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# Future changes in habitat availability for two specialist snake species in the imperiled rocklands of South Florida, USA

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## Abstract

Rockland habitat in South Florida, USA, is a threatened ecosystem that has been lost, fragmented, or degraded because of urbanization or other anthropogenic disturbance. Furthermore, low-lying islands and coastal areas are experiencing sea level rise (SLR) and an increased frequency and intensity of tidal flooding, putting rockland habitats there at increasing risk of ecological change. We evaluated changes in the extent of rockland habitat under various scenarios of future SLR, tidal flooding, and human development for two endemic state-listed threatened species of snakes, the Rim Rock Crowned Snake (*Tantilla oolitica*) and the Key Ring-necked Snake (*Diadophis punctatus acricus*). Both snakes are restricted to South Florida. We used recent and historical species' records to determine each species' habitat range. We then estimated the extent of future habitat loss due to SLR and continued human development, as well as degradation of the remaining habitat. We also asked whether the future potential drivers of habitat loss and degradation differ between the two species and across their habitat ranges. We predicted that saltwater intrusion could negatively affect rocklands by 2050, resulting in degradation of 80% of the existing habitat because of an anticipated 42 cm of SLR. Moreover, our model suggests short-term stochastic events such as storm surge and high tides may increasingly saturate the root zone of rockland vegetation before complete inundation. Under the extreme scenario, we predict most of the rockland habitat used by these two species of snakes may be inundated by 2080. Under the extreme SLR scenario, current rocklands are likely to convert to more halophytic habitat (mangrove or salt marsh wetland) within 50–60 years. Under the low scenario, 31% of rockland habitat may be lost due to human development by 2030. Therefore, mitigation actions may help to conserve specialist species within rockland habitat threatened by human activities and climate change.

**KEYWORDS**

climate change, conservation, fossorial snakes, habitat availability, key ring-necked snake, pine rocklands, rim rock crowned snake, sea level rise, South Florida

## 1 | INTRODUCTION

Globally, climate and land use change are major threats to biodiversity (Dawson et al., 2011; Titeux et al., 2016). As these stressors intensify, effective conservation can be informed by an assessment of their impacts on imperiled species and their habitats. Land use change (from urban development and agriculture) and climate-driven sea level rise (SLR) have greatly degraded and reduced the extent of many natural habitats in peninsular Florida (USA), especially the rocklands ecosystem, an iconic habitat found only in mainland South Florida, the Florida Keys, Bahamas, and Cuba (Jones & Koptur, 2017). Rocklands are outcropping limestone surfaces with skeletal soils or none at all. These areas may be covered by open pine forests (pine rocklands) or closed canopy broadleaved tropical forests (also known as rockland hammocks). In mainland South Florida and the Florida Keys, rockland habitat hosts at least 57 species of endemic plants and animals (Powell & Maschinski, 2012; Snyder et al., 1990; Trotta et al., 2018), including 18 species that are currently federally classified as threatened or endangered, as well as others that warrant evaluation for possible listing under the U.S. Endangered Species Act (ESA, United States Fish and Wildlife Service (USFWS), 2022).

Except for the rocklands on Long Pine Key (LPK), which is protected within Everglades National Park, only 2% of the original Miami Rock Ridge pinelands remains intact because of the combined effect of clearing for agriculture and residential development (Powell & Maschinski, 2012). Of the rocklands that remain, only three individual blocks are larger than 50 ha (Myers & Ewel, 1990; Powell & Maschinski, 2012). Furthermore, in the Florida Keys, much of the rockland habitat has been lost or degraded due to SLR (Maschinski et al., 2011; Ross et al., 1994). In addition to the steady rise in mean sea level, low-lying islands and coastal areas are threatened by flooding during high tide events, which are rapidly increasing in frequency and intensity along US coastlines (Sweet et al., 2018). Such disturbance often facilitates ecosystem change, such as the encroachment of halophytic vegetation (e.g., mangroves such as *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, and *Conocarpus erectus*) to more inland habitats (Alexander, 1974; Subedi et al., 2020).

Most terrestrial organisms have a low tolerance of saltwater, so encroaching tides are a significant threat to rocklands and their biota. The frequency of flooding and salinization of groundwater due to SLR is already increasing in rockland habitat in the Florida Keys (Ross et al., 1994). In coastal terrestrial environments, saltwater intrusion driven by SLR reduces the extent of subterranean fresh water, which is a vital water source for vegetation (Saha et al., 2015). For example, during flooding events, groundwater salinity increases within the root zone of South Florida slash pine (*Pinus elliottii* var. *densa*) and is then assimilated by plants through upward capillary action (Ogurcak, 2016). Saltwater inundation can therefore cause physiological stress and mortality of this characteristic pine, as well as tropical and temperate shrubs, palms, and the rich herbaceous flora of the pine rocklands (Ross et al., 2009). Over long periods of saltwater stress, the freshwater-dependent rockland habitat can be transformed into a salt-tolerant ecosystem that supports species such as mangroves (Ross et al., 2009).

