



Seasick: Why Value Ecosystems Severely Threatened by Sea-Level Rise?

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Received: 7 April 2020 / Revised: 8 September 2020 / Accepted: 8 October 2020
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Abstract

Climate change will alter natural areas on a global scale within the next century. In areas vulnerable to climate change, scientists are regularly challenged to justify the resources needed for research and conservation. We face what may seem like a losing battle, especially in low-lying coastal areas where sea-level rise is predicted to severely degrade or destroy many ecosystems. Using sea-level rise in the low-elevation state of Florida, USA, as a case study, we argue that it is critical to remain engaged in the research, restoration, and conservation of natural areas threatened by climate change for as long as possible. These areas will continue to provide invaluable ecological and societal benefits. Additionally, uncertainty surrounding climate change forecasts and their ecological impact leaves room for optimism, research, and actions that are necessary for developing adaptation plans and mitigating further sea-level rise and other consequences of climate change. We urge scientists and particularly students beginning their careers not to forego research and conservation efforts of these imperiled lands but to face this unprecedented challenge with determination, creativity, and solution-based strategies.

Keywords Anthropocene · Conservation · Florida · Research · Sea-level rise

Introduction

We have entered the Anthropocene, an epoch of unprecedented human-induced alteration of our planet (Zalasiewicz et al.

Communicated by Kenneth L. Heck

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2008). Humans have polluted the air and oceans, facilitated exotic species invasions, and simplified ecosystems (Hooper et al. 2012; Zalasiewicz et al. 2008). However, the greatest threat to the planet's ecology may be climate change, which is expected to alter global weather patterns, species distributions, and ecosystem function within our lifetime (IPCC 2014; Scheffers et al. 2016). Many of these effects already are being felt (Soja et al. 2007; Rowe et al. 2015; Trenberth et al. 2015). Temperatures are already rising, leading to the melting of polar ice caps and expanding water volume in the oceans (Gornitz et al. 1982; Mörner 2017; van den Broeke et al. 2016). These conditions put coastal areas at increased risk with entire ecosystems predicted to be lost or redistributed due to sea-level rise (Nicholls and Cazenave 2010). It is easy to question the value of research and conservation efforts if the loss of conserved areas, particularly in low-lying coastal zones, is inevitable (Table 1; Swaisgood and Sheppard 2010). Should we instead focus our limited resources on areas that face less dire consequences and possess a higher “probability for success” as some champions of conservation triage suggest (Hobbs et al. 2003; Bottrill et al. 2008)? For example, perhaps restoration programs should prioritize areas at higher elevations over those more likely to be lost to sea-level rise (Courchamp et al. 2014; Southeastern Association of Fish and

Table 1 Evidence of de-prioritization of low-lying coastal areas for research, management, restoration, and conservation

Research funding	US President Donald Trump's 2020 federal budget proposal seeks to eliminate the National Sea Grant Program, which, among other missions, conducts research on the impact of climate change on coastal ecosystems (as summarized in Ledford et al. 2019).
Scientific sentiment	Some scientists have argued in favor of conservation triage, which prioritizes conservation efforts based on the value of species and ecosystems when funding is limited (Hobbs et al. 2003; Bottrill et al. 2008). For example, the projected fate of islands in the face of sea-level rise should be considered when prioritizing islands for invasive species eradication (i.e., low-lying islands should receive lower priority because they will likely be lost (Courchamp et al. 2014)).
Management	Assessment by the Center for Biological Diversity indicates insufficient climate action plans/adaptation strategies have been developed by federal wildlife agencies, including the US Fish and Wildlife Service and National Marine Fisheries Service (Center for Biological Diversity 2013).
Land acquisition	National Coastal Wetlands Conservation Grant Program (United States Fish and Wildlife Service 2019) stipulated that all land acquisitions "must ensure long-term conservation (at least 20 years) of coastal resources" and grant dollars may not be used for "acquisition, restoration, enhancement, or management of lands to mitigate habitat losses." The Nature Conservancy (Anderson et al. 2016) and the Southeastern Association of Fish and Wildlife Agencies (2019) provide tools to exclude areas below ~ 1 m above current sea level from conservation land prioritization GIS data layers, a signal that these areas are undesirable for some conservation groups due to their potentially imminent inundation.
Public sentiment	Although the public may support the general concept of "living shorelines" (coastal restoration and erosion protection), they often do not prioritize "habitat restoration" for coastal ecosystems when confronted with other alternatives. A good understanding of the coastal management or restoration project appears to be much more important for generating project support than overall proenvironmental attitudes (Josephs and Humphries 2018).

Wildlife Agencies 2019). Or should conservation of low-lying areas remain a priority despite the threat of sea-level rise (Andréfouet et al. 2015; Kench et al. 2018)?

Extensive resources have been allocated by public and private entities to sustain coastal areas that are at risk of future inundation (Stein et al. 2014; Epanchin-Niell et al. 2017). However, some low-lying coastal areas are being de-prioritized for conservation, restoration, management, and research because they are likely to be lost or degraded (Table 1). In the USA, the federal response to coastal inundation has been muted by the politicization of climate change (Trump 2017; Selby 2019; Chinn et al. 2020) resulting in programs dedicated to coastal research, restoration, conservation, and resiliency planning being recently stripped of funding or eliminated entirely (Department of the Interior 2020; Office of Management and Budget 2020; Office of the Chief Financial Officer 2020). Budgetary shortfalls related to the COVID-19 pandemic are expected to further exacerbate this trend (e.g., McCleery et al. 2020; California Department of Finance 2020; Office of the City Manager 2020). Now, as signs of climate change increase in tandem with reduced funding, we face an unprecedented challenge to save fragile ecosystems.

As early-career scientists in Florida (USA), we are often challenged by colleagues, friends, family, and the public to defend our research and the investments made to the conservation of imperiled species and ecosystems. Florida is a low-

lying state with extensive, biologically diverse tidal shorelines and world-famous wetlands. Much of this may be lost by 2100 if sea levels rise by 2 m (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group 2015; Fig. 1). Using sea-level rise (hereafter, SLR), "the most immediate, the most certain, the most widespread, and the most economically visible" effect of a changing climate (Pilkey and Young 2009, pp. 203), we first highlight the ecological and societal benefits of low-lying ecosystems. We then use Florida as a case study to present arguments for why continued scientific engagement in these vulnerable ecosystems is so important, what we stand to lose from abandoning coastal ecosystems, and what gains can be made from studying and protecting low-lying ecosystems. Despite discouraging projections, we urge other early-career scientists to continue to advocate for research and conservation in ecosystems most vulnerable to SLR.

Importance of Low-Lying Ecosystems to the Earth and to Society

Sea levels are projected to rise globally between 0.5 and 2.0 m by the turn of the century (Church et al. 2013; IPCC 2014; DeConto and Pollard 2016). The consequences of SLR will be most noticeable in low-lying coastal areas and islands worldwide (Reece et al. 2013; Schmidt et al. 2012), threatening

