

Predicting the Impacts of Future Sea-Level Rise on an Endangered Lagomorph

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Received: 14 June 2006 / Accepted: 22 February 2007
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Abstract Human-induced global climate change presents a unique and difficult challenge to the conservation of biodiversity. Despite increasing attention on global climate change, few studies have assessed the projected impacts of sea-level rise to threatened and endangered species. Therefore, we estimated the impacts of rising sea levels on the endangered Lower Keys marsh rabbit (*Sylvilagus palustris hefneri*) across its geographic distribution under scenarios of current conditions, low (0.3-m), medium (0.6-m), and high (0.9-m) sea-level rise. We also investigated the impacts of allowing vegetation to migrate upslope and not allowing migration and of two land-use planning decisions (protection and abandonment of human-dominated areas). Not surprisingly, under all simulations we found a general trend of decreasing total potential LKMR habitat with increasing sea-level rise. Not allowing migration and protecting human-dominated areas both tended to decrease potential LKMR habitat compared with allowing migration and abandoning human-dominated areas. In conclusion, conservation strategies at multiple scales need to be implemented in order to reduce the impact of global climate change on biodiversity and endangered species. At the regional level, managers must consider land-use planning needs that take into account the needs of both humans and biodiversity. Finally, at the local

scale those agencies that are in charge of endangered species conservation and ecosystem management need to rethink static approaches to conservation or else stand by and watch ecosystems degrade and species go extinct. This can be accomplished by bioclimatic reserve systems where climatically underrepresented areas are included in conservation planning along with the standard concerns of threat, opportunity, connectivity, and viability.

Keywords Climate change · Lagomorph · Land use planning · Lower Keys marsh rabbit · Sea-level rise · *Sylvilagus palustris hefneri*

Introduction

Human-induced global climate change presents a unique and difficult challenge to the conservation of biodiversity. Global mean surface temperatures have increased 0.6°C since the late 19th century (IPCC, 2001) and an estimated 41% of wild species have responded to recent climate change, with 74%–91% of these species responding in accordance with climate change predictions (Parmesan and Yohe, 2003). Observed biological responses include range expansion (Parmesan, 1996; Parmesan et al., 1999; Thomas and Lennon, 1999), elevation shifts (Grabherr et al., 1994; Pounds et al., 1999), and changing disease dynamics (Pounds et al., 2006).

Sea-level rise, due to oceanic thermal expansion, melting ice caps/glaciers, and other phenomena, undoubtedly will have many impacts on small islands and coastal lowlands including increased likelihood of coastal flooding, salinization of freshwater wetlands and water tables, and coastal land loss (Fish et al., 2005; IPCC, 2001). Titus and Richman (2001) mapped out coastal areas vulnerable to sea-level rise (i.e., those lying below 1.5 m in elevation)

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along the United States Atlantic and Gulf coasts and found approximately 58,000 km² of land lying below 1.5 m, which is within some estimates of sea-level rise by 2100. These estimates include an increase of 0.31–1.50 m (Daniels et al., 1993), 0.18–0.30 m (Meehl et al., 2005), and 0.09–0.88 m (IPCC, 2001) by the year 2100. Impacts on coastal wetlands (Lee et al., 1992; Michener et al., 1997; Moorhead and Brinson, 1995; Simas et al., 2001), coastal erosion (Feagin et al., 2005; Leatherman et al., 2000), and forests (Ross et al., 1994; Williams et al., 1999) have been assessed, but few studies have evaluated the impacts to threatened and endangered species (for exceptions see Daniels et al., 1993; Fish et al., 2005; Shriver and Gibbs, 2004). Because of the lack of studies on endangered species, we assessed the impact of predicted sea-level rise on the endangered Lower Keys marsh rabbit (*Sylvilagus palustris hefneri*) by estimating changes in its habitat due to projected sea level change.

The Lower Keys marsh rabbit (LKMR) was listed as a federally endangered species by the United States Fish and Wildlife Service (USFWS) in 1990 (USFWS, 1990). Historically, the LKMR occurred on all the Lower Keys surveyed, but rapid development from the 1970s to the present has resulted in a decline of LKMR populations (Forys and Humphrey, 1999a). Over the last 20 years, more than half of the suitable LKMR habitat in the Lower Keys has been lost due to human activities (USFWS, 1999). The USFWS (1999) cited habitat loss and fragmentation caused by development as the primary reasons for the subspecies' decline. Other potential threats to LKMRs include mortality caused by feral cats (*Felis catus*) and raccoons (*Procyon lotor*) (Forys and Humphrey, 1996; Howe, 1988). However, there is no mention of the potential impact of sea level rise on this island endemic (USFWS, 1999). Because its entire distribution occurs on low-lying islands, it is a good candidate for investigating the impact of sea-level rise on an endangered species.

