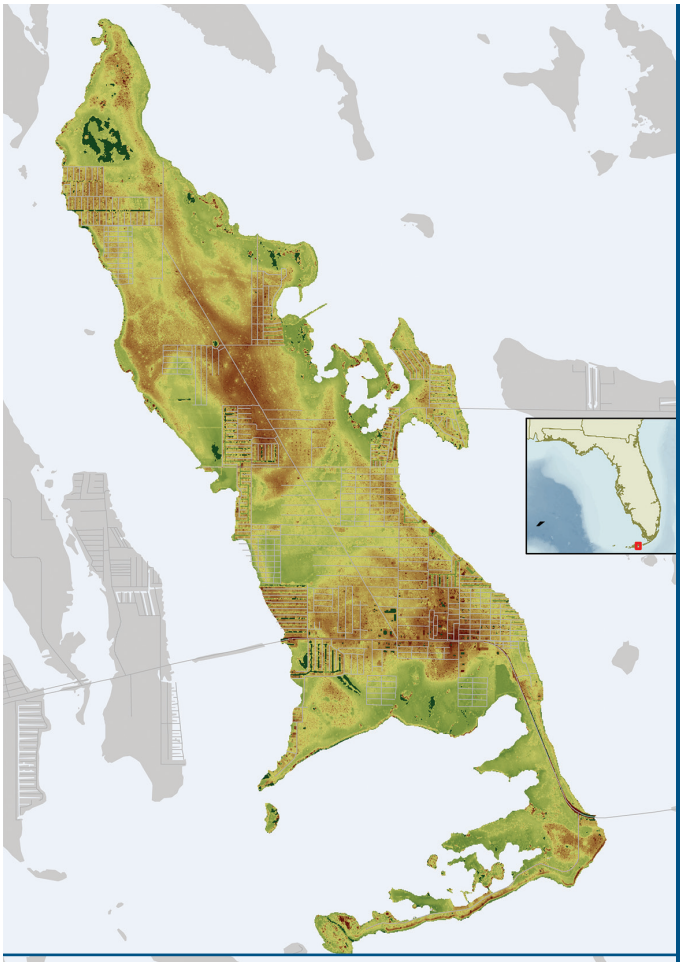
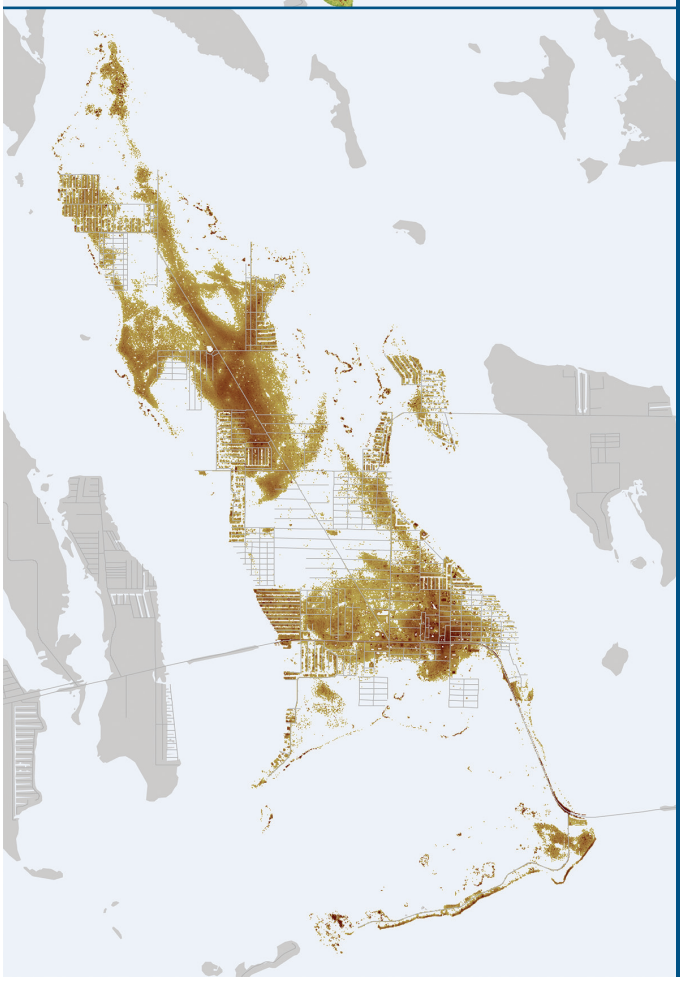




Initial Estimates of the Ecological and Economic Consequences of

Sea Level Rise on the Florida Keys

through the Year 2100

The Nature Conservancy

Protecting nature. Preserving life.™

Initial Estimates of the Ecological and Economic Consequences of Sea Level Rise on the Florida Keys through the Year 2100

Executive Summary

Climate change is happening now at an unprecedented rate. Sea level rise is one of the more predictable and most profound consequences of climate change. In the next one to three centuries, sea level rise is likely to nullify most, if not all, that has been done over the past century to protect the terrestrial plants, animals and natural communities of the Florida Keys. Negative impacts on the built environment and human communities are also likely to be serious and irreversible.

In 2007 The Nature Conservancy acquired high-resolution Digital Elevation Models derived from airborne Light Detection and Ranging (LIDAR) data for Big Pine Key. Future shoreline locations and distribution of major habitats of Big Pine Key in the year 2100 were estimated using sea level rise scenarios described in the scientific literature. Estimation of property value losses for Big Pine Key was based on the same 2100 sea level rise projections using 2008 values. In every scenario the island becomes smaller, marine and intertidal habitat moves upslope at the expense of upland habitat, and property values are diminished. In the best-case scenario, 18 cm (7 in.) of sea level rise, 1,840 acres (34 percent) of Big Pine Key are inundated resulting in the loss of 11 percent of the island's upland habitat. This degree of inundation would displace native species dependent on upland habitat and threaten $40 million of property value. Four other scenarios are modeled for Big Pine Key using the same high-resolution data. With a rise of 140 cm (4.6 ft.), the highest modeled rise, about 5,950 acres (96 percent) of the island would be inundated with all upland habitat and $1.6 billion in property value lost. Beyond Big Pine Key, year 2100 outlooks for the entire Florida Keys were modeled using the best-available elevation data.

Now is the time for a coordinated effort to identify the long-term impacts of sea level rise on the Florida Keys and to begin taking near-term steps to minimize the negative consequences of those impacts. Mitigation of the root causes of climate change and sea level rise — most prominently greenhouse gas emissions and deforestation — is critical and must take place at every scale, from global to local. However, mitigation must be paired with carefully planned and implemented local strategies to help terrestrial natural areas and native species resist and ultimately adapt to inevitable change. Any such strategies must take into account the fact that Florida Keys residents and the government institutions that serve them will also need to resist and adapt to sea level rise.

Introduction

Climate change is happening now at an unprecedented rate.

