1. ADMINISTRATIVE:
PI: Susan C. Walls; office: 352-264-3507; swalls@usgs.gov
Agency: U.S. Geological Survey, Wetland and Aquatic Research Center,
Title: Informing Future Condition Scenario Planning for Habitat Specialists of the Imperiled Pine Rockland Ecosystem of South Florida
Agreement number: 034
Date of report: 23 September 2021
Period of Performance: 9/1/2018 to 3/31/2020
Actual Total Cost: $137,959.20

2. PUBLIC SUMMARY:
This project evaluated habitat conditions for two species found in the imperiled pine rockland ecosystem—the Rim Rock Crowned Snake (*Tantilla oolitica*) and the Key Ring-Necked Snake (*Diadophis punctatus acricus*). 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 occurs only in lower Florida Keys (Enge et al. 2004; Mays and Enge 2016). Both species are very elusive, small (< 20 cm in length) and primarily fossorial. Pine rockland habitat is rapidly disappearing in South Florida, with < 3 percent of its original extent remaining. Saltwater intrusion from hurricanes and sea-level rise (SLR), and human development pose the greatest threats to the longevity of this ecosystem which, in turn, places species that are endemic to this unique habitat at risk of extinction.

The Rim Rock Crowned Snake and the Key Ringed-Necked Snake are being considered for listing by the U.S. Fish and Wildlife Service (USFWS). To aid the agency's decision, it must be able to forecast species' responses to potential future environmental conditions, as well as to different conservation and management actions. Yet, the information needed to complete these forecasts—such as population trends, life history traits, habitat use, and future land use and climate conditions—is often lacking for most rare species. This is especially problematic for assessments of species resiliency to changes in climate and land use.

When these types of data are lacking, information on habitat quality can be used to help determine how a species will respond to change. First, this project gathered current and historical records for both species from various sources such as museum specimens, inventories, and other personal account. Then, we identified potential future changes in habitat that could result from different management actions, such as habitat acquisition or restoration, and environmental conditions, such as changes in the frequency and intensity of tropical storms and rates of SLR. Researchers then explored the potential impacts of these habitat condition changes on the Rim Rock Crowned Snake and Key Ring-Necked Snake.

This information can be used by the USFWS to help make decisions about the need to protect these species under the Endangered Species Act and could inform the conservation, management, and recovery of other at-risk species found in the pine rockland ecosystem. This work supports the Secretary of Interior's priority to create a conservation stewardship legacy by using science to identify best practices to manage land and water resource and adapt to changes in the environment.

3. TECHNICAL SUMMARY:
Our main goal was to develop alternative scenarios (i.e. models) to examine the future consequences of on-going habitat change, management practices and SLR on the viability of populations of Rim Rock Crowned Snake and Key Ring-Necked Snake. The USFWS requested this information to aid in developing their Species Status Assessments (SSA)—a tool used by the agency in determining the potential need for protection under the Endangered Species Act—for each species.

To meet this goal, we (1) used available data and species distribution to assess current conditions in existing pine rockland habitat where these two species are found. We determined the current extent of pine rockland habitat using current and historical species' occurrence records and evaluated any reductions in habitat area attributable to SLR or urbanization. (2) We then used available climate change predictions to assess the future impact of projected climate change and SLR on pine rockland habitat, specifically addressing the potential for future pine rockland areas to become degraded due to high tidal inundation. (3) Last, we used inundation 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 of SLR and development. Inundated areas were modeled by applying SLR projections to the bathtub model approach in ArcGIS (Murdukhayeva et al. 2013), whereas the extent of human development was investigated by the SLEUTH model (Clarke 2008, https://seregion.databasin.org/datasets/e5860ced8b4844e88431cdbefe425e1a/).

Achievements and accomplishments:
SE CASC funding enabled us to employ Dr. Suresh Subedi as a contractor to develop the models used to address the above goals. Dr. Subedi employed habitat suitability and species occurrence data as a proxy for population viability (Ferrer-Sánchez et al. 2016; Préau et al. 2020) because actual demographic data are sparse for these two species. This project yielded informative results that have assisted the USFWS in writing their Species Status Assessment (SSA) for the Rim Rock Crowned Snake and the Key Ring-Necked Snake. This information will be the basis for decisions made by the agency in whether listing either or both species under the Endangered Species Act is warranted.

Contribution to the advancement of scientific knowledge:
Expanding our understanding of how remaining patches of pine rockland habitat will be impacted by changes in climate and land use will help inform conservation and management decisions for these and other threatened species that are endemic to this imperiled ecosystem.

4. PURPOSE AND OBJECTIVES:
This project was intended to serve decision-makers tasked with protecting and conserving these two rare and imperiled snake species. The original objectives we proposed (outlined above under #3) were not modified and they met the needs of the USFWS.

5. ORGANIZATION AND APPROACH:
(a) *Species records and habitat*: We found records from 1934 to 2016 of 49 *T. oolitica* and 47 *D. punctatus acricus* records from various sources such as museum specimens, inventories, and other personal accounts (Figure 1). To delineate pine rockland habitat, we used the Florida

Cooperative Land Cover Map (CLC) v3.3 (https://myfwc.com/research/gis/applications/articles/cooperative-land-cover/). This Florida CLC map resulted from a partnership between the Florida Fish and Wildlife Conservation Commission (FWC) and Florida Natural Areas Inventory (FNAI) and is a statewide land cover classification based on existing data and expert review of aerial photography. As fire inhibits the transition of pine rockland to hammock, rockland hammock patches are often embedded with pine rocklands. We defined "pine rockland" (pine) and "rockland hammock" (hammock) land cover classes as rockland habitat. Both pine and hammock plant communities are composed of species that share a requirement for freshwater resources. In pine rocklands soils are shallow (<10 cm in depth; Ross et al. 2003). Pine rockland has little organic matter and much exposed limestone (Snyder et al. 1990), whereas the soil depth in rockland hammocks is deeper, 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, rockland habitats are mostly found in areas highest in elevation.