The uncertainties associated with any prediction should be understood in order to make sound management decisions. Uncertainties include the methods used for data collection, selection of data to be used in the model, threshold selection, variability inherent in natural systems, and many others. Alternative approaches exist, including risk assessment and continuum modeling. One approach to risk assessment is to construct a probability distribution for a single outcome (e.g., Titus and Narayanan, 1996). A second approach is to calculate critical thresholds where the probability of exceedence about a given threshold is calculated and identified as a hazard (Pittock and Jones, 2000). Finally, continuum modeling uses a DEM and projections of sea-level rise to make predictions of available areas for vegetation types (e.g., the Spatially Explicit Landscape Vegetation Analysis model developed by

T. Doyle of the United States Geologic Survey). In our case, data limitations precluded the use of the above approaches and thus we used a discrete category approach to predicting the impacts of future sea level rise on the Lower Keys marsh rabbit. It is important for managers to understand the uncertainties inherent in making predictions in order to make sound management decisions.

Methods

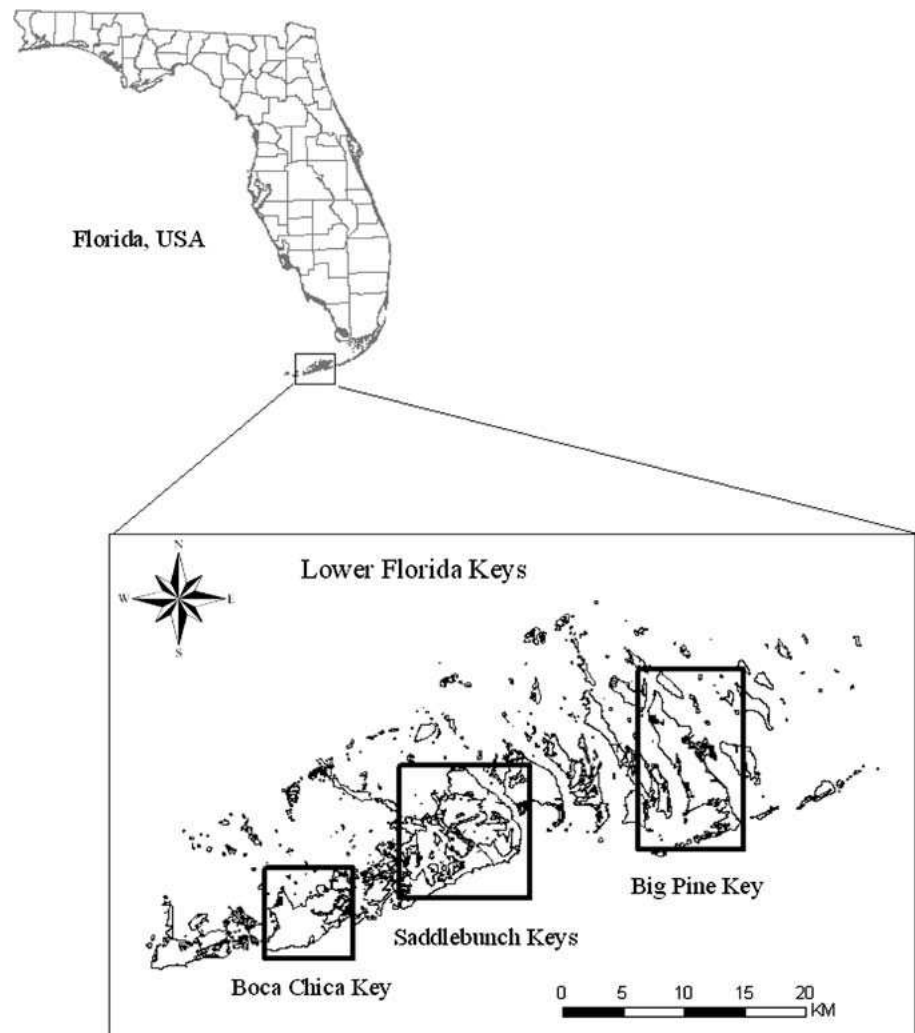
Study Area

The Lower Keys form the terminal portion of an archipelago of islands extending south and west from the mainland of Florida (Fig. 1) and exhibit a subtropical climate due to the Gulf Stream and other maritime influences (Chen and Gerber, 1990; Forys and Humphrey, 1999b). There are distinct wet and dry seasons, with the dry season (November through April) contributing less than one-third of annual precipitation (Forys and Humphrey, 1999a). LKMRs occupy saltmarsh/buttonwood transition zones dominated by salt-tolerant grasses and shrubs including seashore dropseed (*Sporobolus virginicus*), sea daisy (*Borrichia frutescens*), gulf cord grass (*Spartina spartinae*), marsh hay cord grass (*Spartina patens*), and salt-marsh fringe-rush (*Fimbristylis castanea*), often with an open canopy of buttonwood trees (*Conocarpus erectus*), and freshwater marshes (Faulhaber, 2003). Due to alteration of habitat, saltmarshes of the Lower Keys exist as highly fragmented mosaics of patches (Forys and Humphrey, 1999b), and the LKMR now exists as three separate metapopulations (Fig. 1) on (1) Big Pine, (2) Saddlebunch/Sugarloaf Keys (hereafter, the Saddlebunch Keys), and (3) Boca Chica Key (Forys and Humphrey, 1999a). A distribution survey by Faulhaber (2003) found there to be 42 patches of habitat encompassing 284 ha on Big Pine Key, 50 patches encompassing 135 ha on Boca Chica (and neighboring East Rockland and Geiger Keys), and 51 patches totaling 135 ha on the Saddlebunch Keys. Current population estimates range from 100 to 300 individuals across the LKMR distribution (USFWS, 1999).

