Global Change Biology

Global Change Biology (2012) **18**, 3536–3542, doi: 10.1111/gcb.12024

Impacts of a half century of sea-level rise and development on an endangered mammal

JASON A. SCHMIDT*, ROBERT MCCLEERY†, JENNIFER R. SEAVEY†, SUSAN E. CAMERON DEVITT† and PAIGE M. SCHMIDT‡

Department of Wildlife and Fisheries Sciences, Texas A&M University, College Station, TX 77843, USA, †Department of Wildlife Ecology and Conservation, University of Florida, 314 Newins-Ziegler Hall, PO Box 110430, Gainesville, FL 32611, USA, ‡Division of Biological Sciences, United States Fish and Wildlife Service, National Wildlife Refuge System, Tulsa, OK 74129, USA

Abstract

The extraordinary growth of human populations and development in coastal areas over the last half century has eliminated and degraded coastal habitats and threatened the persistence of associated wildlife. Moreover, human-induced sea-level rise (SLR) is projected to further eliminate and alter the same coastal ecosystems, especially low-lying regions. Whereas habitat loss and wildlife population declines from development are well documented, contemporary SLR has not yet been implicated in declines of coastal faunal populations. In addition, the projection of severe synergistic impacts from the combination of development and SLR is well described, yet the scientific literature offers little empirical evidence of the influence of these forces on coastal wildlife. Analysis of aerial photographs from 1959 to 2006 provided evidence of a 64% net loss of the endangered Lower Keys marsh rabbit's (*Sylvilagus palustris hefneri*; LKMR) habitat, the majority due to SLR (>48%). Furthermore, there was a strong negative relationship between the proportion of development per island and the amount of new habitat formed. Islands with modest development (less than 8% of land area) saw formation of new areas of marsh vegetation suitable for rabbits, whereas islands with 8% or more of their lands developed between 1959 and 2006 saw little to no addition of LKMR habitat. Only 8% of habitat loss was directly due to conversion to impervious surfaces, indicating that the greatest threats from development were indirect, including blocking of the inland migration of habitat triggered by SLR. Our results were consistent with an ongoing squeeze of coastal ecosystems between rising seas and development as a threat to LKMR habitat, which raises concern for a wide variety of coastal species. Our results provide evidence that SLR has become a contemporary conservation concern, one that is exacerbated by development, and expected to increase in magnitude as ocean waters continue to rise.

Keywords: coastal development, coastal squeeze, endangered species, Lower Keys marsh rabbit, sea-level rise

Received 25 January 2012 and accepted 29 August 2012

Introduction

Worldwide, coastal ecosystems and species are threatened by human activities (Brown *et al*., 2002). Accelerated population growth and development of coastal areas over the last five decades have caused major conservation challenges for wildlife due to the loss and deterioration of their habitats (Flather *et al*., 1998; Pilkey & Cooper, 2004). In addition, human-induced sea-level rise (SLR) is projected to be a major conservation problem for coastal regions that will worsen over time (Ross *et al*., 1994; Williams *et al*., 1999; Nicholls & Cazenave, 2010; Maschinski *et al*., 2011). In the second half of the last century, worldwide sea levels rose at a rate of 1.7 ± 0.3 mm/yr (Church & White, 2006) through the early 1990s when the rate increased to 3.3 ± 0.4 mm/yr (Ablain *et al*., 2009; Nicholls & Cazenave, 2010).

Correspondence: Robert A. McCleery, tel. + 352 846 0566, fax + 352 392 6984, e-mail: ramccleery@ufl.edu

Sea-level rise has been associated with the loss of wetland habitats, changes in coastal plant communities (Penland & Ramsey, 1990; Warren & Niering, 1993; Ross *et al*., 1994; Williams *et al*., 1999), marine invertebrates (Seavey *et al*., 2011), and bird habitat (Erwin *et al*., 2010). Habitat loss is predicted to be particularly high among low-lying coastal systems because of their vulnerability to SLR (Farbotko, 2010; Maschinski *et al*., 2011). The loss of coastal lands will escalate extinction risks for associated wildlife species, especially those species already experiencing population declines due to other factors (Daniels *et al*., 1993; Markham, 1996; Pimm, 2008).