Unequivocal scientific evidence indicates that climate change is now occurring at an unprecedented rate. Unless noted otherwise, the following facts and figures are from the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Synthesis Report (2007). In the 20th Century, global temperatures increased by 0.7°C (1.3°F). In the past, the planet has gone through cycles of gradual warming and cooling, but the changes taking place today are happening faster than during any past natural cycle. While there are some natural causes to the climate change occurring today, the primary drivers of this rapid climate change are the increased concentrations of greenhouse gases, particularly carbon dioxide in the atmosphere. The global increase in these gases is overwhelmingly caused by the actions of people, most significantly through fossil fuel use and forest loss and degradation. Carbon dioxide concentration is now at its highest level in the atmosphere in over 650,000 years, outweighing all other factors that contribute to climate change.

Sea level rise is one of the more predictable and most profound consequences of climate change.

Global sea level rose about 17 cm (7 in.) in the 20th Century. Most of that rise was due to thermal expansion — the physical swelling of seawater as its temperature increases — and melting land ice. The rate of rise averaged 1.7 mm (0.067 in.) per year during the last century and that rate accelerated during the period 1993 to 2003 to about 3 mm (0.12 in.) per year (Church and White 2006). IPCC 4th Assessment Synthesis Report (2007) sea level rise (SLR) projections range from 18 cm (7 in.) to 59 cm (23.2 in.) for the year 2100. Citing a lack of basis in the published literature, the IPCC excluded "future rapid dynamical changes in ice flow," or the potential for Antarctica and Greenland's ice sheets to melt relatively quickly, from those projections. However, recent publications describing rapid melting in Antarctica and Greenland and other contributing factors lead many scientists, including members of the IPCC, to anticipate SLR greater than the range projected by the IPCC in 2007 (Rahmstorf et al. 2007 and Mitrovica et al. 2009).

Sea level rise will create impacts on the Florida Keys in the decades to come and in the next one to three centuries it is likely to undo most, if not all, that has been done to protect the terrestrial plants, animals and natural communities of the Florida Keys.

Beginning with President Theodore Roosevelt's creation of the Key West National Wildlife Refuge in 1908, government and private sector conservation efforts have effectively protected much of the remarkable flora and fauna of the Florida Keys. Today, an interconnected network of Keys protected areas is comprised of four national wildlife refuges, three national parks, nine state parks and numerous other natural areas owned or

managed by the state, the U.S. Navy, Monroe County, municipal governments and private conservation organizations, including The Nature Conservancy. The combination of natural and developed areas, paired with equally-appealing marine recreation opportunities, makes the Keys one of the State of Florida's and the United States of America's best-known hotspots for nature-based tourism. But in the year 2100, not quite two centuries after the Keys were touched by President's Roosevelt's conservation vision for the United States, terrestrial protected areas and the endemic organisms found in this low-lying island chain are likely to be extinct or clinging to an increasingly precarious existence as the sea rises around them.

Now is the time for a coordinated effort to identify the impacts of sea level rise on the Florida Keys and to develop and implement strategies to help natural areas and native species adapt to inevitable change.

The mission of The Nature Conservancy is to preserve the plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive. Since 1971 the Conservancy has employed traditional and cutting-edge conservation strategies in the Florida Keys. Guided by the best available science and carried out in cooperation with government agencies, other private conservation organizations, business interests and individuals, the Conservancy's land acquisition, natural area management, marine resource stewardship and advocacy initiatives have contributed significantly to protection of the Keys' most important natural areas and their most imperiled species.

Big Pine Key is one of those important natural areas where the Conservancy has invested heavily in conservation. The Conservancy has advocated successfully for public land acquisition funding in Tallahassee and Washington, D.C. and directly acquired 574 acres from numerous willing sellers for inclusion in the National Key Deer Refuge. Conservancy staff and volunteers have worked side-by-side with local, state and federal government agencies on rare species inventories, wetland restoration projects, invasive species control efforts and prescribed fires since 1987. Management and monitoring of the Conservancy's 20-acre Terrestris Preserve in the heart of Big Pine Key gives the organization firsthand experience with the dramatic changes that saltwater storm surges from hurricanes have wrought in the Keys.

In 2007 The Nature Conservancy initiated a sea level rise study focused on Big Pine Key, and in 2009 the study was expanded to the entire Florida Keys.

The Conservancy obtained new, very high-resolution digital elevation data for Big Pine Key and then used a simple "bathtub" modeling technique to derive future shoreline positions, changes in distribution of major habitat types and estimates of lost property value based on future SLR projections from scientific literature. Lower-resolution digital elevation data already available for the entire Florida Keys was used to compare results derived from the high-resolution data for Big Pine Key and to provide a preliminary

assessment of property at risk from SLR throughout the entire Florida Keys through the year 2100. The study is intended to catalyze interest in examining sea level rise impacts and developing adaptation strategies for the Florida Keys and similar islands in Florida and around the Gulf of Mexico and Caribbean Basin. The study and its results are described below.

Methods

Airborne Light Detection and Ranging Data and Digital Elevation Models for Big Pine Key.

The Nature Conservancy contracted with Florida International University's International Hurricane Research Center (IHRC) to collect airborne Light Detection and Ranging (LIDAR) data and develop very high-resolution Digital Elevation Models (DEMs) for Big Pine Key. On January 19, 2007, an Optech Airborne Laser Terrain Mapper (ALTM) 1233 LIDAR mapping system mounted in a Cessna 337 aircraft was used to collect topographic data over Big Pine Key. Data were collected at a nominal altitude of 600 m with the survey consisting of 24 overlapping 430-m-wide swaths. Ground control was provided by an Ashtech Z-12 Global Positions System (GPS) receiver equipped with a choke ring antenna mounted onto a fixed-height tripod. The total coverage of low-lying areas exceeded 15,000 acres. More than 150 million irregularly spaced ground surface elevations were measured with a nominal point spacing of 0.7 m.

Accuracy was assessed by comparing the bare earth DEMs with an independent dataset consisting of 57 GPS control points collected by the IHRC. An additional 63 control points were used for in-situ calibration following each flight. This analysis indicated a vertical root mean squared error of less than 0.09 m. This error corresponds to a vertical accuracy of 0.17 m at the 95 percent confidence level. IHRC provided the Conservancy ungridded X, Y, and Z points of top surface, last return, and bare earth data and high-resolution (1 m and 5m) DEMs produced by gridding both top surface and bare earth point data. Horizontal and elevation data were represented in meters. Horizontal coordinates were in UTM Zone 17, NAD83. The elevations were referenced to NAVD88. Point data and high resolution DEMs were organized into 2000 meter x 2000 meter grid squares or "tiles."

Modeling future shorelines for Big Pine Key based on SLR projections from the scientific literature.

The Nature Conservancy imported the 5-m bare earth DEM into ArcView 3.3 Geographic Information System (GIS) computer software and used the GridPig extension to null all values below 0m — the assumed modern day shoreline — and above 3.28m (10 ft.) based on the highest documented natural elevation of Big Pine Key being about 2.44 m (8 ft.) and allowing for undocumented higher natural elevations or

unnatural elevations such as the U.S. Highway 1 bridge approaches. This created the basis for the simplistic "bathtub" modeling to follow. See Figures 1 through 14.

