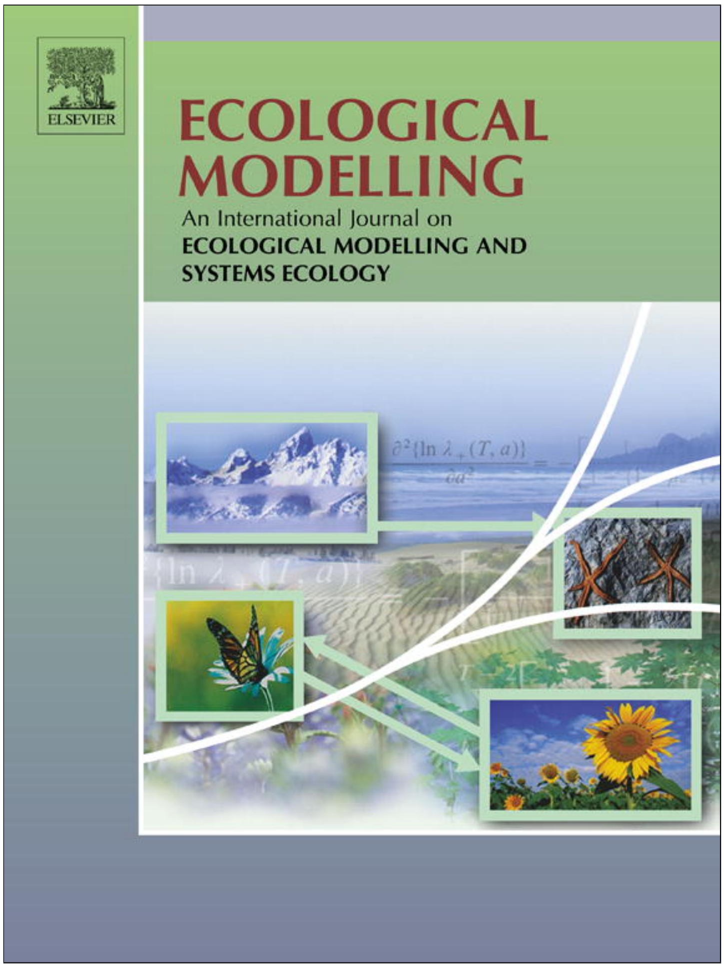
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# Decision analysis for species preservation under sea-level rise

Anna C. Linhoss[a,∗,1], Gregory A. Kiker[b,f], Matthew E. Aiello-Lammens[c], Ma. Librada Chu-Agor[d], Matteo Convertino[b], Rafael Muñoz-Carpena[b], Richard Fischer[e], Igor Linkov[e]

[a] Agricultural and Biological Engineering, Mississippi State University, Starkville, MS 39762, United States
[b] Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32611, United States
[c] Department of Ecology and Evolution, Stony Brook University, New York, NY 11794, United States
[d] Center of Environmental Sciences, Saint Louis University, St. Louis, MO 63103, United States
[e] Engineer Research and Development Center, US Army Corps of Engineers, Vicksburg, MS 69184, United States
[f] School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, South Africa

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ABSTRACT

Sea-level rise is expected to dramatically alter low-lying coastal and intertidal areas, which provide important habitat for shoreline-dependent species. The Snowy Plover (*Charadrius alexandrinus*) is a threatened shorebird that relies on Florida Gulf Coast sandy beaches for nesting and breeding. Selecting a management strategy for the conservation of this species under sea-level rise is a complex task that entails the consideration of multiple streams of information, stakeholder preferences, value judgments, and uncertainty. We use a spatially explicit linked modeling process that incorporates geomorphological (SLAMM), habitat (MaxEnt), and metapopulation (RAMAS GIS) models to simulate the effect of sea-level rise on Snowy Plover populations. We then apply multi-criteria decision analysis to identify preferred management strategies for the conservation of the species. Results show that nest exclosures are the most promising conservation strategy followed by predator management, species focused beach nourishment, and no action. Uncertainty in these results remains an important concern, and a better understanding of decision-maker preferences and the Snowy Plover's life history would improve the reliability of the results. This is an innovative method for planning for sea-level rise through pairing a linked modeling system with decision analysis to provide management focused results under an inherently uncertain future.

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## 1. Introduction

The effects of climate change and sea-level rise (SLR) on biodiversity are an issue of significant and widespread concern (Galbraith et al., 2002; Jetz et al., 2007; Menon et al., 2010; Sala et al., 2000). SLR is expected to dramatically alter low-lying coastal and intertidal areas that provide important habitat for a variety of shoreline-dependent species (Baker et al., 2006; Craft et al., 2009; Fish et al., 2005). Recent projections of habitat loss for shoreline-dependent birds at important staging and wintering coastal sites in the United States range between 20 and 70% (Galbraith et al., 2002). Florida has been identified as one of the states that is most vulnerable to climatic impacts (Clinton and Gore, 1993; National Assessment Synthesis Team, 2000; Noss, 2011). Shorebirds are especially susceptible to the effects of SLR in Florida because of the extensive coastline and low topography of the state. Sustaining the populations of species that depend on coastal habitats in the face of SLR requires that natural resource managers identify and implement ecosystem- and species-specific conservation measures.

Successful conservation plans require that natural resource managers sift through disparate types of information that have varying levels of importance to assorted stakeholders (Kiker et al., 2005). For example, when making a decision, a manager may have to consider budgetary constraints, public popularity, stakeholder values, and ecological tradeoffs. There are also many uncertainties with regard to the effects of SLR on natural resources to consider. First, the SLR predictions themselves are uncertain. Different projections for SLR by 2100 include 0.18–0.59 m (IPCC AR4 WG1, 2007),

*Abbreviations:* CI, confidence interval; DEM, digital elevation model; *F*, fecundity; *f*, number of fledglings; FWC, Fish and Wildlife Conservation; MaxEnt, maximum entropy; MCDA, multi-criteria decision analysis; $S_j$, juvenile survival rate; SLAMM, Sea Level Affecting Marshes Model; SLR, sea-level rise; SMAA, stochastic multi-criteria acceptability analysis; $\sigma$, standard deviation.