Coastlines are dynamic, and habitats frequently shift in response to sea level, erosion, and sedimentation (Davidson-Arnott, 2010). It is conceivable that as sea levels change, fauna will simply follow their preferred habitats as they move across the landscape. However, in many regions, coastal development may aggravate the threat from SLR by inhibiting inland migration of habitats as ocean levels rise (Zhang *et al.*, 2004; Feagin *et al.*, 2005; FitzGerald *et al.*, 2008). As a result, development squeezes ecosystems between the ocean and hardened surfaces such as walls, jetties, roads, and buildings (French, 2001). Therefore, when habitat is lost to rising sea levels, it will not be replaced elsewhere, resulting in a net loss of habitat for coastal species (Feagin *et al.*, 2005). This 'coastal squeeze' is predicted to significantly exacerbate the effects of SLR (Feagin *et al.*, 2005).

Changes in sea levels have not yet been implicated in the declines of coastal faunal populations during the last century. In addition, we have found no empirical evidence of the effects of development and SLR interacting to threaten coastal fauna. Here, we present evidence of the synergistic impacts from rising sea level and coastal development on population decline in an endangered mammal, the Lower Keys marsh rabbit (*Sylvilagus palustris hefneri*; LKMR). The Lower Florida Keys are composed of the islands at the end of a low-lying archipelago extending 338 km off the SW coast of Florida. This region experienced explosive growth in human populations and development on upland habitats from 1970 to 2000 with an almost 10-fold increase in human populations on some of the larger islands (Lopez *et al.*, 2004). Furthermore, sea levels in the region have risen at a rate of 2.4 cm per decade from 1913 to 1990 (Ross *et al.*, 1992), and more recently at a rate of over 3 cm per decade (Mitchum, 2011).

The LKMR is endemic to and was once common throughout the Lower Florida Keys (de Pourtales, 1877; Forys & Humphrey, 1999), but has been declining since at least the 1960s (Forys & Humphrey, 1999; Schmidt *et al.*, 2011). The decline and subsequent designation of the LKMR as a federally endangered species have been attributed to the loss and degradation of suitable habitat by human development (Brown, 1997). Development of the LKMR's habitat was halted in the early 1980s, but since then the population has declined by approximately 50% (Gallagher, 1991; Lopez *et al.*, 2004; Schmidt *et al.*, 2011). As of 2005, LKMRs were likely limited to 13 Islands, where they inhabited transitional vegetative communities between mangroves and upland forests (hammocks and pinelands), as well as low-lying patches of freshwater wetlands found within upland habitats (Faulhaber *et al.*, 2007). Due to LKMR's use of low-lying areas, SLR has been projected to be a serious threat to population persistence (LaFever *et al.*, 2007). This threat has been heightened due to the lack of inland migration of coastal ecosystems in this region resulting from slow rates of sediment deposition, and human development (Morris *et al.*, 2002; LaFever *et al.*, 2007).

To understand the role of SLR and human development on the contemporary decline in the LKMR, we compared LKMR habitat, evident in aerial photography, over a 47-year period from 1959 to 2006. We hypothesized that (1) SLR had a substantial impact on LKMR habitat independent of development, and (2) human development limited the ability of vegetative communities associated with the LKMR to migrate upslope in response to SLR.

Materials and methods

Study area

The LKMR historically occurred throughout the Lower Florida Keys, beginning at No Name Key and terminating with the Island of Key West (Fig. 1). Our study included islands within the bounds of LKMR's current range (considerably reduced from the historic range) that had complete aerial photography cover from 1959 and 2006. Islands under study included: Big Coppitt, Big Pine, Boca Chica, Cudjoe, Geiger, Little Torch, Lower Sugarloaf, Middle Torch, No Name, Ramrod, Saddlebunch, Shark, Sugarloaf, and Summerland Keys. Annete, Big Torch, and Howe Keys were excluded from the study because of incomplete aerial photography.

In the low-lying Florida Keys (mostly below 2 m), minute elevation changes radically influence the vegetative communities (Ross *et al.*, 1992) leading to considerable heterogeneity of vegetative communities across the islands (Ross *et al.*, 1994). The LKMR uses several of these discrete vegetative communities, including: freshwater wetlands, brackish marshes, beach berms, and saltmarsh–buttonwood (*Conocarpus erectus*) transitional zones (Faulhaber *et al.*, 2007). Saltmarsh–buttonwood transitional zone occurs between approximately 20 and 80 cm above mean sea level, and can be roughly classified into three subzones from lowest to highest: intertidal marsh, grassy