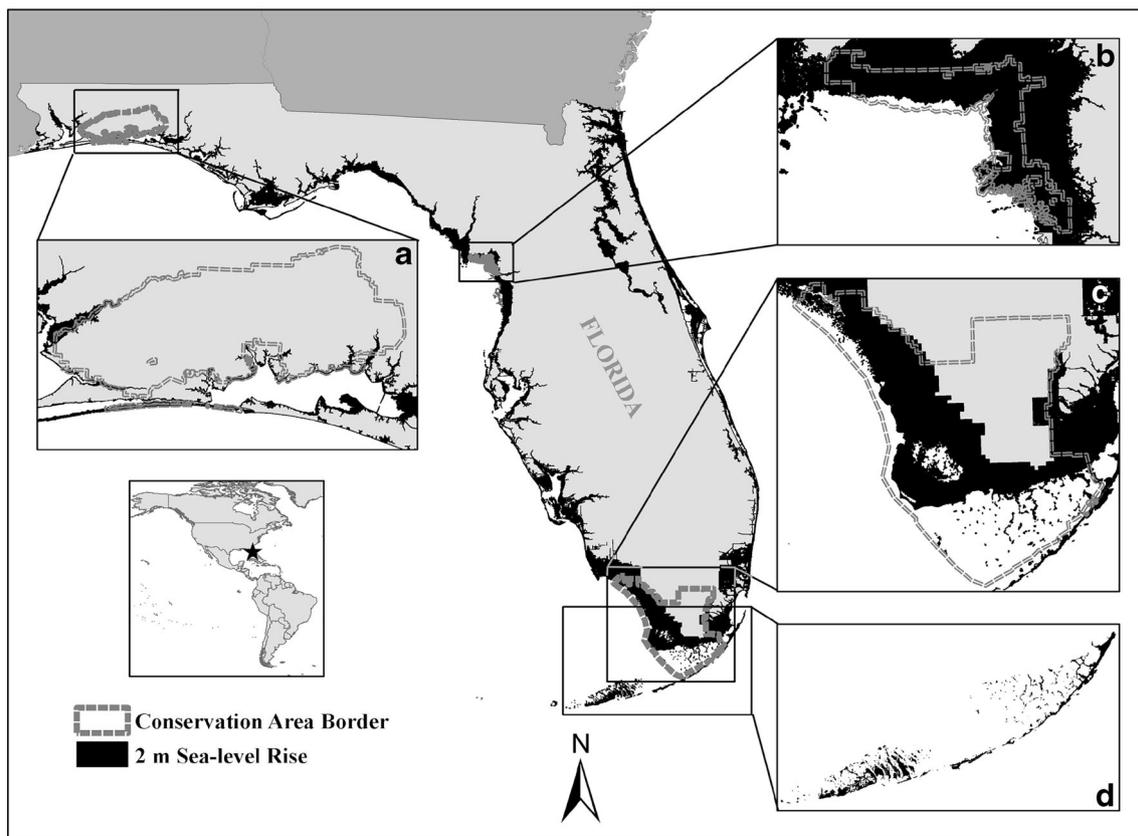


Fig. 1 Examples of coastal conservation areas predicted to experience major losses and ecosystem change due to sea-level rise in Florida, USA (black star): (a) Eglin Air Force Base, (b) Waccasassa Bay Preserve State Park, (c) Everglades National Park, and (d) the Florida Keys. The amount

of land area that is predicted to be covered by 2 m of sea-level rise by 2100 is based on elevation alone and does not account for potential additive effects (National Oceanic and Atmospheric Administration 2012)

many of the ecosystem services these areas currently provide (Nicholls 2011). Approximately 23% of the global population lives within 100 km of a coast (Small and Nicholls 2003), and over 600 million people live below 10 m above sea level (McGranahan et al. 2007). Coastal zones with high population density, low elevations, high rates of land subsidence, and limited adaptive capacity are predicted to be at the greatest risk from SLR (Nicholls and Cazenave 2010). For example, changes to ecosystems (e.g., erosion, flooding) in low-lying atoll nations are expected to render many of these islands uninhabitable (Roy and Connell 1991; Nicholls and Cazenave 2010; Hubbard et al. 2014).

Marked changes to coastal ecosystems due to SLR may be inevitable. Nevertheless, maintaining and restoring healthy, functioning ecosystems through science-based decision-making and conservation actions is more important than ever. Low-lying coastal areas provide critical ecosystem services such as water filtration, barriers against coastal erosion, and habitat for wildlife (Millennium Ecosystem Assessment 2005; Kirwan and Megonigal 2013; McKee et al. 2007). Coastal marshes, mangroves, oyster reefs, and other littoral communities (e.g., seagrass beds and coral reefs) reduce water velocities and flooding from storms (Arkema et al. 2013;

Temmerman et al. 2013). Further, corals and mangroves act as foundational species by supporting thousands of other species (Ellison et al. 2005; Ellison 2019), such as many seabirds that nest on low-lying barrier islands (Spatz et al. 2014). Vegetated coastal ecosystems also mitigate future climate change by sequestering organic carbon, accounting for approximately half of all carbon stored in ocean sediments (Duarte et al. 2013). Protecting and restoring the functionality of these ecosystems will not only reduce the local effects of SLR but will also help to reduce climate change globally.

Healthy coastal ecosystems confer considerable economic value. Tourism drives many national and local economies as millions of tourists visit unique coastal ecosystems and coastal world heritage sites every year (Cui et al. 2013; Dehoorne and Tatar 2013; Ghermandi and Nunes 2013). Ecotourism activities centered around coastal ecosystems such as fishing and wildlife viewing generate billions of dollars annually (Brodie and Pearson 2016; National Marine Fisheries Service 2016; Southwick Associates 2011), and property values tend to increase with proximity to natural areas (Cape Ann Economics 2003; Correll et al. 1978). Healthy commercial fisheries also support livelihoods in coastal communities (National Marine Fisheries Service 2016). As the ecosystems on which these

activities depend continue to degrade due to SLR, our local, regional, and national economies will suffer. Annual losses in ecosystem services due to degradation and decline of the world's wetlands, many of which are found in low-lying coastal areas, are estimated to exceed US\$20 trillion (Gardner et al. 2015).

Functional coastal ecosystems also provide opportunities for the public to learn about and develop a connection to nature. For example, millions of people visit the 180 coastal refuges in the US National Wildlife Refuge System each year, where they learn about the estuarine, ecological, and biogeochemical processes that govern these wetland ecosystems (United States Fish and Wildlife Service 2012). Rare, unique flora and fauna occurring in ecosystems susceptible to SLR also inspire fascination, art, and photography around the world (Orlean 1998; Matilsky 2018; Petri 2016). Educational and artistic opportunities provided by healthy coastal systems will be lost if we abandon or allow these areas to potentially degrade. Further, degraded ecosystems may be perceived as normal and become the new standard for conservation efforts (i.e., shifting baseline syndrome; Papworth et al. 2009). Consequently, a true understanding of healthy ecosystems and associated conservation ethics will not be passed along to future generations (Jackson 1997; Papworth et al. 2009; Pauly 1995).

Coastal ecosystems, like all wild places, possess an inherent or intrinsic value that deserves protection for their esthetic, historical, and cultural significance, and not for any monetary value they confer to humans (Soulé 1985; Taylor 1986). Species represent unique evolutionary lineages (e.g., the island fox [*Urocyon littoralis*], endemic to the Channel Islands of California, Goldstein et al. 1999), and ecosystems represent unique assemblages in time and space (e.g., the Great Barrier Reef and its astounding biodiversity have evolved over the past 600,000 years; Flood and Heatwole 1986; Gray et al. 1992; Planes and Doherty 1997). This intrinsic value is particularly important for species or ecosystems with little apparent economic value that otherwise may receive low conservation priority. By continuing to conserve, learn from, and restore vulnerable ecosystems, we can protect the many values provided by these ecosystems and the species within them for as long as possible.

What We Stand to Lose: Florida as a Case Study for Low-Lying Ecosystems Worldwide

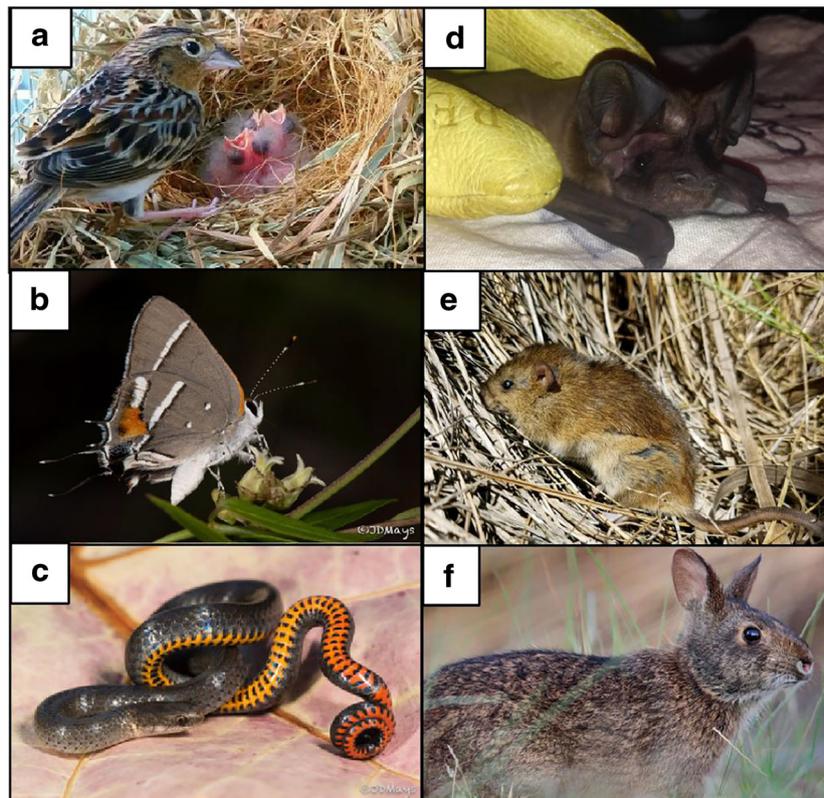
Florida represents the acute challenges faced by conservation biologists working in low-lying coastal ecosystems worldwide and is especially vulnerable to encroaching seas (Fig. 1). Florida is a biodiversity hotspot at the intersection of temperate and tropical biomes with vast expanses of fragile ecosystems that are found around the world including coral reefs, mangroves, coastal forests, tree islands, grasslands, salt marshes,