(b) <u>*Sea-level rise and high-tide projections*</u>: Sea-level rise 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 U.S. Global Change Research Program and the National Ocean Council. The task force developed regional SLR responses on a 1-degree grid covering the coastlines of the U.S. 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, the flexure of the crust and upper mantle (due to melting of land-based ice); and vertical land movement (due to glacial isostatic adjustment, sediment compaction, groundwater and fossil fuel withdrawals, and other non-climatic factors; Sweet et al. 2017). For South Florida, sea-level is projected to increase between 0.4 m (1 ft.) and 3.18 m (8.4 ft.) 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 1) 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 1; Sweet et al. 2018). Minor (more disruptive than damaging), moderate (damaging) or major (destructive) coastal flooding (not associated with tropical storms) —0.5 m, 0.8 m and 1.2 m above a level slightly higher than the multi-year average of the daily highest water levels measured by NOAA tide gauges. (Sweet et al. 2018).

(c) <u>*Human development projection (SLEUTH model)*</u>: 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 (**s**lope, **l**and cover, **e**xcluded regions, **u**rban land cover, **t**ransportation, and **h**ill shade) 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 as developed by Dr. Keith C. Clarke (University of California Santa Barbara, Department of Geography) and modified by the U.S. Geological Survey (USGS). Urban growth probabilities were projected for the Southeast Regional Assessment Project (including all parts of Florida) throughout the 21st century. Datasets and GIS layers were obtained from Data Basin by the Conservation Biology Institute (https://databasin.org/datasets/e5860ced8b4844e88431cdbefe425e1a).

(d) *Effect of sea-level rise*: Inundated areas were modeled by applying SLR projections to a bathtub model approach in ArcGIS (Murdukhayeva et al. 2013). Grid cell became flooded if its elevation was less than the projected sea-level, resulting in inundated areas for a corresponding height increase in sea-level. Elevation data were downloaded through the USGS National Map Download Client (https://viewer.nationalmap.gov/basic/). A digital elevation model (DEM) of 1/9 arc-second resolutions (~3 m) was used to process inundated areas modeled by applying sea-level rise projections.

Future flooding was calculated by increasing the water level above mean sea-level surface by the projected amount of SLR. The model calculated total area flooded for a given SLR scenario, considered both marine overland flooding (e.g., flooded area connected to the ocean) and the groundwater flooding area (e.g., unconnected to the ocean but raised 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.

6. PROJECT RESULTS:
Associated data may be found in Barichivich and Walls (2021).

(a) *Current habitat*: The current area of rockland habitats (pine and hammock together) in the Lower Florida Keys is 5704.9 acres; pine forest makes up 1899.4 acres whereas hammock is 3805.6 acres. Big Pine Key has most of the pine habitat in the Lower Keys region, with an area of 1480.43 acres (78% of total pine rockland area), whereas four other islands, Little Pine Key, No Name Key, Cudjoe Key, and Sugarloaf Key contain only small areas of pine rockland. No pine forest exists in the Upper Keys. However, hammock occurs to a varying extent in many islands in the Upper Keys. The total area of hammock in the Upper Keys is 7005.6 acres. In eastern Miami-Dade, total rockland habitat area (pine combined with hammocks) is 2884.38 acres, with pine covering an area of 2275 acres and hammock covering 609.4 acres (Table 2). About 75% of current pine rockland habitat is under management by state and federal agencies.

(b) *Habitat loss due to SLR*: Using the regional SLR scenarios (low, intermediate and extreme), habitat change (in total area and percentage of current area) was calculated for decadal time intervals from 2030 to 2100. Changes in habitat area were calculated using the entire region (i.e., Miami-Dade County and the Florida Keys) using both pine and hammock habitat types together and separately for each habitat type. A significant amount of current habitat will 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% in habitat reduction by 2100 (Table 3). Under the medium SLR scenario, by 2100 about 69% of total habitat will be lost (Figure 3A), whereas almost all pine rockland habitat (96.7%) will be lost under extreme SLR scenario (Table 3).

Our results showed that threats vary between regions (Lower Keys, Upper Keys, and mainland) due to SLR. In the Lower Keys, a significant amount of current habitat will be lost due to SLR, for instance, 35% loss with 13 cm while almost 100% with 3.18 m SLR; whereas, in mainland (Miami-Dade), SLR threat is relatively low, which is expected, < 1% with 13 cm and 88%loss with 3.18 m SLR as remaining habitats in the mainland are at higher elevations (Figures 3C-D, Table 3).

(c) *Habitat lost due to human development*: Like the results from the model using future SLR scenarios, a large amount of pine rockland habitat will be lost due to human development (Figure 4). Under all three scenarios (extreme, medium and low), habitat loss will range from 31-39% of the current extent by 2100. A significant amount of pine rockland habitat will be lost by 2030 (31-34% for both habitats pine and hammock together and 41-47% for pine only; Figure 4A). The percentage of pine habitat lost will be much higher than hammock habitat, with 41-55% of pine habitat potentially lost between 2030 and 2100.

The predicted extent of current pine rockland habitat loss due to human development varied across three regions (Figure 4B-D). The percentage of habitat lost in the Florida Keys (Lower and Upper Keys) was relatively low (less than 20% in the Upper Keys and less than 30% in the Lower Keys). In contrast, on the mainland (Miami-Dade), a significant amount of habitat loss was predicted (more than 60% by 2050 under any scenarios; Figure 4D).

(d) *Habitat degradation due to high tide effects*: Habit degradation because of increased flooding associated with high tides showed that one third to nearly all of the rockland habitats in south Florida is predicted to be affected to some degree, depending on the rate and magnitude of SLR (Figure 5). For the moderate high tide scenario, projections showed that the high tide effect by 2030 predicted to result in 50 to 60 % of the habitat area being affected; by 2050, increasing high tides predicted to affect 53 to 69 % of the rockland habitat in south Florida, increasing to 56-83% of the area by 2070 (Figure 4A). In the Lower Keys, for the moderate high tide projection, almost the entire current rockland habitat predicted to be affected by 2030 (Figure 5B). In the Upper Keys, by 2030, about 43-50% of habitat (only rockland hammock present) predicted to be affected with moderate high tide (Figure 5C). However, a very low amount of rockland habitat predicted to be affected by high-tide in the mainland (Figure 5D).