Saltwater intrusion and subsequent shrinkage of the freshwater lens (i.e., a shallow layer of freshwater that sits above salt water due to density differences) may be especially detrimental to fossorial fauna that inhabit small holes and crevices in the porous limestone bedrock that is characteristic of South Florida rocklands. For example, the Rim Rock Crowned Snake (*T. oolitica*) and Key Ring-necked Snake (*Diadophis punctatus acricus*) are two fossorial snakes that are endemic to the South

Florida pine rocklands (Mays & Enge, 2016). The Rim Rock Crowned Snake is only found in the oolitic facies of the Miami Limestone east of the Atlantic Coastal Ridge in Miami-Dade County and throughout the rocklands of the Florida Keys. The Key Ring-necked Snake is restricted to rocklands of the Lower Keys (Krysko et al., 2019). The lack of a deep layer of topsoil in the rocklands has likely led to the snakes' specialized uses of subterranean limestone solution holes as microhabitat (Mays & Enge, 2016), especially during the long (5–7 months) dry season. This specialization, coupled with the loss and degradation of their rockland habitat, has led to the decline of these two taxa (Mays & Enge, 2016). Subsequently, both snakes are listed as threatened by the state of Florida and are being evaluated for federal listing under the ESA.

To evaluate whether a species warrants protection under the ESA, the U.S. Fish and Wildlife Service (USFWS) prepares a Species Status Assessment in which information on vital rates and population trends, life history, dispersal, spatial and genetic structure, and habitat use is used to forecast a species' responses to scenarios of future environmental conditions, conservation, and/or management actions (U.S. Fish and Wildlife Service (USFWS), 2016). Such information is often lacking for many imperiled species. If actual demographic data are sparse or difficult to gather due to a species' small population size or cryptic nature, an alternative metric, for example, habitat size or quality, may be used as a proxy for demographic information (Earl et al., 2017; Préau et al., 2020). To aid USFWS with their assessment, we used SLR, tide, and human development models to predict the amount and quality of rockland habitat that would be available to these two snake species under various future scenarios. Specifically, we addressed the following questions: (1) How much of the habitat currently available to these species may be lost due to SLR, changes in high tides, and future urban development? We determined the current extent of rockland habitat using current and historical species' occurrence records and evaluated any reductions in habitat area attributable to SLR, tide, or urbanization. (2) How may degradation of the remaining rockland habitat occur in the future because of SLR? We evaluated the potential for future rockland degradation due to high tidal inundation. (3) Finally, we asked whether threats to conservation of rockland habitat differ between mainland and island areas of South Florida. Expanding our understanding of how remaining patches of rockland habitat may be impacted by changes in climate-driven SLR and land use change can help to inform conservation and management decisions for threatened species endemic to this imperiled ecosystem.

# 2 | MATERIALS AND METHODS

## 2.1 | Study species

The Rim Rock Crowned Snake historically occurred in eastern Miami-Dade County (hereafter, mainland) as well as throughout the Florida Keys, whereas the Key Ring-necked Snake has been identified only in the lower Florida Keys (Mays & Enge, 2016). Both species are very elusive, small (<20 cm in length) and primarily fossorial. Data on their population size, vital rates, and life-history characteristics are limited and there has been little success in locating these species in their natural habitat (Mays & Enge, 2016). We found records, spanning from 1934 to 2015, of 49 Rim Rock Crowned Snake and 47 Key Ring-necked Snake sightings from museum specimens, inventories, and other personal accounts (Figure S1).

Taxonomically, the Rim Rock Crowned Snake is most closely related to the Southeastern Crowned Snake, *T. coronata* (Ernst & Ernst, 2003). Based on this similarity, *T. oolitica* may reach sexual maturity at 2 years of age and have a longevity of at least 5 years old in the wild (Todd et al., 2008). For the Southeastern Crowned Snake, prey consists primarily of centipedes (Todd et al., 2008), but may include other insects and small invertebrates, similar to the diet of other members of the genus *Tantilla* (Ernst & Ernst, 2003).

Surface activity for the closely related *T. coronata* peaks during the hottest months of the year and, for *T. relicta* (a congener that is geographically close to *T. oolitica*) gravid females can be found from March through August in Florida (Todd et al., 2008). This period of reproduction and surface activity corresponds with Florida's summer fire season. It is not known whether fire may affect *T. oolitica*, but there are conflicting results on how fire affects *T. relicta* (Krysko et al., 2019).

The Key Ring-necked Snake appears to be confined to areas near permanent freshwater sources, often contained within small holes in the limestone, in pine rockland and rockland hammock habitat (Lazell, 1989). In general, ring-necked snakes prey on small amphibians, lizards, snakes, insects, slugs, and earthworms that would be found near bodies of water (Ernst & Ernst, 2003). Moist microhabitats appear to be required for all species of *Diadophis* to balance evaporative water loss (Clark, 1967; Myers, 1965). This need for proximity to freshwater makes the Key Ring-necked Snake and its prey, especially amphibians, vulnerable to salinization of freshwater wetlands from storm surge, SLR, and overwash from high tide events (Florida Fish and Wildlife Conservation Commission, 2013a).