estuaries, sand dunes, and tidal flats (Myers and Ewel 1990). Like many other coastal areas worldwide, Florida's coastline has seen enormous increases in development and economic growth fueled in part by tourism. With 3660 km of tidal shoreline (Donoghue 2011), thousands of barrier islands, an average elevation of only 30 m (Carpenter and Provorse 1996), and approximately 10% of land area less than 1 m above sea level (Weiss and Overpeck 2003), many of Florida's human and natural ecosystems will be directly harmed by SLR.

Current models project that many of Florida's coastal ecosystems will be inundated by SLR, which will reduce, eliminate, or alter the spatial distribution of estuaries, beaches, mangrove forests, and salt marshes (Noss 2011; Zhang et al. 2011; Fig. 1). Additionally, coastal areas that remain are likely to be degraded from saltwater intrusion (Saha et al. 2011; Williams et al. 1999), coastal erosion, and higher storm surges (Pilkey and Young 2009). Currently, Florida has one of the highest rates of species endemism in North America (Maltby and Dugan 1994; Estill and Cruzan 2001; Sorrie and Weakley 2001). With many species dependent on coastal ecosystems, Florida's wildlife is extremely vulnerable to SLR (Reece et al. 2013; Box 1). One meter of SLR threatens to inundate nearly all of Everglades National Park (Noss 2011; Fig. 1c), endangering at least 21 rare species in this world heritage site (Saha et al. 2011). With a 1.5-m rise in sea level, the Florida Keys may be 91% inundated (Zhang et al. 2011), with concurrent losses of the region's many endemic species (Maschinski et al. 2011; Reece et al. 2013; Schmidt et al. 2012; Fig. 1d; Box 1). For example, remnant populations of unique orchid species face increased habitat deterioration from SLR and hurricanes (Raventós et al. 2015). As sea levels rise, ecosystems will experience shifts in distribution and composition (Geselbracht et al. 2011), including transitions from coastal forests to saltmarsh and from inland forests to tidal flats. Species reliant on coastal vegetation communities face extinction or regional extirpation if unable to migrate inland (Geselbracht et al. 2011; Hctor et al. 2010; Maschinski et al. 2011; Oetting 2010; Ross et al. 2009). While Florida's coastlines have expanded and contracted for millions of years (Donoghue 2011), those changes were not coupled with anthropogenic habitat alteration. Florida's widespread coastal development will prevent many coastal species from moving inland (Schmidt et al. 2012). Human migration inland from coastal cities will further diminish the availability and continuity of remaining refugia (Hctor et al. 2010; Noss 2011), impeding wildlife dispersal (Davis and Shaw 2001).

What We Stand to Gain from Continued Research and Conservation in Low-Lying Ecosystems

While major changes to coastal ecosystems in Florida and across the globe will most certainly occur, many questions



Box 1 Examples of species predicted to be severely affected by habitat loss and changes associated with sea-level rise in Florida. Species predicted to be extinct by 2100 with ≤ 2 m of sea-level rise and other synergistic effects (Reece et al. 2013): (a) Florida grasshopper sparrow (*Ammodramus savannarum floridanus*) (b) Bartram's scrub-hairstreak (*Strymon acis bartrami*) and (c) Key ringneck snake (*Diadophis punctatus acricus*). Species that are likely vulnerable to sea-level rise due to restricted ranges: (d) Florida bonneted bats (*Eumops floridanus*) are endemic to

south Florida and federally endangered, (e) the Sanibel Island rice rat (*Oryzomys palustris sanibeli*) is endemic to Sanibel Island and has low population densities, (f) lower keys marsh rabbits (*Sylvilagus palustris hefneri*) are endemic to the lower Keys and are federally endangered. Photo credits: (a) RSCF/www.rarespecies.org, (b and c) Jonathan D. Mays (d) Elizabeth C. Braun de Torrez, (e) Wesley W. Boone, (f) Chad Anderson/ United States Fish and Wildlife Service

remain. We face important knowledge gaps about (1) the spatiotemporal uncertainty surrounding SLR, (2) the resistance and resilience of species and ecosystems, (3) how to best mitigate the effects of SLR, and (4) the effectiveness of adaptive management techniques—all of which could be better understood by continued research and conservation in low-lying ecosystems (Table 2). This information is critical for understanding and mitigating climate change both locally and globally.

Remaining Uncertainty and Questions About Sea-Level Rise and Its Ecological Effects

Spatiotemporal Uncertainty Surrounding SLR

Perhaps most critically, scientists remain uncertain about the spatial variation, timing, rate, and magnitude of projected SLR (Miller and Douglas 2004; Nerem et al. 2018; Noss 2011; Sukop et al. 2018). Predictions of SLR and resulting impacts

on ecosystems vary considerably depending on different emission scenarios and ecological factors (DeConato and Pollard 2016; Church et al. 2013). For example, if sea levels rise 0.64, 1, or 2 m by 2100, the Waccasassa Bay region of Florida's gulf coast could experience net losses of 69%, 83%, or 99% in coastal forests but net gains of 17%, 142%, or 3837% in tidal flats, respectively (Geselbracht et al. 2011; Fig. 1b). Similarly, estimates of change to coastal ecosystems at six major Florida estuaries vary greatly in magnitude, and even direction, depending on the level of predicted SLR (Geselbracht et al. 2015). Factors such as erosion, vegetation community composition, and the health of vegetation communities further complicate our ability to accurately predict future conditions (Geselbracht et al. 2011). For example, depending on model parameterization, Chu-Agor et al. (2011) found that the extent of low-elevation habitats such as salt marshes and beaches at Eglin Air Force Base in Florida could either decrease or increase over the next 100 years (Fig. 1a). Such uncertainty regarding the extent, composition, and health of

Table 2 Examples of outstanding knowledge gaps that will help us better understand and prepare for the effects of sea-level rise (SLR) on vulnerable coastal species and ecosystems