Sea-Level Rise Impacts

We estimated the proportion of each vegetation type within each of four elevation categories in ArcGIS (v. 9.1; ESRI, Redlands, CA) using a United States Geological Survey (USGS) digital elevation model (DEM; with 30-m horizontal and 0.3-m vertical resolution) and digitized vegetation map of the Lower Florida Keys (Faulhaber, 2003). The elevation categories were 0–0.3, 0.3–0.6, 0.6–0.9, and >0.9 m. We then simulated three sea-level rise

Fig. 1 Location of the Lower Florida Keys and the three metapopulations of the Lower Keys marsh rabbit (*Sylvilagus palustris hefneri*): Big Pine Key, Saddlebunch Keys, and Boca Chica Key



scenarios—low (0.3 m), medium (0.6 m), and high (0.9 m)—by 2100. These three scenarios are slightly higher than those predicted by the IPCC (2001), 0.09, 0.48, and 0.88 m, and those from the Key West, Florida, tide gauge projected into the future, 0.15, 0.45, and 0.95 m (Mauhl and Martin, 1993). This was done for several reasons. First, recent literature (Overpeck et al., 2006; Rahmstorf et al., 2006) indicated that the IPCC (2001) predictions may be low. Second, data from Key West showed an increasing rate of sea-level rise from 1925 onward, indicating that past sea-level rise may not be a good predictor of future sea-level rise. Finally, our DEM precluded the use of the exact IPCC (2001) predictions due to coarse elevation categories. Our DEM included elevation categories of 0–0.3, 0.3–0.6, 0.6–0.9, and >0.9 m, meaning that we were restricted in the amount that we could raise sea levels.

First, we assumed that plants would be able to migrate upslope as the sea level rises (Michener et al., 1997; Moorhead and Brinson, 1995). We assumed that vegetation in the 0- to 0.3-m category migrated to the 0.3- to 0.6-m

category, vegetation in the 0.3- to 0.6-m category migrated to the 0.6- to 0.9-m category, and vegetation in the 0.6- to 0.9-m category migrated to the >0.9-m category. To do this, we took the proportion of each vegetation type in each of these categories in the year 2000 and multiplied this by the total area in the next higher category for the 2000 dataset. For example, in the low rise scenario, all cells in the DEM with the value of 0–0.3 m were inundated with water, but the vegetation previously at this elevation migrated upslope to the cells with values of 0.3- to 0.6-m elevation.

