

Combined impacts of sea level rise and invasive species on *Cordylanthus maritimus* (Salt Marsh Bird's Beak) in Upper Newport Bay, California

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Abstract

Salt Marsh Bird's Beak (*Cordylanthus maritimus* subsp. *maritimus*) is a hemiparasitic halophyte that is endemic to coastal salt marshes of southern California and is both state and federally endangered. By the year 2100, sea level is projected to rise by up to 3 meters, which will decrease the biodiversity of salt marshes and lead to changes in plant community assemblages, impacting the narrow ecological niche of *C. maritimus*. Here, we address how sea level rise will impact the habitable range of *C. maritimus*, and we examine how these impacts will be compounded by the presence of an invasive plant species, Algerian sea lavender (*Limonium ramosissimum*). We used LiDAR data, plant distributions, and sea level rise projections for the Upper Newport Bay Ecological Reserve to create species distribution models and map current and future ranges for both species. The areas of these ranges and the area of overlap between both species were calculated for 2020, 2050, and 2100 under varying sea level rise scenarios. Although overlap between the two species' ranges currently exists, *C. maritimus* inhabits a smaller area at relatively lower elevations than *L. ramosissimum*. Across all 2050 and 2100 scenarios, we project *L. ramosissimum* will occupy at least 161% and 292% more habitable area than *C. maritimus*, respectively. More than 96% of the projected habitable area for *C. maritimus* may also be suitable for *L. ramosissimum*, increasing competition between the two species and highlighting a critical need to strategically control invasive *L. ramosissimum* in Upper Newport Bay.

Introduction

Coastal salt marshes are characterized by high productivity and biodiversity, and their limited range and unique abiotic traits increase their tendency to have specialized and adapted plant species (Teixeira et al. 2014; Grewell 2008). These specialized plants, particularly the halophytes, are highly adapted to environments with high salinity and periodic tidal inundation, and their presence provides critical habitat for other organisms, including crustaceans, arthropods, and estuarine birds (Teixeria et al. 2014). Halophytes also reduce soil salinity and improve oxygen conditions in marsh soil that would otherwise often be under anoxic conditions (Grewell 2008); thus, their presence mitigates abiotic stressors for other plants in the salt marsh and creates a more habitable environment for other less salt-tolerant species. Therefore, the presence of halophytes is critical to coastal salt marsh biodiversity and resilience, and their loss will change the composition of the plant communities, reducing species richness.

Coastal salt marshes consist of low, middle, and high marshes, creating unique habitat niches for plants and wildlife that are likely to be negatively impacted by future sea level rise (SLR). Globally, SLR is projected to increase by 0.25-3m (IPCC 2014), which will cause a decrease in salt marsh habitats and their endemic halophytes (Lee et al. 2014; Simas et al. 2001; Thorne et al. 2018). This decrease in abundance will be particularly pronounced if the salt marsh remains static, with no sedimentation; it is projected that 20–60% of the world's coastal wetlands will become inundated within the century if sedimentation is unable to keep pace with SLR (Kirwan et al. 2010). Therefore, the persistence of salt marsh ecosystems depends on the ability for halophytes to vertically shift their elevation ranges to keep pace with SLR (Nelson and Zavaleta 2012).

California coastal salt marshes are particularly vulnerable to SLR, due to relatively low sedimentation rates, steep topography, and or the presence of urban environments where landward transgression would be inhibited (Thorne et al. 2018). On the western coast of the US, up to 95% of salt marshes under high SLR scenarios are likely to become mudflats or inundated entirely by 2110 (Thorne et al. 2018). Endangered and endemic species in California salt marshes are therefore particularly vulnerable to SLR without upland habitat to support landward transgression (Fagherazii et al. 2019).

Cordylanthus maritimus (Salt Marsh Bird's Beak) is a hemiparasite found primarily in the middle marsh and is protected by the federal and state endangered species acts (Zedler et al. 2001). The California Natural Diversity Database (CNDDB) classifies this species as a California Rare Plant Rank of 1B.2, meaning it's listed as rare, threatened, or endangered in CA and elsewhere. Historically, *C. maritimus* was widely distributed but its range has become increasingly restricted due to a variety of factors including warmer temperatures, a lack of genetic diversity, extreme tide events, and urbanization (Milano et al. 2020; Noe et al., 2019). Currently, *C. maritimus* remains in only eight salt marshes in California, with five occurring in southern half of the state (Noe et al. 2019). In recent years, the presence of invasive species has impeded efforts to restore *C. maritimus* populations. *Limonium ramosissimum* (Algerian Sea Lavender) was recently introduced from the Mediterranean and became naturalized in disturbed salt marshes throughout California (Barbour et al. 2007). In contrast to the small, realized niche of *C. maritimus*, *L. ramosissimum* has a wide distribution in both salt marshes and upland habitats, and causes a decrease in species richness (Archbald & Boyer 2014). Since *C. maritimus* relies on native plant species as host, the loss of native plant species richness due to invasive species will have an additional negative affect on their recovery. Moreover, it remains unclear how populations of *C. maritimus* will respond in the future both SLR and interspecific competition with *L. ramosissimum*.