∗ Corresponding author at: 130 Creelman Street, Mississippi State University, Starkville, MS 39762, United States. Tel.: +1 662 325 1983; fax: +1 662 325 3853.
*E-mail address:* alinhoss@abe.msstate.edu (A.C. Linhoss).
[1] Formerly at Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32611, United States.

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0.62–0.88 m (Horton et al., 2008), 1.4 m (Vermeer and Rahmstorf, 2009), and up to 2 m (Allison et al., 2009; Pfeffer et al., 2008). These estimates are based on both historical and empirical methodologies and may incorporate or exclude the contribution from melting ice sheets. There are also uncertainties about how the natural environment will respond to the rise in sea level. Models and empirical relationships used to forecast the effects of SLR may simplify relationships, assume a steady state, and exist within data gaps and limitations. Finally, management strategies themselves may have uncertain consequences and cost–benefit tradeoffs. It is important to consider disparate types of information as well as their associated uncertainties to make robust management decisions. This process demands an organized and methodical toolset that can parse the often dissimilar and complex data within an adaptive management framework.

Multi-criteria decision analysis (MCDA) provides a systematic tool for identifying a preferred course of action when considering multiple forms of dissimilar information and differing value judgments among stakeholders (Kiker et al., 2005; Linkov et al., 2006). MCDA explores existing information and its relevance or limitations toward ranking potential management objectives. It provides a clear structure for decision-making in which management alternatives are identified, measures (or criteria) are established to evaluate the alternatives, and a decision matrix is developed to assess the alternatives according to the measures.

Management and conservation of threatened and endangered shoreline-dependent species in the face of SLR is particularly suited to the use of MCDA because of the diversity of stakeholders, information streams, and value judgments involved. In Florida, the effect of SLR on the Snowy Plover (*Charadrius nivosus*) is especially troublesome because of its threatened status, its dependence on shoreline habitat, and the habitat loss and increasing human disturbance currently occurring in areas for breeding and nesting, brood-rearing, wintering, and migratory stopover (Guilfoyle et al., 2006). Aiello-Lammens et al. (2011) used a linked modeling framework that integrates geomorphological, habitat, and metapopulation models to show that SLR will cause a decline in suitable habitat, carrying capacity, and populations for the Snowy Plover in Florida.

In response to the forecasts for SLR, resulting threats to beach habitat, and implications for the Snowy Plover, we assessed management alternatives for conservation of the species in Florida through MCDA. Specifically, the objectives of this research were to (1) use a linked modeling framework to assess Snowy Plover response to SLR, (2) define and simulate management alternatives for Snowy Plover protection, and (3) assess management alternatives within an MCDA framework using uncertain information. The decision methodology used here (1) defines the problem and objective, (2) identifies different management alternatives, (3) develops measures for assessing these alternatives, (4) assigns values and uncertainty to those measures under each alternative, (5) establishes a decision matrix for assessing alternatives using measures under specific goals, (6) evaluates a variety of weighting scenarios, and (7) synthesizes the results (after Kiker et al., 2008).

## 2. Methods

### 2.1. Study species and area

The Snowy Plover (*Charadrius alexandrinus*) is a small shorebird with populations throughout the temperate and subtropical regions of the world. The subspecies known as the Cuban Snowy Plover (*C. a. tenuirostris*) largely breeds and overwinters in Florida, where they rely on coastal sandy beaches for habitat (Lamonte et al., 2006). Males are responsible for chick-rearing, and females often produce two broods in one breeding season. The breeding season in Florida lasts from March to mid-summer. Breeding success for this population is dependent upon the availability of dune habitat as well as a lack of human development and disturbance (Lamonte et al., 2006). A loss of nesting habitat and widespread human disturbance, especially on coastal beaches used for recreation, has led to a decline in the population of the Snowy Plover on both the western and eastern US coasts (Lamonte et al., 2006; Colwell et al., 2005). The Florida Fish and Wildlife Conservation Commission (FWC, 2013) lists Snowy Plovers as threatened, and the US Shorebird Conservation Plan (2004) lists them as an Extremely High Priority for conservation.

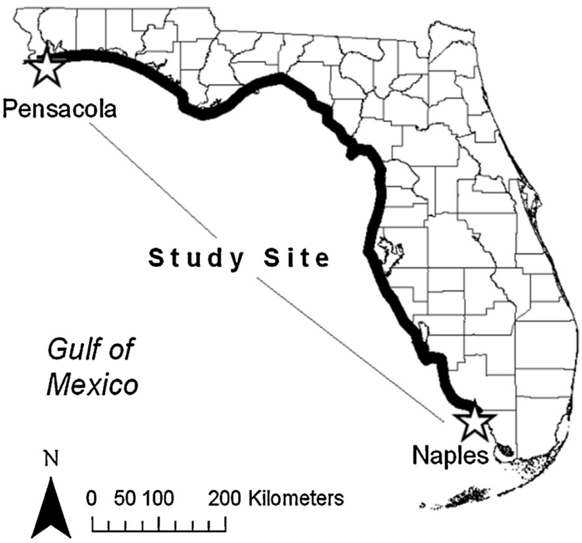


**Fig. 1.** Study site. The Florida Gulf Coast is marked in bold.

In Florida, Snowy Plovers are found along the Gulf Coast, mainly in the Panhandle and Peninsula (Aiello-Lammens et al., 2011). Therefore, the scale considered for this analysis is the Gulf Coast of Florida, including all of the populations of Snowy Plovers therein. Populations of plovers throughout the coast may mix and interbreed. Simulating connectivity captures a more realistic picture of the effects of management practices than focusing on single populations. The study area spans the Gulf Coast from Pensacola to Naples using a 10-km inland buffer and a 120-m grid resolution for simulations (Fig. 1) (Aiello-Lammens et al., 2011; Chu-Agor et al., 2012).