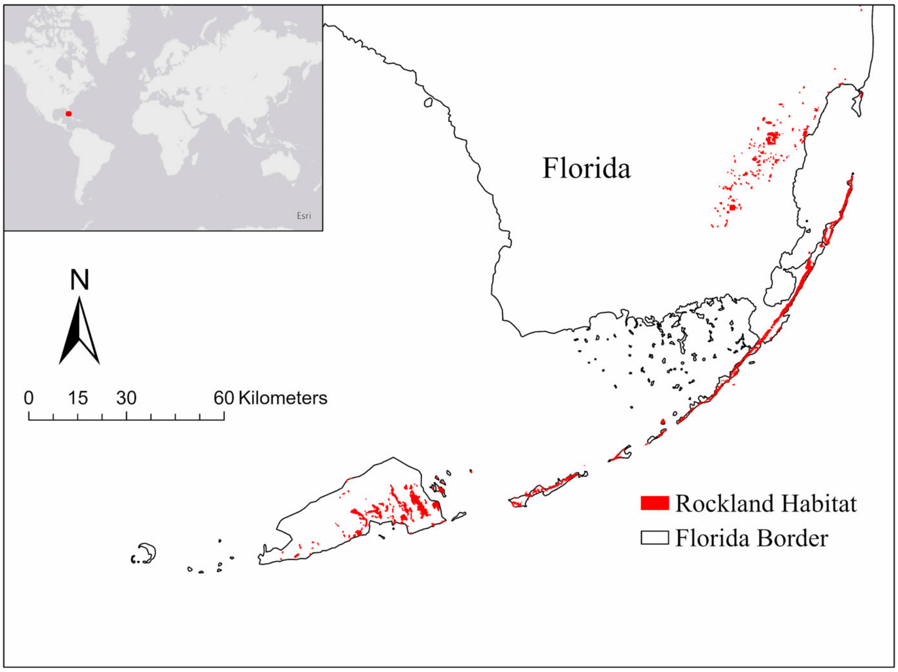


FIGURE 1 Study area showing locations of current rocklands habitat for two snake species in Florida based on Florida Cooperative Land Cover Map (CLC) v3.4

## 2.2 | Habitat

Because demographic data are limited for these two species, we used habitat based on species occurrence data as a proxy for population viability (Ferrer-Sánchez & Rodríguez-Estrella, 2016; Préau et al., 2020). Both snake species are found primarily in rocklands with abundant rock crevices. In Florida, rockland habitat occurs along the southern extreme of the Atlantic Coastal Ridge, which extends from Miami southwest to LPK in the Everglades National Park. This habitat is also scattered throughout the lower Florida Keys with the most extensive rocklands occurring on Big Pine Key (Figure 1). We excluded LPK rockland habitat (Everglades National Park) from our analysis because there were no occurrence records of either snake in this region.

To delineate rockland habitat, we downloaded the Florida Cooperative Land Cover Map (CLC) v3.4 (https://myfwc.com/research/gis/applications/articles/cooperative-land-cover/). The Florida CLC resulted from a partnership between the Florida Fish and Wildlife Conservation Commission (FWC) and Florida Natural Areas Inventory and is a statewide land cover classification based on existing data and expert review of aerial photography. Based on historical records, both snake species occur in "pine rockland" (pine) and "rockland hammock" (hammock) classes of the CLC, which we combined into a simplified classification of "rocklands." Pine and hammock plant communities are composed of species that share a requirement for limited freshwater resources. However, these two community types differ in that pine rocklands typically have shallow soils (<10 cm in depth, Ross et al., 2003) with little organic matter, much exposed limestone (Snyder et al., 1990), and a high fire return frequency (Ross et al., 2009). Soil depth in rockland hammocks is greater, ranging from 13 to 37 cm (Subedi et al., 2019), with less exposed limestone outcroppings and a thicker leaf litter layer. Within the landscape of South Florida, rocklands are found most frequently at the highest elevations.

## 2.3 | SLR and high-tide projections

SLR scenarios for the study area were developed by Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force, jointly convened by the US Global Change Research Program and the National Ocean Council (https://scenarios.globalchange.gov/sea-level-rise). The task force developed regional SLR responses on a 1° grid covering the coastlines of the US mainland and territories. These responses were derived by adjusting key factors important at regional scales, including shifts in oceanographic factors, changes in the earth's gravitational field and rotation, and flexure of the crust and upper mantle (due to melting of land-based ice). Other influential factors included vertical land movement due to glacial isostatic adjustment, sediment compaction, groundwater and fossil fuel withdrawals, and other nonclimatic features (Sweet et al., 2017). For South Florida, sea level is projected to rise between 0.4 and 3.18 m by 2100; these rates are expected to be higher than the global average. We applied predictions (Sweet et al., 2017) of low, medium, and extreme SLR scenarios for southeastern Florida for 2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100 (Table S1) to our calculated available habitat for each snake species.

Similarly, the National Oceanic and Atmospheric Administration (NOAA) has established three coastal flood severity thresholds (minor, moderate, and major) based upon water level heights empirically calibrated to NOAA tide gauge measurements from years of impact monitoring by its Weather Forecast Offices. We used projected future changes in high tide thresholds for three regions in South Florida (Table S2, Sweet et al., 2018). Minor (more disruptive than damaging), moderate (damaging) or major (destructive) coastal flooding (not associated with tropical storms), begin about 0.5, 0.8, and 1.2 m above a level slightly higher than the multiyear average of the daily highest water levels measured by NOAA tide gauges (Sweet et al., 2018).

Inundated areas were modeled by applying SLR projections in a "bathtub model" approach in ArcGIS (Murdukhayeva et al., 2013). As such, a grid cell (~3 m) becomes flooded if its elevation is less than the projected sea level, resulting in inundated areas for a corresponding height increase in sea level. Elevation data were downloaded through the U.S. Geological Survey (https://apps.nationalmap.gov/downloader/). This digital elevation model (DEM) of 1/9 arc-second resolutions (~3 m) with a vertical unit of 1 m was used to process inundated areas modeled by applying SLR projections.

