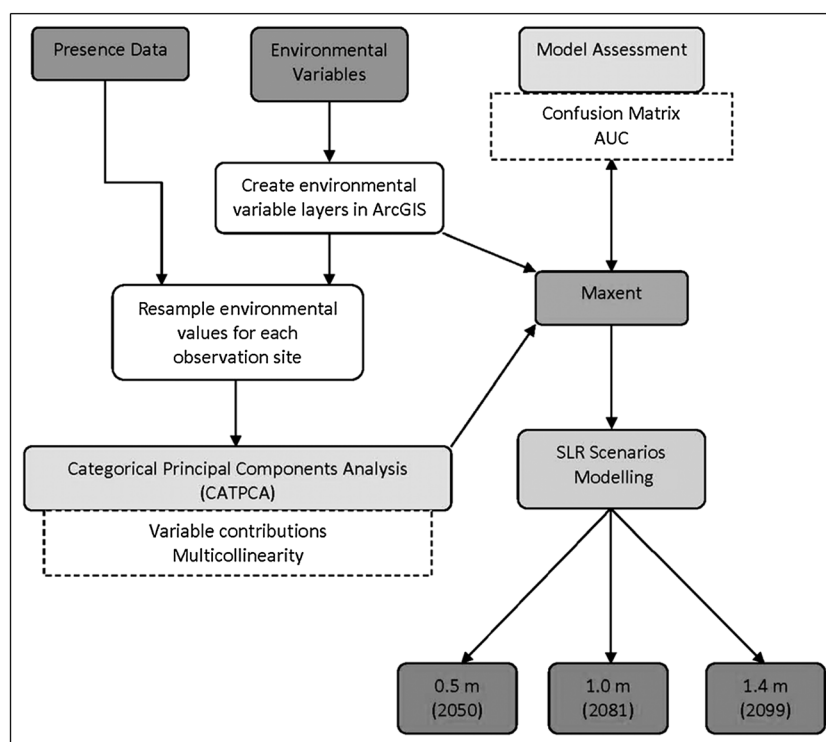


Figure 4. Flow chart for methods.

information as in the original variables by identifying highly correlated variables (Jolliffe, 2002; Rogerson, 2006). Categorical PCA (CATPCA) was used to avoid multicollinearity and to evaluate relationships among variables.

Categorical principal components analysis maintains the underlying principles of ordinary PCA and applies optimal scaling quantification to accommodate variables of different types (Kroonenberg *et al.*, 1997; Meulman *et al.*, 2004). As its main advantage, CATPCA allows non-linear relationships between variables and incorporates variables in mixed measurement levels (numerical, ordinal, and nominal) (Michailidis and de Leeuw, 1998; Vaughan and Ormerod, 2005; Ellis *et al.*, 2006). The results of CATPCA were analysed to determine collinear variables as well as contributing factors. The final selection of variables was then incorporated into Maxent for further analyses (Figure 4).

### Maxent

Species distribution modelling predicts the distribution of a species by combining the known occurrence records of the species and environmental variables, and by identifying important conditions in which the species maintains its population (Pearson *et al.*, 2007). In recent years, it has increasingly been used

in a wide range of fields (Guisan and Thuiller, 2005; Elith *et al.*, 2011). In this research, Maxent was used to model the potential distribution of northern elephant seals. Maxent refers to a maximum entropy method that identifies the statistical probability of the distribution of a species that is most spread out based on values of explanatory variables (Phillips *et al.*, 2006). Maxent randomly draws background values of environmental variables and compares them with those values associated with species presence in order to constrain an estimated species distribution (Phillips *et al.*, 2006). In other words, Maxent estimates a distribution that agrees with all available information while avoiding assumptions (e.g. that data are unbiased) that are not supported by data (Phillips *et al.*, 2006; Pearson *et al.*, 2007). Advantages of Maxent include: (1) its abilities to use presence-only data as well as to incorporate both categorical and continuous data; (2) it can be used when a limited amount of training data are available; and (3) Maxent presents information on variable contributions for each model and automatically creates a continuous probability surface (Phillips *et al.*, 2006). On the other hand, Maxent's disadvantages include a tendency to overestimate probabilities outside the study region from which it draws background values (Phillips *et al.*, 2006; Pearson *et al.*, 2007). Elith *et al.* (2011)

demonstrated that models based on Maxent are particularly susceptible to any sampling bias of sample collection effort. As all elephant seal haul-outs in the study area were included, sampling bias of this type is not applicable here. Despite these drawbacks, it has been shown to perform relatively well in comparison with other modelling methods, especially in determining the importance of habitat variables and illustrating how they affect species distributions (Elith *et al.*, 2006; Phillips *et al.*, 2006, 2009; Pearson *et al.*, 2007; Thorne *et al.*, 2012).