Here, we address the response of *C. maritimus* to the combined impacts of SLR and invasive *L. ramosissimum*. To create habitat niche models for each species, we combined the distributions of *C. maritimus* and *L. ramosissimum* with LiDAR data in the Upper Newport Bay Ecological Reserve (UNBER) located in Orange County, California. Using these habitat ranges, we then used various SLR projections to model future habitable ranges for each species. Our habitat models will assist land managers with predicting the future ranges of both species and with prioritizing potential restoration sites for reintroduction of *C. maritimus*. We also provide an estimate for likely locations of invasive *L. ramosissimum*, both now and in the future, so that restoration efforts can be maximized with limited resources.

Methods

Study Area

Upper Newport Bay Ecological Reserve (UNBER) is located in Orange County, California and encompasses approximately 304 hectares of endangered wetland, salt marsh, and transitional habitat (117°52'55.03"W 33°38'56.152"N). Designated an Ecological Reserve in 1975, UNBER has a long history of disturbance

that includes salt production and dredging operations and rapid urbanization of the surrounding watershed.

The current topography of the terrestrial environment was established by the removal 1.9 million m³ of sediment during the 1980's (Gerstenberg, 1989). Today UNBER has a maximum elevation of 11.75 m, with the majority of the salt marsh consisting of lower elevations, with a mean of 1.97 m above sea level. The changes in elevation support distinct habitats that include mudflats and lower, middle, and upper marshes. Native plant species that serve as hosts plants for *C. maritimus* include: *Batis maritima*, *Disticlis spicata*, *Frankenia salina*, *Limonium californicum*, *Jaumea carnosa*, and *Salicornia pacifica*.

Niche Models

Distributions of *C. maritimus* and *L. ramosissimum* were established between January and December 2019. LiDAR data of UNBER was used for the high-resolution digital elevation values in our models. LiDAR data used covers 6,775 km² of California coastal areas and was compiled during 108 flights between October 2009 and August 2011. Water bodies, including tidal water bodies such as UNBER were hydro flattened to mean sea level. The LiDAR data used the NAD83 datum and therefore all datasets were transformed to NAD83 prior to use.

Plant occurrence data were overlaid onto the LiDAR data in ArcGIS (ESRI), and a preferred range in elevation for each plant species was obtained. This preferred elevation range was then used in conjunction with the LiDAR data to map the overall potential habitable areas of each species using elevation alone. That is, we calculated the total area within the habitable elevation range for each plant species using the LiDAR data, and the habitable areas reported are maximum ranges based on the observational data obtained in the field.

Other factors that are often included in species distribution models, such as vegetation alliance, soil, and precipitation data, were excluded from our models due to the relatively small study area, homogeneity of the study site, and strong influence of elevation over species distribution. Elevation is the largest factor for the distribution of these species because the salinity of the soil and level of inundation is dependent on proximity to mean sea level. This approach produces fewer limiting factors in our projection models and represents a best-case scenario for *C. maritimus*. As *L. ramosissimum* is a niche generalist and has been found in high densities outside of the reserve, using elevation data alone is a conservative estimate for the range of this invasive species. These species distribution models, based on preferred elevation above mean sea level, were then used to model how the total habitable area of each species may change due to rising sea levels.

Sea Level Scenarios and Models

Sea level rise projections were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Fourth National Climate Assessment (Sweet et al. 2017). The sea level rise projections for UNBER vary based on different climate change scenarios and range from a 0.25- 0.85m increase by 2050, and

from a 0.50- 3.1m increase by 2100 (Table 1). While these SLR projections do not include potential sedimentation rates, previous studies have noted that sedimentation rates are low for UNBER (Thorne et al. 2018) and that by the year 2100 UNBER will likely be mudflat or fully inundated. Additionally, the uncertainty for the sea level rise projections is greater than the expected sedimentation rates (2.5mm per year), and we have therefore chosen to omit sedimentation from our models (Thorne et al. 2018).

Table 1

Representative concentration pathway scenarios as defined by the Intergovernmental Panel on Climate Change (IPCC) and their corresponding sea level rise projections for the Upper Newport Bay

Representative Concentration Pathway	Sea level rise (m) by 2050	Sea level rise (m) by 2100
Intermediate Low	0.25	0.50
Intermediate	0.38	1.07
Intermediate High	0.54	1.76
High	0.71	2.51
Extreme	0.85	3.11

Five different projection scenarios of sea level rise for both the year 2050 and 2100 were used in our models. These scenarios are dependent on various representative concentration pathways (RCPs) projected for the coming century (IPCC 2014). Representative concentration pathways are based on projected CO₂ emissions by the end of the 21st century and correspond to changes of radiative forcing (i.e., heat) that will lead to varying rates of SLR. Projected SLR for 2050 and 2100 for the five different scenarios (intermediate low, intermediate, intermediate high, high, and extreme) are summarized in Table 1 (Sweet et al. 2017).