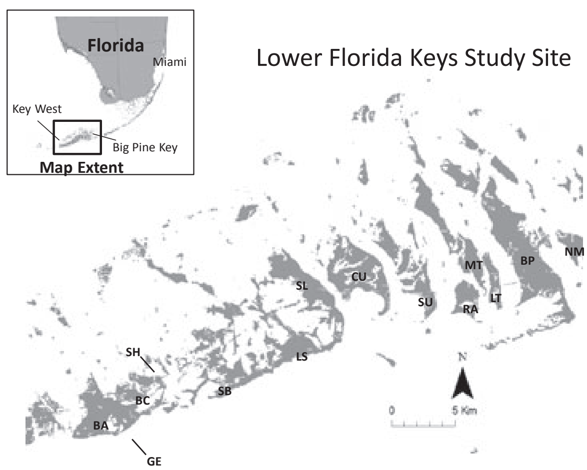

Fig. 1 Lower Florida Keys study area showing distribution of Islands, Lower Florida Keys, USA. The acronyms for each island correspond to those in Table 1.

saltmarsh, and buttonwood transitional (McNeese & Taylor, 1998). These transition zones are bordered by mangroves at elevations below 20 cm, and forested habitat, such as hammocks and pine uplands at elevations above 80 cm (Fig. 2; Ross *et al.*, 1994). In addition, freshwater wetlands occur in low-lying areas where the water table is close to the surface, or in depressions that collect precipitation (Ross *et al.*, 1992). Coastal beach berm vegetation is composed of trees, shrubs, and xerophytic plants growing on accumulations of wind-driven material situated parallel to coastlines (Florida Natural Areas Inventory [FNAI], 2010).

Habitat delineation

To delineate patches of LKMR habitat (occupied and potential) from 1959, we first obtained approximately 300 individual panchromatic black-and-white aerial photographs of the Lower Florida Keys from 24 February 1959 from the Florida Department of Transportation (0.3 m resolution). Using ArcMap 9.3 (Environmental Systems Research Institute [ESRI], 2009) we geometrically corrected the images using image-to-image registration (Jensen, 2005). Then we georeferenced the resulting images and created a single 1959 image using a distance-weighted mosaicing that assigned cell values based on the distance from the pixel to the edge (Jensen, 2005). To delineate LKMR habitat from 2006, we obtained processed aerial photographs from the Monroe County GIS Department collected between the dates of 5 February 2006 and 8 March 2006. These images were 3-band true color images with a spatial resolution of 0.15 m. Using the images from 1959 to 2006, we hand-digitized binary land cover maps at a 1 : 2000 m resolution creating vector files delineating patches of LKMR habitat and nonhabitat. We found the black-and-white imagery from 1959 had sufficient spectral range to delineate target habitat types (Fig. 2). Delineated habitat included transition zones, brackish marsh, freshwater wetlands, and coastal beach berms preferred by LKMR (Faulhaber *et al.*, 2007) that could be digitized to a 0.1 ha minimum mapping unit.

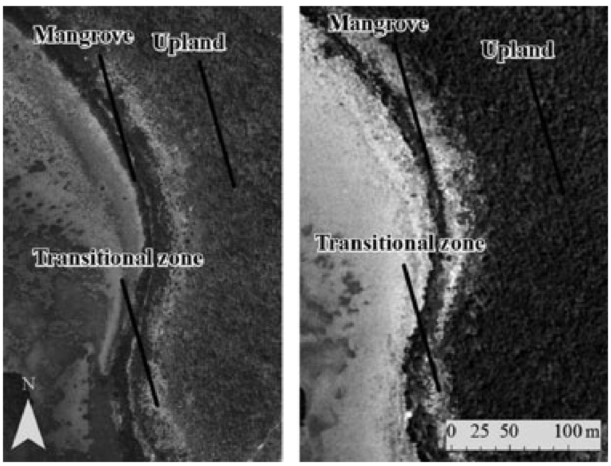

Fig. 2 Classification of major vegetative communities (mangrove, transitional zone, and uplands) in the lower Florida Keys, Florida, USA, from 1959 to 2006 aerial photography.