Future flooding was calculated by increasing the water level above mean sea level surface by the projected amount of SLR (i.e., bathtub model). The model calculated total area flooded for a given SLR scenario, considering both marine overland flooding (e.g., flooded area connected to the ocean) and groundwater flooding (e.g., area unconnected to the ocean but inundated due to SLR). We focused primarily on how much area is projected to be inundated due to SLR regardless of its connection to ocean water because the underlying geology in our study area is highly porous and transmissive (i.e., permeable) and the freshwater aquifer is not completely isolated from the brackish water at the coastal margins (Ogurcak & Price, 2019). Therefore, although the bathtub model approach does not account for any shoreline dynamics, it is appropriate for this application because of the nature of rocklands' geology in South Florida. Using the regional SLR scenarios (low, intermediate, and extreme), habitat change (in total area and percentage of current area) was calculated by decade

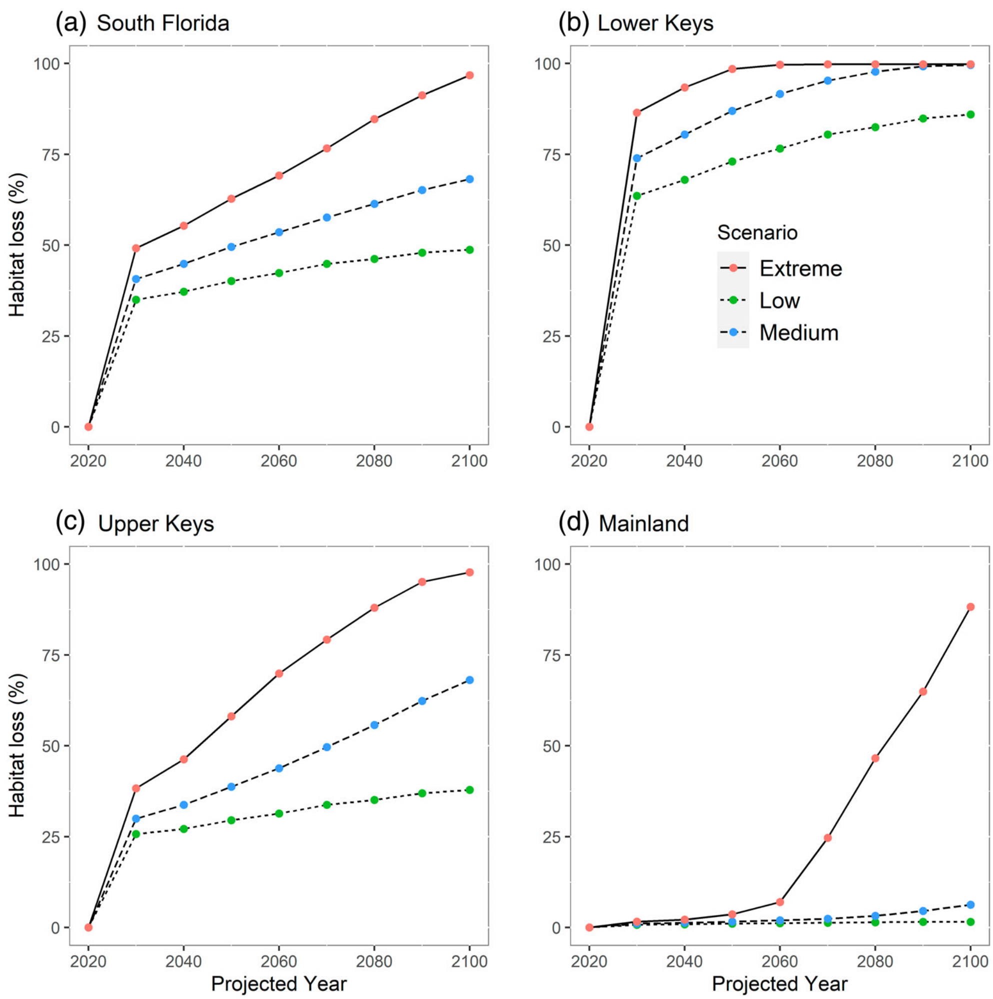


**FIGURE 2** Percentage of predicted Rockland habitat loss due to sea level rise (SLR) under three scenarios (extreme, medium, and low SLR). (a) South Florida combined (Lower Keys, Upper Keys and Mainland), (b) Lower Keys only, (c) Upper Keys only, and (d) mainland only

from 2030 to 2100. Changes in habitat area were calculated over the entire region (i.e., mainland South Florida and the Florida Keys) using both pine rockland and rockland hammock habitat types together.

Similarly, habitat degradation was calculated by increasing the water level above mean sea level surface by the projected high tide thresholds. The model calculated total area flooded for a given high tide threshold scenario. This approach is appropriate for rockland systems because short-term stochastic events such as high tides inundate the root zone as well as depositing salts in soil for freshwater terrestrial vegetation, thus deteriorating existing habitat before it is completely inundated (Ross et al., 2009).

## 2.4 | Human development projection (SLEUTH model)

Three development scenarios (extreme, medium, and low urban expansion) were parameterized and their effects on the urban extent of the study area were investigated using the SLEUTH model at a decadal scale (from 2030 to 2100). The resulting dataset contained the extent of urbanization for each year predicted by the SLEUTH model (Clarke, 2008; https://seregion.databasin.org/datasets/e5860ced8b4844e88431cdbefe425e1a/). Further model modification and implementation was performed at the Biodiversity and Spatial Information Center at North Carolina State University. Urban growth probabilities were projected for the Southeast Regional Assessment Project (including all parts of Florida) throughout the 21st century. Datasets and geographical information system layers were obtained from Data Basin by the Conservation Biology Institute (https://databasin.org/datasets/e5860ced8b4844e88431cdbefe425e1a). Data are deposited in Barichivich and Walls (2021) U.S. Geological Survey's Science Base (https://doi.org/10.5066/P9TRHCLU).