Values reported for UNBER are based on projections of the Mean Higher High Water (MHHW) values for each projection scenario. The MHHW is particularly important for *C. maritimus* because it cannot survive in completely inundated areas. If mean sea level was used, the middle marsh would become inundated more frequently and for longer periods of time during higher tides. Thus, MHHW is a more valuable measure of the *C. maritimus* habitat.

Two different species distribution models for UNBER were created. The first model assumed that each species would not be able to respond quickly to changing sea level, and therefore would be unable to shift their habitable range shoreward in a rising seabed. Using the distribution models created for their preferred habitat (i.e. elevation) range, the upper bound of the current range was kept the same, with only the lower bound of the range changing due to inundation with rising sea levels. That is, we used the LiDAR data to determine how rising sea level would change the total habitable area of each species if they were to experience no shift in their current range in response to rising sea level.

The second model assumed that landward transgression of each species was possible, and that vertical migration would occur in response to rising sea levels. In this model, both the lower and upper bounds of

the habitable range were adjusted using the LiDAR data according to the projected SLR scenario. Each model was generated for all five of the scenarios, for 2050 and 2100, yielding ten models for *C. maritimus* and ten models for *L. ramosissimum*. All future ranges were compared to present day ranges. As a final step, we overlaid the model predictions for the future ranges of the two species and determined the areas of overlap allowing us to predict how the habitable range of *C. maritimus* may be impacted by *L. ramosissimum* in conjunction with rising seas.

Results

C. maritimus

Based on distribution data obtained from field observations, *C. maritimus* inhabits a narrow range in elevation, with all observations occurring between 0.35m and 0.69m above mean sea level (MSL); mean elevation was 0.57m above MSL. Thus, the current habitable range of *C. maritimus* was modeled by selecting all elevation values in the LiDAR data that fall between 0.35-0.69m (Fig. 1). Figure 1 shows the entire possible habitable range of *C. maritimus* based solely on elevation, and does not necessarily indicate the presence of the species in those locations. Under present conditions (2020), the total habitable range for *C. maritimus* in UNBER is 1.48 km², though the realized niche for the species is much more limited.

The first set of models, which assumed *C. maritimus* could not rapidly shift its habitable range, did not prove useful for our projections. In 9 out of the 10 scenarios, the projected SLR exceeded that of the habitable range upper boundary, suggesting that the entire population may be completely inundated by the year 2050 for all but the most conservative (Intermediate Low) scenario.

For the second suite of models, the projected *C. maritimus* habitable ranges calculated for each of the SLR scenarios assume that it will respond to rising sea level by shifting its habitable range to higher elevations, so both the lower and upper bound for the species were shifted (Fig. 2).

Thus, the following projections are likely a best-case scenario for *C. maritimus*, as the more conservative approach led to complete inundation (i.e. species loss) by the year 2100. By 2050, the habitable range for *C. maritimus* amounted to 47–68% reduced from 2020 values, depending on SLR scenario, assuming landward transgression of the species (Fig. 2; Table 2). By 2100, the habitable range was reduced from 46–95% of 2020 values (Fig. 2, Table 2). The total habitable range of the species will be reduced to 0.77km² by the year 2100, given a best-case scenario SLR projection (intermediate low).

Table 2

Total habitable area projections (*C. maritimus*) for the year 2050 and 2100, based on known (observed) habitable elevation range preferences. This was derived from an approach where the species was able to respond to rising sea level by adjusting its elevation range (i.e. a sea level rise of 0.5 m resulted in landward migration of the species by 0.5m).

Representative Concentration Pathway	Habitable Area 2050 (km ²)	Decrease in Habitable Area (2020 to 2050)	Habitable Area 2100 (km ²)	Decrease in Habitable Area (2020 to 2100)
Intermediate Low	0.50	66.2%	0.77	48.0%
Intermediate	0.60	59.5%	0.19	87.2%
Intermediate High	0.79	46.6%	0.14	90.5%
High	0.72	51.4%	0.11	92.6%
Extreme	0.48	67.6%	0.08	94.6%

L. ramosissimum

The current habitable range (year 2020) for *L. ramosissimum* was found to be between 0.36 and 2.05 m, with a mean elevation of 0.72m above mean sea level. The total current habitable range (3.21 km²) for this invasive species was modeled by selecting all elevation values within this preferred elevation range (Fig. 3). This current total habitable range is approximately 117% larger for *L. ramosissimum* than for *C. maritimus*.

The relative decreases in habitable area (46–67% of 2020 values) were less extreme for *L. ramosissimum* than for *C. maritimus* across most of the 2050 projection scenarios (except for the intermediate high and high projection scenarios for the year 2050) (Fig. 4, Table 3). Relative decreases were greater for *C. maritimus* across all projection scenarios when these were extended to the year 2100. This combined with the relatively smaller habitable range of *C. maritimus* at the start (2020) led to significant encroachment of *L. ramosissimum* into the remaining *C. maritimus* habitat by the year 2100.

Table 3

Total habitable area projections (*L. ramosissimum*) for the year 2050 and 2100, based on known (observed) habitable elevation range preferences. This was derived from an approach where the species was able to respond to rising sea level by adjusting its elevation range (i.e. a sea level rise of 0.5 m resulted in landward migration of the species by 0.5m).