Habitat accuracy assessment

We assessed the accuracy of the 2006 habitat classification with ground-truthed GPS points during January–April 2008. We sampled systematically every 30 m throughout the study area in and around areas of known LKMR use, we classified locations where we observed LKMR fecal pellets as 'habitat' and locations with impervious surfaces, water, or dominated by vegetative communities not known to support LKMRs (i.e., mangrove, hardwood hammock) as 'non-habitat'. To assess the accuracy of our classification, we calculated omission and commission errors (Jensen, 2005). In addition, we calculated the kappa coefficient (κ_{hat}) to determine if our habitat classification was statistically better than random (Rosenfield & Fitzpatrick-Lins, 1986; Congalton, 1991). Our measures of accuracy for omission errors of habitat and nonhabitat were 98.9% and 90.8%, respectively, and our measures of accuracy for commission errors for habitat and nonhabitat were 98.6% and 92.2%, respectively. The overall accuracy of the 2006 classification was 97.8% and the κ_{hat} coefficient was 0.90, representing very strong agreement between our habitat classification and ground truthing (Landis & Koch, 1977). Although we were unable to ground truth the 1959 classification; we believe the error of the 1959 classification is comparable with the 2006 error rate because of the high accuracy of identifying habitat and nonhabitat (Fig. 2).

Delineation of development

We used impervious surfaces and canals added from 1959 to 2006 as a measure of human development (Arnold & Gibbons, 1996; McKinney, 2002). To calculate impervious areas in 2006 photography we employed Feature Analyst for ArcGIS ver. 4.2 (Visual Learning Systems, 2009). We converted the resulting impermeable surface raster files into vector polygons for further analysis. In addition, we hand digitized all canals (vector polygons) that were absent in 1959 but present in 2006.

Delineation of SLR

Accurate, high-resolution elevation data from the beginning of the study period is not available. Thus, to determine the extent to which SLR had reduced LKMR habitats, we focused on the spatial location of mangrove communities because they form the seaward boundary of potential LKMR habitat. In the Florida Keys, mangrove communities are not considered primary habitat for LKMRs (Ross *et al.*, 1994; Forys & Humphrey, 1999; Faulhaber *et al.*, 2007). As ocean levels rise, mangrove communities are projected to migrate upslope into areas occupied by other vegetative communities that cannot tolerate the increasingly saline environment (Kathiresan & Bingham, 2001). We visually inspected the elevation of mangrove communities by overlaying LiDAR (light detection and ranging) data collected from January to February 2008 (Gesch *et al.*, 2002) onto the 2006 aerial photography. Although the

2-year difference between available aerial photography and high-resolution elevation data is not ideal, we assumed that the elevational changes during this period were negligible relative to the overall study length. We found mangroves occurred up to at least 20 cm above mean sea level, and therefore, set 20 cm as a conservative cut off for LKMR habitat lost to SLR. We intersected the 20 cm contour with 1959 LKMR habitat, to generate a vector file with all LKMR habitat below 20 cm, representing the area of LKMR habitat lost to SLR.

Habitat change metrics

We calculated a number of metrics to determine changes in LKMR habitat over the study period, per island and for the entire study area. First, we calculated the total area of habitat lost between 1959 and 2006 by calculating the area of LKMR habitat at both times and subtracting the area of the 2006 habitat from the area of habitat in 1959. To calculate how much habitat from 1959 was lost to development, we overlaid the 2006 human development layer on the 1959 habitat patches and calculated the area of intersection. To estimate the amount of LKMR habitat lost to SLR, we calculated the area of 1959 habitat that was below 20 cm mean sea level based using the 2008 LiDAR data. After subtracting the habitat lost from development and SLR from the total amount of habitat lost, we considered the remaining area to be lost from other factors not directly attributable to either SLR or development. We calculated the area of new LKMR habitat added since 1959 by overlaying 2006 habitat patches onto 1959 patches and identifying areas of habitat present in 2006 but not present in 1959. Finally, we calculated the percentage of net habitat lost in 2006 by dividing the amount of habitat lost plus any habitat that was added, by the total area of habitat in 1959. All of our spatial calculations were completed using ArcMap ver. 9.3 and the geoprocessing extension (ESRI, 2009).

Statistical analysis

Without a time series of historical aerial photographs to directly observe the movement of habitats in relation to development, we chose to test our hypothesis that development limits inland habitat migration under SLR by correlating the area of development and the creation of new LKMR habitat over the study period 1959–2006. We fitted both linear and logistic regressions to the relationship between the percent of the island developed (new areas developed between 1959 and 2006 and total development in 2006) and the proportion of new LKMR habitat added relative to habitat lost between 1959 and 2006. To determine if there was a relationship between habitat lost to other factors and development on each Island, we correlated the proportion of development on each island from 1959 to 2006 to the proportion of habitat lost to other factors over the same period.