### Model assessment

The quality and determination of the best models generally depend on predictive accuracy (Fielding and Bell, 1997). In this study, two methods are used to assess the model's predictive accuracy: a confusion matrix and the area under the curve (AUC) values using the 'receiver operating characteristics' (ROC) technique (Figure 4). A confusion matrix is commonly used to summarize model performance by observed and predicted presence (positive)/absence (negative) measures (Fielding and Bell, 1997). While a full confusion matrix can be used to calculate a variety of accuracy measures, half of the matrix (true and false positives) was employed in this study, as only presence data were available.

To complement the confusion matrix and perform a more robust measurement, AUC values in ROC plots were calculated as an index that provides a measure for the overall accuracy of the model (Fielding and Bell, 1997). A ROC curve plots true positive fractions (sensitivity) against false positive fractions ( $1 - \text{specificity}$ ) for all decision threshold values (high to low), as opposed to a single decision value in the confusion matrix (Fielding and Bell, 1997). Fielding and Bell (1997) recommend AUC values for model comparisons, as they are independent of threshold effects, especially as single thresholds have been criticized as arbitrary (Pearce and Ferrier, 2000). Maxent automatically calculates AUC values for each model. AUC values range from 0.5 to 1.0. A value of 1.0 indicates perfect prediction while 0.5 represents no predictability (Pearce and Ferrier, 2000).

### SLR scenarios

The LiDAR elevation data were used to model three SLR scenarios: 0.5, 1.0, and 1.4 m in 2050, 2081, and 2099, respectively (Figure 4). These estimated scenarios were also used in the most

recent report on projected SLR impacts on the California coast (Heberger *et al.*, 2009). Mean high water (MHW) from the NOAA National Tidal Datum was used as a shoreline, and elevation values were referenced to NAVD 88 (North American Vertical Datum of 1988). The models were applied to haul-out sites most frequently used by larger groups of seals in South Beach, North Drakes Beach and Point Reyes Headlands. To evaluate impacts of SLR on potential habitats of northern elephant seals, the area of inundated habitats was calculated for each scenario. In addition, these scenarios were compared visually to detect spatial impacts of SLR.

## RESULTS

### Multicollinearity

Results of the CATPCA showed two groups of collinear variables. MWH and RCVI were highly correlated, while geomorphology, curvature, curvature profile, and curvature plan had close relationships. On the other hand, the results indicated that distance and slope were more independent and less correlated than other variables (Table 3).

### Maxent

Four models were created by Maxent (Table 4). Results showed that four variables (distance, mean wave height, slope, and geomorphology) were important predictor variables. Habitat suitability increased with distance from public access and decreased with higher wave height. Sandy beaches and gradual slopes are optimal habitat. Distance from public access points was the most significant contributor in all models. Model 4 included all

Table 3. Component loadings showing variable contributions to each component. If an absolute value is high, variable contribution to a component is high

Component loadings	Dimension	
	1	2
Slope	0.96	-0.02
Curvature	-0.85	-0.38
Curvature (plan)	-0.86	-0.25
Curvature (profile)	0.66	0.37
Distance	-0.80	0.92
Geomorphology	-0.63	-0.41
RCVI	-0.76	0.62
Mean wave height	-0.70	0.69

Table 4. AUC values, contributing variables and the percentages of true and false positives for Maxent models

Model	Variables (% variable contribution)	AUC	True positive (%)	False positive (%)
1	Distance (42), Geomorphology (36), MWH (22)	0.97	100	0
2	Distance (49.5), MWH (29.9), Slope (20.6)	0.97	93.75	6.25
3	Distance (45.3), Geomorphology (36.3), Slope (18.5)	0.97	100	0
4	Distance (36.8), Geomorphology (30.8), MWH (17.2), Slope (15.7)	0.98	100	0

four variables while other models contained only three. Although model accuracies were relatively similar, their spatial predictions differed slightly from one another (Figure 5). In all models, higher levels of suitability were found at beaches backed by cliffs, but not present at paleo-dune-backed beaches. All models predicted some level of

habitat suitability at PRH, SB, NDB, CRL, Limantour Spit, and Tomales Point. Model 2 produced relatively higher predictive values at Tomales Point, Point Reyes Beach, and Limantour Spit than the other models. Model 3 also indicated relatively high values at Tomales Point and showed more variability at PRH.