Acquisition of the high-resolution elevation data corresponded with the release of the IPCC 4th Assessment Synthesis Report in February 2007. The IPCC was established in 1988 as an objective source to summarize peer-reviewed literature detailing human impact on the global climate. The panel was created by and is open to member countries of the United Nations Environment Programme and the World Meteorological Organization. Relevant non-governmental, international and intergovernmental organizations also participate. The IPCC issues reports and technical papers at regular intervals to update the state of knowledge on climate change. These assessments are widely distributed, well regarded and used to guide decision making. The latest report provided current predictions for both global warming and sea level rise based on modeled scenarios of greenhouse gas emissions. These IPCC scenarios provided an obvious source of sea level rise projections upon which to base modeling of potential future shorelines for Big Pine Key.

Big Pine Key Scenarios 1, 2 and 3, below, are adapted directly from the IPCC's Special Report on Emission Scenarios (2000). These scenarios are based on the computed amount of change in the climate system due to various potential amounts of anthropogenic greenhouse gases and aerosols in 2100. Each scenario describes a future world with varying levels of atmospheric pollution leading to corresponding levels of global warming and corresponding levels of SLR.

Big Pine Key Scenario 1, +18 cm (7 in.) in 2100, is based on IPCC Scenario B1.

This scenario describes a world with global population that peaks in mid-century and declines thereafter, with rapid change in economic structures toward a service and information economy, with the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives. This is the IPCC's best-case scenario and SLR modeling conducted on this scenario by the IPCC resulted in a range of +18 to +38 cm in 2100. For the Big Pine Key SLR modeling effort +18 cm (7 in.) is considered the best-case scenario. See Figures 2 through 6.

Big Pine Key Scenario 2, +35 cm (13.7 in.) in 2100, is based on IPCC Scenario A1B.

The A1 scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The A1B group of the A1 scenario family is distinguished by use of a balance of fossil fuel and non-fossil fuel energy sources. This is the IPCC's "middle of

the road" scenario and SLR modeling conducted on this scenario by the IPCC resulted in a range of +21 to +48 cm in 2100. For the Big Pine Key SLR modeling effort the middle of this range, +35 cm, was chosen. See Figure 7 and 8.

Big Pine Key Scenario 3, +59 cm (23.2 in.) in 2100, is based on IPCC Scenario A1F1.

The A1F1 scenario uses the same underlying presumptions as A1B but with one change. Instead of a balance of fossil fuel and non-fossil energy sources, the A1F1 scenario models a fossil fuel-intensive future. This is the IPCC's worst-case scenario and SLR modeling conducted on this scenario by the IPCC resulted in a range of +26 to +59 cm in 2100. For the Big Pine Key SLR modeling effort +59 cm is considered the worst-case IPCC scenario. See Figures 9 and 10.

The IPCC-based SLR ranges used in Big Pine Scenarios 1, 2 and 3 exclude "future rapid dynamical changes in ice flow," or the potential for Antarctica and Greenland's ice sheets to melt relatively quickly. The authors of the 2007 IPCC report cite a lack of basis in the published literature for this potentially very significant contributor to SLR. The authors of the report do not rule out the possibility that melt water from Antarctica and Greenland will contribute to additional SLR beyond the modeled amounts. Rahmstorf et al., in their January 2007 paper in Volume 315 of the journal *Science*, took a different approach to estimating future SLR. Their contribution, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," was in the vanguard of studies highlighting the potential limitations of the IPCC scenarios. They make a compelling argument for potential rise of +50 cm to +140 cm of SLR in 2100. Big Pine Key Scenarios 4 and 5, below, are adapted directly from the Rahmstorf et al. range of potential SLR.

Big Pine Key Scenario 4, +100 cm (39.3 in.) in 2100, is near the middle of the Rahmstorf et al. range.

The low end of the Rahmstorf et al. range is 50 cm, only slightly lower than the IPCC's worst-case scenario. The middle of the Rahmstorf et al. range is 95 cm, substantially higher than the IPCC's worst-case scenario. For the Big Pine Key SLR modeling effort a figure slightly higher than the middle of the Rahmstorf et al. range was selected: +100 cm was selected as a scenario in order to enhance comparability between the Big Pine Key SLR modeling effort and other unpublished studies that have used or will use +100 cm in their modeling. See Figures 11 and 12.

Big Pine Key Scenario 5, +140 cm (55.1 in.) in 2100, is the high end of the Rahmstorf et al. range.

In addition to the IPCC scenarios and the Rahmstorf et al. range there are a multitude of other SLR scenarios for the year 2100 that may be found in the published scientific literature. However, +140 cm, the high end of the Rahmstorf et al. range, is the highest modeled scenario used in the Big Pine Key SLR modeling effort. See Figures 13 and 14.

Modeling changes in dominance of generalized habitat types for Big Pine Key in response to SLR.

With modeled future shorelines established for Big Pine Key, the Conservancy quantified changes in dominance among generalized habitat types found on the island. In the 1994 publication, "Sea level rise and the reduction in pine forests in the Florida Keys," Ross et al. contributed a publication of foundational importance to the Big Pine Key study. In that paper they surveyed upper Sugarloaf Key elevations, vegetation distribution, groundwater salinity and other factors and examined historic aerial photographs from 1935 to 1991, ultimately learning that the area of pine forest on Sugarloaf Key declined from an initial 88 ha (217 acres) before 1935 to 30 ha (74 acres) by 1991. Transformation of pine forest to more salt-tolerant vegetation types proceeded continuously over that time period and advanced from lower to higher elevation, leading the authors to attribute the decline in pine forest area to SLR.

Generalized habitat types defined by Ross et al. occupy distinct elevation bands influenced by frequency of inundation by tidal waters. The tidal zone, dominated by mangroves, ranges from sea level to about 50 cm (20 in.) above sea level and is continuously saturated with saline or hypersaline water. The transitional zone dominated by salt-tolerant vegetation in woodlands, shrublands and salt marshes ranges from about 50 cm (20 in.) to 80 cm (31 in.) above sea level and is frequently very dry but periodically submerged in salt water. The upland zone, dominated by pine forests and broadleaf, "hammock" forests as well as most of the built environment, occupies most of the area higher than 80 cm (31 in.) above sea level and is flooded by salt water only during significant storm surges. To these three generalized habitat types, a fourth type described as "water over land" was added to account for areas at or above sea level in 2007 that SLR modeling suggests will be inundated in a given scenario.

The Conservancy modeled changes in these generalized habitat types in response to the selected SLR scenarios. Simply stated, as sea level rises, water over land displaces tidal habitat, which moves upslope and in turn displaces transitional habitat, which moves upslope and displaces upland habitat. This change is depicted in pie graphs showing the total area of Big Pine Key as mapped in 2007, 2523 ha (6235 acres), with wedges indicating percentages of the total area occupied by a given habitat type. In the 2007 baseline, water over land occupies zero percent of the total area, tidal occupies 43 percent, transitional occupies 28 percent and upland occupies 29 percent (see Figure 1). At the modeled extreme, in Big Pine Key Scenario 5 (+140 cm,) water over land occupies 96 percent of the total area, tidal habitat occupies the remaining 4 percent and all transitional and upland habitats have been displaced. See Figures 13 and 14.