Knowledge gap	Research questions and needs	Benefit of information gained
(1) Spatiotemporal uncertainty of climate change effects	<p>(a) How does spatial variation in factors such as vegetation change and erosion affect the rate of SLR?</p> <p>(b) Which specific geographic areas and ecosystems will be most affected by SLR and why?</p> <p>(c) How will the location and rate of SLR affect the maintenance of ecosystem functioning and ecosystem services?</p>	<p>(a) Better predictions of the location, rate, and magnitude of SLR</p> <p>(b) Effective prioritization of resources for the most at-risk areas; mechanistic understanding of potential shifts in ecosystem distribution and composition</p> <p>(c) Effects of SLR on interacting processes (e.g., biogeochemical cycling, disturbance regimes, predator-prey dynamics) and potential SLR feedbacks</p>
(2) Resistance and resilience	<p>(a) How do we identify which ecosystems are most vulnerable and which are resilient to SLR?</p> <p>(b) How can protection and restoration of coastal ecosystems slow rates of SLR? (Zhang et al. 2018). How do species interactions affect habitat restoration outcomes?</p> <p>(c) How adaptable are species to novel ecosystems created by SLR? At what quantitative threshold do sensitive species/ecosystems reach a point of rapid and irreversible change? (Powell et al. 2017)</p>	<p>(a) Increased focus on ecosystems vulnerable to SLR may improve ecosystem resistance and resilience</p> <p>(b) Effective restoration and management that enhance species' resistance and resilience to SLR</p> <p>(c) Identification of critical thresholds across species' life stages and/or latitudinal gradients that support coastal management and decision-making (Powell et al. 2017)</p>
(3) Mitigating the effects of SLR	<p>(a) How quickly (if at all) will species and ecosystems be able to migrate inland to escape SLR? What barriers (e.g., human migration, interspecies interactions) will impede their movement? What landscape features can facilitate species' movement?</p> <p>(b) How should conservation resources be prioritized (e.g., to climate change mitigation, adaptation, and/or restoration) in the face of SLR to reduce its effects?</p> <p>(c) How much can coastal restoration compensate for habitat that is lost and/or degraded from SLR? (Rudd and Lawton 2013)</p> <p>(d) What are effective ways to create and maintain "living shorelines" that enhance ecosystem function and services? How can human priorities be incorporated with restoration goals? (Zhang et al. 2018)</p>	<p>(a) Creation and management of wildlife corridors that facilitate migration and mitigate the effects of SLR on species</p> <p>(b) More effective use of limited conservation resources to mitigate SLR effects; identification of feasible and cost-effective strategies to reduce effects of SLR</p> <p>(c) Provide alternate habitat for coastal species that have lost habitat to SLR</p> <p>(d) Enhance ecosystem services and function to resist SLR while also meeting human needs (multi-use)</p>
(4) Adaptive management	<p>(a) What are management strategies that can help species adapt to environmental conditions created by SLR until the ecosystem returns to its pre-SLR conditions (if possible)? How long will these strategies be effective in facilitating long-term survival of species if the ecosystem cannot be restored (e.g., terrestrial ecosystem is now underwater)?</p> <p>(b) How much should managed realignment of coasts (inland movement of structures used to prevent flooding, usually of areas originally claimed from the sea) be included in adaptive management plans? (Rudd and Lawton 2013)</p>	<p>(a) Better understanding of species' capacity to adapt and migrate; mechanistic understanding of species' ecology (e.g., physiological limitations, habitat associations, and species interactions) across a range of environmental conditions</p> <p>(b) Identification of sites where restoration will be successful; systematic, long-term monitoring and basic research in areas where we know little about coastal habitat change (Zhang et al. 2018)</p>

future coastal areas makes it difficult to predict the persistence and magnitude of future ecosystem services provided by these areas (Kirwan et al. 2016). Before we can effectively prioritize conservation areas and develop appropriate responses, we need to refine our predictions of which specific areas will be impacted by SLR, how much SLR will actually occur in those places, and how far into the future we should expect these changes to occur.

Resistance and Resilience

Even if we were completely sure of the spatial variation, rate, and magnitude of SLR, we do not fully understand how species and ecosystems will respond to the associated changing conditions. The complex effects of SLR on factors such as species' ability to adapt and move, interspecies interactions, and their resulting effects on ecosystems and how

well ecosystems are able to function under changing conditions remain uncertain yet are key to determining the vulnerability of species and ecosystems (Reece and Noss 2014; Reece et al. 2013). For example, low-lying atoll reef islands in the central Pacific, commonly considered to be doomed by SLR, may actually increase in land area as they accrete vertically and change shape in response to shifting sediments, if they are not impeded by development (Webb and Kench 2010; Kench et al. 2018). Similarly, coral reefs in Tahiti appeared to avoid reef drowning during the last deglaciation period by rising in tandem with rapidly rising seas (Camoin et al. 2012), and the Marshall Islands were formed under rising sea levels (Kench et al. 2014). It is unclear how barrier islands and coral reefs in Florida will respond to SLR, but their response and resiliency depend on many factors, including recovery from storm events, sediment texture, and damage incurred from coral bleaching and disease (Maynard et al. 2015; Perry et al. 2018), and thus can be expected to vary regionally depending on geology (e.g., Houser et al. 2018). Andréfouet et al. (2015) contend that the number of islands predicted to be completely drowned is grossly overestimated because simplistic models assume that islands are passive geological entities rather than dynamic landforms able to respond to SLR.

Species and ecosystems will likely respond differently to SLR. Some species may respond quickly if they are able to adapt (e.g., physiologically) or move inland, shifting community composition to favor species better suited for the new conditions (Smith et al. 2009). For example, landward migration of some mangrove trees and coastal marsh grass may be able to keep pace with slow rates of SLR (Gilman et al. 2008; Kirwan et al. 2016), giving marshes and mangroves a competitive advantage over plants which are intolerant of inundation and saltwater intrusion. On Florida's Gulf Coast, historic SLR has led to net tidal marsh expansion (Raabe and Stumpf 2016), and models of 1-m SLR predict net increases of marshes (e.g., tidal freshwater, brackish, salt) and mangrove forests, with decreases in other coastal communities (e.g., cypress swamps, inland freshwater marshes, coastal forests; Geselbracht et al. 2015). Changing ocean conditions and SLR are likely to alter many interacting processes, such as biogeochemical cycling, disturbance regimes, and population dynamics, which will in turn impact ecosystem resilience, structure, and function (Grimm et al. 2013; Doney et al. 2012). For example, losses in ecosystem connectivity among mangroves, coral reefs, and parrotfish affect the resiliency of coral reefs to recover from hurricane disturbance (Mumby and Hastings 2007). These types of alterations to ecosystem function can be difficult to predict without first understanding the complex ecology of these ecosystems. Until we better understand the consequences of different ecosystem responses

and the underlying processes, we will not know how resilient ecosystems will be in the face of SLR.

Research Needs to Better Prepare Coastal Ecosystems for the Effects of Sea-Level Rise

Once we better understand how species and ecosystems will respond to SLR, we need to determine the most effective conservation strategies going forward for both existing ecosystems and newly aggregated communities. As conservation scientists, we need to fill critical research gaps to understand how to reduce the effects of SLR on species and ecosystems and develop local adaptation strategies to minimize adverse ecological effects of SLR if mitigation is not possible. These research findings can then be used to inform conservation efforts for similar ecosystems worldwide.

Mitigating Effects of SLR

First, we need to identify the most effective ways to improve and restore the health and resiliency of existing coastal ecosystems to protect the critical ecosystem services they currently provide (Erwin 2008; Zedler 2016). Maintaining healthy coastal ecosystems will help protect adjacent land from erosion and reduce the potential impacts of SLR. To do this, we must develop effective tools to remove invasive species, restore native species, and protect these areas from development and other stressors. Ecosystems that are partially inundated by SLR will need even better management because the impact of exotic species is likely to become greater in shrinking, fragmented habitats (Andréfouet et al. 2015). In Florida, Burmese pythons (*Python molurus bivittatus*) have caused precipitous declines in mammal populations and threaten the ecological functioning of the entire Greater Everglades Ecosystem (McCleery et al. 2015); control of pythons is increasingly important as their impact on faunal communities will likely be exacerbated as habitat is constricted with SLR. Many scientists and land managers working to conserve Florida's vulnerable coastal areas and species are committed to improving ecosystem resiliency through restoration efforts and available silvicultural and hydrological tools (Mark Danaher, US Fish and Wildlife Service, *pers. comm.*). For example, the Comprehensive Everglades Restoration Program, which represents the largest wetland restoration effort in the world, is directly combating increased SLR and salinity through the restoration of freshwater flow (Dessu et al. 2018). The threat of SLR makes the protection of estuaries and threatened and endangered species even more critical (Kim Dryden, USFW, *pers. comm.*). Rather than taking the attitude that these areas are going underwater so they are undeserving of our attention, scientists working in these areas view restoration planning and investment in coastal areas as

even more valuable in the face of SLR (Lori Miller, US Fish and Wildlife Service, *pers. comm.*).

Adaptive Management

Increasing storm surges and SLR will ultimately render certain areas uninhabitable by humans as SLR outpaces restoration efforts (e.g., Dessu et al. 2018) and coastal areas cannot be raised above the approaching water. Coastal communities may need to adapt by migrating inland or to higher ground. Noss et al. (2014) suggested that the most viable adaptation strategy for many natural coastal communities in Florida may be protection and restoration of their current extent in order to facilitate natural and assisted species migration. With a vast network of conservation areas along the coasts and in the interior (~4,000,000 ha) and the largest taxpayer-funded conservation land acquisition program in the USA (Florida Forever; Mercas 2016), Florida is capable of improving existing areas and purchasing new lands to achieve this goal.