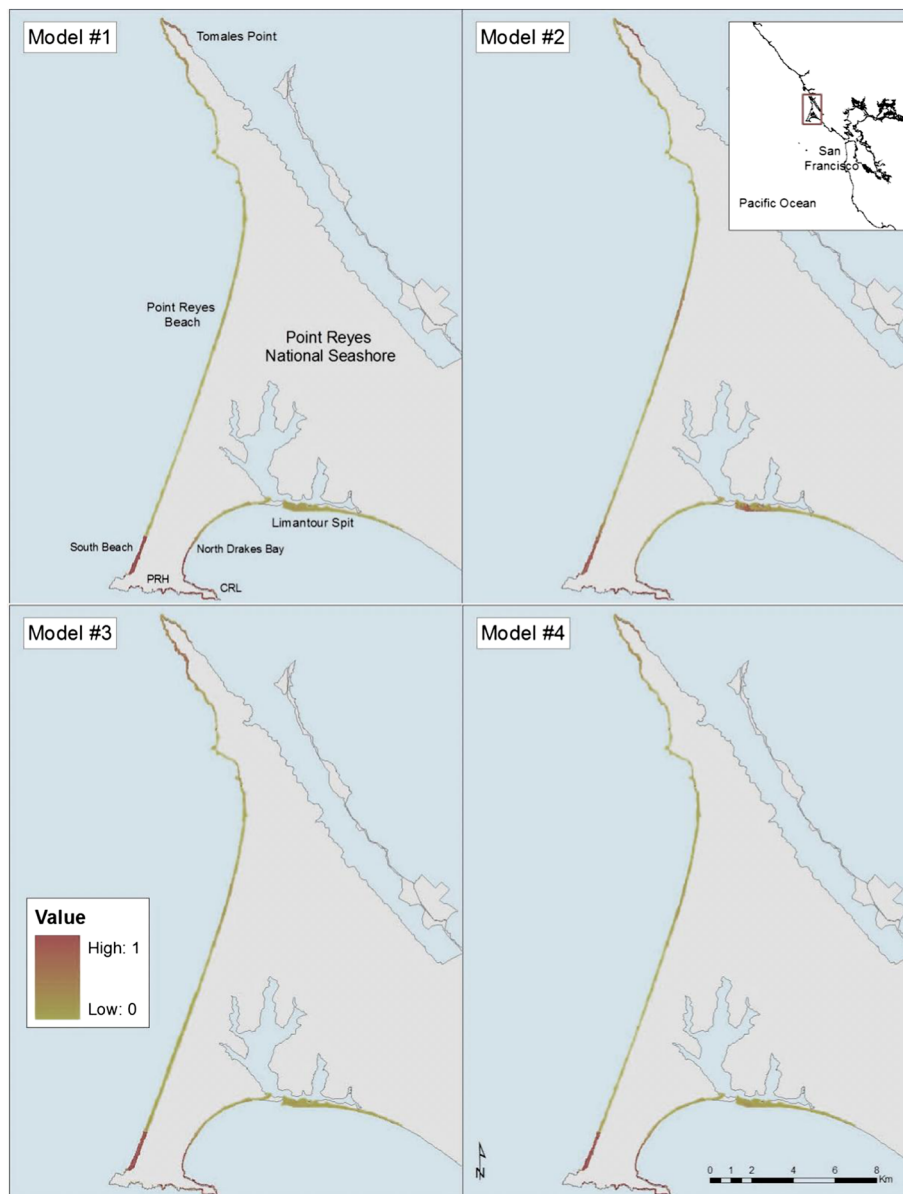


Figure 5. The predicted probability surfaces of Maxent models.