Representative Concentration Pathway	Habitable Area 2050 (km ²)	Decrease in Habitable Area (2020 to 2050)	Habitable Area 2100 (km ²)	Decrease in Habitable Area (2020 to 2100)
Intermediate Low	1.94	39.6%	1.72	46.4%
Intermediate	1.83	42.9%	0.74	76.9%
Intermediate High	1.66	48.3%	0.58	81.9%
High	1.35	57.9%	0.45	86.0%
Extreme	1.05	67.3%	0.42	86.9%

While the current (2020) range of *L. ramosissimum* is larger than the range *C. maritimus*, using the niche models to calculate total habitable area, we project that *L. ramosissimum* will be able to inhabit an increasingly larger area than *C. maritimus* through time (Fig. 5, Table 3). On average for 2050 scenarios, *L. ramosissimum* has a 161.1% larger habitable area than the *C. maritimus* range. For 2100 scenarios, *L. ramosissimum* ranges has a 291.6% larger habitable area. The extreme 2100 scenario gives *L. ramosissimum* a 421.4% larger range than the *C. maritimus*. When comparing habitable ranges, we found that across all of the sea level rise scenarios for both 2050 and 2100, 96% or more of the *C. maritimus* habitat falls within the range of *L. ramosissimum*. In the Extreme 2100 scenario, 98% of the *C. maritimus* range falls within the *L. ramosissimum* range.

Discussion

The current potential habitable area of *C. maritimus* is 54% smaller than *L. ramosissimum*, due to its more narrow preferred elevation range above MSL. While the habitable ranges of both species in the marsh will be substantially reduced by the year 2100 because of SLR, our projections also indicate that *L. ramosissimum* will be able to inhabit an increasingly larger portion of the *C. maritimus* niche through time. Additionally, *L. ramosissimum* has a higher maximum elevation range within the marsh, reaching higher elevations above MSL, likely hindering any potential landward transgression of *C. maritimus*. Therefore, *L. ramosissimum* not only outcompetes *C. maritimus* for habitable space, but it also will likely prevent the species from occupying higher elevations in response to SLR.

As the high and extreme SLR projection scenarios are more likely than an intermediate scenario based on our current CO₂ emissions trajectories, these maps represent a best-case scenario for *C. maritimus* and should inform land management practices in light of future climate change. Our models predict the precise locations within the marsh where conservation efforts for the removal of *L. ramosissimum* should be prioritized, given limited resources and labor. The need to conserve land at slightly higher elevations

where *C. maritimus* may need to find refuge in the future is imperative. That is, given that some amount of habitat loss is inevitable in the next 30 years, regardless of projection scenario, removal of *L. ramosissimum* should also be targeted in regions where it is likely to infringe upon the future range of *C. maritimus*. Therefore, these maps highlight areas that may be critical for the survival of *C. maritimus* beyond the 21st century and may need to be considered when managing habitat to promote *C. maritimus* populations in the future.

Our maps indicate that *L. ramosissimum* may invade much of the *C. maritimus* habitat in the future. This is likely due to several factors that give *L. ramosissimum* a competitive edge over *C. maritimus*. Unlike *C. maritimus*, seeds of *L. ramosissimum* disperse by hydrochory, floating on fluctuating tides and currents (Jimenez et al. 2017). Once established in salt marshes, *L. ramosissimum* forms dense monocultures that decreases available hosts for *C. maritimus* (Archbald & Boyer 2014; Milano et al. 2020). In other coastal salt marshes across Californian, *L. ramosissimum* has also spread rapidly, especially throughout the San Francisco Bay Estuary (Archbald & Boyer 2014). Given its competitive advantages, *L. ramosissimum* will likely eradicate *C. maritimus* from UNBER and California within the next 30 years without conservation efforts to control and eradicate its spread.

Reduction in *C. maritimus* habitats through time may have critical cascading effects on other marsh species, including endangered migrating bird species. The invasion of *L. ramosissimum* in UNBER, has impacted several federal and state listed birds who rely on a diverse array of native vegetation for nesting (Zembal et al. 2016). Just as *C. maritimus* relies on a diverse array of native marsh plants, birds also rely heavily on native vegetation. Therefore, conservation of endangered flora and fauna in California must focus on removing invasive species like *L. ramosissimum*. It is therefore of critical concern to conserve the remaining marsh habitat suitable to *C. maritimus* in order to protect the species from future sea level rise and invasive species. Our maps highlight regions where removal of *L. ramosissimum* should be prioritized, and they provide targeted sites for the future restoration of *C. maritimus* within UNBER.