Our second approach assumed that no migration upslope occurred. This assumption is reasonable given that the rate of sea-level rise may be too great for plants to track upslope (Bush et al., 2004), and that abandonment of coastal lowlands is unlikely (Titus, 1991), thus squeezing coastal plant communities between anthropogenic land barriers and rising sea levels (Feagin et al., 2005). Under this scenario when rising sea levels inundated an elevation category, we assumed that vegetation within that elevation was lost (i.e.,

no upslope migration occurred). Under low sea-level rise, for example, all cells in the DEM with values of 0–0.3 m are inundated with water and vegetation previously at this elevation is lost.

We simulated each of the three sea-level rise scenarios with and without migration and with two potential land-use planning decisions: protection of human dominated areas and abandonment of these areas (Titus, 1991). Human-dominated areas include developed areas and roads. Protection was simulated by keeping human dominated areas constant throughout the simulations. Abandonment was simulated by allowing recolonization of human-dominated areas by vegetation at each elevation category in proportion to the area abandoned.

We calculated the total area (hectares) of potential LKMR habitat under each simulation and both the net and the relative change between 2000 and 2100. This was done on each of the three main metapopulations: (1) Big Pine Key, (2) Boca Chica Key, and (3) Saddlebunch Keys. Using the net change in potential LKMR habitat, we calculated the net change in the total number of LKMRs between 2000 and 2100 using current population estimates.

Results

Big Pine Key

Overall, we estimated 1172 ha of total potential LKMR habitat on Big Pine Key, Boca Chica Key, and the Saddlebunch Keys under current conditions, with most (565 ha) occurring in the middle elevation category

(Fig. 2). Big Pine Key has an estimated 294 ha of potential LKMR habitat, with most occurring in the middle elevation category as well, followed by the high, highest, and low elevation categories, respectively (Fig. 2). Under sea-level rise with migration of vegetation upslope, we found the amount of habitat decreased for both land-use planning decisions (i.e., protection and abandonment of developed areas), with a greater decrease occurring with protection (Fig. 3, graph 1a). With no migration of vegetation upslope and protection of developed areas, the amount of habitat decreased with increasing sea-level rise, while with abandonment it increased under *low* sea-level rise and then decreased under medium and high sea-level rise scenarios (Fig. 3, graph 1b). We also found greater potential habitat with no migration under low sea-level rise, and less under medium and high, compared with no sea-level rise (Fig. 3, graph 1b). Finally, under all sea-level rise scenarios abandonment of developed areas resulted in a greater amount of potential habitat than protection of developed areas (Fig. 3).

Boca Chica Key

Boca Chica Key has 209 ha of potential LKMR habitat under current conditions, with most occurring in the low elevation category, followed by the middle, highest, and high categories, respectively (Fig. 2). As with Big Pine Key, the amount of habitat decreased with increasing sea-level rise for both protection and abandonment, with a greater decrease due to protection. This was true for both migration and no migration treatments (Fig. 3, graphs 2a and 2b, respectively). Comparing migration and no

Fig. 2 Total potential Lower Keys marsh rabbit (LKMR) habitat (hectares) under current conditions. Potential LKMR habitat includes the following vegetation types: buttonwoods, freshwater marsh, low saltmarsh, and high saltmarsh