Results

Over the 47-year period from 1959 to 2006, 1266 ha of LKMR habitat were lost, whereas 416 ha of LKMR habitat were created (Table 1). This amounted to a net loss of 64% of LKMR habitat. Considering all LKMR habitat in 1959 (1603 ha), the loss of habitat had three sources: 765 ha (48%) by SLR, 123 ha (8%) by development, and 378 ha (24%) by other factors (Fig. 3a, b, c). The area of habitat present per Island in 1959 ranged from 9.6 to 393.3 ha, and in 2006 the area of habitat ranged from 0.0 to 288.0 ha. Big Pine Key held most of the LKMR habitat, containing 24.5% of all habitat in 1959 and 22.7% in 2006.

The area of impervious surfaces in the study area almost doubled from 1959 (552 ha) to 2006 (1039.2 ha). Nevertheless, on all but one island (Shark Island), SLR

Table 1 Loss [development, sea-level rise (SLR), other cause] and addition of LKMR habitat (ha) from 1959 to 2006

		Source of habitat lost					
Island name	1959 Habitat	Development	SLR	Other	Total	Habitat added	% Net loss
Big Coppitt (BC)	10.6	2.3	3.7	2.9	8.9	1.3	72
Big Pine (BP)	393.3	19.7	168.2	100.1	288	135.6	39
Boca Chica (BA)	189.7	6.7	76.3	38.2	121.2	96.2	13
Cudjoe (CU)	137.7	32.4	36.3	47.8	116.5	12	76
Geiger (GE)	39.0	10.8	15.1	8.6	34.5	6.6	72
Little Torch (LT)	58.5	8.5	27.9	15.2	51.6	8.7	73
Lower Sugarloaf (LS)	151.7	9.8	68.5	34.3	112.6	48.4	42
Middle Torch (MT)	56.9	1.9	33.6	16.3	51.8	11.8	70
No Name (NM)	73.4	4.0	41.5	10.8	56.3	24.5	43
Ramrod (RA)	47.0	9.1	19.3	17.7	46.1	5.6	86
Saddlebunch (SB)	201.7	3.4	138.4	24.9	166.7	39.3	63
Shark (SH)	9.6	4.3	1.8	3.5	9.6	0	100
Sugarloaf (SL)	107.2	5.0	61.6	29.6	96.2	22.5	69
Summerland (SU)	126.2	4.8	73.1	28.1	106	3.8	81
Total	1602.6	122.7	765.3	378	1266.0	416.3	64

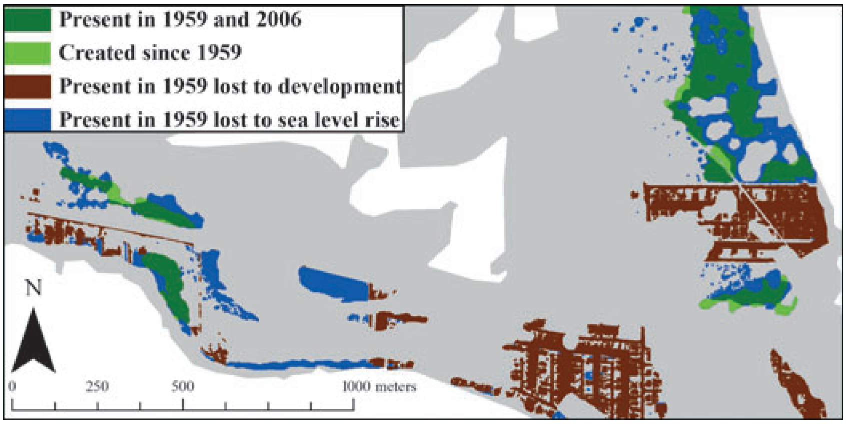

Fig. 3 A portion of the study area showing Lower Keys marsh rabbit habitat on Cudjoe Key that was, present in 1959 and 2006, created since 1959, present in 1959 and lost to development, and present in 1959 and lost to sea level rise.

accounted for more direct loss of habitat than development. There was a highly significant, negative curvilinear relationship between the proportion of the island developed between 1959 and 2006 and proportion of new habitat added ($F = 32.4$, $P < 0.01$, $R^2 = 0.73$; Fig. 4). There was also a highly significant, negative curvilinear relationship between the total proportion of development and proportion of new habitat added ($F = 14.4$, $P < 0.01$, $R^2 = 0.54$). The linear relationship between development between 1959 and 2006 and the proportion of new habitat added were also negative but not as strong ($F = 4.64$, $P = 0.05$, $R^2 = 0.28$). There was not a significant linear relationship between total proportion of an Island developed and the proportion of new habitat added ($F = 1.49$, $P < 0.20$, $R^2 = 0.14$). Islands with modest development (less than 8% of land area between 1959 and 2006) had new areas of habitat added (Fig. 3d), whereas islands with 8% or more of lands development between 1959 and 2006 saw little to no addition of LKMR habitat (Table 1). In addition, there was a strong, positive linear relationship between the proportion of an island that was developed from 1959 to 2006 and the proportion of LKMR habitat lost to other unknown factors ($F = 26.9$, $P < 0.01$, $R^2 = 0.69$).