### Model assessment

The results of the confusion matrix and AUC values showed that all four models had a high predictive capability (Table 4).

### SLR scenarios

The results of SLR scenarios showed that areas of haul-out inundation would consistently increase for all models as sea level rises (Table 5). The 2050 scenario would flood nearly half of the potential habitats predicted by Maxent models, and approximately two-thirds of habitats would be inundated and unavailable for the seals by 2099 (Table 5). Visual inspection revealed that the 2050 scenario would inundate most current seal habitats at PRH, CRL, and NDB, and only SB seems to provide adequate fallback space (Figure 6). All SLR scenarios would flood potential areas at Tomales Point and Limantour Spit where models produced relatively high predictive values.

## DISCUSSION

From the Maxent models, it was possible to predict how the distribution of breeding habitats of northern elephant seals at Point Reyes Peninsula might vary in response to sea-level change scenarios. These predictions have identified coastal areas potentially suitable for the seals to colonize and expand to. All models produced consistent results for the areas to which seals could potentially redistribute. PRH, CRL, NDB, SB, Limantour Spit and Tomales Point were predicted to be suitable areas. According to the models, Limantour Spit and Tomales Point possess suitable conditions for seals to establish new breeding colonies, as PRH, CRL, NDB and SB represent current breeding habitats. The result corresponds to the fact that individual seals have been present but not breeding at Limantour Spit almost annually for the past

Table 5. Estimated habitat areas of inundation by three SLR scenarios. Inundated areas are calculated for habitats estimated by each Maxent model

SLR (year)	Habitat area inundated (km <sup>2</sup> )				Habitat area inundated (%)			
	#1	#2	#3	#4	#1	#2	#3	#4
2050	1.16	1.04	1.15	0.91	49.2	46.5	52.1	49.5
2081	1.42	1.27	1.36	1.11	60.3	56.7	61.4	60.5
2099	1.62	1.44	1.50	1.26	68.8	64.2	68.0	68.2

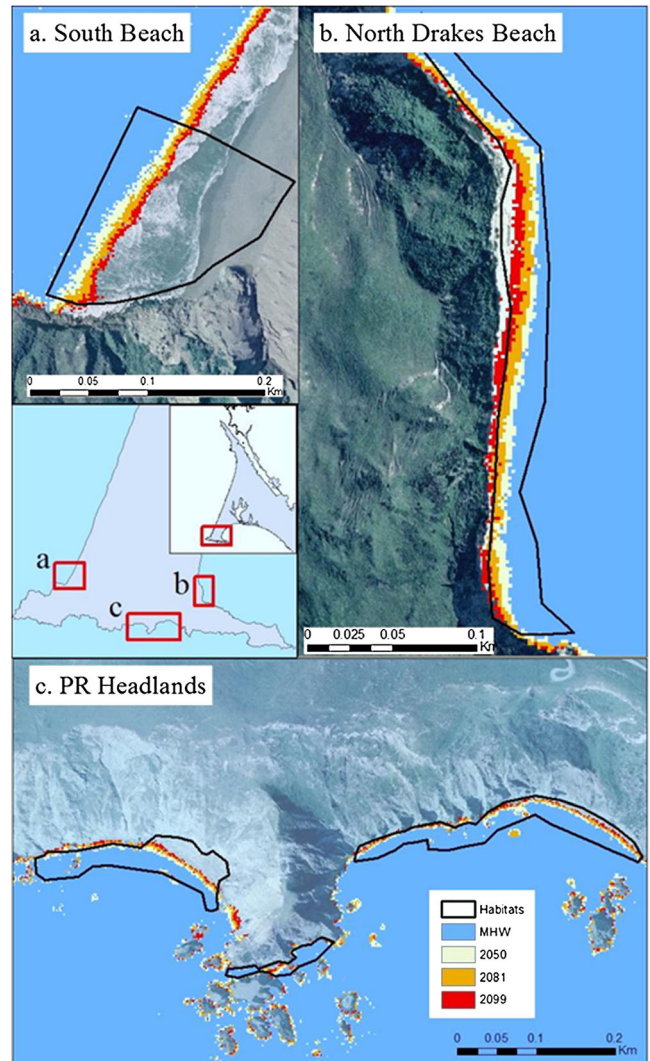


Figure 6. Maps of SLR scenarios with habitats. SLR scenario maps are shown for habitats at Point Reyes Headlands, South Beach, and North Drakes Beach.

