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Coupled impacts of sea-level rise and tidal marsh restoration on endangered California clapper rail

Hua Zhang, Steven M. Gorelick *

Environmental Earth System Science, Stanford University, Stanford, CA 94305, United States

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ABSTRACT

We develop a predictive multi-process framework to quantitatively assess the spatially variable, interlinked dynamics of sea-level rise, wetland transition, habitat suitability and connectivity, and shorebird distribution and abundance. Bird behavior is represented in a spatially explicit agent-based model that tracks responses of individuals to predicted changes in local habitat quantity and quality. We apply this framework to the endangered California clapper rail (*Rallus longirostris obsoletus*) in the San Francisco Estuary, US, under a range of sea-level rise and conservation scenarios aimed at clapper rail recovery. The framework enables quantification of the relationship between critical habitat destruction and clapper rail population decline. The most influential factors that characterize the quality of tidal marsh habitat are salinity, which is a proxy for higher quality nesting environment and abundance of macroinvertebrates, and tidal conditions, which affect flood and predation threats. Results suggest that clapper rail viability should remain at the present level for moderate sea level rise. However, for a rise of 1.66 m, extinction risk increases from 0.01 to 0.36. The framework enables quantitative evaluation of proposed conservation efforts, and should complement existing theory and empirical inferences. Compared with sub-regional efforts, estuary-wide conservation is more effective in improving reproduction and dispersal success and accommodates a sea-level rise of an additional ~10 cm before population falls below criticality. Should sea level rise to the predicted maximum, proposed conservation efforts are likely to be ineffective in preventing California clapper rail extinction by 2100.

1. Introduction

Global warming is expected to accelerate the current rate of sea-level rise (SLR), inundating many low-lying coastal and intertidal areas (Galbraith et al., 2002; Jenouvrier, 2013). This could result in the loss and fragmentation of tidal marshes and pose a severe threat to the viability of many coastal wildlife species that depend on these wetlands as crucial habitats. This is particularly important for shorebird species with strong site fidelity, as they are more vulnerable to environmental changes due to their limited dispersal ability (Gardali et al., 2012). As the loss of these species could have significant effects on the biodiversity and service functions of coastal ecosystems, conservation of endangered shorebird species has become the primary goal of many coastal wetland restoration projects. There is a need to provide scientific support aimed at evaluating the impact of SLR on species loss and designing regional conservation and habitat restoration efforts.

* Corresponding author. Tel.: +1 650 725 2950; fax: +1 650 498 5099.
E-mail address: gorelick@stanford.edu (S.M. Gorelick).

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We present an interlinked multi-process framework that builds on studies exploring SLR-induced habitat change and its impact on shorebird populations. Iwamura et al. (2013) presented a clever global graph-theoretic approach to estimate migratory network vulnerability resulting from habitat loss due to SLR. Galbraith et al. (2002) demonstrated the use of a landscape model to project SLR-induced loss of tidal marsh habitat and the effects on shorebird population. Landmark works have developed a variety of key tools and insights: landscape and species distribution models were used to explore the gradual changes in habitat (Convertino et al., 2012b; Woodrey et al., 2012), the limits on breeding density (Brittain and Craft, 2012), and the effects of sediment availability and tide conditions on shorebird distribution and abundance (Veloz et al., 2013). In particular, recognizing that the exclusion of population dynamics may lead to under- or over-estimation of habitat quality (Heinrichs et al., 2010), species distribution models have been increasingly coupled with population models to bridge habitat change and population fluctuations. These works employ simplified single-population models (Nur et al., 2012; Nur and Sydeman, 1999) and complicated metapopulation simulation of multiple populations across complex landscapes (Aiello-Lammens et al., 2011; Convertino et al., 2013; Traill et al., 2011).

Although prior research has made substantial inroads into the study of SLR impacts on shorebird habitat and population change, significant challenges remain that we address here. First, past models do not reflect the influences of habitat quality on the processes of search, exploration and range establishment during dispersal (e.g., impacts of human-made barriers). Second, dispersal flux has only represented the average conditions for the entire population. It has not fully characterized uncertainty associated with the individual's choice at different dispersal stages. Third, previous studies focused on the deconstructive effects of SLR on shorebird habitat but did not consider the potential resilience of tidal marshes contributed by anthropogenic or natural factors. The potential impacts of regional wetland restoration under SLR are rarely taken into consideration. To our knowledge, only a few studies (Convertino et al., 2013; Veloz et al., 2013) quantitatively examined the effects of wetland restoration; but, it was not within those studies' purview to analyze population dynamics over a range of possible SLR rates or consider the implementation times and durations of restoration projects. Finally, in addition to increased inundation, SLR will also alter the hydraulic, chemical and biotic conditions of coastal ecosystems (Cloern and Jassby, 2012; Harley et al., 2006; Kirwan et al., 2010), and these factors have not been adequately modeled even though they can enhance or diminish shorebird habitat.