Discussion

The LKMR is in a precarious position given the planet's changing climate; their use of lowing-lying marshes on Islands with human development make them highly susceptible to negative impacts from rising seas. Examining the loss of LKMR habitat over the last half century, it is clear that SLR was the largest driver of habitat loss. The direct loss of habitat from development appears marginal compared to 48% loss of LKMR habitat directly due to SLR.

It is possible that an 8% loss of LKMR habitat was an underestimation of the impacts of development. We found a strong correlation between development and the loss of habitat from unexplained factors. This indicates that there may be some indirect effects of human development impacting LKMR habitat. Our analysis considered impervious surfaces only and we did not account for areas where vegetative cover has been altered in association with development. It is also likely that some of the unexplained habitat loss was due to brush encroachment of marshes caused by suppression of fire, an indirect result of development and human populations (Schmidt *et al.*, 2010). In addition, this study did not account for degradation of habitat from the effects of fragmentation, fire suppression, and alien and invasive species that have accompanied

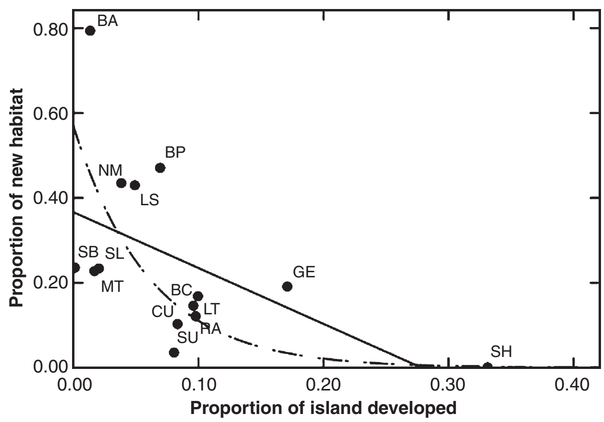

Fig. 4 New Lower Keys marsh rabbit habitat created as a proportion of habitat lost on 14 Islands (circle symbol labeled with island abbreviations, see Table 1) in the Lower Florida Keys from 1959 to 2006 as a function of the portion of the island developed during the same time frame. Both linear (solid line) and logistic (dashed line) regressions are displayed.

development (Forys & Humphrey, 1999; Schmidt *et al.*, 2010).

There is little doubt that population growth and development in Florida Keys has taken a toll on endemic mammals such as the LKMR (Humphrey, 1992; Forys & Humphrey, 1999), but possibly the greatest threats from development were from the indirect loss of habitat. Our study clearly illustrates how coastal development can magnify the negative effects of SLR on wildlife habitat. Our results were consistent with the predictions of coastal squeeze: we found a strong negative correlation between the amount of development on an islands and the amount of new LKMR habitat created. The only islands with significant additions of new habitat were those with less than 8% development. Islands with a greater proportion of development saw little to no addition of LKMR habitat during the 47 years of this study.

Our study makes clear that contemporary SLR is not a new problem for the conservation of coastal wildlife, rather one that has been acting for the last several decades and is projected to get worse. As our climate continues to change, it will create further challenges for the conservation of species in the Florida Keys (Maschinski *et al.*, 2011) and in low-lying coastal areas worldwide. Although development may not be the greatest threat to the persistence of coastal wildlife, mitigation or limitation of its impacts may be the most plausible option, given the small spatial and temporal scales where the management of endangered species occurs. In our study, we found the creation of new LKMR habitats on islands with minimal development, and it was clear from fecal pellet surveys that the newly created expanses of habitat were in fact used by LKMRs (Fig. 3d). Thus, our results suggest that the impacts of SLR could likely be reduced by limiting development and creating conditions that allow for the creation of new habitat.