### 2.2. Linked modeling framework

A linked modeling framework has been previously established to simulate the response of the Snowy Plover to SLR in Florida (Aiello-Lammens et al., 2011; Chu-Agor et al., 2012). Within this framework, Sea Level Affecting Marshes Model (SLAMM; Warren Pinnacle Consulting, Inc.) simulates wetland migration, MaxEnt (Phillips et al., 2006; Phillips and Miroslav, 2008) simulates spatial habitat availability based on predicted spatial and temporal changes in wetland and shoreline habitats, and RAMAS GIS (Akçakaya, 2005) simulates Snowy Plover population changes based on the predicted habitat suitability maps. A detailed description of this linked modeling framework can be found in Aiello-Lammens et al. (2011) and Chu-Agor et al. (2012, 2013). We extend this framework to simulate the effects of management decisions on the Snowy Plover population under two SLR scenarios. For example, nourishment strategies aimed at augmenting beach habitat can be simulated in SLAMM, and nest exclosures aimed at reducing predator access to eggs and chicks can be simulated in RAMAS.

SLAMM was used to simulate the habitat shifts of beaches and wetlands under two SLR scenarios. SLAMM divides the spatial domain into independent cells and assigns land cover categories to each cell. Each land cover type is associated with environmental boundary conditions such as elevation, salinity, and proximity to open water. As sea-level rises, wetland land cover types are inundated and migrate inland according to the boundary conditions. SLAMM simulates annual SLR using curves from the Intergovernmental Panel on Climate Change 2007 Climate Change report (IPCC AR4 WG1, 2007), which are then scaled to the user-defined SLR levels. Results from SLAMM give annual land cover maps including coverage for wetland and beach habitat types within the study area. Detailed methodologies for the SLAMM simulations of the Gulf Coast of Florida are found in Chu-Agor et al. (2011, 2012, 2013).

Previous studies on SLAMM describe its advantages, most important inputs, investigate model uncertainty, and show the model to be competent in its simulations. Mcleod et al. (2010) evaluated a number of SLR models and stated that the advantages of SLAMM include its flexibility in scale and ability to portray the vulnerability of ecosystems and the effect of saltwater intrusion on habitats. Chu-Agor et al. (2011) performed a sensitivity analysis of SLAMM at a site in Florida and showed that approximately 90% of the variability in the outputs was attributed to the uncertainty in four inputs: vertical error, historic SLR, accretion, and sedimentation. Geselbracht et al. (2011) assessed the competence of SLAMM in depicting changes in wetland land cover due to SLR using a hindcast. They stated that "while the results of the SLAMM hindcast agree with field observations of the effects of SLR on the study area along the Gulf coast of Florida, SLAMM made some substantial adjustments to the initial conditions map." The authors go on to suggest that this may be due to the fact that habitats, which are at elevations already affected by historic SLR, may be in the process of transitioning.

Based on the results from SLAMM, the habitat suitability for Snowy Plovers along the Gulf Coast of Florida was modeled using MaxEnt (Phillips et al., 2006; Phillips and Miroslav, 2008). MaxEnt spatially simulates the probability distribution of species occurrence according to the principle of maximum entropy using environmental variables such as existing nest occurrences, land cover, and geology. Results from MaxEnt give annual habitat suitability maps for the study area. Detailed methodologies regarding the application of this model to the Snowy Plover in Florida are provided by Convertino et al. (2011a,b).

Based on the results from MaxEnt, a spatially explicit metapopulation model for the Florida Gulf Coast population of the Snowy Plover was developed using RAMAS GIS (Akçakaya, 2005). Inputs in RAMAS include age- and sex-structure, mating system, initial spatial metapopulation structure (including subpopulations), dispersal rate, survival rate, and fecundity. Ceiling type density dependence was assumed following the U.S. Fish and Wildlife Service Recovery Plan (2007). The results from RAMAS give annual maps of the distribution of Snowy Plover populations for the study area as well as carrying capacity and threat of extinction. The detailed methodology for these simulations has been summarized by Aiello-Lammens et al. (2011) and Chu-Agor et al. (2012).

### 2.3. MCDA

Decisions regarding climate change and environmental resources are inherently challenging and require coordination, consensus, and complementarity between people, their management processes, and their systems analysis tools. Multi-criteria decision analysis is useful for integrating heterogeneous and uncertain scientific information (e.g., monitoring data, simulation results, and cost) with management and stakeholder value judgments to compare alternatives. MCDA represents a collection of approaches for structuring the decision-making process to organize the vast array of information provided by site-specific sampling, simulation results, decision-maker intuition, environmental factors, and situation criticality (Linkov et al., 2006). In addition, a weighting structure can be developed to reflect priorities and interests of different stakeholder groups or those with an interest in the decision.

Stochastic multi-criteria decision analysis (SMAA) is a decision support methodology that stochastically explores uncertain measures (or criteria) to determine preferred alternatives for decision-makers (Lahdelma et al., 1998). SMAA uses utility functions to assign a value to the decision-maker's preference for each measure. One of the advantages of SMAA is that it can be used when the importance or weight of the measures is either known or unknown (Tervonen and Figueira, 2008). When weights are unknown, SMAA explores the entire weight space to find the preferences that make each alternative preferred. SMAA calculates the rank acceptability index, central weight vector, and confidence factor. The rank acceptability index describes the percentage of times that each alternative ranks as most preferred while considering the uncertainty in the measures and varying the weighting schemes when these are undefined. The central weight vector depicts the typical weights for each measure that make an alternative preferred. Interpreting central weights under ordinal weighting schemes is problematic and so for this analysis, the central weight results are only presented for the scenarios that are not assigned weights. The confidence factor is the probability that an alternative ranks first under the central weight vector and can be used to assess the reliability of the central weight vector and input data. SMAA-2 is an extension to SMAA whereby all ranks, not just the preferred rank, are explored (Lahdelma and Salminen, 2001; Tervonen, 2012). The rank acceptability in the SMAA-2 methodology calculates the probability that each alternative achieves each rank. We employ SMAA-2 here to provide a structural and quantitative approach for considering the range of issues germane to the Snowy Plover conservation problem/solution in a systematic, rational, and efficient manner.