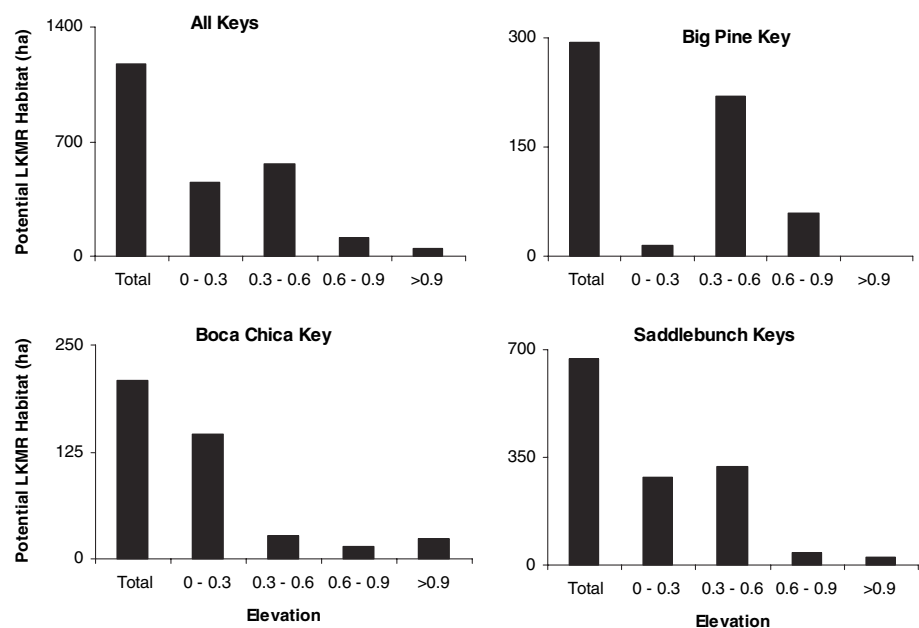
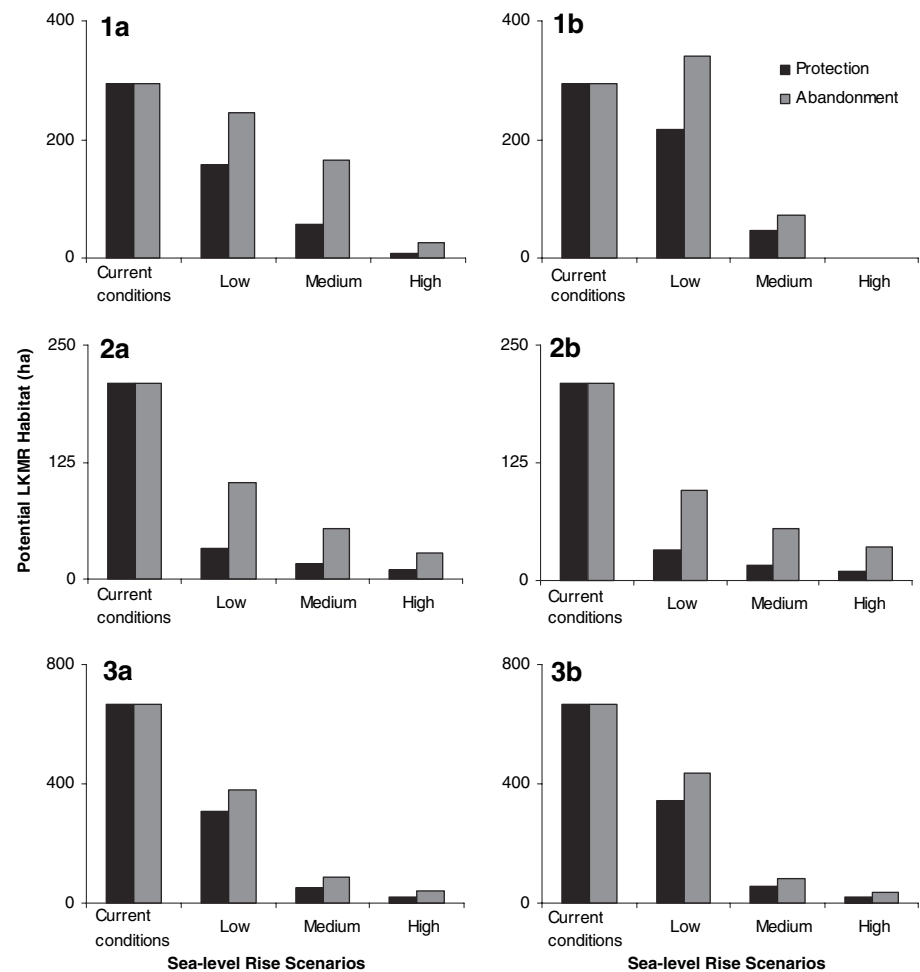


Fig. 3 Potential Lower Keys marsh rabbit (LKMR) habitat (hectares) under scenarios of sea-level rise, land-use planning, and allowing migration (a) and not allowing migration upslope (b) for Big Pine Key (1), Boca Chica Key (2), and the Saddlebunch/Sugarloaf Keys (3), Florida. Potential LKMR habitat includes the following vegetation types: buttonwoods, freshwater marsh, low saltmarsh, and high saltmarsh. Sea-level rise scenarios are as follows: current conditions, low = 0.3-m rise, medium = 0.6-m rise, and high = 0.9-m rise. Land-use planning compares protection (black bars) with abandonment (gray bars) of human-dominated areas (i.e., development and roads)



migration, there was greater potential habitat with migration under *low* sea-level rise and less under *medium* and *high* sea-level rise scenarios. Again, as with Big Pine Key, abandonment of developed areas results in more habitat than protection of such areas (Fig. 3).