Two broad strategies should be considered for the LKMR and other coastal wildlife facing SLR. First, management actions should focus on decreasing coastal squeeze by facilitating inland habitat migration. In areas with significant human development, this will likely involve potentially costly, but highly effective choices, such as purchasing private property and restoring degraded areas to promote ecosystem connectivity. Second, management actions should aim to improve the general health of coastal ecosystems by reducing other negative anthropogenic impacts. For the LKMR and other endemic species in the Florida Keys these actions may include invasive species control and increased prescribed fires. Some actions may be politically challenging, but strong human intervention is needed to ameliorate the ongoing and future impacts of rising seas.

Acknowledgments

Financial support for this project was provided by The University of Florida Institute of Food and Agricultural Sciences and Texas A&M University Agrilife. J. R. S. acknowledges support from U.S. Federal Stimulus Funds provided by American Recovery and Reinvestment Act. We thank M. P. Moulton and two anonymous reviewers for comments on previous versions of this manuscript, N. J. Silvy and R. A. Feagin for technical and conceptual advice, and R. E. Loughridge, D. L. Gallant. J. Ivy, and A. J. Dedrickson for help with the collection of field data.

References

Ablain M, Cazenave A, Valladeau G, Guinehut S (2009) A new assessment of the error budget of global mean sea level rate estimated by satellite altimetry over 1993–2008. *Ocean Science*, **5**, 193–201.

Arnold CL, Gibbons CJ (1996) Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American Planning Association*, **62**, 243–258.

Brown LN (1997) *Mammals of Florida*. Windward Publishing Co., Miami, FL.

Brown K, Tompkins EL, Adger WN (2002) *Making Waves Integrating Coastal Conservation and Development*. Earthscan, London.

Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, **33**, L01602.

Congalton RG (1991) A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, **37**, 35–46.

Daniels RC, White TW, Chapman KK (1993) Sea-level rise: destruction of threatened and endangered species habitat in South Carolina. *Environmental Management*, **17**, 373–385.

Davidson-Arnott R (2010) *Introduction To Coastal Processes and Geomorphology*. Cambridge University Press, New York.

Environmental Systems Research Institute [ESRI] (2009) *ArcMap 9.3*. Environmental Systems Research Institute, Redlands, CA.

Erwin R, Brinker D, Watts B, Costanzo G, Morton D (2010) Islands at bay: rising seas, eroding islands, and waterbird habitat loss in Chesapeake Bay (USA). *Journal of Coastal Conservation*, **15**, 51–60.

Farbotko C (2010) Wishful sinking: disappearing islands, climate refugees and cosmopolitan experimentation. *Asia Pacific Viewpoint*, **51**, 47–60.

Faulhaber CA, Perry ND, Silvy NJ, Lopez RR, Frank PA, Hughes PT, Peterson MJ (2007) Updated distribution of the Lower Keys Marsh rabbit. *Journal of Wildlife Management*, **71**, 208–212.

Feagin RA, Sherman DJ, Grant WE (2005) Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Frontiers in Ecology and the Environment*, **3**, 359–364.

FitzGerald DM, Fenster MS, Argow BA, Buynevich IA (2008) Coastal impacts due to sea-level rise. *Annual Review of Earth Planetary Science*, **36**, 601–647.

Flather CH, Knowles MS, Kendall IA (1998) Threatened and endangered species geography. *BioScience*, **48**, 365–376.

Florida Natural Areas Inventory [FNAI] (2010) *Guide to the Natural Communities of Florida: 2010 Edition*. Florida Natural Areas Inventory, Tallahassee, FL.

Forys EA, Humphrey SR (1999) Use of population viability analysis to evaluate management options for the endangered Lower Keys Marsh rabbit. *Journal of Wildlife Management*, **63**, 251–260.

French PW (2001) *Coastal Defenses: Processes, Problems, and Solutions*. Routledge, New York.

Gallagher D (1991) Impact of the built environment on the natural environment. In: *Monroe County Environmental Story* (ed Gato J), pp. 226–229. Monroe County Environmental Education Task Force, Big Pine Key, FL.

Gesch D, Oimoen M, Greenlee S, Nelson C, Steuck M, Tyler D (2002) The national elevation dataset. *Photogrammetric Engineering and Remote Sensing*, **68**, 5–11.

Humphrey SR, ed. (1992) *Rare and Endangered Biota of Florida. Vol. I. Mammals*. University Press of Florida, Gainesville, FL.