7. ANALYSIS AND FINDINGS: See section 6, above.

8. CONCLUSIONS AND RECOMMENDATIONS:
Discuss the results of the project and what you found out.
Under all SLR scenarios, our models predicted that habitat on small islands with lower elevation was most likely to be lost. Under the most extreme SLR scenario, most current habitat predicted to be permanently or semi-permanently flooded within 40-50 years. Under this scenario, we hypothesize that current rockland habitats 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 Keys often persists because of effective protected area management, which includes maintaining connectivity of interior areas and freshwater availability via healthy freshwater lenses. In urbanized areas, however, future

habitat loss will likely reflect an interaction between development and SLR, which could accelerate ecosystem change in the rockland forests of South Florida, including altered groundwater quality. Indeed, even in protected areas, saltwater intrusion may transform rockland freshwater habitat to halophytic habitat (Ross et al. 2009).

We estimate that, by 2030, 54% of the remaining pine rockland habitat -- about half of that remnant 3%-- in South Florida and the Florida Keys predicted to be lost due to urban development, most of which has occurred preferentially at the highest elevations. Such activity places our focal species and other endemic flora and fauna of rockland communities at an increased risk of extinction. Our lowest estimate of habitat loss, 24%, from a 0.4 m rise in sea-level, would still be a substantial reduction of rockland in the Florida Keys. The remnant rockland remaining after accounting for SLR could become salt-tolerant habitat and vulnerable to loss to urban development. Since 1970, new residential development has targeted relatively high elevation rockland areas (Lopez et al. 2004) that is at a lower risk of flooding from SLR or tidal activity. If current development trends continue, we predict that the amount of rockland habitat will decrease significantly with a concomitant loss of habitat for endemic species.

Our results also indicated that habitat loss due to urbanization differed between the Florida Keys and the mainland. Historically, urban development decreased the extent of pine rockland in the 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 of the Florida Keys (Gallagher 1991), with most of the remaining habitat placed under state or federal management. By contrast, in Miami-Dade County, much of the remaining fragments of rockland are privately owned and are thus at a greater risk for future development. The Florida Keys contain 76% of the 453 patches of rockland hammock identified by Cox et al. (1994), and 52.5% of all the patches are <1 ha in size (Enge 1997). Our results showed that, with the projected rate of urban development, at least 60% of the existing rockland habitat in Miami-Dade County will be lost by 2030. Therefore, human development on the mainland is a serious threat to the conservation of biological diversity in South Florida in this decade.

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 submerged (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 tides, when saltwater could inundate the root zone of terrestrial vegetation. Our results predicted that a large amount of habitat will be degraded with projected high tide across all regions in 10 years (i.e., more than 50% of current habitat). In the pine rockland environment, where trees predominantly use fresh ground water directly, especially during the dry season (Saha et al. 2009), an increase in underground salinity will have a detrimental effect on plant transpiration. Further, our results showed that the remaining rockland habitat in the Lower Keys—the only area where *D. punctatus acricus* is found—is expected to suffer 50-80% degradation by 2030 due to high-tide.

A rise 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 (Sternberg and

Swart 1987; Ish-Shalom and others 1992; Ross et al. 1994; Ogurcak 2016, Subedi et al. 2020). Slash pine (*P. elliotii* var. *densa*), a dominant canopy species in the rocklands, is sensitive to <2ppt salinity (Subedi et al. 2020). Therefore, even in upland areas that are not inundated, increasing the salinity of the shallow ground water table can cause extensive freshwater vegetation die-off, leading to habitat degradation and unfavorable conditions for *T. ollotica* and *D. punctatus acricus*. In some areas, pine rockland forest is indeed being replaced by mangrove-dominated halophytic communities and other transitional communities (i.e. buttonwood in the Florida Keys; Ross et al. 1994).

Pine rockland also has scant soils with pockets of organic matter that accumulate in solution holes and shallow depressions in the oolitic limestone (Enge 1997). Piles of rock rubble and crevices in the limestone provide refugia for fossorial snakes. In addition, the limestone is well drained and standing water is seldom present at these higher elevations. This microhabitat serves as a vital refugium in which snakes may avoid predation, temperature extremes, and fires that eliminate pine needle litter (Porras and Wilson 1979). However, SLR and high tide could flood the subterranean water table with saline water, thus affecting the microhabitat that these fossorial snakes use.

Model uncertainties
Our analyses indicate that SLR may result in significant loss of terrestrial habitat for pine rockland species in South Florida and the Florida Keys. Our projected scenarios treat the islands' current 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 take into account ancillary factors that could substantially influence the future of the islands. These include shoreline erosion causing land loss, redistribution of sediments (resulting in both gains and losses of land area), onshore sand deposition by overwash during high wave activity, change in fire dynamics, as well as changes in litter accumulation and invasive species. An increase in the groundwater table during SLR could also displace underground refugia for semi-fossorial snakes like *T. ollitica* and *D. punctatus acricus*. 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.

Did you encounter any problems during the project?

Our only issue was a glitch in employing Dr. Subedi, which occurred about a month into the project. Consequently, he was not employed by our contractor for several months until the issue was resolved. Once Dr. Subedi was able to resume work, however, he completed the requested products <u>*in advance*</u> of the deadline originally established by USFWS.

What project tasks were not completed and why?

We completed all proposed project tasks

What would you do differently if you did this project again?

The previously mentioned glitch delayed project progress, though we were able to complete the work ahead of schedule. A different hiring mechanism may have allowed the work to progress more smoothly.