The MCDA presented here uses the results from the linked modeling process (SLAMM, MaxEnt, RAMAS) as the basis for forecasted future conditions. The MCDA criteria structure is represented in Fig. 2 with greater detail provided in later sections. Here, the overarching goal is coastal protection, and a nested sub-goal is Snowy Plover protection. Including the sub-goal of Snowy Plover protection allows a decision-maker to examine alternatives based purely on the efficacy of the alternatives without regard to human interests. Measures used to assess goal performance include simulated beach area in 2100 (hectares), total cost (dollars), and public popularity (a simplified, unitless index) as well as simulated Snowy Plover carrying capacity (percent change from 2010), population decline (percent change from 2010), habitat suitability (hectares), and risk of terminal extinction by 2100 (probability). Alternative management strategies include no action, species-focused beach nourishment, nest exclosures, and predator management (discussed in more detail below).

#### 2.3.1. Incorporating uncertainty

Uncertainty is incorporated into this MCDA in 4 ways, including: (1) using probability distribution functions to describe measures, (2) varying the weighting schemes, (3) simulating multiple SLR scenarios, and (4) considering two goals. Probability distributions are assigned to each measure in order to describe the uncertainty in the models and the measurements. To address the uncertainty inherent in the weighting of the measures, we consider four

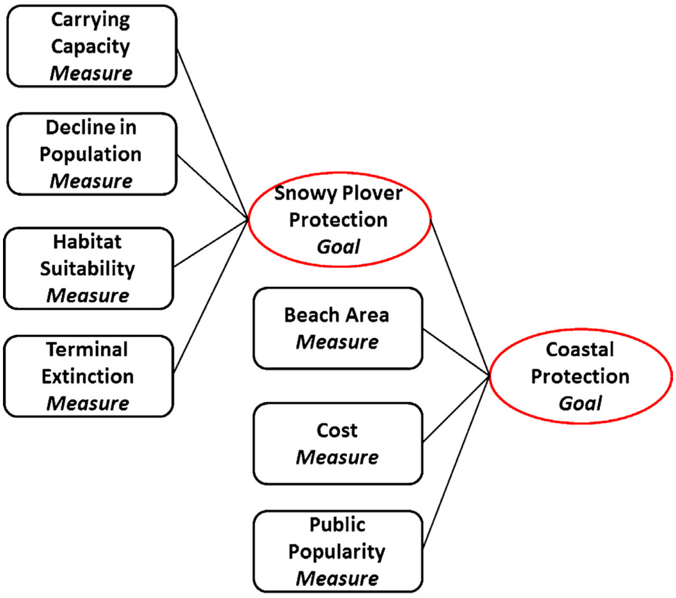


**Fig. 2.** Multi-criteria decision analysis structure. This structure is used to integrate linked model results under two strategic goals: an overarching goal concerning coastal protection and a sub-goal of Snowy Plover protection. Measures used to assess goal performance include simulated beach area in 2100 (hectares), total cost (dollars), and public popularity (a simplified, unitless index) as well as simulated Snowy Plover carrying capacity (percent change from 2010), population decline (percent change from 2010), habitat suitability (hectares), and risk of terminal extinction by 2100 (probability).

different weighting scenarios: bird-focused, human-focused, mixed, and missing weights. Two SLR scenarios (1- and 2-m SLR by 2100) were simulated as separate MCDA models to account for some of the additional uncertainty regarding future conditions. Two goals were assessed: overall coastal protection and a nested, sub goal of Snowy Plover protection. This results in a variety of comparable MCDA models and allows for the comparison of alternatives under a range of system representations.

*2.3.2. Species management alternatives*

Four alternatives are presented for the entire Florida Gulf Coast: no action, species-focused nourishment, nest exclosures, and predator management.

**No action**: In the no-action alternative, no beach nourishment activities were simulated, and demographic input values for RAMAS were based on the medium-level inputs (as opposed to low or high values) from the report by Aiello-Lammens et al. (2011) (Table 1). Currently, beach nourishment is being conducted in Florida on critically eroded beaches located in populated areas (FDEP, 2012). Because of the Snowy Plover preference for nesting in undeveloped beaches, this type of nourishment is not expected to impact the species population and was therefore not simulated.

**Species-focused nourishment**: Currently beach nourishment activities in Florida are generally located in populated areas and do not overlap with Snowy Plover nesting locations. To address the possibility of species protection as an objective of nourishment, a nourishment plan based on the location of the Snowy Plover nests

**Table 1**
Values for medium and maximum demographic inputs to the RAMAS model (Aiello-Lammens et al., 2011).

| Input | Medium | Maximum |
|---|---|---|
| Number of fledglings | 0.592 | 0.716 |
| Juvenile survival | 0.574 | 0.646 |
| Adult survival | 0.691 | 0.763 |

(Aiello-Lammens et al., 2011) was developed. Nourishment sites were designated in areas where more than one nest was found within a 2-km distance. This criterion is based on the assumption of similar geomorphic conditions within this range, and because nourishment based on the presence of a single, isolated nest is unrealistic. In this alternative, 161 km of total beach length was designated for nourishment. Nourishment was simulated in SLAMM by raising the beach elevation to 1-m throughout the nourished sites every 10 years until 2100 (Chu-Agor et al., 2012). SLAMM, MaxEnt, and RAMAS were run based on the revised nourishment maps to simulate the resulting impacts to the Snowy Plover population. In these simulations, nourishment activities were assumed to have no direct adverse effects on populations or subsequent nesting, and only increased the habitat area. As with the no-action alternative, RAMAS model demographic inputs are based on the medium-level inputs found in the report by Aiello-Lammens et al. (2011) (Table 1).

**Nest exclosures**: The third alternative involves simulating the use of nest exclosures to augment the fecundity of the Snowy Plover. Next exclosures are fences that are placed immediately around nests allowing the birds access but prevent predator access. Studies have indicated that the use of nest exclosures can increase nesting success (Colwell et al., 2008; Lauten et al., 2009). For example, Lauten et al. (2009) showed that exclosures increased the nesting success rate from 38 to 44% along the Oregon coast.