To determine the area occupied by each generalized habitat type under a given SLR scenario, the Conservancy again used the DEM clipped to 0 m through 3.28 m then incorporated a sliding scale to the elevations. In 2007, the baseline year, the scale was 0-

50 cm for tidal, 50-80 cm for transitional and greater than 80 cm for upland habitat. Using the example of Big Pine Key Scenario 1 (+18 cm), as sea level rises, the scale shifts such that +18 cm is the new 0, 0-18 cm is now water over land, 18-68 cm is now tidal, 68-98 cm is now transitional and greater than 98 cm is now upland. The areas of each generalized habitat were computed using the DEM in ArcGIS computer software. The program calculates the number of grid cells in each habitat type and that number is multiplied by 25 (5x5m cells) to derive square meters of each habitat type. See Figures 1 through 14.

Modeling SLR-driven loss of property values for Big Pine Key and the Florida Keys.

A 2008 report from Florida State University (FSU) titled, "Climate Change in Coastal Areas in Florida: Sea Level Rise Estimation and Economic Analysis to Year 2080," provided estimates of risks of inundation and storm surges associated with increasing sea level in six Florida counties including Monroe County. Using the IPCC's SLR estimates and then-current property value data, Industrial Economics, Incorporated (IEc) and FSU developed GIS elevation models to identify the area, value, and per-acre value of land at risk under different SLR scenarios for three of the six counties - Miami-Dade, Duval, and Escambia - but not including Monroe County.

In January 2009 the Conservancy contracted with IEc to conduct an assessment of property value change associated with SLR for Big Pine Key and the entire Florida Keys using the same techniques used for the FSU study. IEc used the LIDAR-generated 1m and 5m resolution DEMs developed by the IHRC for an in-depth examination of Big Pine Key. For a broader examination of the entire Florida Keys, IEc used the best-available DEM from the National Elevation Dataset (NED) with 30 m resolution. Prior to running the IEc SLR model, the LIDAR and NED data were set to a "zero elevation" calculated using three NOAA tide gauges in the region: Key West, Vaca Key and Virginia Key. This analysis used December 2008 GIS parcel data provided by the Monroe County Property Appraisers Office. The values reported are based on "just value" corrected by adding 15 percent, a standard correction used to estimate "market value." Each parcel's geometric center was defined and the elevation of that center point was determined by overlaying the DEMs with the parcel data. By making an assumption that the center elevation is representative of the elevation of the entire parcel, the SLR scenario in which the property was assumed to be at risk of inundation could be determined. Value for a given parcel determined to be inundated was subtracted from the total value for the lower Keys region (See Figures 15 and 16 and Table 1), middle Keys region (See Figures 17 and 18 and Table 1), upper Keys region (See Figures 19 and 20 and Table 1) or the entire Florida Keys (See Table 1) or for Big Pine Key (See Table 2).

Results

The results of the analyses are presented as a series of figures and tables on pages 9-26.