Based on what you've learned, what are logical next steps related to the project you have completed?

- *Model root-zone inundation and estimate degradation of habitat not directly inundated by SLR.*
- *Apply this model to other imperiled species, i.e. Florida Keys Mole Skink*
- *Use this model to develop and assess management scenarios meant to mitigate further declines and potentially reverse losses of habitat critical to these species.*
- *Develop decision support tools based on these models.*

9. MANAGEMENT APPLICATIONS AND PRODUCTS:
Describe how you expect your study findings to be used in the management of natural or cultural resources.

The expectations for the outcome of this study were two-fold. **First**, our findings contribute to the advancement of scientific knowledge by expanding our understanding of how remaining patches of rockland habitat will be impacted by changes in climate and land use. **Second**, our results can help inform conservation and management decisions for these and other threatened species that are endemic to this imperiled ecosystem. At the request of the USFWS, we developed alternative scenarios (i.e. models) to examine the future consequences of on-going habitat change, management practices and SLR on the viability of populations of Rim Rock crowned snake and Key ringneck snake. The USFWS requested this information to aid in developing their Species Status Assessments (SSA) and Recovery Implementation Strategies (RIS)—a tool used by the agency in determining the potential need for protection under the Endangered Species Act—for each species.

Habitat loss and fragmentation are major impediments to the recovery and management of endangered species (Klimstra et al. 1974, Folk 1991, U.S. Fish and Wildlife Service 1999). We predicted that, by 2030, 60-75% of pine rockland habitat will be lost in the Miami-Dade region of South Florida solely due to development. Almost 70% of the remaining pine rocklands are managed by state or federal agencies in the islands that comprise the Florida Keys. Yet, to our knowledge, existing conservation or management plans do not address the future ecosystem change that SLR will bring. Considering the extensive fragmentation of remaining pine rockland habitat, the low vagility of these species (Krysko et al. 2019) and the threat of saltwater inundation to their remaining habitat, *T. oolitica* and *D. punctatus acricus* currently face a high risk of extinction. As land is lost to sea level rise and to development, the remaining amount of habitat will not only be smaller in total size but could also be reduced to smaller and more isolated fragments. As these habitats shrink and are encroached upon by development, maintaining a fire regime that will sustain pine rocklands will be increasing difficult. Managers may wish to use this model to determine which tracts of habitat are likely to be the most viable in the future in terms of size and connectivity of fragments, rather than just focus on total area of habitat projected. This would help not only predict the future conditions for the snake species, but also to direct management actions including habitat protection and management.

Additional considerations for managers and decision makers are to identify high elevation, core pine rockland sites situated within landscapes and target them as recipients for translocations, leading to the establishment of new, viable populations of these species.

What managers, administrators, and decision makers did you work with during the project? Please include names, agencies, and their roles in the study (e.g., advisor, aided with project design, contributed data, tested a decision support tool).

Jeff Howe and John Tupy, South Florida Ecological Services Office, Vero Beach, FL. Emails: jeffrey_howe@fws.gov; john_tupy@fws.gov.

Both Jeff and John acted as advisors and aided with project design.

What decision analysis methods were used in this study? What decision support tools were developed through your study?

None

To the best of your knowledge, what specific resource management decisions will be made or improved upon because of the results and/or products of this research?

As previously mentioned, The USFWS requested this information to aid in developing their Species Status Assessments (SSA) and Recovery Implementation Strategies (RIS)—a tool used by the agency in determining the potential need for protection under the Endangered Species Act—for each species. Development and approval of these SSA's are underway.

Provide a quote attributable to a stakeholder/partner in your project that describes the way(s) in which results of your project have or will be used.

Excerpts from various emails from John Tupy, USFWS:
"Thank you for all of your hard work Suresh. We are currently finalizing our SSA report drafts to be sent to Service reviewers which incorporates your information and results. We will be in touch if we have questions or need to discuss some of your results further."

"Suresh did an excellent job summarizing the data and providing what we needed for the two snake reports."

"I finally got a chance to look this report over and it looks great. The introduction and background info is especially helpful. Great job on the diagram too. It will be interesting to see how results differ in the other regions, especially mainland."

10. OUTREACH AND COMMUNICATION:
Dr. Subedi gave two presentations on this work:
- Oral presentation in the Coastal and Estuarine Species Breakout Session of the Southeast Climate Adaptation Science Center Symposium November 2019
- webinar as part of SE CASC Science Series in December 2020

One publication is currently in preparation:

Subedi, S.C., J.A. Hogan, W.J. Barichivich, M.S. Ross, S.C. Walls, R. Boyles and J. Tupy. Future Changes in Habitat Availability for Two Specialist Snake Species in the Imperiled Pine Rockland of South Florida, U.S.A.

Describe how the study results were or will be communicated to managers and decision-makers. We were in frequent communication with USFWS personnel, mainly by e-mail but we also had several conference calls throughout the course of the study.

DATA AVAILABILITY

Data are available in Barichivich and Walls (2021).

LITERATURE CITED:

Barichivich, W.J., and Walls, S., 2021. Data release for Predicting the impacts of future sea level rise on specialist snake species in the imperiled pine rockland ecosystem of South Florida: U.S. Geological Survey data release, https://doi.org/10.5066/P9TRHCLU.

Cox, J., R. Kautz, M. MacLaughlin, and T. Gilbert. 1994. Closing the gaps in Florida's wildlife habitat conservation system. Florida Game and Fresh Water Fish Comm. Off. Environ. Serv., Tallahassee. 239pp.

Enge, K.M. 1997. Habitat occurrence of Florida's native amphibians and reptiles. Tech. Rep. No. 16. Florida Game and Fresh Water Fish Comm., Tallahassee. 44 pp + vi.

Ferrer-Sánchez, Y., and R. Rodríguez-Estrella. 2016. How rare species conservation management can be strengthened with the use of ecological niche modelling: The case for endangered endemic Gundlach's Hawk and Cuban Black-Hawk. *Global Ecology and Conservation* 5:88–99.