10 years, perhaps because of human disturbance (NPS, unpublished data).

All models showed that distance, geomorphology, mean wave height, and slope predict habitat suitability well. However, distance from nearest public access points, such as parking lots or hiking trails, surrogates for human disturbance, was the most significant factor in all models and combinations of haul-out variables. As mentioned previously, models showed suitable habitat at beaches backed by cliffs, but not paleo-dune-backed beaches. This may be a function of where the seals first colonized and the proximity of adjacent habitat, or may be related to seals seeking remote areas where steep rocky cliffs prevent human access but paleo-dune cliffs do not. Mean wave height was also important, indicating seals may seek protection from physical disturbances from higher waves.

Although models do not reflect annual or seasonal variations, observations have shown that seals move from exposed sites to protected sites during times of intense waves and heavy winter storms (Petree, 1999; Allen *et al.*, 2012). These results also support a National Park report that suggested effective law enforcement and greater public awareness had led to seal population growth and colony expansion (Adams *et al.*, 2007).

Other variables may also influence habitat selection; however, the availability of information limited the parameters considered in this study. While all models had high predictive capability, they might not integrate all relevant factors (Fielding and Bell, 1997). A greater number of environmental factors could be incorporated if additional high resolution data sets were available, such as local current direction and wave height. High-resolution data sets for geomorphic variables would be useful for a local-scale coastal study, as geomorphic processes are complex and significant along the coastline (Barnard *et al.*, 2009). Protection from disturbance and safety from storms and waves are unlikely to be the only critical factors for seal distribution, and further research is needed to identify other important variables. Nevertheless, the discriminatory ability of the models indicated that those four explanatory variables were at least closely associated with the occurrence of the species (Pearce and Ferrier, 2000). It is necessary to make the best possible use of limited resources for critical conservation and management planning (Vaughan and Ormerod, 2005), and these results will provide important insights to future studies.

Other uncertainties might involve the ecology of northern elephant seals. While absence data were not used, some characteristics of absence locations might be similar to some presence locations, making the models difficult to classify (Fielding and Bell, 1997). As in other species distribution models, the occurrence locations might not present all necessary information to characterize the fundamental habitats of the species, as Point Reyes Peninsula is geographically a small area (Phillips *et al.*, 2006). In addition, spatial autocorrelation might have biased the distribution of highly suitable areas and the predictability of the models (Segurado *et al.*, 2006). However, the Point Reyes coastline possesses relatively small physical and geomorphic variations, compared with a broader terrestrial region, so that variations

in sample points must be sufficient to represent the entire area.

SLR models indicated that the 2050 scenario would inundate approximately half of potential elephant seal breeding habitats at Point Reyes Peninsula. Current habitats and high suitability areas would mostly be inundated by 2050. However, the extent of inundation among these sites was variable for each scenario. The eastern section of Tomales Point and the north portion of NDB would retain some space for the seals in the 2050 scenario, and SB and Point Reyes Beach would even provide ample space in the 2099 scenario. Other locations would probably face inundation by 2050. In general, the 'bath-tub' inundation at three sea levels would not be substantially different in the models because cliffs or cliff-backed beaches compose much of the Point Reyes coastline.

The SLR models in this study only considered inundation that depends primarily on elevation. In reality SLR would be associated with other physical and geomorphic processes. These processes might include more frequent, higher and intense waves, extreme erosion, increased tide influence, and severe storms (Titus and Richman, 2001; Poulter and Halpin, 2008). While SLR alone would have a limited effect, a combination of these activities might substantially affect habitat type and distribution. Shoreline erosion or accretion would particularly affect the inundation of the coastline (Titus and Richman, 2001; Poulter and Halpin, 2008). Cliff and dune erosion and sand deposition might also become more extreme owing to increased coastal activities by SLR effects (Cooper *et al.*, 2004), and these processes might create or shift potential habitats. While the relative rates of cliff and dune retreat and beach erosion are difficult to analyse, these geomorphic processes are significant in coastal areas (Bird, 2008). Concurrent cliff erosion and sand deposition might possibly shift habitats inland slightly. In addition, cliff or dune erosion might simply create additional habitats by supplying sand. Human structures such as parking lots would also have impacts on these processes by preventing erosion of shorelines, thus not allowing habitats to shift or to be created.