# 3 | RESULTS

## 3.1 | Current habitat

The current area of rockland habitat in the lower Florida Keys is 2309 ha; pine forests make up 769 ha whereas hammock is 1540 ha. One of the Florida Keys, Big Pine Key,

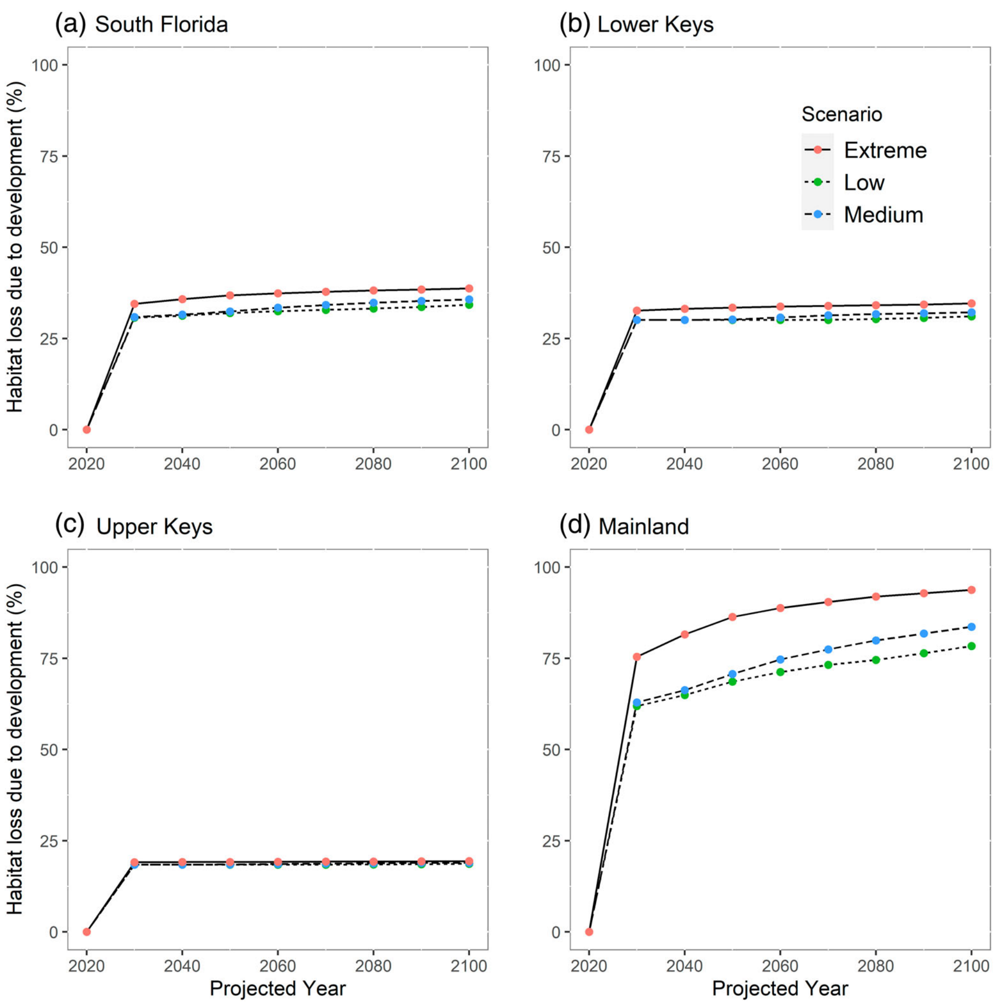


FIGURE 3 Percentage of predicted rockland habitat lost under three development scenarios (low, medium, and extreme) for both pine and hammock together across (a) whole area in South Florida combined (Lower Keys, Upper Keys, and mainland), (b) Lower Keys only, (c) Upper Keys only, and (d) mainland only

has most of the pine habitat in the Lower Keys region, with an area of 599 ha (78% of total rocklands area). The four other islands, Little Pine Key, No Name Key, Cudjoe Key, and Sugarloaf Key contain only small areas of rocklands. No pine forest exists in the Upper Keys. However, rockland hammock occurs to a varying extent in many islands in the Upper Keys. The total area of rocklands in the Upper Keys is 2835 ha. On the mainland, total rocklands area is 1168 ha (excluding LPK), with pine covering an area of 921 ha and hammock covering 247 ha (Table S3).

### 3.2 | Habitat loss due to SLR

Our modeling efforts predict a significant amount of current habitat may be lost due to projected SLR. Patterns in habitat loss under each SLR scenario for both habitat types are very similar, ranging from 48 to 99% reduction in habitat by 2100 (Figure 2a). Under the low and medium SLR scenario, by 2100 about 48 and 69% of rockland habitat is predicted to be lost, respectively, whereas almost all rockland habitat (96.7%) is lost under the extreme SLR scenario (Figure 2a).

Threats from SLR vary among the Lower Keys, Upper Keys, and mainland South Florida. In the Lower Keys, SLR-induced loss of current rockland habitat is predicted to be greatest. For instance, our model projected a 35% loss of habitat at a low SLR of 13 cm yet an almost 100% loss at the highest SLR of 3.18 m. In contrast, on the mainland, where remaining habitats are at higher elevations, our model predicted <1% of habitat loss with 13 cm of SLR and 88% loss with 3.18 m SLR (Figure 2c,d).