RAMAS simulates fecundity according to $F = f \times S_j$, where $F$ is fecundity, $f$ is the number of fledglings (here number of fledglings per male), and $S_j$ is the juvenile survival rate. To represent an increase in fecundity from the use of nest exclosures, $f$ was increased, and RAMAS was rerun. The value of $f$ used here to simulate nest exclosures is based on the high number of fledglings established by Aiello-Lammens et al. (2011) (0.716, Table 1). This input value was determined by Chu-Agor et al. (2012) to represent the potential for management to improve fecundity. No nourishment activities are simulated in this alternative.

**Predator/human management**: The fourth alternative involves simulating the management of predators, such as through lethal methods, and of humans, such as by limiting dog and human access to beaches. Studies have documented the impacts that humans have on the survival of Snowy Plover juveniles and adults. For example, Ruhlen et al. (2003) showed that at Point Reyes National Seashore, California, chick mortality was approximately 3 times higher on weekends and holidays than on weekdays. Colwell et al. (2008) also showed that the use of a symbolic fence in a highly trafficked area increased fledgling success from 15 to 37%. However, this increase in fledgling success was not seen consistently throughout all of their sites.

The predator management alternative was based on the ranges for adult survival established by Aiello-Lammens et al. (2011). The high value for adult survival (Table 1) was used to represent the potential for predator and human management to improve the survival of the Snowy Plover. As with the input value in the nest exclosure alternative, this value was determined by Chu-Agor et al. (2012) to represent the potential for management to improve Snowy Plover survival. RAMAS was simulated based on this input value. No nourishment activities are simulated in this alternative.

**Decision/performance measures**: Ecologic, economic, and social measures (or decision criteria) were used to judge the success of the management alternatives. These measures include beach area, cost, public popularity, carrying capacity, population decline, habitat suitability, and risk of extinction (Fig. 2).

**Cost**: The cost metric estimates the total cost of implementation per year for each alternative. The cost of the no-action alternative was set to $0.

Beach nourishment is currently being conducted in Florida in designated critical erosion areas, which generally occur in places of high development. The total cost for fiscal years 2012-2022 for

**Table 2**
Percent beach remaining in 2100: median and 5% and 95% confidence intervals (CIs).

| Alternative/scenario | 5% CI | Median | 95% CI |
|---|---|---|---|
| No action 1-m SLR | 56 | 87 | 118 |
| No action 2-m SLR | 38 | 69 | 100 |
| Nourishment 1-m SLR | 65 | 96 | 127 |
| Nourishment 2-m SLR | 50 | 81 | 112 |

beach nourishment along critical erosion areas in the Gulf Coast of Florida, as estimated by the Florida Beach Management Plan, is $413,035,800 (FDEP, 2012). This includes feasibility studies, design, construction, and monitoring. The total length of planned beach nourishment projects for the same time period is approximately 175 km. A simple linear ratio was used to relate the cost of nourishment for critical erosion areas to the cost of beach nourishment for Snowy Plover conservation. The Snowy Plover nourishment scenario proposes 161 km of beach nourishment based on areas where two or more nests are found within 2 km. Thus, a cost of $379,992,936 can be assumed for the Snowy Plover nourishment alternative. The range of uncertainty for this cost was set to −25 to +50% of the median cost at the 5% and 95% confidence intervals.

The cost of the nest exclosure and predator management alternatives was estimated according to the report by Hornaday et al. (2007), which estimates $149,946,000 for the cost of the recovery for the western Snowy Plover along the Pacific Coast by 2047. This plan includes a variety of conservation measures, including nest exclosures, predator management, and restricting beach access as well as additional techniques such as limiting military use, enhancing habitat, and monitoring. The estimates for the nest exclosure and predator management alternatives in this MCDA were each assumed to be half the annual cost of the Hornaday et al. (2007) study. Accordingly, the annual cost for the predator management and nest exclosure alternatives is $3,748,650. An uncertainty range to this cost of ±50% at the 5% and 95% confidence interval was assigned to the cost measures.

**Beach area**: The beach area measures describes the percentage of the beach remaining in 2100 (Table 2). Beach area is an important measure for humans, Snowy Plovers, and additional ecological functions. Results were obtained from the SLAMM simulations of 1- and 2-m SLR under the no-action and nourishment alternatives. A range of uncertainty was assigned to the percent beach area remaining based on the results of Chu-Agor et al. (2011), who conducted an uncertainty analysis of SLAMM along a 20-km stretch of Santa Rosa Island at the Eglin Air Force Base, Florida. These results indicated a median remaining beach area at 2100 of 95 ha. The variation in these results ranged between −10 and −100 ha with a normal distribution. From this, an uncertain bound was assigned for the beach area throughout the entire Gulf Coast at 2100 with a 95% confidence interval of ±31% of the median value of simulated beach area.

**Public popularity**: This measure is a simple index of public acceptance for each alternative. The scale ranges from 0.5 to 1.5 with no change in public perception set to 1, a negative perception as less than 1, and a positive perception as greater than 1 (Table 3). Nourishment was considered to be a positive alternative because of the added value of recreational beach. Nest exclosure was considered to have no impact on public perception. Predator management was considered negative because of potential restrictions to beach access and predator elimination strategies. These values are based on expert opinion. Though this is a very simple and rather arbitrary measure we felt it was important to include because of the importance of stakeholder input. As it is somewhat arbitrary, we provide an option for viewing results that do not include this measure through the Snowy Plover protection goal.