Jensen JR (2005) *Introductory Digital Image Processing: A Remote Sensing Perspective* (3rd edn). Pearson Prentice Hall, Upper Saddle River NJ.

Kathiresan K, Bingham BL (2001) Biology of mangroves and mangrove ecosystems. *Advances in Marine Biology*, **40**, 81–251.

LaFever D, Lopez R, Feagin, R, Silvy N (2007) Predicting the impacts of future sea-level rise on an endangered lagomorph. *Environmental Management*, **40**, 430–437.

Landis J, Koch G (1977) The measurement of observer agreement for categorical data. *Biometrics*, **33**, 159–174.

Lopez RR, Silvy NJ, Wilkins RN, Frank PA, Peterson MJ, Peterson MN (2004) Habitat-use patterns of Florida key deer: implications of urban development. *Journal of Wildlife Management*, **68**, 900–908.

Markham A (1996) Potential impacts of climate change on ecosystems: a review of implications for policymakers and conservation biologists. *Climate Research*, **6**, 179–191.

Maschinski J, Ross M, Liu H, O'Brien J, von Wettberg E, Haskins K (2011) Sinking ships: conservation options for endemic taxa threatened by sea level rise. *Climatic Change*, **107**, 147–167.

McKinney ML (2002) Urbanization, biodiversity, and conservation. *BioScience*, **52**, 883–890.

McNeese PL, Taylor JG (1998) *Florida Keys Advance Identification of Wetlands (ADID) Project Technical Summary Document, Final Draft*. Lewis Environmental Services, Marathon, FL.

Mitchum GT (2011) *Sea Level Changes in the Southeastern United States: Past, Present, and Future*. Florida Climate Institute/Southeast Climate Consortium, 2011. Available at: http://floridaclimateinstitute.org/images/reports/201108mitchum_sealevel.pdf (accessed 12 October 2011).

Morris JT, Sundareshwar PV, Nietch CT, Kjerfve B, Cahoon DR (2002) Responses of coastal wetlands to rising sea level. *Ecology*, **83**, 2869–2877.

Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. *Science*, **328**, 1517–1520.

Penland S, Ramsey KE (1990) Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908–1988. *Journal of Coastal Research*, **6**, 323–342.

Pilkey OH, Cooper JAG (2004) Society and sea level rise. *Science*, **303**, 1781–1782.

Pimm SL (2008) Biodiversity: climate change or habitat loss – which will kill more species? *Current Biology*, **18**, 117–119.

de Pourtales LF (1877) Hints on the origin of the flora and fauna of the Florida Keys. *American Naturalist*, **11**, 137–144.

Rosenfield GH, Fitzpatrick-Lins K (1986) A coefficient of agreement as a measure of thematic classification accuracy. *Photogrammetric Engineering and Remote Sensing*, **52**, 223–227.

Ross MS, O'Brien JJ, Flynn LJ (1992) Ecological site classification of Florida Keys terrestrial habitats. *Biotropica*, **24**, 488–502.

Ross MS, O'Brien JJ, Sternberg LDS (1994) Sea-level rise and the reduction in pine forests in the Florida Keys. *Ecological Applications*, **4**, 144–156.

Schmidt PM, McCleery RA, Lopez RR, Silvy NJ, Schmidt JA (2010) Habitat succession, hardwood encroachment and raccoons as limiting factors for Lower Keys marsh rabbits. *Biological Conservation*, **143**, 2703–2710.

Schmidt JA, McCleery RA, Schmidt PM, Silvy NJ, Lopez RR (2011) Population estimation and monitoring of an endangered lagomorph. *Journal of Wildlife Management*, **75**, 151–158.

Seavey JR, Pine WE, Frederick P, Sturmer L, Berringan M (2011) Decadal changes in oyster reefs in the Big Bend of Florida's Gulf Coast. *Ecosphere*, **2**, 1–4. article 114.

Visual Learning Systems (2009) *Feature Analyst ver. 4.2 for ArcGIS*. Visual Learning Systems, Missoula, MT.

Warren RS, Niering WA (1993) Vegetation change on a Northeast Tidal Marsh: interaction of sea-level rise and marsh accretion. *Ecology*, **74**, 96–103.

Williams K, Ewel KC, Stumpf RP, Putz FE, Workman TW (1999) Sealevel rise and coastal forest retreat on the west coast of Florida, USA. *Ecology*, **80**, 2045–2063.

Zhang K, Douglas BC, Leatherman SP (2004) Global warming and coastal erosion. *Climatic Change*, **64**, 41–58.