As scientists, we have the opportunity to identify critical current and future inland ecosystems, including migration corridors, in order to prioritize the use of limited conservation resources (Zhu et al. 2015; Roberts and Hamann 2016). However, we need continued research to understand species' and ecosystems' capacities to adapt to new environmental and ecological conditions, as we still do not know the current habitat associations and basic ecological requirements of many species. For example, we know little about the habitat associations of the federally endangered Florida bonneted bat (*Eumops floridanus*), a species endemic to South Florida that is of high conservation value and likely vulnerable to sea-level rise and other environmental changes (Reece and Noss 2014; Box 1d). Without information on roost structure and habitat preference (Braun de Torrez et al. 2016), conservationists cannot delineate and protect future refugia for bonneted bats to help reduce the effects of SLR. Additionally, recent evidence indicates that Sanibel Island rice rats (*Oryzomys palustris sanibeli*), confined to an island < 1.5 m above sea level (Florida Fish and Wildlife Conservation Commission 2013; Box 1e), inhabit mangrove marshes (Boone unpublished data) in addition to freshwater wetland habitats (Humphrey et al. 1986). However, as sea levels rise, we do not know if this subspecies can survive exclusively in mangrove marshes as freshwater becomes scarce. Detailed information on habitat associations, species' occurrences, and movement patterns are necessary so that we can inform conservation strategies for species in threatened ecosystems. Further, we need to determine if currently protected ecosystems are likely to shift in range; if so, we need to consider the feasibility and value of extending the protected areas' boundaries and removing barriers that may impede species migration. Our continued engagement in the research, conservation, and management of threatened ecosystems may slow their rate of decline.

Conclusions Regarding the Road Ahead

There is little doubt that we will see a dramatic anthropogenic environmental change in our lifetime. Due to the remaining uncertainty about ecosystems' and species' responses to climate change, we find ourselves trying to make decisions in a continuously changing environment. Although extremely challenging, these uncertainties leave room for optimism, research, and conservation actions that are critical for sustaining the viability of our planet and its incredible biodiversity. We argue that continuing to actively engage in research, conservation, and restoration of the most imperiled ecosystems for as long as possible confers many immediate and long-term benefits at both the local and global scales. We need to give at-risk ecosystems a chance to respond and adapt, as well as give ourselves time to develop strategies to reduce climate change effects when possible and/or adapt when needed. Remaining engaged in these ecosystems even if they are ultimately lost will provide invaluable insight into the complex effects of climate change, enabling scientists to develop more effective mitigation, adaptation, and decision-support strategies for similar ecosystems in other parts of the world. However, this is largely dependent on persuading the public and our politicians to invest in the protection of natural areas as the first and most important line of defense against SLR. There is far too much at stake to give up prematurely. We encourage scientists, particularly students beginning their careers, to face this unprecedented challenge with determination, creativity, and solution-based strategies.

Acknowledgments We thank the graduate students and post-doctoral researchers in Robert McCleery's lab for valuable discussions regarding the premise and arguments that inspired this article. We also greatly appreciate the input from several colleagues who have dedicated their careers to researching, managing, and fighting for vulnerable species and ecosystems in South Florida: Mark Danaher (Supervisory Wildlife Biologist, Florida Panther National Wildlife Refuge), Kim Dryden (Fish and Wildlife Biologist, Everglades Restoration, US Fish and Wildlife Service), and Tylan Dean (Everglades National Park). Finally, we thank the anonymous reviewers and editors for valuable input on various drafts of this paper.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

- Anderson, M.G., A. Barnett, M. Clark, J. Prince, A.O. Sheldon, and B. Vickery. 2016. *Resilient and connected landscapes for terrestrial conservation*. Boston: The Nature Conservancy.
- Andréfouet, S., H. Jourdan, P.S. Kench, C. Menkes, E. Vidal, and H. Yamano. 2015. Conservation of low-islands: high priority despite

- sea-level rise. A comment on Courchamp *et al.* *Trends in Ecology & Evolution* 30 (1): 1–2.
- Arkema, K.K., G. Guannel, G. Verutes, S.A. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, and J.M. Silver. 2013. Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change* 3 (10): 913–918.
- Bottrill, M.C., L.N. Joseph, J. Carwardine, M. Bode, C. Cook, E.T. Game, H. Grantham, S. Kark, S. Linke, E. McDonald-Madden, R.L. Pressey, S. Walker, K.A. Wilson, and H.P. Possingham. 2008. Is conservation triage just smart decision making? *Trends in Ecology & Evolution* 23 (12): 649–654. <https://doi.org/10.1016/j.tree.2008.07.007>.
- Braun de Torrez, E.C., H.K. Ober, and R.A. McCleery. 2016. Use of a multi-tactic approach to locate an endangered Florida bonneted bat roost. *Southeastern Naturalist* 15 (2): 235–242. <https://doi.org/10.1656/058.015.0204>.
- Brodie, J., and R.G. Pearson. 2016. Estuarine, coastal and shelf science. *Estuarine, Coastal and Shelf Science* 183 (Part B): 438–451. <https://doi.org/10.1016/j.ecss.2016.05.008>.
- California Department of Finance. 2020. California state budget 2020–21. State of California. <http://www.ebudget.ca.gov/FullBudgetSummary.pdf>.
- Camoin, G.F., C. Seard, P. Deschamps, J.M. Webster, E. Abbey, J.C. Braga, Y. Iryu, N. Durand, E. Bard, B. Hamelin, Y. Yokoyama, A.L. Thomas, G.M. Henderson, and P. Dussouillez. 2012. Reef response to sea-level and environmental changes during the last deglaciation: Integrated Ocean Drilling Program Expedition 310, Tahiti Sea Level. *Geology* 40 (7): 643–646. <https://doi.org/10.1126/science.1168754>.
- Cape Ann Economics. 2003. *Land values and open space – Leon County*. San Francisco: Trust for Public Land.
- Carpenter, A., and C. Provorse. 1996. *The world almanac of the U.S.A.* Mahwah: World Almanac Books.
- Center for Biological Diversity. 2013. Letter to U.S. Fish and Wildlife Service and National Marine Fisheries Service https://www.biologicaldiversity.org/campaigns/sea-level_rise/pdfs/Center_letter_to_FWS_and_NMFS_sea_level_rise_final.pdf
- Chinn, S., P.S. Hart, and S. Soroka. 2020. Politicization and polarization in climate change news content, 1985–2017. *Science Communication* 42 (1): 112–129.
- Chu-Agor, M.L., R. Muñoz-Carpena, G. Kiker, A. Emanuelsson, and I. Linkov. 2011. Exploring vulnerability of coastal habitats to sea level rise through global sensitivity and uncertainty analyses. *Environmental Modelling and Software* 26 (5): 593–604.
- Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and A.S. Unnikrishnan. 2013. Sea level change. In *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. Cambridge: Cambridge University Press.
- Correll, M.R., J.H. Lillydahl, and L.D. Singell. 1978. The effect of greenbelts on residential property values: some findings on the political economy of open space. *Land Economics* 54 (2): 207–217.
- Courchamp, F., Hoffmann, B. D., Russell, J.C., Leclerc, C., Bellard, C., 2014. Climate change, sea-level rise, and conservation: keeping island biodiversity afloat.
- Cui, Y., E. Mahoney, and T. Herbowicz. 2013. *Economic benefits to local communities from national park visitation, 2011. Natural Resource Report NPS/NRSS/EQD/NRTR-2013/631*. Fort Collins: National Park Service.
- Davis, M.B., and R.G. Shaw. 2001. Range shifts and adaptive responses to Quaternary climate change. *Science* 292 (5517): 673–679.
- DeConto, D., and R. Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature* 531 (7596): 591–597.
- Dehoorne, O., and C. Tatar. 2013. Ecotourism at the heart of development strategies: elements for reflections based on the Caribbean experience. *Tourismos*. 8: 213–231.
- Department of the Interior. 2020. Fiscal year 2021; the Interior budget in brief. <https://www.doi.gov/sites/doi.gov/files/uploads/2021-highlights-book.pdf>.
- Dessu, S.B., R.M. Price, T.G. Troxler, and J.S. Kominoski. 2018. Effects of sea-level rise and freshwater management on long-term water levels and water quality in the Florida Coastal Everglades. *Journal of Environmental Management* 211: 164–176.
- Doney, S.C., M. Ruckelshaus, J. Emmett Duffy, J.P. Barry, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N.N. Rabalais, W.J. Sydeman, and L.D. Talley. 2012. Climate change impacts on marine ecosystems. *Annual Review of Marine Science* 4 (1): 11–37. <https://doi.org/10.1146/annurev-marine-041911-111611>.
- Donoghue, J.F. 2011. Sea level history of the northern Gulf of Mexico coast and sea level rise scenarios for the near future. *Climatic Change* 107 (2): 17–33. <https://doi.org/10.1007/s10584-011-0077>.
- Duarte, C.M., I.J. Losada, I.E. Hendriks, I. Mazarrasa, and N. Marbá. 2013. The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change* 3 (11): 961–968.
- Ellison, A.M. 2019. Foundation species, non-trophic interactions, and the value of being common. *iScience* 13: 254–268.
- Ellison, A.M., M.S. Bank, B.D. Clinton, E.A. Colburn, K. Elliott, D.R. Ford, D.R. Foster, B.D. Kloeppe, J.D. Knoepp, and G.M. Lovett. 2005. Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. *Frontiers in Ecology and the Environment* 9: 479–486.
- Epanchin-Niell, R., C. Kousky, A. Thompson, and M. Walls. 2017. Threatened protection: sea level rise and coastal protected lands of the eastern United States. *Ocean and Coastal Management* 137: 118–130.
- Erwin, K.L. 2008. Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetlands Ecology and Management* 17 (1): 71–84. [https://doi.org/10.1016/0304-3770\(75\)90016-9](https://doi.org/10.1016/0304-3770(75)90016-9).
- Estill, J.C., and M.B. Cruzan. 2001. Phytogeography of rare plant species endemic to the southeastern United States. *Castanea* 66: 3–23.
- Flood, P.G., and H. Heatwole. 1986. Coral cay instability and species-turnover of plants at Swain Reefs, southern Great Barrier Reef, Australia. *Journal of Coastal Research* 2: 479–496.
- Florida Fish and Wildlife Conservation Commission. 2013. *A species action plan for the Sanibel Island rice rat*. Tallahassee, Florida.
- Gardner, R.C., S. Barchiesi, C. Beltrame, C. Finlayson, T. Galewski, I. Harrison, M. Paganini, C. Perennou, D. Pritchard, A. Rosenqvist, and M. Walpole. 2015. *State of the world's wetlands and their services to people: a compilation of recent analyses (March 31, 2015)*. Ramsar Briefing Note No. 7. Ramsar Convention Secretariat: Gland.
- Geselbracht, L., K. Freeman, E. Kelly, D.R. Gordon, and F.E. Putz. 2011. Retrospective and prospective model simulations of sea level rise impacts on Gulf of Mexico coastal marshes and forests in Waccasassa Bay, Florida. *Climatic Change* 107 (2): 35–57. <https://doi.org/10.1007/s10584-011-0084>.
- Geselbracht, L.L., K. Freeman, A.P. Birch, J. Brenner, and D.R. Gordon. 2015. Modeled sea level rise impacts on coastal ecosystems at six major estuaries on Florida's Gulf Coast: implications for adaptation planning. *PLoS One* 10 (7): e0132079. <https://doi.org/10.1371/journal.pone.0132079.s007>.
- Ghermandi, A., and A.L.D. Nunes. 2013. A global map of coastal recreation values: results from a spatially explicit meta-analysis. *Ecological Economics* 86: 1–15.