**Table 3**
Public popularity for each alternative.

| Alternative | Value |
|---|---|
| No action | 1.0 |
| Nourishment | 1.5 |
| Nest exclosure | 1.0 |
| Predator management | 0.5 |

**Table 4**
Hectares of suitable habitat (≥0.6) in 2100: median and 5% and 95% confidence intervals (CIs).

| Alternative/scenario | 5% CI | Median | 95% CI |
|---|---|---|---|
| No action 1-m SLR | 4893 | 7091 | 9289 |
| No action 2-m SLR | 4176 | 6052 | 7928 |
| Nourishment 1-m SLR | 5432 | 7873 | 10,314 |
| Nourishment 2-m SLR | 4954 | 7180 | 9406 |

**Table 5**
Percent carrying capacity remaining in 2100: median and 5% and 95% confidence intervals (CIs).

| Alternative/scenario | 5% CI | Median | 95% CI |
|---|---|---|---|
| No action 1-m SLR | 27 | 59 | 86 |
| No action 2-m SLR | 17 | 38 | 56 |
| Nourishment 1-m SLR | 31 | 69 | 99 |
| Nourishment 2-m SLR | 31 | 70 | 101 |

**Habitat suitability**: Habitat suitability was determined from the MaxEnt results. Results were obtained from the SLAMM/MaxEnt simulations of 1- and 2-m SLR under the no-action and nourishment alternatives. For this measure, cells throughout the study site with a habitat suitability index that indicates nesting habitats (greater than or equal to 0.6) were summed. Results are reported as the area of suitable habitat in 2100 (Table 4). Habitat suitability is closely related to beach area. Therefore, uncertain bounds for this measure was set using the same data and method described in the beach area measures and assigned a 95% CI of ±31% of the median value of habitat suitability.

**Carrying capacity**: In this study, carrying capacity is defined as the maximum number of individual Snowy Plovers that the study area can sustainably support. Carrying capacity was determined from the SLAMM/MaxEnt/RAMAS simulations of 1- and 2-m SLR under the no-action and nourishment alternatives. Results are reported as the percent carrying capacity remaining in 2100 (Table 5). Carrying capacity is closely related to beach area. Therefore, uncertain bounds for this measure was set using the same data and method described in the beach area measures and assigned a 95% confidence interval of ±31% of the median value of carrying capacity.

**Decline in population**: Decline in population was determined from the RAMAS results based on the SLAMM/MaxEnt/RAMAS simulations of 1- and 2-m SLR scenarios under the no-action, nourishment, predator management, and nest exclosure alternatives. Results are reported as the percent decline in population for the Gulf Coast between 2010 and 2100 (Table 6). Uncertain bounds

**Table 6**
Percent decline in population by 2100: median, −1 standard deviation ($-\sigma$), and +1 standard deviation ($+\sigma$).

| Alternative/scenario | $-\sigma$ | Median | $+\sigma$ |
|---|---|---|---|
| No action 1-m SLR | 78 | 90 | 101 |
| No action 2-m SLR | 86 | 93 | 99 |
| Nourishment 1-m SLR | 78 | 86 | 94 |
| Nourishment 2-m SLR | 79 | 85 | 92 |
| Nest exclosures 1-m SLR | 22 | 48 | 74 |
| Nest exclosures 2-m SLR | 59 | 71 | 83 |
| Predator management 1-m SLR | 21 | 47 | 72 |
| Predator management 2-m SLR | 59 | 71 | 83 |

**Table 7**
Percent risk of extinction in 2100: median, −1 standard deviation (−σ), and +1 standard deviation (+σ).

| Alternative/scenario | −σ | Median | +σ |
|---|---|---|---|
| No action 1-m SLR | 17 | 20 | 23 |
| No action 2-m SLR | 25 | 28 | 30 |
| Nourishment 1-m SLR | 13 | 16 | 19 |
| Nourishment 2-m SLR | 12 | 15 | 18 |
| Nest exclosures 1-m SLR | 0 | 0 | 3 |
| Nest exclosures 2-m SLR | 0 | 0 | 3 |
| Predator management 1-m SLR | 0 | 0 | 3 |
| Predator management 2-m SLR | 0 | 0 | 3 |

for this measure were set according to the stochastic set of runs produced in RAMAS, which are reported as ±1 standard deviation. This range is intended to represent the natural variability due to the stochastic nature of demographics, catastrophes, and temporal and spatial relationships and not the uncertainty of the model itself (RAMAS, 2012).

**Risk of extinction**: Risk of extinction was also determined from the RAMAS results. Results were obtained from SLAMM/MaxEnt/RAMAS simulations of 1- and 2-m SLR under the no-action, nourishment, predator management, and nest exclosure alternatives. Results are reported as the risk of terminal extinction after 90 years (from 2010 to 2100) (Table 7) (Aiello-Lammens et al., 2011). Uncertain bounds for the simulation scenarios were set according to the stochastic set of runs produced in RAMAS, which are reported with ±1 standard deviation. This range is intended to represent the natural variability due to the stochastic nature of demographics, catastrophes, and temporal and spatial relationships and not the uncertainty of the model itself (RAMAS, 2012).

**Weights for decision/performance measures**: We recognize that all of these measures may not be assigned the same level of importance by different stakeholders. To address this, four weighting schemes are investigated within the SMAA-2 framework under the coastal protection goal: bird-focused, human-focused, mixed, and missing weights (Table 8). The measures are ranked and weighed ordinally. The schemes are not intended to represent any particular stakeholder. Rather, these schemes are intended to allow the comparison of preferences across strategic weighting schemes to highlight areas of possible consensus and/or disagreement. In the absence of the human-focused measures (i.e., beach area, public popularity, and cost) the measures that fall under the Snowy Plover protection sub-goal are all assigned the same relative weights between the bird-focused, human-focused, and mixed schemes. Therefore, the Snowy Plover Protection sub-goal is assigned two weighting schemes: informed weights and missing weights.

**Table 8**
Ordinal weighting scheme for measures.

| Measure | Bird focused | Mixed | Human focused | Missing weights |
|---|---|---|---|---|
| Beach area | 7 | 6 | 4 | N/A |
| Cost | 2 | 2 | 1 | N/A |
| Public popularity | 6 | 4 | 3 | N/A |
| Carrying Capacity | 5 | 7 | 7 | N/A |
| Decline in population | 3 | 3 | 5 | N/A |
| Habitat suitability | 4 | 5 | 6 | N/A |
| Risk of extinction | 1 | 1 | 2 | N/A |

**Table 9**
Confidence factors.

| Measure | Coastal protection | | Snowy Plover protection | |
|---|---|---|---|---|
| | 1-m | 2-m | 1-m | 2-m |
| No action | 0.124 | 0.103 | 0.076 | 0.046 |
| Predator management | 0.380 | 0.347 | 0.487 | 0.459 |
| Exclosures | 0.635 | 0.598 | 0.498 | 0.460 |
| Nourishment | 0.311 | 0.562 | 0.217 | 0.523 |

## 3. Results and discussion

By inspecting the results in Table 9 we see that the confidence factors show that no action has a low probability of achieving the preferred rank under the central weight vector in both sea-level rise scenarios and under both goals. For this reason, the no action alternative can be rejected. The nourishment alternative has a higher confidence factor under the 2-m SLR scenarios than under the 1-m SLR scenarios. This is because nourishment did not take into account the percent loss of beach area or the potential inland movement of beaches; it only re-nourished the beaches to the original condition every 10 years. Finally, the exclosure alternative has the highest confidence interval in all but one case.