### 3.3 | Habitat lost due to human development

Similar to the projected effects of future SLR, our model predicts large rocklands reductions due to human development (Figure 3). Under all three development scenarios (low, medium and extreme), habitat loss is predicted to range from 34 to 39% of the current extent by 2100. A significant amount (31–34%) of rockland habitat is predicted to be lost by 2030 (Figure 3a).

The extent of current rocklands loss due to human development varies across the three regions (Figure 3b–d). The predicted percentage of habitat lost in the Florida Keys (Lower and Upper Keys) is relatively low (<20% in the Upper Keys and <30% in the Lower Keys). In contrast, on the mainland (Miami-Dade), our model predicts a significant amount of habitat loss (> 60% by 2050 under any scenario; Figure 3d).

### 3.4 | Habitat degradation due to high tide effects

One third to nearly all of the rockland habitat in south Florida is predicted to be degraded due to increased flooding associated with high tides, depending on the rate and magnitude of SLR (Figures 4 and S2–S4). For the major high tide projections, a significant amount of rockland habitat is predicted to be affected, ranging from

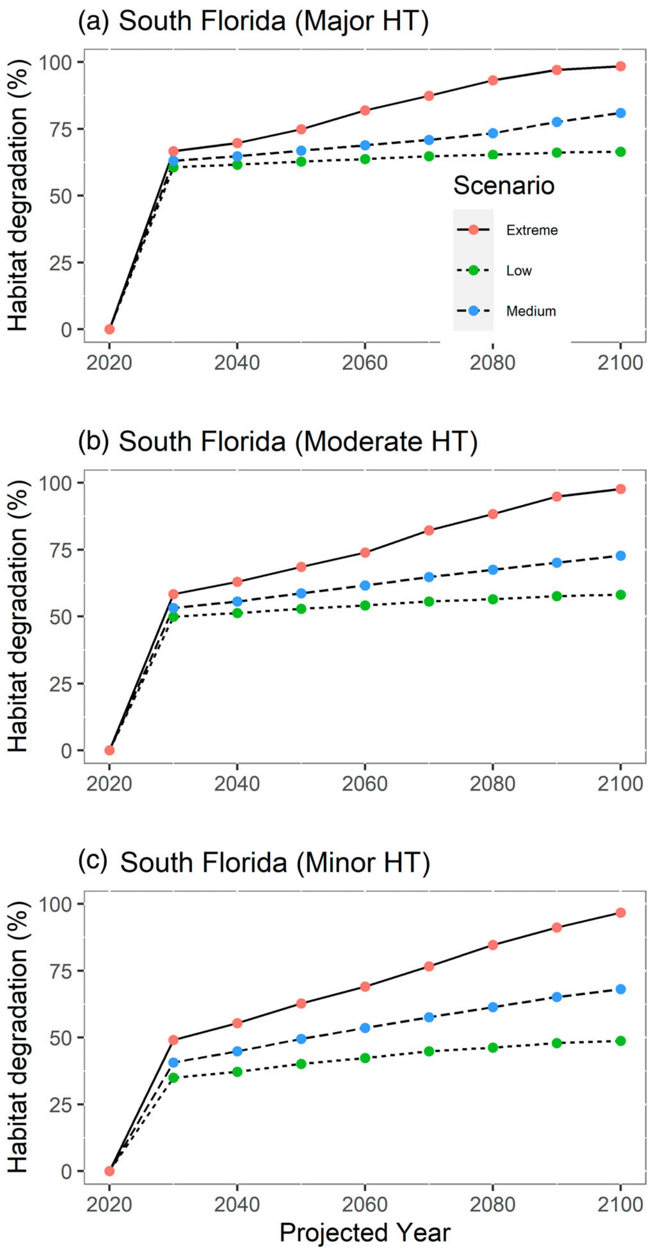


**FIGURE 4** Percentage of predicted affected rockland habitat under three high tide projections (major, moderate, and minor) for extreme, medium, and low sea level rise scenarios in decadal time intervals. Percentage of predicted affected habitat for South Florida combined (Lower Keys, Upper Keys, and mainland) (a) major high tide, (b) moderate high tide, and (c) minor high tide

60 to 66% by 2030 and from 67 to 99% by 2100 (Figure 4a). For the moderate high tide scenario, projections showed that the high tide effect by 2030 results in 50–60% of the habitat area being affected; by 2100, moderate high tides affects 58–97% of the rockland habitat in South Florida (Figure 4b). For the minor high tide projections, high tide affects 35–49% of rockland habitat by 2030 and 48–96% by 2100 (Figure 4c). In the Lower Keys, a significant amount of rockland habitat is predicted to be degraded due to high tide: 63–100% for minor high tide projection, 87–100% for the moderate high tide projection, and almost the entire current rockland habitat will be affected for major high-tide projections (Figure S2). In the Upper Keys, model predictions indicate that by 2030, 25–95% of habitat will be affected with high tide by 2100 (Figure S3). However, under similar scenarios, our model suggests a very small amount of rockland habitat will be affected by high tide on the mainland (Figure S4).

## 4 | DISCUSSION

The Rim Rock Crowned Snake and the Key Ring-necked Snake are endemic to the imperiled rocklands of South Florida. Both species are habitat specialists and exhibit low vagility; therefore, we assume the loss and degradation of rockland habitat has led to their decline. In the absence of demographic information needed to evaluate their vulnerability to extinction, we used changes in habitat quantity and quality as proxies to estimate the impacts of SLR and anthropogenic development on the likelihood of persistence of these two species. The results of our analyses offer a framework that could be used to guide listing decisions, evaluate recovery approaches, develop timelines, establish habitat conservation targets, identify management triggers, and inform monitoring frequency or reintroduction strategies for these and ecologically similar species (Kissel et al., 2014).