Declarations

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Author Contributions: Material preparation and data analysis was performed by Hannah Spear and David Banuelas. The first draft of the manuscript was written by Elizabeth Crook and Hannah Spear and all

authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

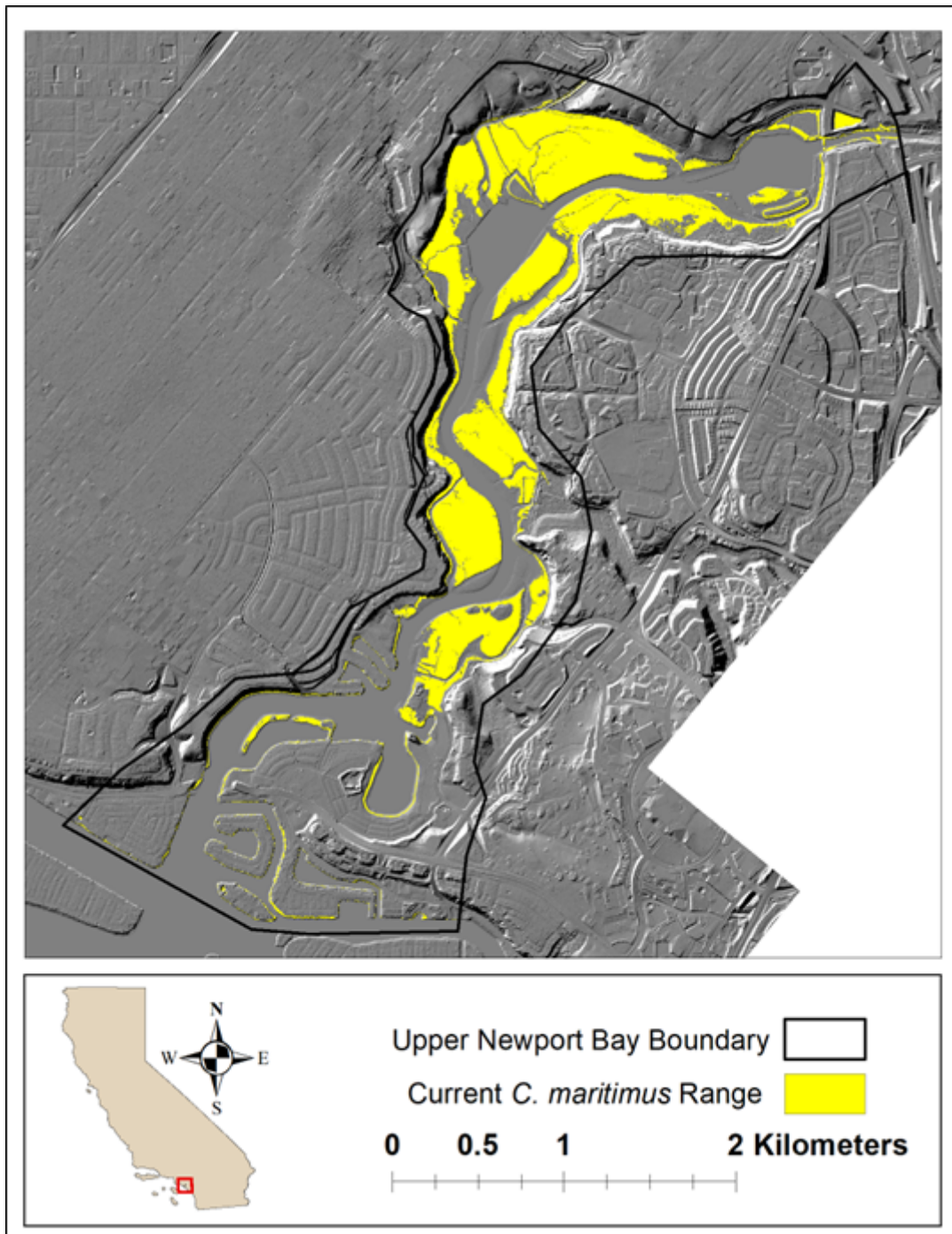


Figure 1

Present day (2020) distribution model of *C. maritimus* in Newport Bay Ecological Reserve using LiDAR to select for the preferred elevation range of 0.35- 0.69m above sea level (highlighted yellow regions). Note that this area encompasses the entire suitable habitat for *C. maritimus* based solely on elevation; it does not show actual occurrence of the species