Krysko K.L., K.M. Enge, and P.E. Moler 2019. Amphibians and Reptiles of Florida. University of Florida Press, Gainesville, FL.

Murdukhayeva, A., P. August, M. Bradley, C. LaBash, and N. Shaw. 2013. Assessment of inundation risk from sea level rise and storm surge in northeastern coastal national parks. *Journal of Coastal Research* 29:1–6.

Ogurcak, D.E. 2016. The Effect of Disturbance and Freshwater Availability on Lower Florida Keys' Coastal Forest Dynamics. Ph.D dissertation. Florida International University.

Porras, L., and L.D. Wilson. 1979. New distributional records for *Tantilla oolitica* Telford (Reptilia, Serpentes, Colubridae) from the Florida Keys. *Journal of Herpetology* 13:218–220.

Préau, C., I. Nadeau, Y. Sellier, F. Isselin-Nondedeu, R. Bertrand, M. Collas, C. Capinha, and F. Grandjean. 2020. Niche modelling to guide conservation actions in France for the endangered crayfish *Austropotamobius pallipes* in relation to the invasive *Pacifastacus leniusculus*. *Freshwater Biology* 65:304–315.

Ross, M.S., J.J. O'Brien, and L. Sternberg. 1994. Sea-level rise and the reduction in pine forests in the Florida Keys. *Ecological Applications* 4:144–56.

Ross M.S., C.L. Coultas, and Y.P. Hsieh 2003. Soil-productivity relationships and organic matter turnover in dry tropical forests of the Florida Keys. *Plant and Soil* 253:479–492.

Ross M.S., J.J. O'Brien, R.G. Ford, K. Zhang, and A. Morkil. 2009. Disturbance and the rising tide: the challenge of biodiversity management on low-island ecosystems. *Frontiers in Ecology and the Environment* 7:471–478.

Saha, A.K., L. O'Reilly, L.D.S. Sternberg, and F. Miralles-Wilhelm. 2009. Linking water sources with foliar nutrient status in upland plant communities in the Everglades National Park, USA. Ecohydrology: Ecosystems Land and Water Process Interactions, *Ecohydrogeomorphology* 2:42–54.

Subedi, S.C., Sternberg, L., DeAngelis, D.L., Ross, M.S. and Ogurcak, D.E., 2020. Using carbon isotope ratios to verify predictions of a model simulating the interaction between coastal plant communities and their effect on ground water salinity. *Ecosystems,* 23(3), pp.570-585.

Subedi, S.C., Hogan, J.A., Ross, M.S., Sah, J.P. and Baraloto, C., 2019. Evidence for trait-based community assembly patterns in hardwood hammock forests. *Ecosphere, 10(12),* p.e02956.

Sweet, W.V., G. Dusek, J. Obeysekera, and J. Marra. 2018. Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold. NOAA Tech. Rep. NOS CO-OPS 86, 44p.

Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas. 2017. Global and regional sea level rise scenarios for the United States. NOAA Tech. Rep. NOS CO-OPS 83.

Snyder, J.R., A. Herndon, and W.B. Robertson. 1990. South Florida rockland. in: Myers, R.L., Ewel, J.J. (Eds.), Ecosystems of Florida. University of Central Florida Press, Orlando, FL, pp. 230–277.

Table 1. High tide thresholds (in meters, m) predicted by Sweet et al. 2018.

High tide flooding threshold	Lower Keys	Upper Keys	South-eastern Miami-Dade
Minor	0.52	0.51	0.53
Moderate	0.82	0.81	0.82
Major	1.19	1.18	1.20

Table 2. The current extent of available habitat in South Florida (pine rockland and rockland hammock) and percentage habitat within the protected acres across three regions (see Barichivich and Walls [2021] for data).

Region	Habitat type (acres)		Total habitat (acres)	Total Protected area (acres)	% of protected area
	Pine Rockland	Rockland Hammock			
Lower Keys	1899.4	3805.6	5705	4192.5	73.5
Upper Keys	0	7005.6	7005.6	5190.5	74.1
Miami-Dade	2275	609.4	2884.4	2184.4	75.7

Table 3. Predicted habitat changes with regional sea-level rise (SLR) (see Barichivich and Walls [2021] for data).

SLR (m)	Year	Scenario	Habitat lost (%)	Pine lost (%)	Rockland Hammock lost (%)	Habitat lost LK	Habitat lost UK	Habitat lost MD
0.13	2030	Low	34.9	22.9	39.3	63.5	25.7	0.7
0.23	2030	Medium	40.7	28.2	45.2	73.9	29.9	1.0
0.41	2030	Extreme	49.1	35.3	54.1	86.4	38.3	1.6
0.17	2040	Low	37.2	25.1	41.6	67.9	27.1	0.8
0.31	2040	Medium	44.8	31.8	49.5	80.4	33.7	1.3
0.6	2040	Extreme	55.3	40.0	60.9	93.3	46.3	2.1
0.22	2050	Low	40.1	27.7	44.6	73.0	29.5	1.0
0.42	2050	Medium	49.5	35.6	54.5	86.9	38.7	1.6
0.89	2050	Extreme	62.7	45.0	69.2	98.4	58.0	3.6
0.26	2060	Low	42.3	29.6	46.9	76.5	31.3	1.1
0.54	2060	Medium	53.5	38.7	58.9	91.6	43.7	2.0
1.23	2060	Extreme	69.1	47.3	77.1	99.6	69.8	7.0