### 4.1 | Habitat loss

We evaluated changes in the extent of rockland habitat under various scenarios of future SLR and human development, using recent and historical species' records to determine each species' current habitat range. Under all SLR scenarios, our *models projected* that habitat on small islands with lower elevation were most vulnerable to habitat loss. Under the most extreme SLR scenario, most current habitats are predicted to be permanently or semi-permanently flooded within 40–50 years. Under this scenario, current rockland habitat will likely be changed to brackish wetlands, mangrove, or salt marshes, depending on the level of inundation, salinity, and soil conditions. At elevations of 1 m or higher, current rockland habitat in the Florida Keys often persists because of effective habitat management, especially periodic prescribed fires, which enable open pine forest conditions to be maintained. In urbanized areas, however, future habitat loss will likely reflect an interaction between development and SLR, which could accelerate ecosystem change in the pine rockland forests of South Florida, including altered groundwater quality as well as difficulty of burning in heavily urbanized landscapes. Indeed, even in protected areas, saltwater intrusion may transform rockland forest communities to halophytic vegetation (Ross et al., 2009).

We estimate that, by 2030, up to 54% of rocklands habitat in South Florida may be lost due to urban development, most of which has occurred preferentially on dry areas at higher elevations. Significant areas of current habitat could be developed by 2030 because those parcels are privately owned. Publicly held/managed lands are less prone to development/land use conversion. Endemic flora and fauna of rockland communities may be at an increased risk of extinction in the near future with increased development or land use conversion. Additionally, significant areas of rockland habitat is predicted to be lost due to SLR by the end of the 21st century, whereas the remaining rockland habitat could potentially transition to salt-tolerant vegetation cover and could remain vulnerable to loss due to urban development. Since 1970, new residential development has targeted relatively high elevation rockland areas (Lopez et al., 2004) that are at a lower risk of flooding from SLR or tidal activity. If current development trends continue, we predict that the amount of rocklands could decrease significantly with a concomitant loss of habitat for endemic species.

Our results indicated that habitat loss due to urbanization differed between the Florida Keys and the mainland. Historically, urban development decreased the extent of rocklands in the Florida Keys. However, the enactment of federal and state laws (e.g., the Florida Coastal Management Act; Title XXVII, Chapter 380, Part II, Florida Statute) led to a substantial decline in upland development in the Keys (Gallagher, 1991), with most of the remaining habitat placed under state or federal management. In contrast, on the mainland, most of the remaining fragments of rocklands are privately owned and are thus at a greater risk for future development. Our results show that, with the projected rate of urban development, at least 60% of the existing rockland habitat on the mainland could be lost by 2030, as most of the privately owned rockland habitats are likely to be developed in 10 years and remaining habitats will be inside the protected areas. Therefore, human development on the mainland is likely a serious threat to the conservation of biological diversity in South Florida in the near future.

## 4.2 | Habitat degradation

Short-term stochastic events related to SLR, such as storm surge and high tides, will increasingly inundate the root zone of pine and other terrestrial vegetation, thus deteriorating existing habitat before it is completely inundated (Ross et al., 2009). Although rockland habitat at low elevation is likely to be most vulnerable to overland flooding due to SLR and related tidal dynamics, habitat at higher elevation is also at risk of degradation from high tide which could inundate the root zone of terrestrial vegetation. Our results showed that a large amount of habitat is predicted to be degraded by high tides and subsequent root-zone salinization across all regions by 2030 under all scenarios considered. In the rocklands environment, where trees predominantly use fresh ground water directly, especially during the dry season (Saha et al., 2009), an increase in belowground salinity may cause mortality of many of the rockland plant species. Further, our model suggests the remaining rockland habitat in the Lower Keys—the only area where the Key Ring-necked Snake is found—is predicted to be degraded by 50–80% by 2030 due to high tides.

An increase in salinity in shallow ground water will reduce the availability of freshwater in the root zones of pine and other vegetation, thus leading to tree mortality due to SLR. South Florida Slash pine, a dominant canopy species in pine rocklands, is sensitive to <2 ppt salinity (Subedi et al., 2020). Therefore, even in upland areas that are not inundated, increasing salinity of the shallow ground water can cause extensive terrestrial vegetation die-off, leading to habitat degradation and presumably unfavorable conditions for Rim Rock Crowned Snake and Key Ring-necked Snake. In some areas, pine forest is indeed being replaced by mangrove-dominated halophytic communities and other transitional communities (i.e., *C. erectus* in the Florida Keys; Ross et al., 1994).

Rocklands have, at most, a very thin soil layer that covers crevices, shallow depressions and solution holes in the underlying limestone. These microhabitats provide critical refugia in which snakes may avoid predation, temperature extremes, and fires that eliminate pine needle litter (Enge, 1997; Porras & Wilson, 1979). At present, overland flooding in rocklands is rare and surface drainage is very rapid due to high porosity of the limestone surface, thus minimizing the risk of flooding of fossorial refugia. However, future SLR and high tide events could flood the subterranean water table with saline water, thus affecting the microhabitat that these fossorial snakes use.