Despite over a decade of analysis, two simple questions remain: (1) What is the maximum sea-level rise under which shorebirds can survive? (2) How does sea-level rise affect the viability of shorebirds under various conservation schemes? Current approaches fail to systematically capture the complexity and uncertainty in the changing habitat-species relationship. What is needed is to characterize the chain of coupled changes in sea level, land cover, habitat, as well as shorebird distribution and demography in a dynamic and spatial manner. Therefore, our approach is to (1) quantify the structural and functional features of habitat connectivity and identify its role in population viability, (2) incorporate an agent-based model of bird behaviour, and (3) consider the effects of SLR, the uncertainty arising from the magnitude of SLR, and the potential impacts of restoration on shorebird population. Specifically, our multi-process framework integrates population viability analysis based on individual-based (agent-based) population modeling, considering wetland transition, species distribution, habitat suitability, and habitat connectivity to assess shorebird survival risk in response to SLR. We demonstrate the approach through a case study of the endangered California clapper rail (Rallus longirostris obsoletus, hereafter clapper rail) in the San Francisco Estuary, US (the Estuary).

2. Methods and materials

The framework to evaluate the effects of SLR consists of four interlinked process modules (Fig. 1 and Fig. S1): (i) the wetland transition module, which projects the change in wetland distribution under SLR, (ii) the habitat suitability module, which evaluates the quality of habitat based on predicted presence of species, (iii) the demography module, which analyzes population dynamics constructed from individual- (agent-) based simulation, and (iv) the connectivity module, which assesses the overall connectivity of the habitat system and identifies high-priorities for conservation. The modules are connected in a framework driven by multiple scenarios of SLR and wetland restoration. At annual time steps, module (i) and module (ii) together determine the quantity and quality of habitat available for the species. The behaviour of the species is then simulated by module (iii). Over the entire modeling period, module (iv) summarizes the connectivity between habitat units based on module (iii). Prior to predictions under SLR scenarios, the integrated model was tuned based on the observed distribution and trend of clapper rail population in 257 San Francisco Estuary marshes over 2008–2011.

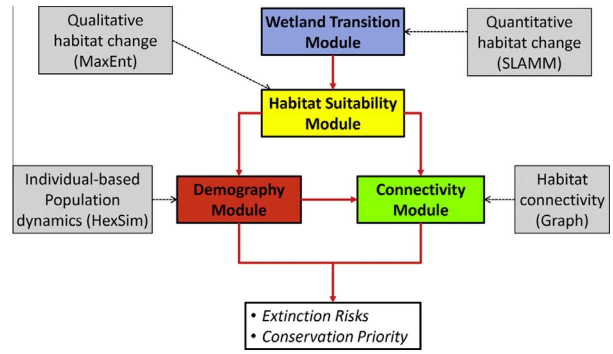

Fig. 1. Integrated model framework for evaluating the impacts of sea-level rise on shorebird habitat and population.

2.1. Study species and area

The clapper rail, a Federal- and State-listed endangered shorebird species, is an obligate salt marsh inhabitant, as tidal wetlands provide abundant macroinvertebrate food sources and necessary protection from predators. The preferred habitats are low marshes, below mean higher-high water, with well-developed tidal channels and abundant vegetation, such as Pacific cordgrass (*Spatina foliosa*) and pickleweed (*Salicornia virginica*) (Foin et al., 1997). Clapper rail are typically solitary and their home range is limited (Albertson, 1995; Overton, 2007). Historically abundant in the Estuary, present-day clapper rail struggle to survive in extremely fragmented salt marshes in contrast to others in the rail family (Foin et al., 1997; Schwarzbach et al., 2006). Detections are difficult, making estimates uncertain, but an estimate of clapper rail population for 2009–2011 was 1167 (Liu et al., 2012b), down from 1425 based on surveys from 2005 to 2008 (Liu et al., 2009). Recent work also suggests that the current population has declined to less than the 2005–2008 estimate; only 267–349 birds were detected in 2011 (Olofson Environmental Inc., 2011). Clapper rail recovery has been a major impetus for activities aimed at conserving and restoring tidal marshes across the Estuary.

We demonstrate the multi-process model analysis in the intertidal and subtidal portions of the San Francisco Estuary, consisting of Suisun Bay, San Pablo Bay and San Francisco Bay of 2112 km^2 containing 158 km^2 of tidal salt marshes and 541 km^2 of other wetland types (Fig. 2). Present-day Estuary tidal marshes have declined to ∼15% of historical (1850) area (Foin et al., 1997). There are 97 planned and ongoing tidal marsh restoration projects (Veloz et al., 2013) totalling 140 km^2. Our study is the first to quantitatively consider the potential effects of restoration on shorebird population changes.

2.2. Wetland transition module

The initial step in the procedure is to estimate the quantity and distribution of tidal marshes by representing geomorphological processes resulting in coastal wetland conversions and shoreline modifications during long-term SLR. This was accomplished using a deterministic simulation tool that has been widely employed to project wetland change in many coastal regions, the Sea Level Affecting Marshes Model (SLAMM) (Brittain and Craft, 2012; Chu-Agor et al., 2012; Clough et al., 2012). The Estuary was divided