Saddlebunch Keys

The Saddlebunch Keys have 669 ha of potential LKMR habitat, with most in the middle elevation category followed by the low, high, and highest categories, respectively (Fig. 2). As with the above keys, the amount of habitat decreased with increasing sea-level rise for both protection and abandonment, with a greater decrease due to protection. This was true for both migration and no migration (Fig. 3, graphs 3a and 3b, respectively). Comparing migration and no migration treatments we found no clear trends (i.e., the results depended on both treatment and land-use decision; Fig. 3, graphs 3a and 3b). Finally, as with Big Pine Key and Boca Chica Key, abandonment resulted in more habitat than protection of developed areas (Fig. 3).

Overall Trends

Not surprisingly, under migration and no migration, and both land-use planning decisions (protection and abandonment), we found a general trend of decreasing total potential LKMR habitat with increasing sea-level rise (Table 1). The only clear pattern when comparing migration and no migration for all three metapopulations was that no migration resulted in more potential habitat under low sea-level rise, and migration resulted in more habitat under medium and high sea-level rise (Table 1). Abandonment of developed areas resulted in greater potential habitat than protection under all sea-level rise scenarios and treatments (Fig. 3).

We also found the greatest relative decrease in potential habitat to occur between low and medium sea-level rise, followed by between medium and high sea-level rise and between current conditions and low sea-level rise, respectively (Table 1). This held true except for migration with abandonment, where the greatest difference was between medium and high sea-level rise, followed by the difference between low and medium and between current conditions

Table 1 Total area (hectares) of potential Lower Keys marsh rabbit habitat on Big Pine Key, Boca Chica Key, and the Saddlebunch/Sugarloaf Keys under scenarios of future sea-level rise, migration or no migration of vegetation upslope, and protection or abandonment of developed areas

Sea-level rise scenario	Migration		No migration	
	Abandonment	Protection	Abandonment	Protection
Current conditions	1172	1172	1172	1172
Low	729 (1.5)	496 (2.5)	871 (1.5)	594 (2)
Medium	307 (2.5)	123 (4)	210 (4)	119 (5)
High	94 (3.5)	40 (3)	70 (3)	29 (4)

Note. Numbers in parentheses indicate the relative (proportional) decrease in habitat between sea-level rise scenarios

and low sea-level rise, respectively (Table 1). Using changes in potential habitat and current population estimates of LKMRs, we found the potential for 42–223 rabbits under low sea-level rise, 10–79 under medium sea-level rise, and 2–24 under high sea-level rise (Table 2).

Discussion

As with any prediction, our approach includes uncertainties surrounding our assumptions. First, we used the modeled sea-level rise predictions made by the IPCC (2001) for our scenarios. The IPCC (2001) predictions are based on oceanic thermal expansion and do not include sea-level rise due to melting ice caps/glaciers and local effects such as land subsidence. Recent literature (Overpeck et al., 2006) indicates that sea levels may rise much higher than the IPCC (2001) predictions. Second, our simulation approach was necessarily simplistic due to data limitations. A fine-scaled approach using a DEM and habitat associations (e.g., the Spatially Explicit Landscape Vegetation Analysis model developed by T. Doyle of the United States Geological Survey) would be preferred. However, the only available DEM was too coarse to discern habitat/elevation associations, and thus this approach was not possible. Therefore, our results should be used heuristically by comparing predicted impacts relative to each other, rather than as absolute predictions of the impact of future sea-level rise on the LKMR.

Not surprisingly, the future is bleak for the LKMR, an endemic insular species, under rising sea levels. If the primary cause of the KMR's decline is habitat loss (USFWS, 1999), further loss due to rising sea levels may exacerbate this issue. In 1996 the LKMR Recovery Team issued four main recovery objectives: (1) acquisition of suitable habitat, (2) control of predation by feral and domestic cats, (3) monitoring of existing populations, and (4) reintroduction to unoccupied suitable habitat (USFWS, 1999). Interestingly, there is no mention of global climate change and sea-level rise in these objectives or anywhere in the recovery plan for this species (USFWS, 1999). Other endemic and insular species of the Florida Keys also will be impacted by rising sea levels. Global climate change may inhibit recovery efforts of endangered species such as the Florida key deer (*Odocoileus virginianus clavium*), endangered silver rice rat (*Oryzomys palustris natator*), and LKMR as well as cause the disappearance of endemic species such as the key ringneck snake (*Diadophis punctatus acricus*) and striped mud turtle (*Kinosternon baurii*) before much is known about these species. State and federal natural resource agencies responsible for coordinating the conservation of threatened and endangered species can no longer take the static approach of protecting suitable habitat because what is suitable now may not be so in the future as the climate changes (Midgley et al., 2002; Pyke, 2004).