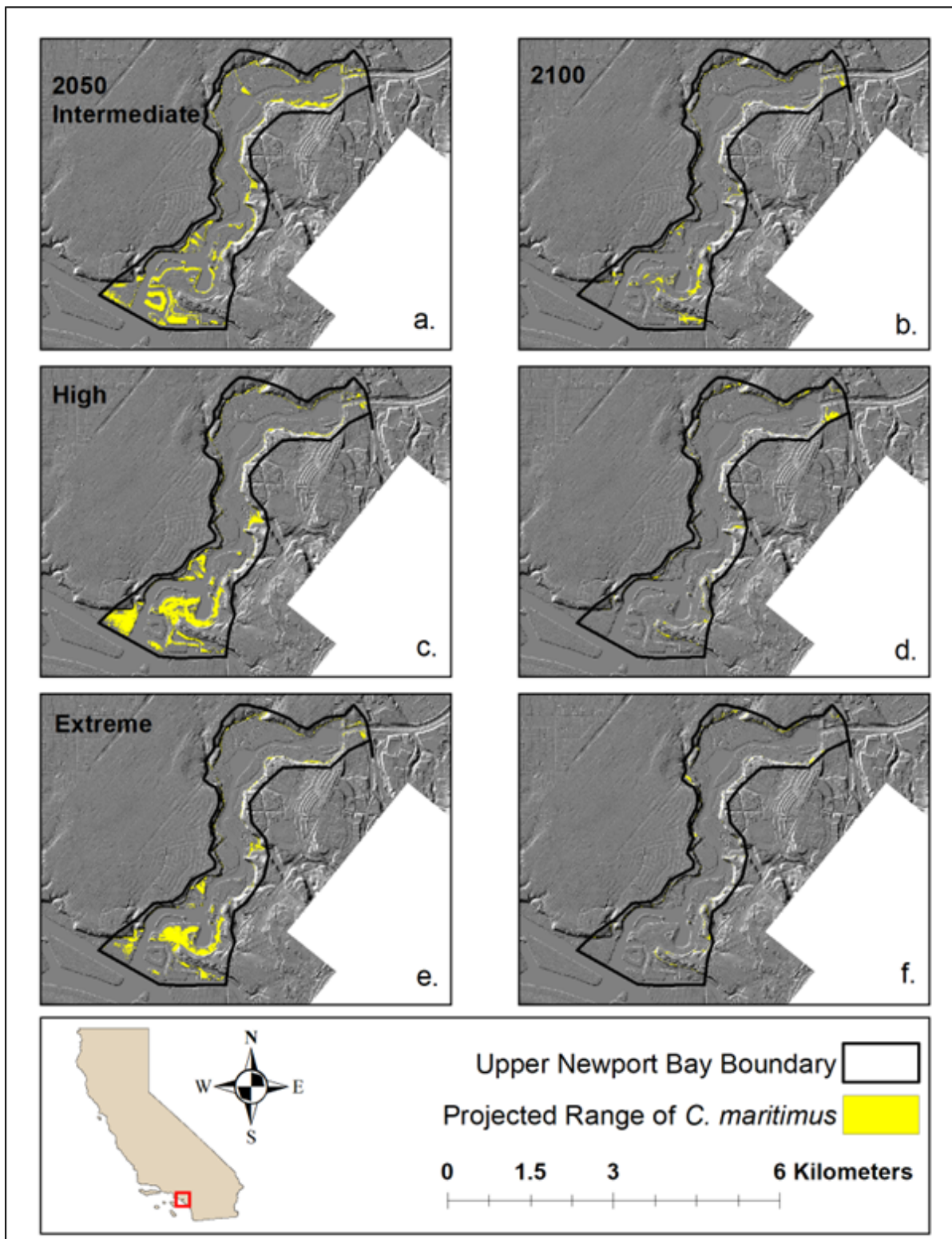


Figure 2

Projected *C. maritimus* ranges for 2050 (a, c, e) and 2100 (b, d, f) in Newport Bay Ecological Reserve for the Intermediate (a, b), High (c, d), and Extreme (e, f) sea level rise scenarios