## 4.3 | Implications for conservation and management

Habitat loss and fragmentation are major impediments to the recovery and management of many endangered species (Huxel & Hastings, 1999). Our results predict that, by 2030, almost three quarters of rockland habitat will be lost in the mainland region of South Florida under any scenario. Almost 70% of the current rocklands are managed by state or federal agencies in the Florida Keys. Our results show inclusion of ecosystem change as a result of SLR in conservation or management plans may be helpful to conserve current rockland habitats. Considering the extensive fragmentation of remaining rockland habitat, the low dispersal ability of these species (Krysko et al., 2019) and the threat of saltwater inundation to their remaining habitat, Rim Rock Crowned Snake and Key Ring-necked Snake currently face a high risk of extinction.

To reduce this risk, one option for managers and decision makers to consider is to identify high elevation, core pine rocklands sites situated within landscapes that still have connectivity and target them for translocations to establish new, viable populations of these species. However, this likely would not be feasible for the Key Ring-necked Snake: the potential translocation of this subspecies to less vulnerable areas outside of their Florida Keys distribution (e.g., LPK in Everglades National Park) would place it in cohabitation with the Southern Ring-necked Snake (*D. punctatus punctatus*), which already occurs on LPK (Krysko et al., 2019). In the absence of any isolating mechanism, such action would ultimately result in the loss of the translocated population's genetic distinction at the subspecies level.

On the South Florida mainland, the Rim Rock Crowned Snake occurs on remaining fragments of pine rockland within the dense urban matrix of Miami Dade County. This habitat is situated on the Miami Rock Ridge, a limestone ridge with elevation of 2–7 m above sea level (Powell & Maschinski, 2012). LPK occupies an area of 5676 ha within Everglades National Park, of which the vast majority of habitat (5131.5 ha) is pine rockland and 545 ha is rockland hammock (Subedi, unpublished. data). However, the Rim Rock Crowned Snake is not known to have ever occurred on LPK. Although the habitat in LPK would likely be currently suitable for translocations of this species, it would be difficult, at best, to obtain enough individuals of this rare and secretive species for this effort to be successful. Moreover, flooding during future high tide events is a threat for LPK as well; we applied our modeling approach to LPK and found that there would be less habitat loss for all SLR scenarios but that high tide projections resemble those for the Florida Keys and mainland South Florida.

Although conservation translocations appear to be problematic for these species, other conservation options may include: (1) acquisition, restoration, protection, and management of suitable habitat; (2) removal of non-native species like the red imported fire ant (*Solenopsis invicta*); and (3) research on the life history and ecology of these species to better understand how they may respond to habitat degradation from SLR and high tides (Florida Fish and Wildlife Conservation Commission, 2013a, 2013b; Hines, 2011; Ross et al., 2009). For the Florida Keys, in general, Ross et al. (2009) proposed addressing hydrological barriers (e.g., by installing culverts underneath roads to prevent impoundment of tidal waters and by filling canals and ditches to prevent saltwater from entering freshwater ecosystems). Hines (2011) highlighted the importance of rehydration of the aquifer, which may be especially critical for moisture-sensitive centipedes that are the primary prey of Rim Rock Crowned Snakes.

### 4.4 | Model uncertainties

Our analyses indicate that SLR may result in significant loss of terrestrial habitat for rockland species in South Florida. Our projected scenarios treat the current land configurations as static, though some are more likely to be dynamic. Therefore, the projections should be viewed as the simple demonstration of the potential effects of SLR. Furthermore, the passive flooding scenarios we present here do not consider other factors that could substantially influence the future of the coastal areas in South Florida. These may include land loss due to shoreline erosion, redistribution of sediments, and sand deposition by overwash during high tide activity. An increase in the groundwater table during SLR could also displace underground refugia for semi-fossorial snakes like Rim Rock Crowned Snake and Key Ring-necked Snake. Thus, it is possible that the impact of factors other than passive flooding associated with SLR could lead to slightly greater or lesser loss of habitat than presented here.

## 5 | CONCLUSIONS

We evaluated changes in the extent of rockland habitat under various scenarios of future SLR, tidal flooding, and human development to estimate the impacts of long-term environmental change on this iconic habitat and two of its imperiled species. Our results predict most of the terrestrial habitat used by rockland specialists could be lost due to SLR by 2070 under the extreme SLR scenario, indicating that SLR will likely change current rockland habitat into more halophytic habitat (e.g., mangrove or salt marsh wetland) within 50–60 years. Moreover, our models predict short-term stochastic events, such as storm surge and high tides, increasingly inundating the root zone of pine and other terrestrial vegetation before complete inundation. Even the lowest estimates of habitat loss (54% with a 0.4-m rise in sea level) could result in substantial loss of rocklands in the Florida Keys, along with a shift to salt-tolerant habitat and further loss to development. Therefore, mitigation actions such as acquisition, restoration, protection, and management of suitable habitat may help to conserve upland habitat for specialist species where they are threatened by urbanization and global climate change. We demonstrate that even a small increase in sea level could affect a large amount of the remaining rockland habitat, an area currently used by numerous states and federally listed species. Incorporating sea level projections into short-term management planning and long-term conservation strategies can help to ensure the persistence of threatened species in imperiled habitats like the pine rocklands of South Florida.

### AUTHOR CONTRIBUTIONS

Suresh C. Subedi, Susan C. Walls, William J. Barichivich, and Ryan Boyles conceived and designed the research. Suresh C Subedi, Susan C. Walls, William J. Barichivich, and J. Aaron Hogan collected the data. Suresh C. Subedi analyzed the data and wrote the initial draft. All the authors contributed in writing, editing, and revisions.

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### CONFLICT OF INTEREST

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data are available at https://doi.org/10.5066/P9TRHCLU (Barichivich & Walls, 2021).

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