The rank acceptability index is computed for each SLR scenario and under each weighting scheme for the coastal protection goal (Fig. 3) and the Snowy Plover protection goal (Fig. 4). Under the coastal protection goal there is general consensus in assigning exclosures as the preferred alternative and predator management and the second-most preferred. Nourishment and no action follow with a less clear delineation of which ranks third and fourth depending on the weighting scheme and SLR scenario. This figure is important as it shows that it does not matter if you are a stakeholder who is human-focused or bird-focused or if SLR will be 1- or 2-m, in any case the exclosure alternative generally ranks first.

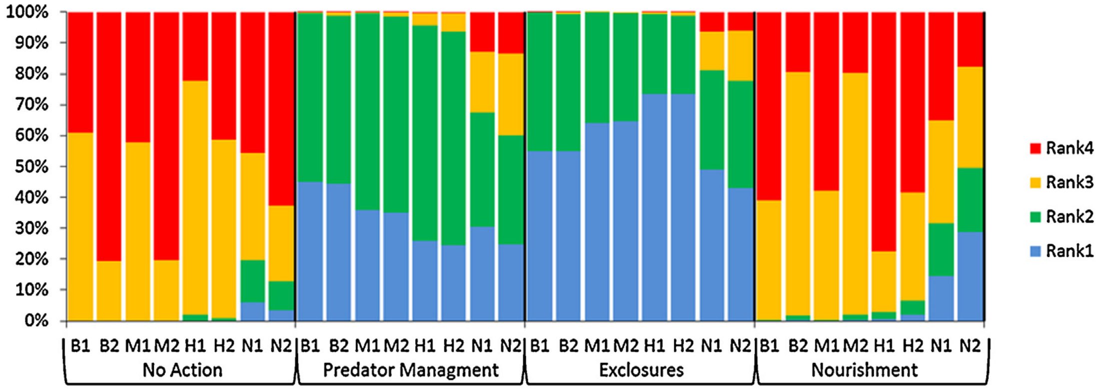


**Fig. 3.** Rank acceptability index for the coastal protection goal under 4 weighting schemes and 2 sea-level rise scenarios. *Abbreviations*: B = bird-focused weighting scheme; M = mixed weighting; H = human focused weighting; N = missing weights; 1 = 1-m sea-level rise by 2100; 2 = 2-m sea level rise by 2100.

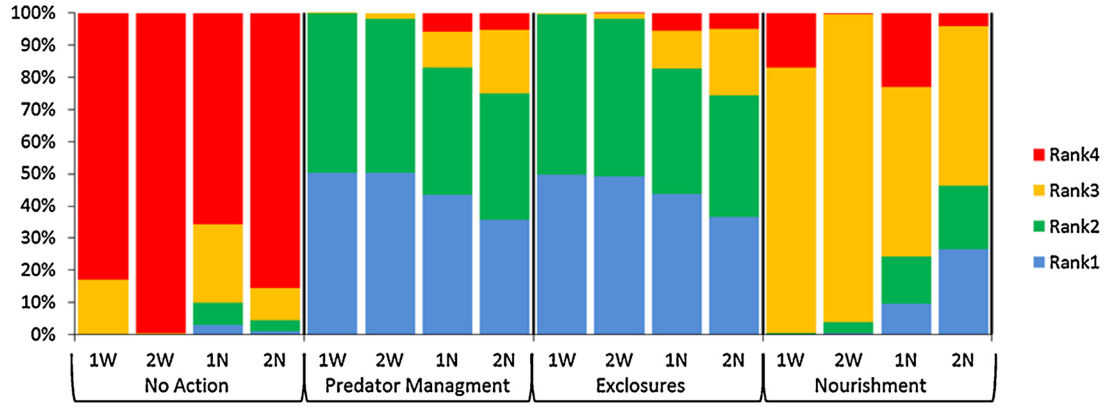


**Fig. 4.** Rank acceptability index for the Snowy Plover protection goal under 2 weighting schemes and 2 sea-level rise scenarios. *Abbreviations*: W = informed weighting scheme; N = missing weights; 1 = 1-m sea-level rise by 2100; 2 = 2-m sea level rise by 2100.