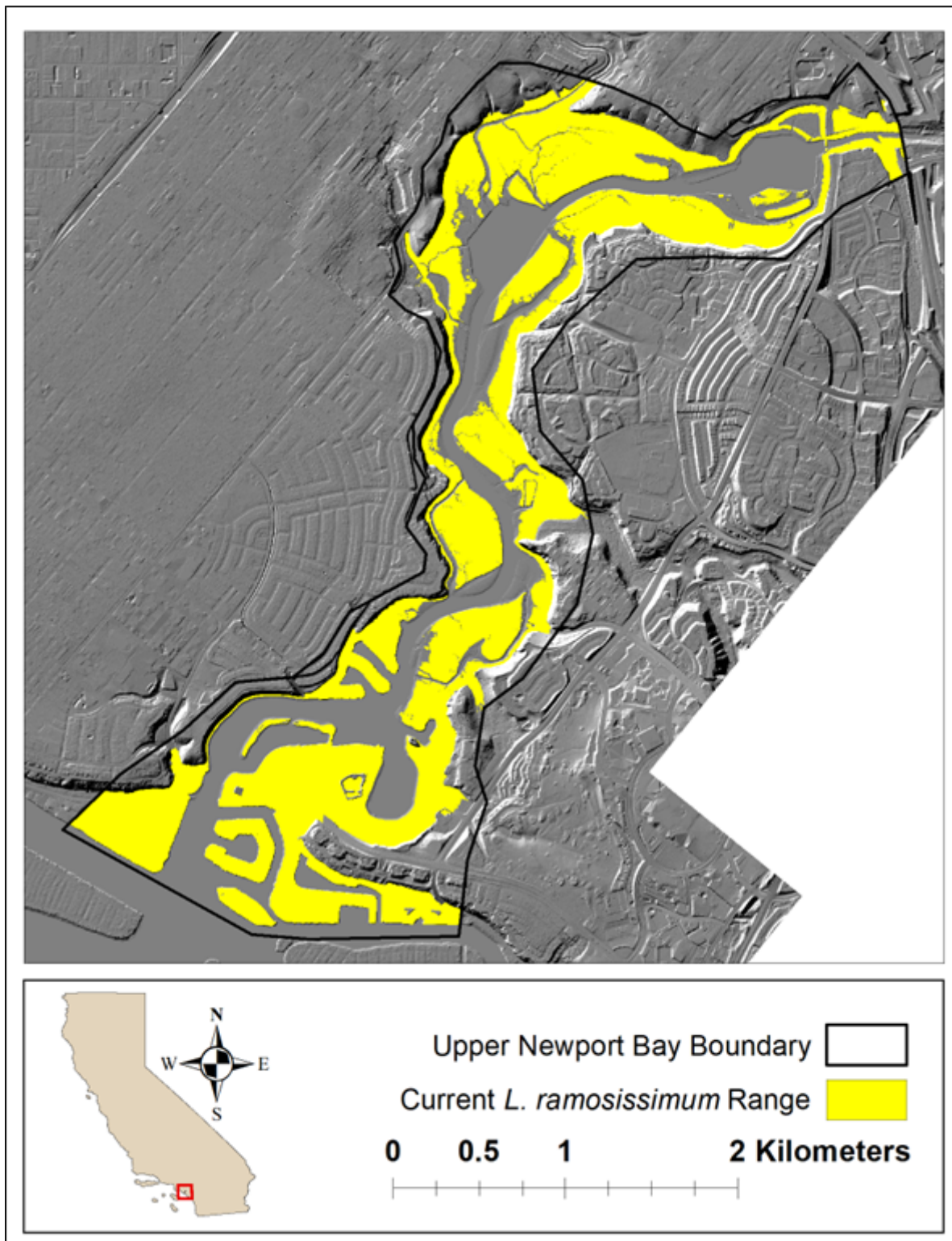


Figure 3

Present day (2020) species distribution model for the invasive plant, *L. ramosissimum* (Algerian Sea Lavender). The preferred habitable range of the plant is shown, or any elevation between 0.36 – 2.05 m above sea level