Although complex coastal processes make it difficult to predict, we have documented these effects on the habitats of seals. For example, landslides have occurred on a cliff-backed cove at

PRH and deposited sediments, creating more space for seals (Allen *et al.*, 2012). SB, PRH, and south-western CRL are susceptible to intense erosion, and PRH has already experienced complete flooding in years of severe winter storms and times of high tides (Petree, 1999; Allen *et al.*, 2012). NDB would be less exposed to extreme wave activities and receive less SLR impacts, and direct observation has shown that the population is growing and individual seals are moving to NDB (Petree, 1999; Adams *et al.*, 2007; Allen *et al.*, 2012).

Uncertainties in SLR models are also caused by the processing of the LiDAR data. While high-resolution data significantly improve SLR models, the interpolation technique and post-processing of LiDAR points used to create topographic models might cause large variability in inundation estimates (Poulter and Halpin, 2008). In addition, predicted scenarios of future climate change are considered inherently uncertain (Pearson *et al.*, 2006).

Another challenge was limited sample size. Small sample sizes pose challenges to statistical analyses and predictive performance of models, and a greater sample size would develop more accurate models (Hernandez *et al.*, 2006). Nevertheless, Maxent has been shown to outperform other models at small sample sizes and produce useful results with sample sizes as small as 5, 10, and 25 occurrences (Hernandez *et al.*, 2006; Wisz *et al.*, 2008). Consequently, this sample size of 16 occurrences (haulouts) was sufficient to produce useful results.

### Recommendations

For SLR planning, it is critical to develop high-resolution data sets for a variety of environmental variables. Models are effective and useful, but the quality and reliability of models depend on the quality of data. If models are created with reliable, high-resolution data, modelling of habitat changes and distributions can then be useful for conservation planning and management (Hannah *et al.*, 2002). High-resolution elevation data would also improve SLR models, and are especially critical in low SLR scenarios as the influence of fine-scale topography is greater (Poulter and Halpin, 2008).

It may also be necessary to examine population distribution and density at breeding sites when determining suitable habitats. Even if sites are suitable, seals would have to move to other sites

when occupied sites reach spatial carrying capacity. In studies of other phocid seals, habitats suitable for pupping may influence individual site selection (Twiss *et al.*, 2001). A local-scale study of coastal habitats also requires geomorphic analyses, and it is crucial to include geomorphic processes into the models. While this project has examined SLR-driven beach habitat loss, analysis of indirectly SLR-driven cliff and dune retreats and longshore sand replenishment should be incorporated. Although the US Geological Survey has included shoreline erosion and accretion rates in their coastal vulnerability assessment (Pendleton *et al.*, 2005), finer-scale analyses of the relative rates of cliff retreat and beach erosion would help point to where concerns of SLR may be more critical (Barnard *et al.*, 2009).

SLR scenarios indicated that current habitats and high suitability areas would mostly be inundated by 2050. As rising sea levels would undoubtedly affect areas along the Point Reyes coast that possess limited suitable habitats for the seals to colonize, conservation measures in response to SLR should be considered in the near future, such as greater protection from human disturbance at sites of suitable habitat or removal of infrastructure, including parking lots, from supratidal zones. The resulting analyses and spatially explicit depiction of seal habitats can be used to integrate potential climate change effects into the spatial distribution of northern elephant seals, provide a better understanding of the species and its relationship with a changing environment, outline a protocol applicable and adaptable for similar research, and provide adaptive management strategies to preserve seal terrestrial habitats. This project contributes to ongoing research on northern elephant seals within Point Reyes National Seashore by providing policy makers, scientists, and park managers with a tool to consider management strategies, as modelling of habitat changes and distributions is widely used in conservation and climate change scenario planning (Guisan and Thuiller, 2005; Allen *et al.*, 2011). Conservation of biodiversity requires climate change-integrated strategies that monitor and address potential impacts of climate change (Hannah *et al.*, 2002; Anderson *et al.*, 2009). Similarly, conservation strategies and planning should integrate a process that includes not only present conditions, but also future patterns (Hannah *et al.*, 2002).

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