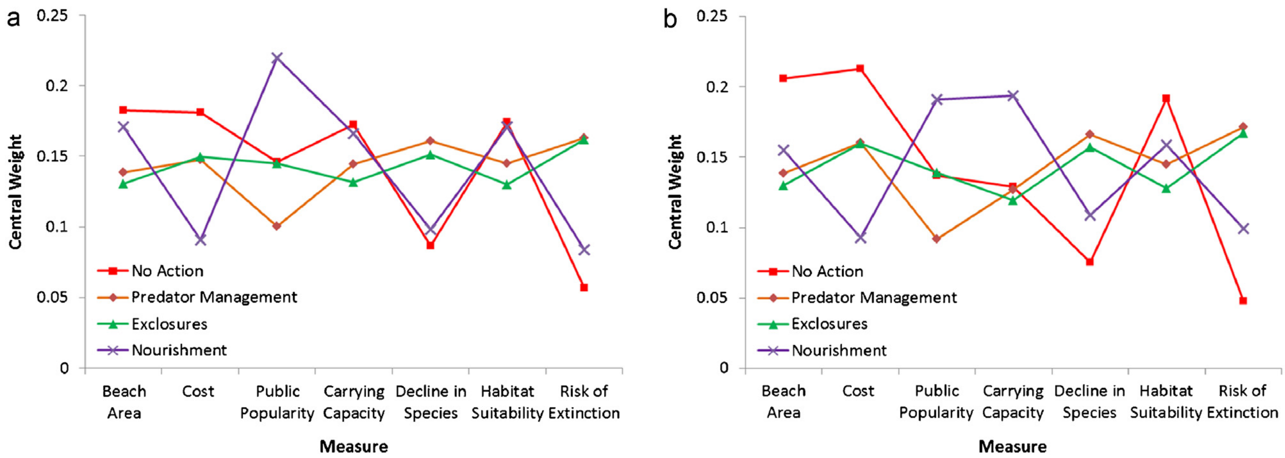


**Fig. 5.** Central weights for the coastal protection goal under (a) 1-m sea-level rise by 2100 and (b) 2-m sea-level rise by 2100.

The acceptability index for the Snowy Plover sub-goal shows that predator management and exclosures tie for ranking 1st followed by nourishment and no action (Fig. 5). This is because the exclosure and predator management simulations both have similar, strong impacts on the decline in population and risk of extinction measures. Nourishment had a less impact on these two measures though it did somewhat improve the habitat suitability and carrying capacity measures. The no action alternative did not have a positive effect on any of these measures, though the cost is low.

The central weight vectors show typical weights that make each alternative preferred under both the 1- and 2-m SLR scenarios for the coastal protection goal (Fig. 5). We do not show the central weights for the Snowy Plover protection goal because they are effectively included in the coastal protection goal. Under both SLR scenarios, the weights for the measures under the exclosure and predator management alternatives are distributed fairly evenly. The predator management alternative is given a slightly lower weight under the public popularity measure because this alternative is perceived as having a slightly negative public appeal. The nourishment and no action alternatives, on the other hand, show that unequal weighting is necessary for achieving the rank of the preferred alternative. Specifically, the central weight vectors show that in order for the nourishment and no action alternatives to be preferred, the decline in species and risk of extinction measures must have low relative weights. These two measures are integral to snowy plover conservation.

## 4. Conclusions

The work presented here offers a framework for decision-making regarding species preservation under SLR that is transferable across species and locations. The study incorporates results from two strategic goals, four management alternatives, four weighting schemes, and two SLR scenarios into a unified structure for exploring a variety of results within a management framework. We discuss conclusions from this analysis with respect to practical management implications, limitations, and future work. These results show that there is a general consensus in the ranking of the alternatives. Nest exclosures are generally the preferred alternative, with predator management following closely behind. Nourishment and no action rank third and fourth or tie depending upon the goal (Figs. 3 and 4); however, no action has a low confidence factor.

The quality of the input data imposes limitations on the reliability of model results. The results presented by Chu-Agor et al. (2011) showed that, in the SLAMM model, four input factors (DEM vertical error for the lower elevation range, historic trend of SLR, accretion, and sedimentation rates) controlled 88–91% of the output variance of SLAMM in predicting changes in the beach habitat of Eglin Air Force Base. Furthermore, Aiello-Lammens et al. (2011) found that the RAMAS model is most sensitive to survival rate and fecundity. A better understanding of the life history of the Snowy Plover is a key area where additional study will decrease the uncertainty in choosing a preferred alternative. Decreasing model uncertainty would restrict the probability distributions for the MCDA inputs, resulting in more reliable results. Stakeholder input into the MCDA weighting schemes and the public popularity measure would add further credibility to the results.

Any model makes generalizations and assumptions regarding how a system functions, which leads to limitations in applicability. It is important to highlight these limitations to assure that the study is applied appropriately. It is well documented that Snowy Plovers prefer habitats in undeveloped areas (Colwell et al., 2005; Lamonte et al., 2006). In the SLAMM/MaxEnt runs, developed areas were masked out of the analysis. This strategy was taken in SLAMM to preserve the developed areas and not allow them to convert to wetlands. As a result, in this simulation, MaxEnt is not able to represent the proximity of development as criteria for habitat suitability. Additionally, in SLAMM, all existing developed areas are maintained at current levels because future development is unknown. These limitations should be considered when applying conclusions from this work to areas that are near or in developed areas. Specifically, nourishment, nest exclosure, and predator management plans should consider the proximity of developed areas.

Nest exclosures and predator management ranked very similarly between all of the measures. The largest difference between the two alternatives was that predator management scored lower in the public popularity measure. Colwell et al. (2008) indicated that overall, the use of exclosures may actually increase the mortality of fledglings because the same predators also prey on chicks after they leave the exclosures. Hypothetically, this would decrease the utility of the nest exclosure alternative. However, due to a lack of quantitative data, the survival of juveniles was kept constant in both the nest exclosure and predator management alternatives in this modeling effort. A decision between the implementation of nest exclosures or predator management should involve additional work to understand the public perception of these strategies and the effects of nest exclosures on fledgling mortality.

The effect of nourishment on Snowy Plovers remains unclear. It is likely that there is not a direct relationship between habitat availability and Snowy Plover population size. Assumptions and limitations of how nourishment affects Snowy Plovers can be found in reports by Convertino et al. (2011c) and Lott (2009). For example, a negative correlation was found by Lott (2009) between beach nourishment and Snowy Plover populations. Additionally, nourishment can have detrimental effects on food-web structures (de la Huz and Lastra, 2008; Greene, 2002; Guilfoyle et al., 2006; Menn, 2002). Nourishment plans should take into consideration the ecological and habitat requirements of a species, such as the timing of a nourishment project and the microhabitats designed within the nourishment project.

This MCDA showed that a no-action approach to Snowy Plover conservation is generally the least desirable management strategy and nest exclosures is the most preferred management strategy. Currently, on the US west coast, nest exclosures are the primary technique for Snowy Plover conservation (Colwell et al., 2008). The results and conclusions presented here give managers specific preferred alternatives for protecting shorebird threatened, endangered, and at-risk species in the face of SLR and habitat loss.

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