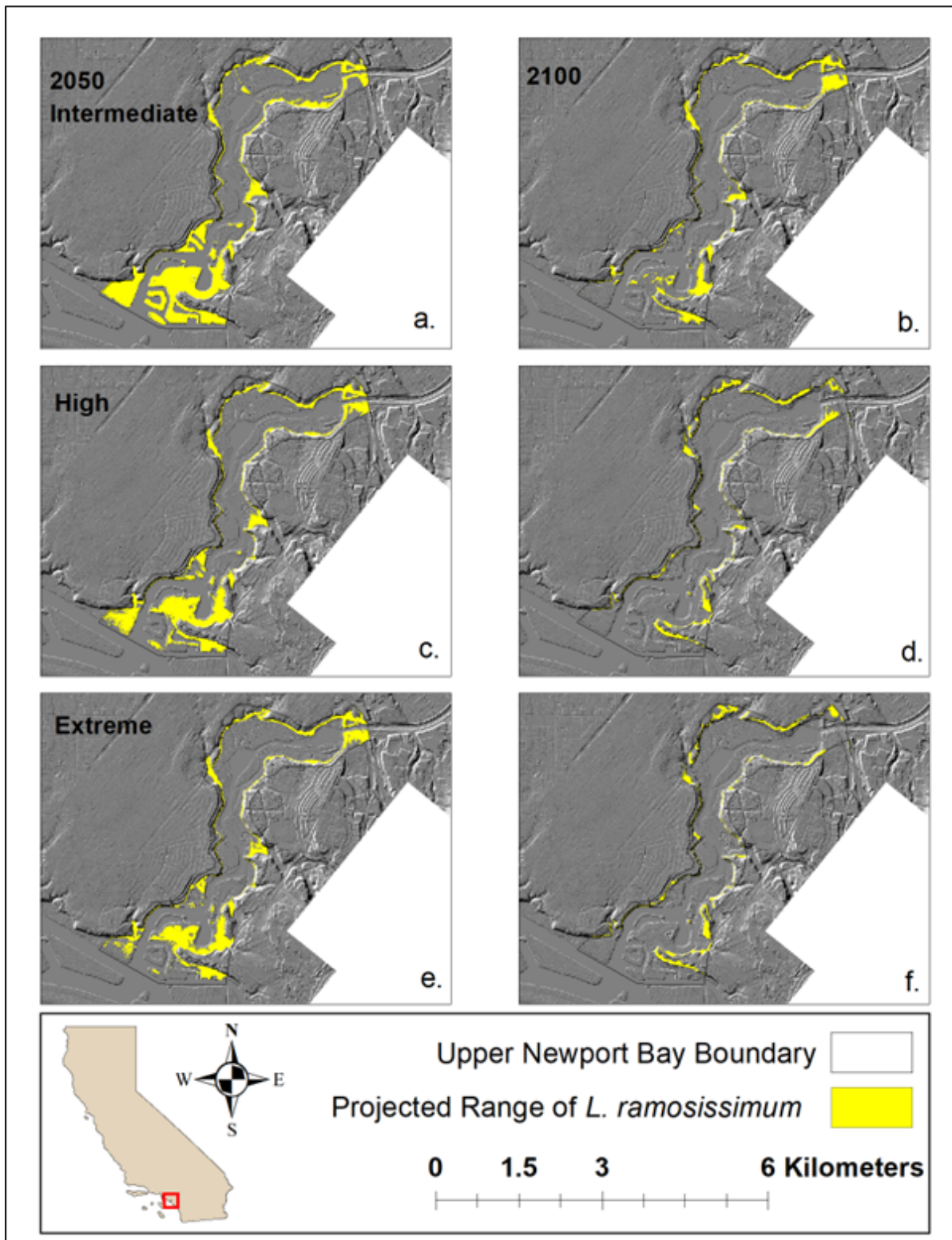


Figure 4

Projected *L. ramosissimum* ranges for 2050 (a, c, e) and 2100 (b, d, f) in Newport Bay Ecological Reserve for the Intermediate (a, b), High (c, d), and Extreme (e, f) sea level rise scenarios

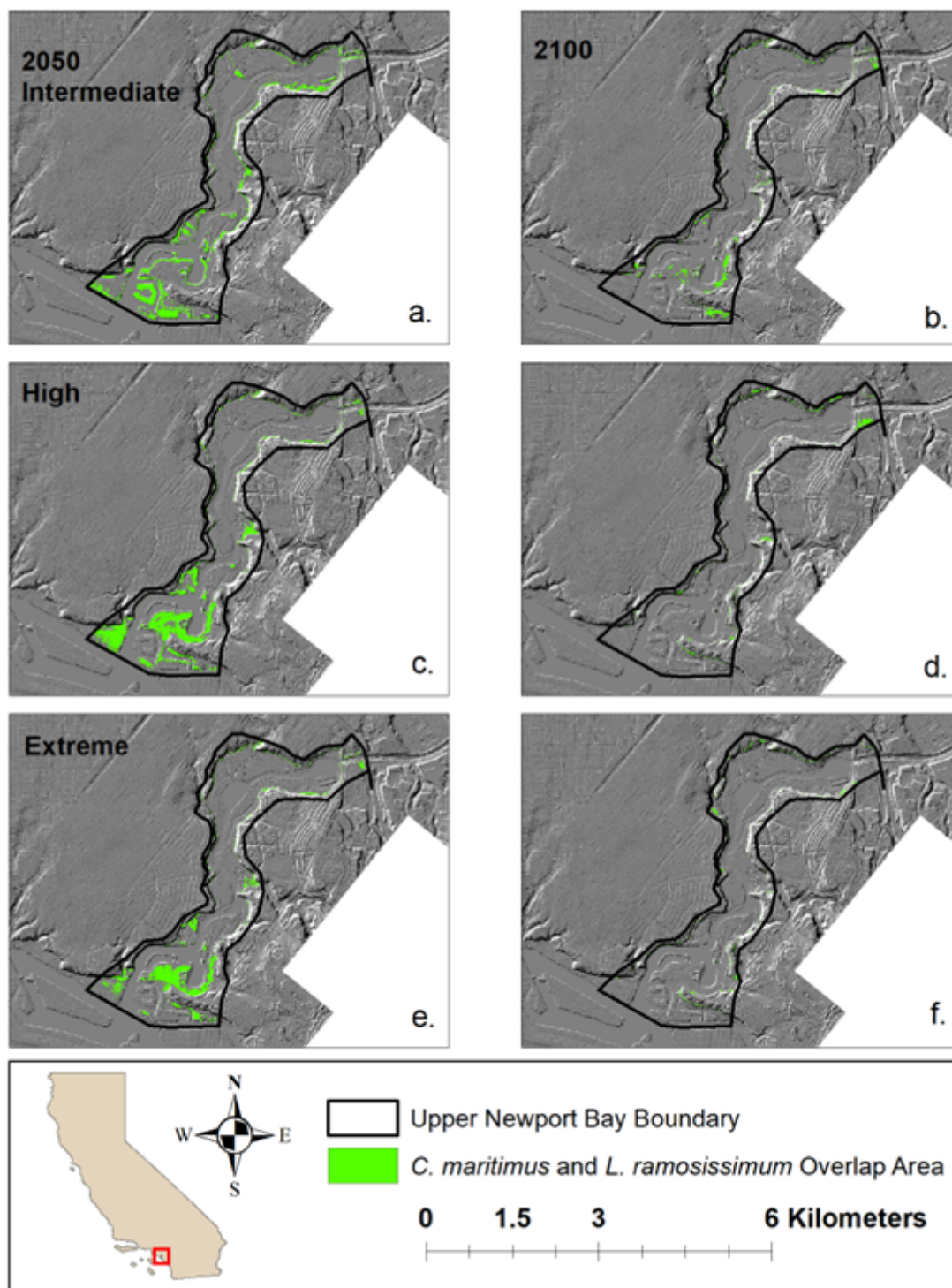


Figure 5

Projected overlap of *C. maritimus* and *L. ramosissimum* ranges for 2050 (a, c, e) and 2100 (b, d, f) in the Newport Bay Ecological Reserve for the Intermediate (a, b), High (c, d), and Extreme (e, f) sea level rise scenarios