- Gilman, E.L., J. Ellison, N.C. Duke, and C. Field. 2008. Threats to mangroves from climate change and adaptation options: a review. *Aquatic Botany* 89 (2): 237–250.
- Goldstein, D.B., G.W. Roemer, D.A. Smith, D.E. Reich, A. Bergman, and R.K. Wayne. 1999. The use of microsatellite variation to infer population structure and demographic history in a natural model system. *Genetics* 151 (2): 797–801.
- Gornitz, V., S. Lebedeff, and J. Hansen. 1982. Global sea level trend in the past century. *Science* 215 (4540): 1611–1614.
- Gray, S.C., J.R. Hein, R. Hausmann, and U. Radtke. 1992. Geochronology and subsurface stratigraphy of Pukapuka and Rakahanga atolls, Cook Islands: late Quaternary reef growth and sea level history. *Palaeogeography, Palaeoclimatology, Palaeoecology* 91 (3–4): 377–394.
- Grimm, N.B., F.S.C. Chapin III, B. Bierwagen, P. Gonzalez, P.M. Groffman, Y. Luo, F. Melton, K. Nadelhoffer, A. Pairis, P.A. Raymond, J. Schimel, and C.E. Williamson. 2013. The impacts of climate change on ecosystem structure and function. *Frontiers in Ecology and the Environment* 11 (9): 474–482.
- Hobbs, R.J., V.A. Cramer, and L.J. Kristjanson. 2003. What happens if we cannot fix it? Triage, palliative care and setting priorities in salinising landscapes. *Australian Journal of Botany* 51 (6): 647.
- Hocter, T., Zwick, P., and M. Carr. 2010. Large-scale implications of SLR on conservation priority areas and human settlement in Florida. Presentation at symposium, “Keeping Our Heads Above Water: Surviving the Challenges of Sea-Level Rise in Florida,” Archbold Biological Station, Lake Placid, Florida, 18–20 January 2010.
- Hooper, D.U., E.C. Adair, B.J. Cardinale, J.K. Byrnes, B.A. Hungate, K.L. Matulich, A. Gonzalez, J.E. Duffy, L. Gamfeldt, and M. O’Connor. 2012. A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature* 486: 105–108.
- Houser, C., P. Barrineau, B. Hammond, B. Saari, E. Rentschler, S. Trimble, P. Wernette, B. Weymer, and S. Young. 2018. Role of the foredune in controlling barrier island response to sea level rise. In *Barrier dynamics and response to changing climate*, ed. L. Moore and A. Murray. Cham: Springer.
- Hubbard, D., E. Gischler, P. Davies, L. Montagnioni, G. Camoin, W.C. Dullo, C. Storlazzi, M. Field, C. Fletcher, E. Grossman, C. Sheppard, H. Lescinsky, D. Fenner, J. McManus, and S. Scheffers. 2014. Island outlook: warm and swampy. *Science* 345 (6203): 1461.
- Humphrey, S.R., Repenning, R.W., and H.W. Setzer. 1986. Status survey of five Florida mammals. University of Florida Cooperative Fish and Wildlife Research Unit, Technical Report No. 22, Gainesville, Florida, USA.
- Intergovernmental Panel on Climate Change. 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
- Jackson, J.C. 1997. Reefs since Columbus. *Coral Reefs* 16 (Supplemental Information): S23–S32.
- Josephs, L.I., and A.T. Humphries. 2018. Identifying social factors that undermine support for nature-based coastal management. *Journal of Environmental Management* 212: 32–38.
- Kench, P.S., S.D. Owen, and M.R. Ford. 2014. Evidence for coral island formation during rising sea level in the Central Pacific Ocean. *Geophysical Research Letters* 41 (3): 820–827.
- Kench, P.S., M.R. Ford, and S.D. Owen. 2018. Patterns of island change and persistence offer alternate adaptation pathways for atoll nations. *Nature Communications* 9 (1): 1–7. <https://doi.org/10.1038/s41467-018-02954-1>.
- Kirwan, M.L., and P. Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* 504 (7478): 53–60.
- Kirwan, M.L., S. Temmerman, E.E. Skeehan, G.R. Guntenspergen, and S. Fagherazzi. 2016. Overestimation of marsh vulnerability to sealevel rise. *Nature Climate Change* 6 (3): 253–260. <https://doi.org/10.1038/nclimate2909>.
- Ledford, H., S. Reardon, E.R. Mega, J. Tollefson, and A. Witze. 2019. Trump seeks big cuts to science funding – again. *Nature*. <https://doi.org/10.1038/d41586-019-00719-4>.
- Maltby, E., and P.J. Dugan. 1994. In *Wetland ecosystem protection, management, and restoration: an international perspective, in Everglades: the ecosystem and its restoration*, ed. S. Davis and J.C. Ogden. Boca Raton: CRC Press.
- Maschinski, J., M.S. Ross, H. Liu, J. O’Brien, E.J. von Wettberg, and K.E. Haskins. 2011. Sinking ships: conservation options for endemic taxa threatened by sea level rise. *Climatic Change* 107 (1–2): 147–167.
- Matilsky, B.C. 2018. *Endangered species: artists on the front line of biodiversity*. Bellingham: Whatcom Museum 144 pp.
- Maynard, J., R. van Hooijdonk, C.M. Eakin, M. Puotinen, M. Garren, G. Williams, S.F. Heron, J. Lamb, E. Weil, B. Willis, and C.D. Harvell. 2015. Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nature Climate Change* 5 (7): 688–694.
- McCleery, R.A., A. Sovie, R.N. Reed, M.W. Cunningham, M.E. Hunter, and K.M. Hart. 2015. Marsh rabbit mortalities tie pythons to the precipitous decline of mammals in the Everglades. *Proceedings of the Royal Society B: Biological Sciences* 282 (3): 20150120–20150270. <https://doi.org/10.1111/j.1749-4877.2012.00304.x>.
- McCleery, R.A., R.J. Fletcher, L.M. Kruger, D. Govender, and S.M. Ferreira. 2020. Conservation needs a COVID-19 bailout. *Science* 369 (6503): 515–516.
- McGranahan, G., D. Balk, and B. Anderson. 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization* 19 (1): 17–37.
- McKee, K.L., D.R. Cahoon, and I.C. Feller. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography* 16 (5): 545–556.
- Mercas, D., 2016. Conservation land acquisition (Florida Forever). Florida Tax Watch Issue 1.1002. Tallahassee, FL, USA.
- Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: synthesis*. Washington, D.C.: World Resources Institute.
- Miller, L., and B. Douglas. 2004. Mass and volume contributions to twentieth-century global sea level rise. *Nature* 428 (6981): 406–409.
- Mörner, N. 2017. Thermal expansion. *Encyclopedia of Coastal Science*: 1–3. https://doi.org/10.1007/978-3-319-48657-4_375-1.
- Mumby, P.J., and A. Hastings. 2007. The impact of ecosystem connectivity on coral reef resilience. *Journal of Applied Ecology* 45 (3): 854–862. <https://doi.org/10.1007/s00380000121>.
- Myers, R.L., and J.J. Ewel. 1990. *Ecosystems of Florida*, 1–12. University of Central Florida Press.
- National Marine Fisheries Service. 2016. Fisheries Economics of the United States, 2016. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-F/SPO-163.
- National Oceanic and Atmospheric Administration. 2012. Tidal surface models. Coastal Services Center Vertical Datum Transformation. <http://vdatum.noaa.gov>.
- Nerem, R.S., B.D. Beckley, J.T. Fasullo, B.D. Hamlington, D. Masters, and G.T. Mitchum. 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences* 7: 201717312.
- Nicholls, R.J. 2011. Planning for the impacts of sea level rise. *Oceanography* 24 (2): 144–157.
- Nicholls, R.J., and A. Cazenave. 2010. Sea-level rise and its impact on coastal zones. *Science* 18 (328): 1517–1520.