Figure 1. Big Pine Key: 2007 Sea Level

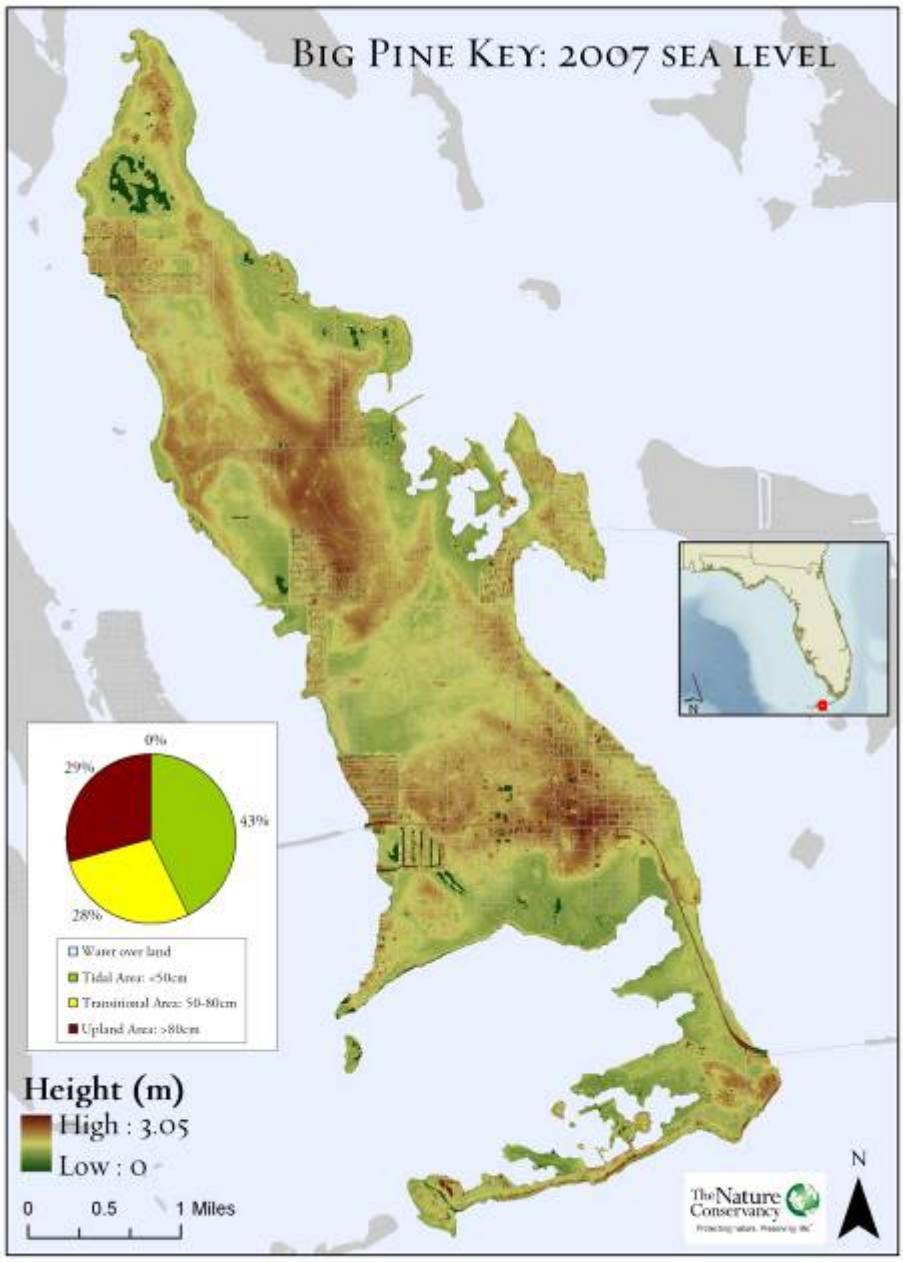


Figure 2. Big Pine Key Scenario 1: +18 cm (7 in.) 2100

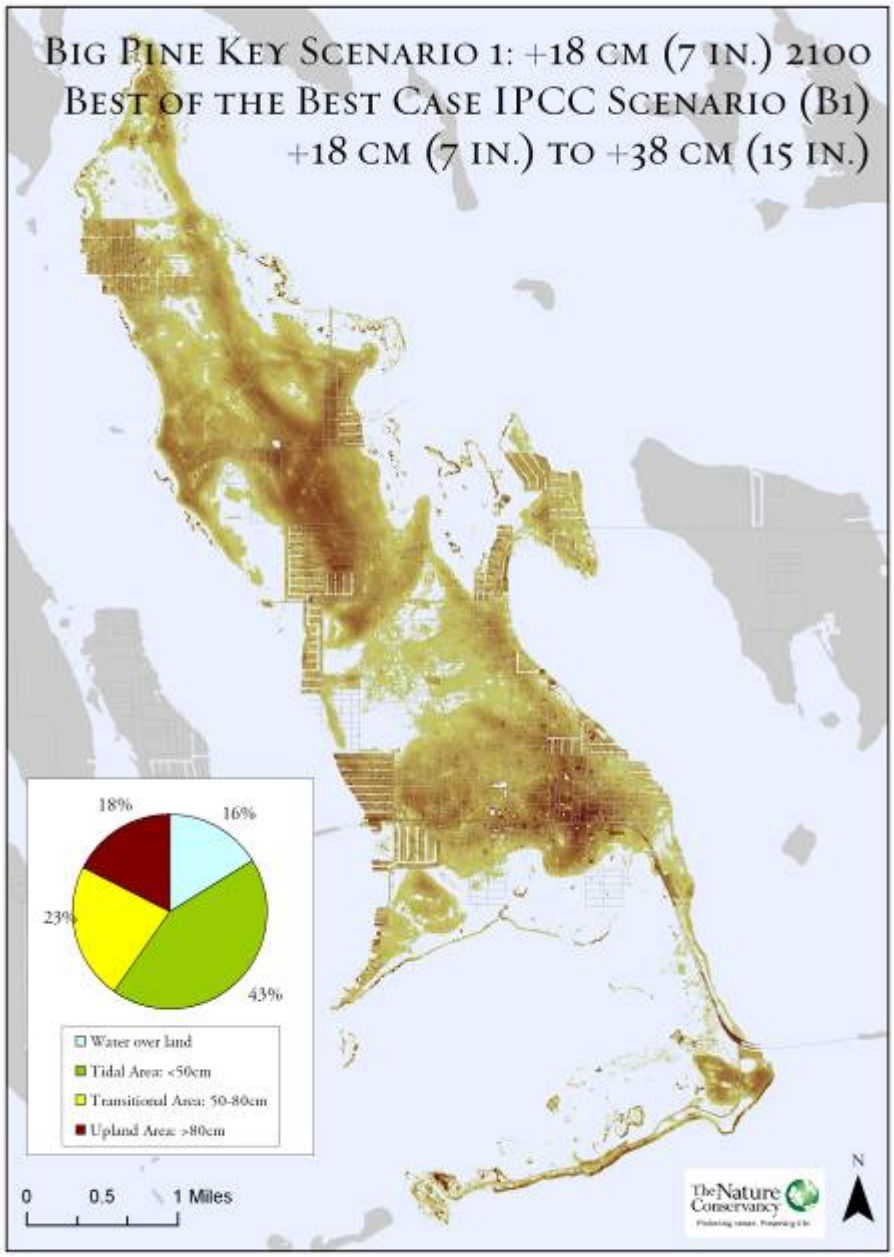


Figure 3. Big Pine Key Scenario 1: +18 cm (7 in.) 2040, 2070, 2100 Time Series