SLR (m)	Year	Scenario	Habitat lost (%)	Pine lost (%)	Rockland Hammock lost (%)	Habitat lost LK	Habitat lost UK	Habitat lost MD
0.31	2070	Low	44.8	31.8	49.5	80.4	33.7	1.3
0.68	2070	Medium	57.6	41.5	63.4	95.2	49.6	2.4
1.63	2070	Extreme	76.6	58.1	83.4	99.7	79.1	24.7
0.34	2080	Low	46.2	33.0	51.0	82.4	35.1	1.4
0.83	2080	Medium	61.3	44.1	67.6	97.7	55.6	3.2
2.09	2080	Extreme	84.6	71.4	89.4	99.7	88.0	46.5
0.38	2090	Low	47.9	34.4	52.8	84.8	36.9	1.5
1	2090	Medium	65.1	46.1	72.1	99.2	62.3	4.5
2.61	2090	Extreme	91.2	81.9	94.6	99.7	95.1	64.9
0.4	2100	Low	48.7	35.0	53.7	85.9	37.8	1.5
1.17	2100	Medium	68.1	46.9	75.9	99.5	68.1	6.2
3.18	2100	Extreme	96.7	94.9	97.4	99.7	97.7	88.2

Figure 1. Historical records of both snake species across South Florida and Florida Keys: A) *T. oolitica* and B) *D. punctatus acricus* (see Barichivich and Walls [2021] for data).

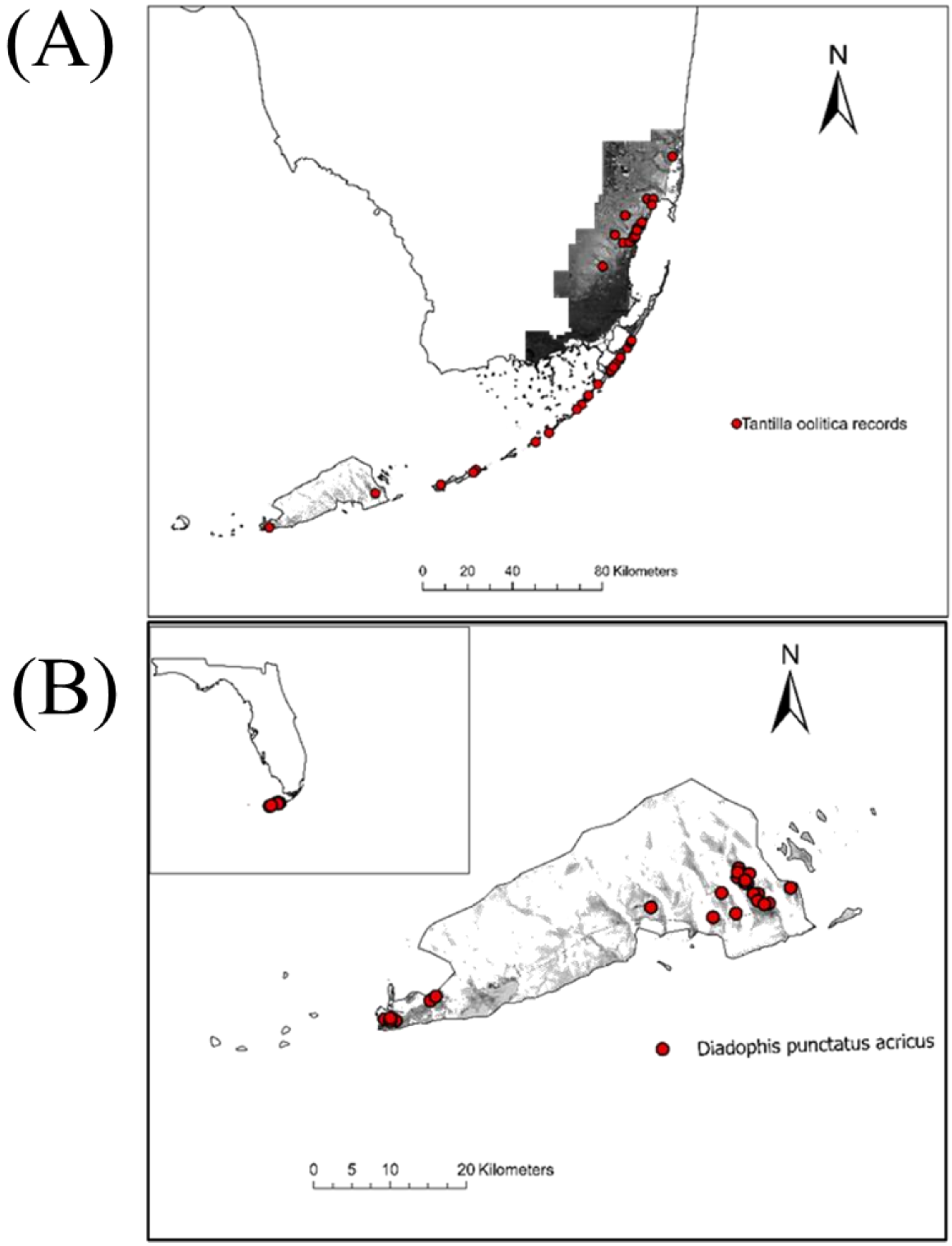

Figure 2. (A) Location of Florida within USA. Locations of current pine rockland habitat for two snake species in (B) Eastern Miami-Dade, (C) the Lower Keys and (D) Upper Keys of Florida, USA. Pine rockland habitat in Long Pine Key is shown on the map but was not considered as current habitat for snake species because of the lack of records for either species in this area (see Barichivich and Walls [2021] for data).