- Noss, R.F. 2011. Between the devil and the deep blue sea: Florida's unenviable position with respect to sea level rise. *Climatic Change* 107 (1-2): 1–16.
- Noss, R.F., Reece, J.S., Hctor, T., and J. Oetting. 2014. Adaptation to sea-level rise in Florida: biological conservation priorities. Final Report to The Kresge Foundation.
- Oetting, J. 2010. A survey of rare species threatened by sea level rise in Florida. Presentation at symposium, "Keeping Our Heads Above Water: Surviving the Challenges of Sea-Level Rise in Florida," Archbold Biological Station, Lake Placid, Florida, 18–20 January 2010. <http://www.flconservationscience.org/pdfs/Oetting.pdf>.
- Office of Management and Budget. 2020. A budget for America's future; budget of the U.S. government. Executive office of the President of the United States. https://www.whitehouse.gov/wp-content/uploads/2020/02/budget_fy21.pdf.
- Office of the Chief Financial Officer. 2020. fy 2021 epa budget in brief. United States Environmental Protection Agency. <https://www.epa.gov/sites/production/files/2020-02/documents/fy-2021-epa-bib.pdf>.
- Office of the City Manager. 2020. Proposed fiscal year 2021 budget. City of Norfolk, Virginia. <https://www.norfolk.gov/DocumentCenter/View/60387/FY-2021-Proposed-Budget-Documents>.
- Orlean, S. 1998. *The orchid thief*. New York: Random House 284pp.
- Papworth, S.K., J. Rist, L. Coad, and E.J. Milner-Gulland. 2009. Evidence for shifting baseline syndrome in conservation. *Conservation Letters* 2: 93–100.
- Pauly, D. 1995. Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology & Evolution* 10 (10): 430.
- Perry, C.T., L. Alvarez-Filip, N.A.J. Graham, P.J. Mumby, S.K. Wilson, P.S. Kench, D.P. Manzanillo, K.M. Morgan, A.B.A. Slangen, D.P. Thomson, F. Januchowski-Hartley, S.G. Smithers, R.S. Steneck, R. Carlton, E.N. Edinger, I.C. Enochs, N. Estrada-Saldivar, M.D.E. Haywood, G. Kolodziej, G.N. Murphy, E. Pérez-Cervantes, A. Suchley, L. Valentino, R. Boenish, M. Wilson, and C. Macdonald. 2018. Loss of coral reef growth capacity to track future increases in sea level. *Nature* 558 (7710): 396–400.
- Petri, A.E. 2016. Meet the rare swimming wolves that eat seafood. National Geographic. August 3rd. <https://www.nationalgeographic.com/news/2016/08/sea-oceans-wolves-animals-science/>.
- Pilkey, O.H., and R. Young. 2009. *The rising sea*, 203pp. Washington, D.C.: Island Press.
- Planes, S., and P.J. Doherty. 1997. Genetic relationships of the colour morphs of *Acanthochromis polyacanthus* (Pomacentridae) on the northern Great Barrier Reef. *Marine Biology* 130 (1): 109–117.
- Powell, E.J., M.C. Tyrrell, A. Milliken, J.M. Tirpak, and M.D. Staudinger. 2017. A synthesis of thresholds for focal species along the U.S. Atlantic and Gulf Coasts: a review of research and applications. *Ocean and Coastal Management* 148: 75–88. <https://doi.org/10.1016/j.ocecoaman.2017.07.012>.
- Raabe, E.A., and R.P. Stumpf. 2016. Expansion of tidal marsh in response to sea-level rise: Gulf Coast of Florida, USA. *Estuaries and Coasts* 39 (1): 145–157.
- Raventós, J., E. González, E. Mújica, and A. Bonet. 2015. Transient population dynamics of two epiphytic orchid species after hurricane Ivan: implications for management. *Biotropica* 47 (4): 441–448.
- Reece, J.S., and R.F. Noss. 2014. Prioritizing species by conservation value and vulnerability: a new index applied to species threatened by sea-level rise and other risks in Florida. *Natural Areas Journal* 34 (1): 31–45.
- Reece, J.S., R.F. Noss, J. Oetting, T. Hctor, and M. Volk. 2013. A vulnerability assessment of 300 species in Florida: threats from sea level rise, land use, and climate change. *PLoS One* 8 (11): e80658. <https://doi.org/10.1371/journal.pone.0080658>.
- Roberts, D.R., and A. Hamann. 2016. Climate refugia and migration requirements in complex landscapes. *Ecography* 39 (12): 1238–1246.
- Ross, M.S., J.J. O'Brien, R.G. Ford, K. Zhang, and A. Morkill. 2009. Disturbance and the rising tide: the challenge of biodiversity management on low-island ecosystems. *Frontiers in Ecology and the Environment* 7 (9): 471–478.
- Rowe, K.C., K.M.C. Rowe, M.W. Tingley, M.S. Koo, J.L. Patton, C.J. Conroy, J.D. Perrine, S.R. Beissinger, and C. Moritz. 2015. Spatially heterogeneous impact of climate change on small mammals of montane California. *Proceedings of the Royal Society B* 282 (1799): 20141857. <https://doi.org/10.1098/rspb.2014.1857>.
- Roy, P., and J. Connell. 1991. Climatic change and the future of atoll states. *Journal of Coastal Research* 7: 1057–1075.
- Rudd, M.A., and R.N. Lawton. 2013. Scientists' prioritization of global coastal research questions. *Marine Policy* 39: 101–111. <https://doi.org/10.1016/j.marpol.2012.09.004>.
- Saha, A.K., S. Saha, J. Sadle, J. Jiang, M.S. Ross, R.M. Price, L.O. Sternberg, and K.S. Wendelberger. 2011. Sea level rise and South Florida coastal forests. *Climatic Change* 107 (2): 81–108. <https://doi.org/10.1007/s10584-011-0082-0>.
- Scheffers, B.R., L. De Meester, T.L. Bridge, A.A. Hoffmann, J.M. Pandolfi, T. Corlett, S.M. Butchart, P. Pearce-Kelly, K.M. Kovacs, D. Dudgeon, M. Pacifici, C. Rondinini, W.B. Foden, T.G. Martin, C. Mora, D. Bickford, and J.M. Watson. 2016. The broad footprint of climate change from genes to biomes to people. *Science* 354: 7671.
- Schmidt, J.A., R.A. McCleery, J.R. Seavey, S.E. Devitt, and P.M. Schmidt. 2012. Impacts of a half century of sea-level rise and development on an endangered mammal. *Global Change Biology* 18 (12): 3536–3542.
- Selby, J. 2019. The Trump presidency, climate change, and the prospect of a disorderly energy transition. *Review of International Studies* 45 (3): 471–490.
- Small, C., and R.J. Nicholls. 2003. A global analysis of human settlement in coastal zones. *Journal of Coastal Research* 19: 584–599.
- Smith, M.D., A.K. Knapp, and S.L. Collins. 2009. A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology* 90 (12): 3279–3289. <https://doi.org/10.1890/08-1815>.
- Soja, A.J., N.M. Tchepakova, N.H.F. French, M.D. Flannigan, H.H. Shugart, B.J. Stocks, A.I. Sukhinin, E.I. Parfenova, F.S. Chapin III, and P.W. Stackhouse Jr. 2007. Climate-induced boreal forest change: predictions versus current observations. *Global and Planetary Change* 56 (3-4): 274–296.
- Sorrie, B.A., and A.S. Weakley. 2001. Coastal plain plant endemics: phytogeographic patterns. *Castanea* 66: 50–82.
- Soulé, M.E. 1985. What is conservation biology? *Bioscience* 35: 727–734.
- Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact). 2015. Unified sea level rise projection for Southeast Florida. A document prepared for the Southeast Florida Regional Climate Change Compact Steering Committee. 35 p.
- Southeastern Association of Fish and Wildlife Agencies. 2019. Online guide to using the southeast blueprint. <http://secassoutheast.org/blueprint.html>.
- Southwick Associates. 2011. The 2011 economic benefits of wildlife viewing in Florida. Prepared for Florida Fish and Wildlife Conservation Commission.
- Spatz, D.R., K.M. Newton, R. Heinz, B. Tershy, N.D. Holmes, S.H.M. Butchart, and D.A. Croll. 2014. The biogeography of globally threatened seabirds and island conservation opportunities. *Conservation Biology* 28 (5): 1282–1290.
- Stein, B.A., Glick, P., Edelson, N., Staudt, A., 2014. Climate-smart conservation: putting adaptation principles into practice. National Wildlife Federation, Washington, D.C. https://www.nwf.org/~media/PDFs/Global-Warming/Climate-Smart-Conservation/NWF-Climate-Smart-Conservation_5-08-14.pdf