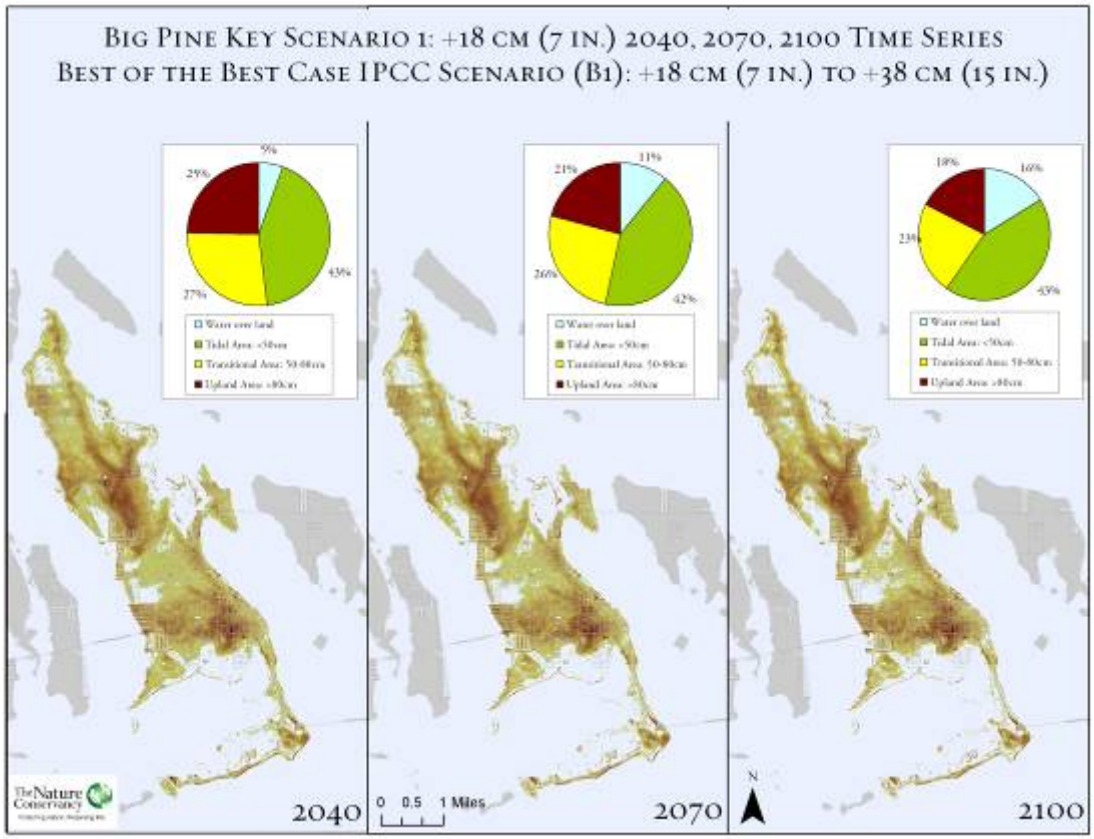


Figure 4. Big Pine Key Scenarios 1-5 – Parcels at Risk Using 1 m LIDAR

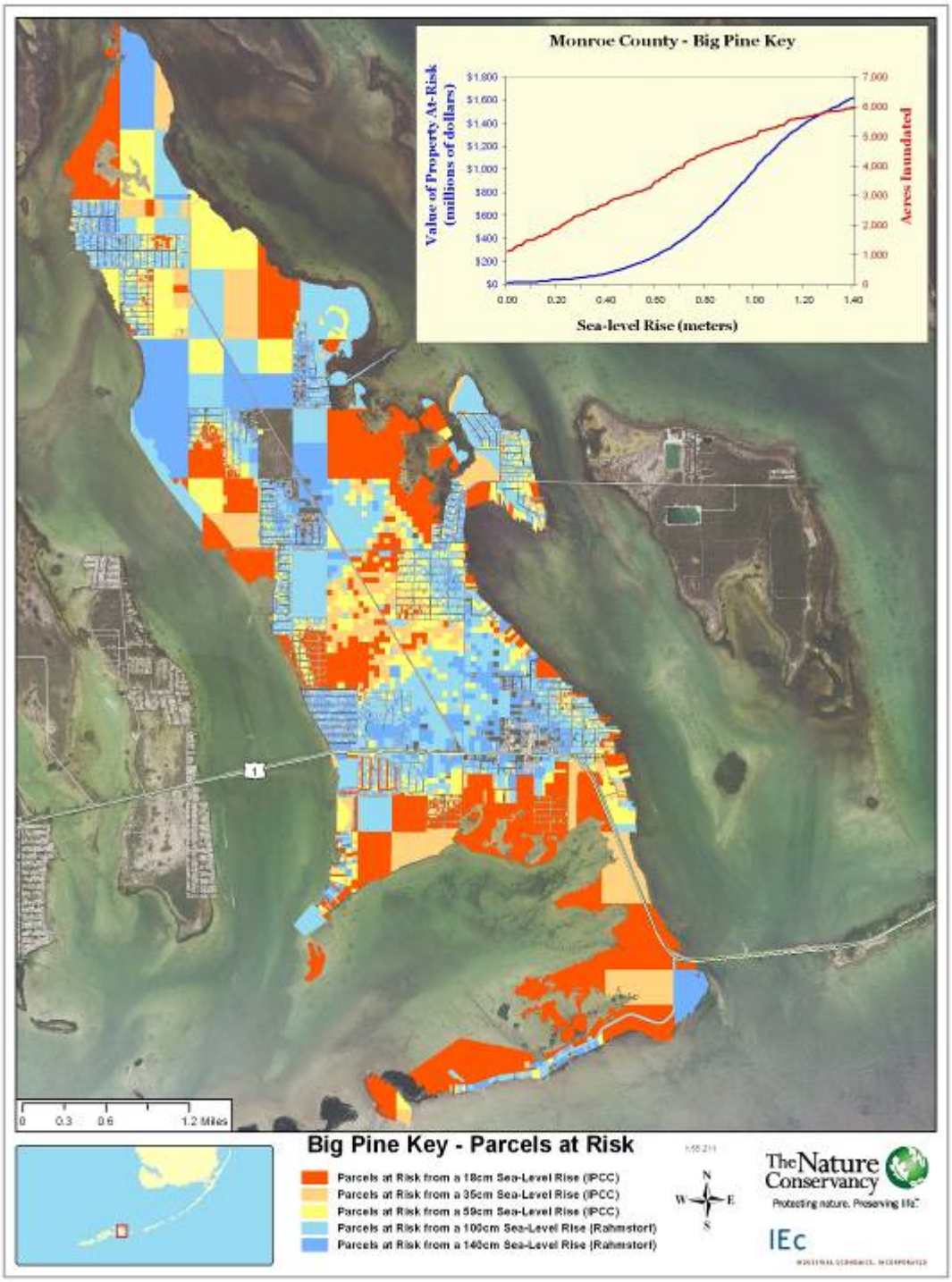


Figure 5. Big Pine Key – Parcels at Risk 1 m LIDAR and 5 m LIDAR Comparison

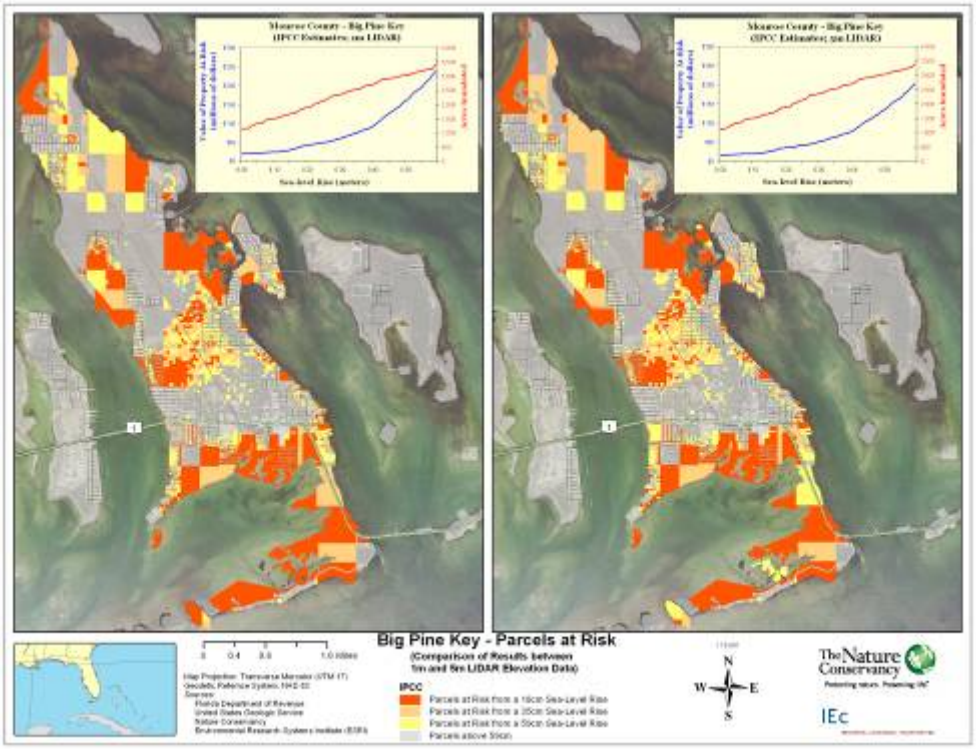