There are three important findings from our research. First, the rate of sea-level rise (or climate change in

Table 2 Total number of Lower Keys marsh rabbits under scenarios of future sea-level rise, migration or no migration of vegetation upslope, and protection or abandonment of developed areas

Sea-level rise scenario	Migration		No migration	
	Abandonment	Protection	Abandonment	Protection
Current conditions	100–300	100–300	100–300	100–300
Low	62–187	42–127	74–223	51–152
Medium	26–79	10–31	18–54	10–30
High	8–24	3–10	6–18	2–7

Note. The proportional change in habitat was used to calculate the proportional change in Lower Keys marsh rabbit population

general) is very important. We found less loss in habitat when vegetation migrates upslope than when it does not (Fig. 3). This is not surprising, as migration appears to have been the primary way that species responded to past climate change (Bush et al., 2004; Noss, 2001). This result indicates that the rate of rising sea levels is important in determining the impact of global climate change on coastal species and ecosystems. If the rate of sea-level rise is slow enough, vegetation will be able to migrate upslope in response (i.e., our migration scenarios) and the loss of habitat and species will be reduced. However, if the rate is greater than the historic variability of a system, species may not be able to keep up with the change (i.e., our no migration scenarios) and the loss of habitat and species will be much higher. As Noss (2001) pointed out, “The challenge for conservationists is not to prevent change. It is to keep rates, scales, and intensities of change in ecosystems within the historic range of variability for those systems—or, at least, to come close” (p. 580).

The second finding is that absolute magnitude of sea-level rise is important. This is an intuitive conclusion, but one that has important implications for biodiversity and ecosystem management. We found increasing impacts with increasing sea-level rise as would be expected, but we also found that the greatest impact occurred from the *medium* sea-level rise scenario (Table 1). This makes sense, as the majority of potential Lower Keys marsh rabbit habitat occurs at the elevation most affected by a *medium* rise in sea level (Fig. 2a).

The third finding is that abandonment of human dominated areas (i.e., development and roads) is important for coastal biodiversity conservation. Abandonment should allow coastal plant communities to migrate more easily upslope as opposed to being squeezed between anthropogenic land barriers and rising sea levels (Feagin et al., 2005), as will happen when we protect human-dominated areas (Titus, 1991). Our results indicate that under all sea-level rise scenarios and treatments (i.e., migration vs. no migration), abandonment results in more habitat than does protection. This is not a surprising result, but it illustrates that importance of land-use decisions under global climate change and rising sea levels. There has been a dramatic decline in coastal wetlands in places like China and the Netherlands, where people have protected development (i.e., built dikes) for centuries (Titus, 1991). Local and regional land-use decisions will have a dramatic impact on how ecosystems and species respond to global climate change.

Conclusions

In conclusion, conservation strategies at multiple scales need to be implemented in order to reduce the impact of

global climate change on biodiversity and endangered species. At the regional level, managers must consider land-use planning needs that take into account the needs of both humans and biodiversity. Finally, at the local scale those agencies that are in charge of endangered species conservation and ecosystem management need to rethink static approaches to conservation or else stand by and watch ecosystems degrade and species go extinct. This can be accomplished by bioclimatic reserve systems that protect climatically representative areas for a given species or suite of species (Pyke and Fischer, 2005). In particular, climatically underrepresented areas need to be included in conservation planning along with the standard concerns of threat, opportunity, connectivity, and viability (Pyke, 2004). These areas also need to be connected by corridors of habitat to allow the dispersal needed to adjust to climate change (Pearson and Dawson, 2003). Organisms and communities of organisms must have the opportunity to adjust (i.e., move or adapt) to human-induced climate change or we may face another wave of extinction.

Acknowledgments We would like to thank Amy Snelgrove for GIS assistance and Kristin LaFever for critical review of the manuscript. We would also like to thank Craig Faulhaber, Neil Perry, and Elizabeth Forsy for allowing us the use of their data as well as their insights into LKMR natural history and ecology. D.H.L. would like to thank the United States Navy Southern Research Division, in particular, Rodney Fleming, for funding his graduate research.

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