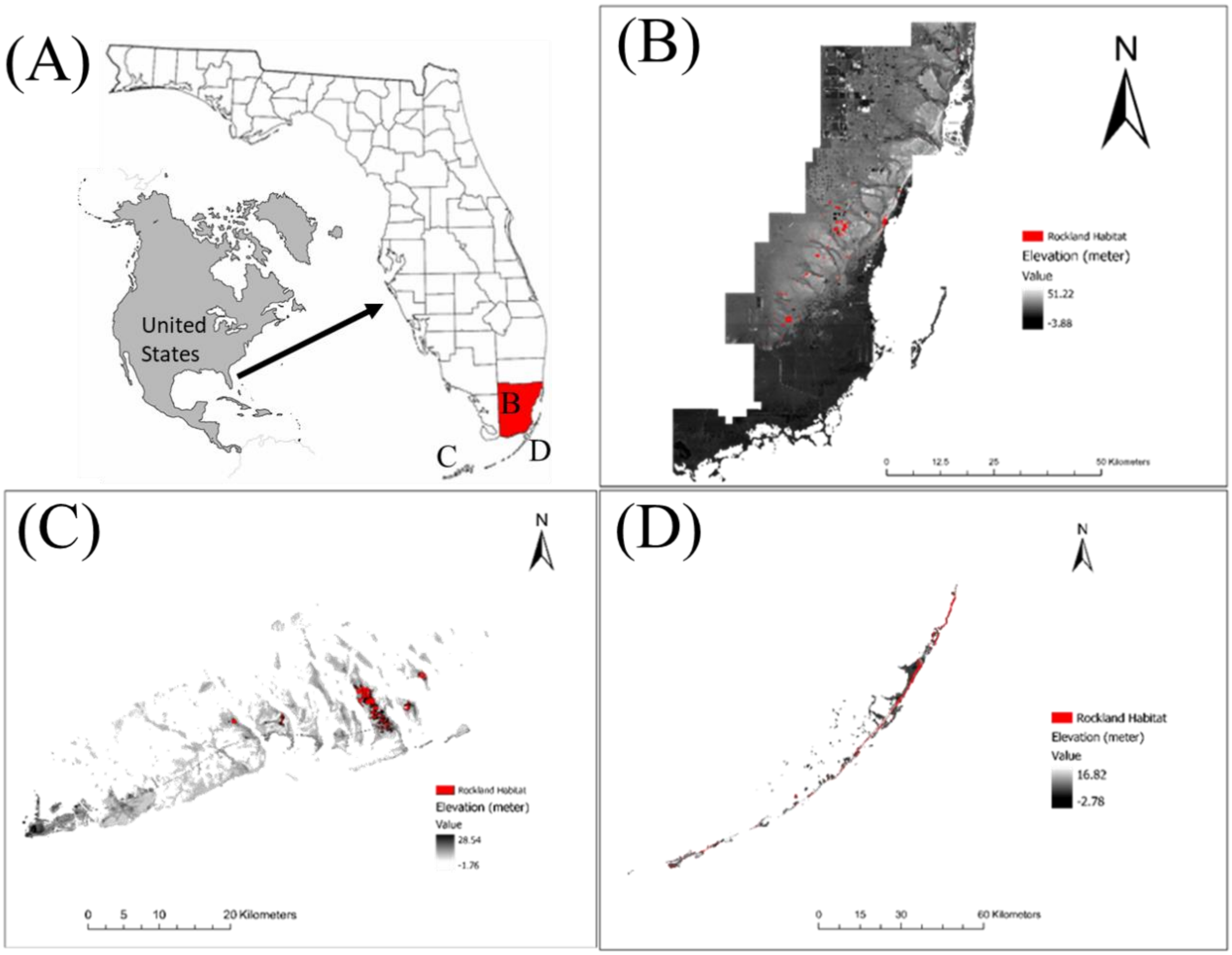

Figure 3. Habitat loss due to sea-level rise under three scenarios (extreme, medium and low) A) the whole region (Florida Keys and Mainland together), B) Lower Keys only, C) Upper Keys only, and D) Miami-Dade (Mainland) only (see Barichivich and Walls [2021] for data).
.