Figure 6. Big Pine Key – Parcels at Risk 1 m LIDAR and 30 m NED Comparison

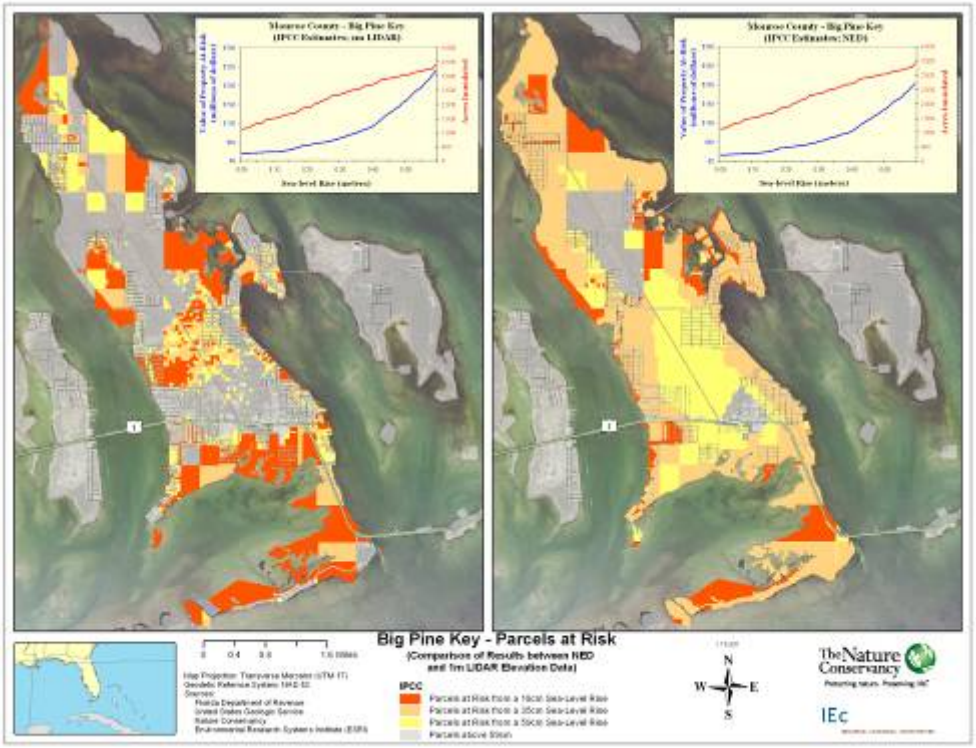


Figure 7. Big Pine Key Scenario 2: +35 cm (13.7 in) 2100

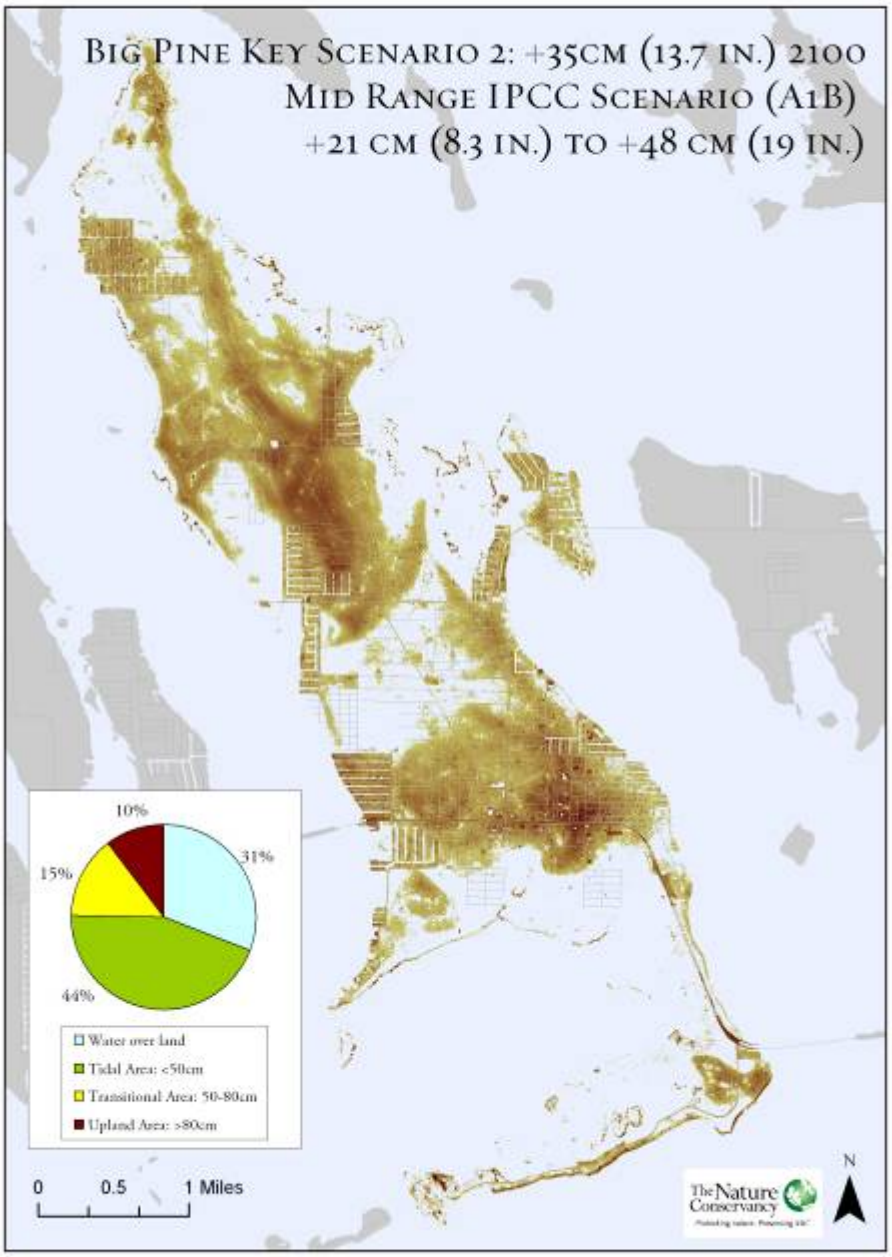


Figure 8. Big Pine Key Scenario 2: +35 cm (13.7 in.) 2040, 2070, 2100 Time Series