- Sukop, M.C., M. Rogers, G. Guannel, J.M. Infanti, and K. Hagemann. 2018. High temporal resolution modeling of the impact of rain, tides, and sea level rise on water table flooding in the Arch Creek basin, Miami-Dade County Florida USA. *Science of the Total Environment* 616: 1668–1688.
- Swaisgood, R.R., and J.K. Sheppard. 2010. The culture of conservation biologists: show me the hope! *BioScience* 60 (8): 626–630.
- Taylor, P.W. 1986. *Respect for nature: a theory of environmental ethics*, 73–74. Princeton University Press.
- Temmerman, S., P. Meire, T.J. Bouma, P.J. Herman, T. Ysebaert, and H.J. De Vriend. 2013. Ecosystem-based coastal defense in the face of global change. *Nature* 504 (7478): 79–83.
- Trenberth, K.E., J.T. Fasullo, and T.G. Shepherd. 2015. Attribution of climate extreme events. *Nature Climate Change* 5 (8): 725–730.
- Trump, D.J. 2017. “Statement by President Trump on the Paris Climate Accord” The Rose Garden, The White House, Washington DC. June 1, 2017.
- United States Fish and Wildlife Service. 2012. Coastal Program Strategic Plan National Summary (Part 3) 2012–2016. https://www.fws.gov/coastal/pdfs/StrategicPlan2012_2016SummaryDocumentFinal.pdf. Accessed August 25th, 2019.
- United States Fish and Wildlife Service. 2019. National Coastal Wetlands Conservation Grant Program Fiscal Year 2020 Notice of Funding Opportunity.
- van den Broeke, M.R., E.M. Enderlin, I.M. Howat, P. Kuipers Munneke, B.P.Y. Noël, W.J. van de Berg, E. van Meijgaard, and B. Wouters. 2016. On the recent contribution of the Greenland Ice Sheet to sea level change. *The Cryosphere* 10 (5): 1933–1946. <https://doi.org/10.5194/tc-10-1933-2016>.
- Webb, A.P., and P.S. Kench. 2010. Global and planetary change. *Global and Planetary Change* 72 (3): 234–246. <https://doi.org/10.1016/j.gloplacha.2010.05.003>.
- Weiss, J., and J. Overpeck. 2003. Maps of areas susceptible to sea level rise. Environmental Studies Laboratory, Department of Geosciences, University of Arizona.
- Williams, K., K.C. Ewel, R.P. Stumpf, F.E. Putz, and T.W. Workman. 1999. Sea-level rise and coastal forest retreat on the west coast of Florida, USA. *Ecology* 80 (6): 2045–2063.
- Zalasiewicz, J., M. Williams, A. Smith, T.L. Barry, A.L. Coe, P.R. Bown, P. Brechley, D. Cantrill, A. Gale, P. Gibbard, F.J. Gregory, M.W. Hounslow, A.C. Kerr, P. Pearson, R. Knox, J. Powell, C. Waters, J. Marshall, M. Oates, P. Rawson, and P. Stone. 2008. Are we now living in the Anthropocene. *GSA Today* 1 (18): 4.
- Zedler, J.B. 2016. What’s new in adaptive management and restoration of coasts and estuaries? *Estuaries and Coasts* 40 (1): 1–21. <https://doi.org/10.1007/s12237-016-0162-5>.
- Zhang, K., J. Dittmar, M. Ross, and C. Bergh. 2011. Assessment of sea level rise impacts on human population and real property in the Florida Keys. *Climatic Change* 107 (1-2): 129–146. <https://doi.org/10.1007/s10584-011-0080-2>.
- Zhang, Y.S., W.R. Cioffi, R. Cope, P. Daleo, E. Heywood, C. Hoyt, C.R. Smith, and B.R. Silliman. 2018. A global synthesis reveals gaps in coastal habitat restoration research. *Sustainability* 10 (4): 1040. <https://doi.org/10.3390/su10041040>.
- Zhu, M., X. Xi, T.S. Hoctor, and M. Volk. 2015. Global ecology and conservation. *Global Ecology and Conservation*. 4: 48–62. <https://doi.org/10.1016/j.gecco.2015.05.007>.