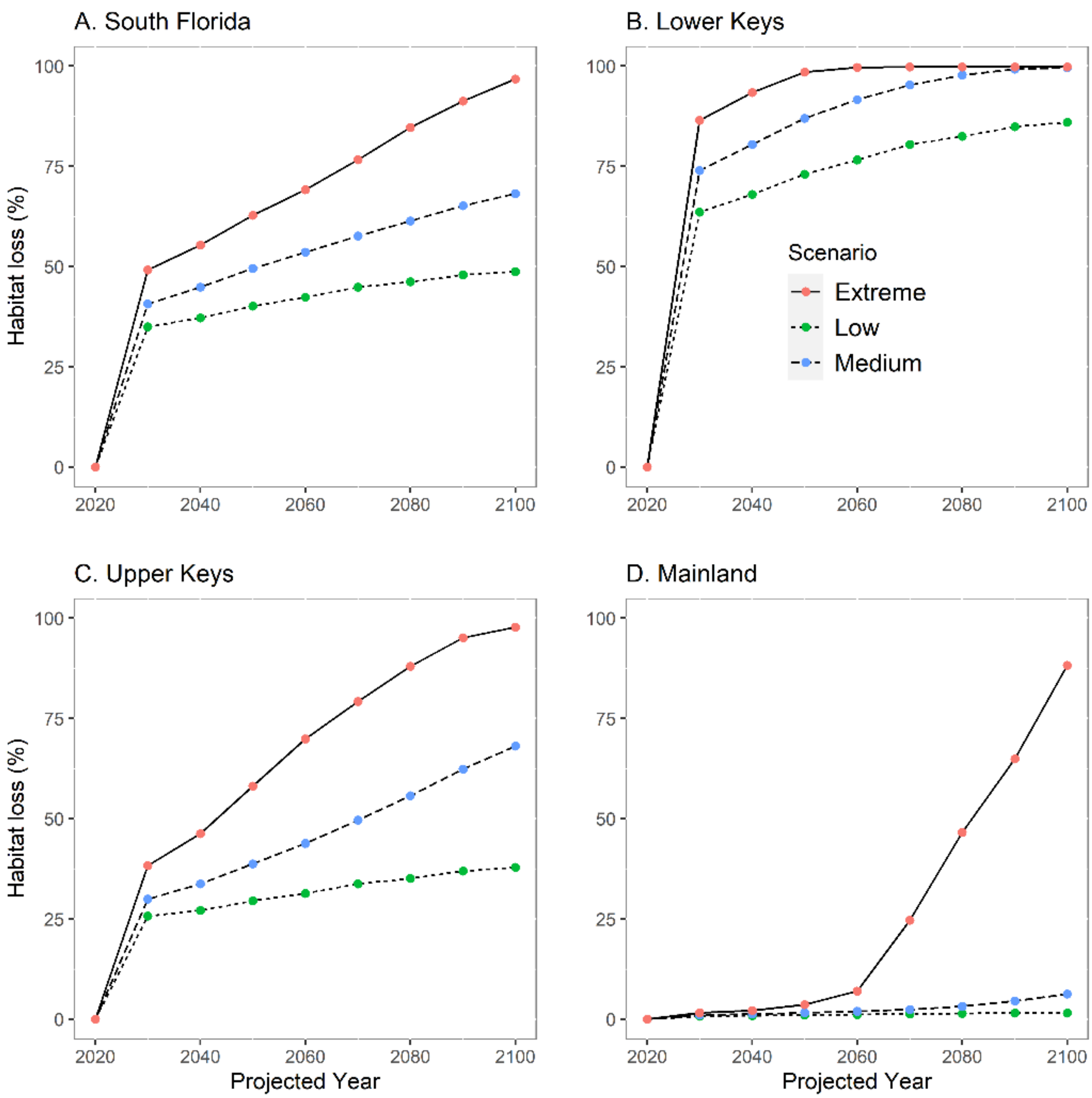

Figure 4. Percentage of pine rockland habitat lost under three development scenarios (low, medium, and extreme) for both pine and hammock together across A) whole area in South Florida, B) Lower Keys only, C) Upper Keys only, and D) Miami-Dade (Mainland) only (see Barichivich and Walls [2021] for data).

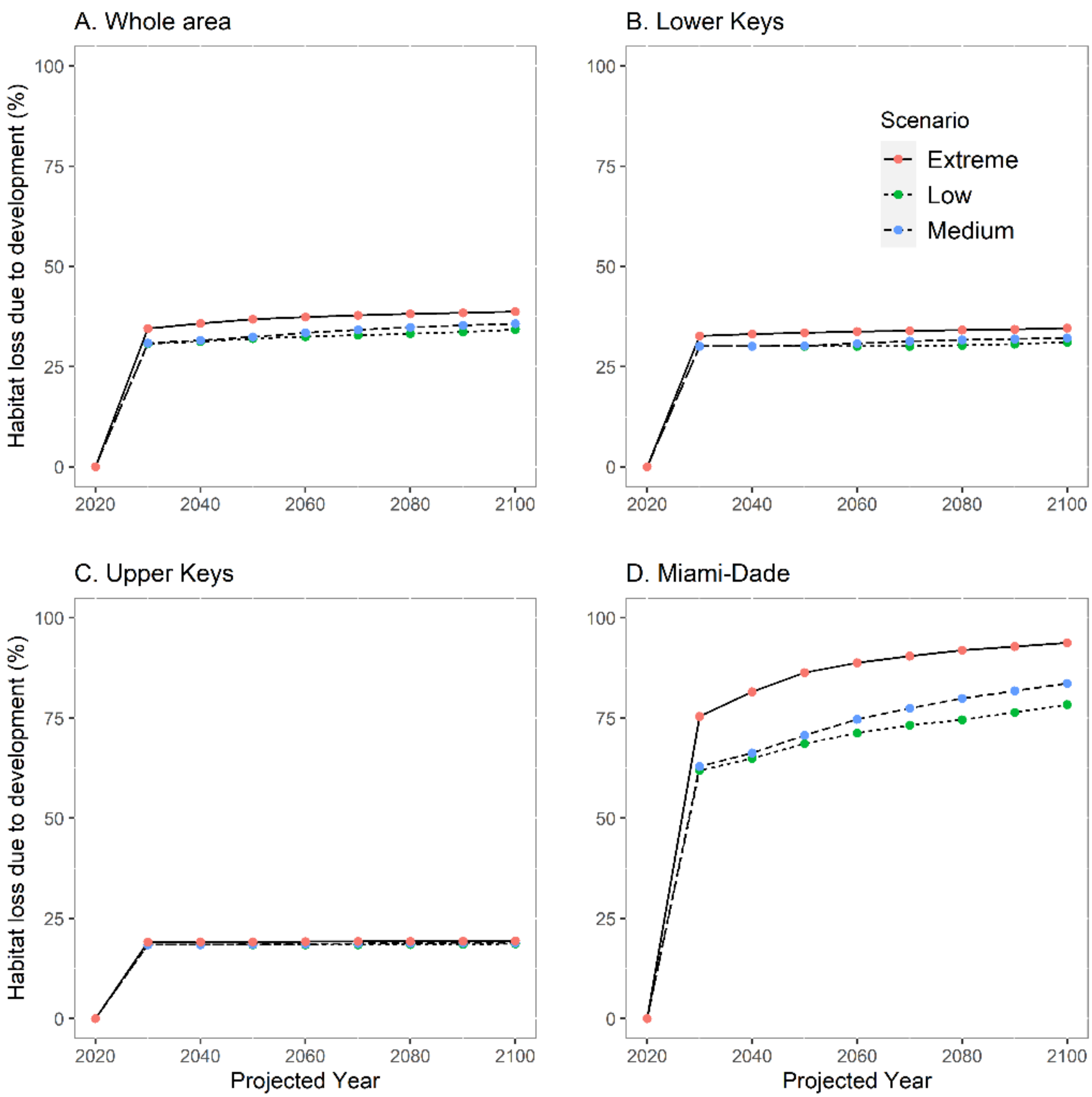

Figure 5. Percentage of affected habitat under a moderate high tide projection (ST1) for extreme (red symbols), medium (blue symbols) and low (green symbols) sea level rise scenarios in decadal time intervals. Percentage of affected habitat for A) South Florida combined (Lower Keys, Upper Keys, and Mainland)) B) Lower Keys only, C) Upper Keys only, and D) Mainland only (see Barichivich and Walls [2021] for data).