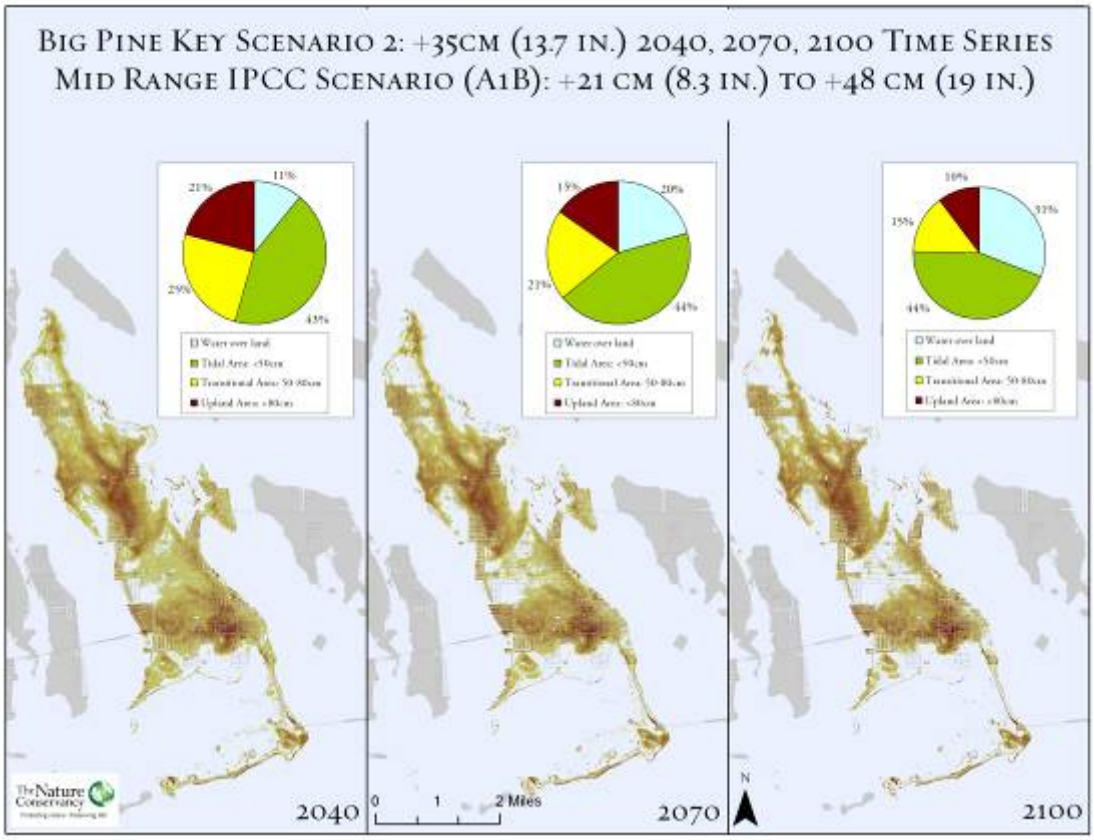


Figure 9. Big Pine Key Scenario 3: +59 cm (23.2 in.) 2100

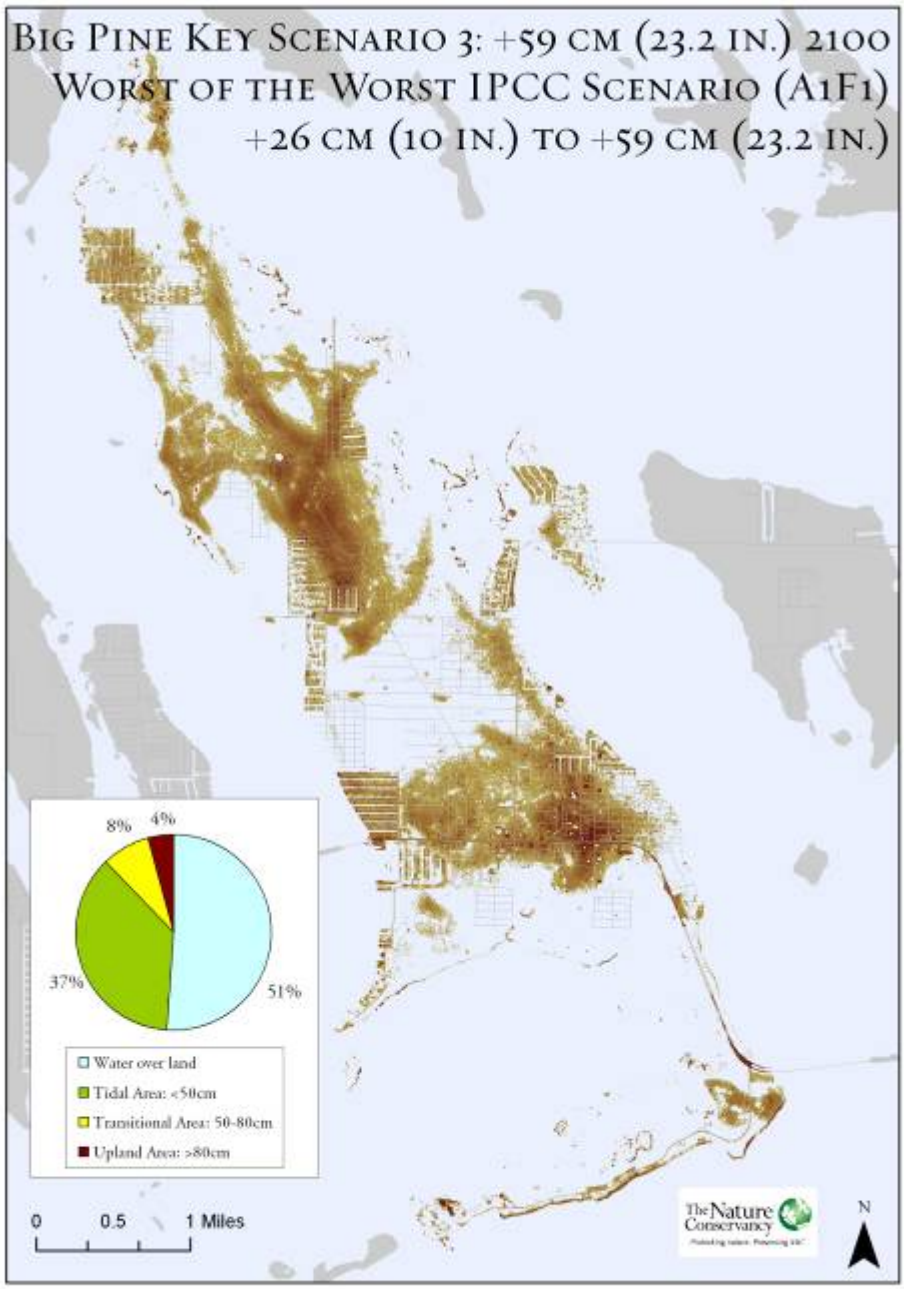


Figure 10. Big Pine Key Scenario 3: +59 cm (23.2 in.) 2040, 2070, 2100 Time Series

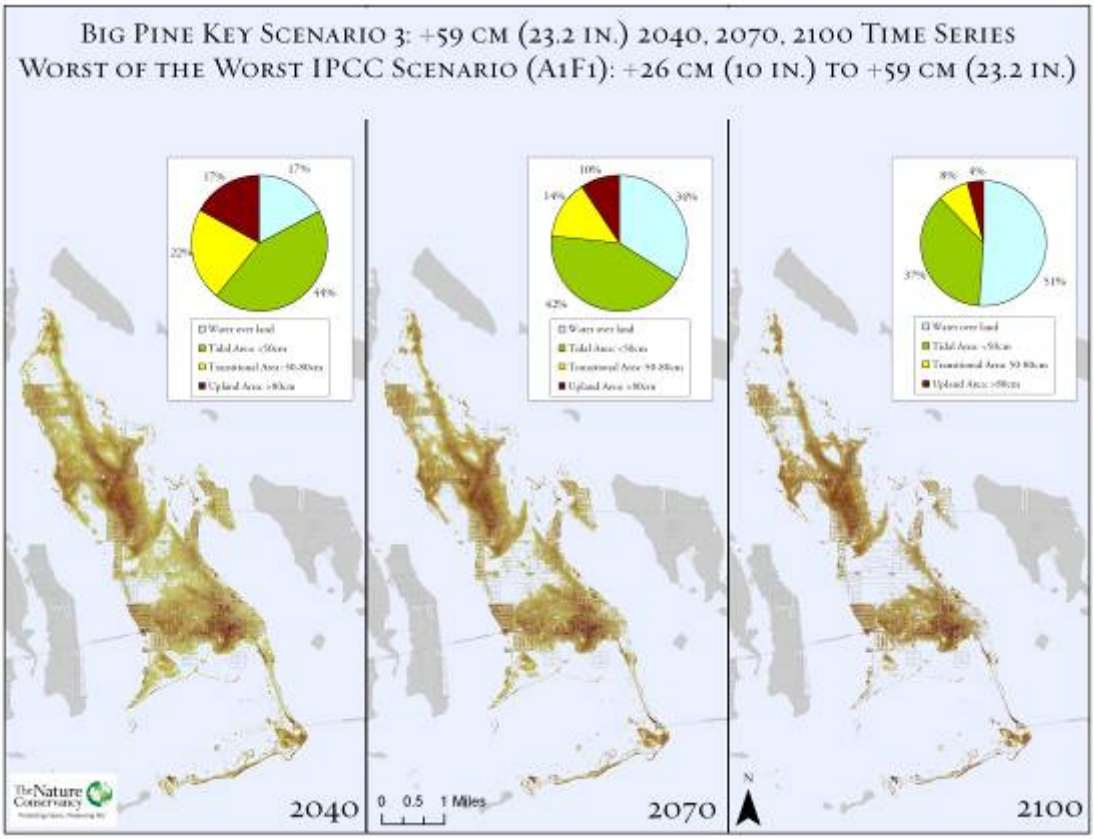


Figure 11. Big Pine Key Scenario 4: +100 cm (39.3 in.) 2100

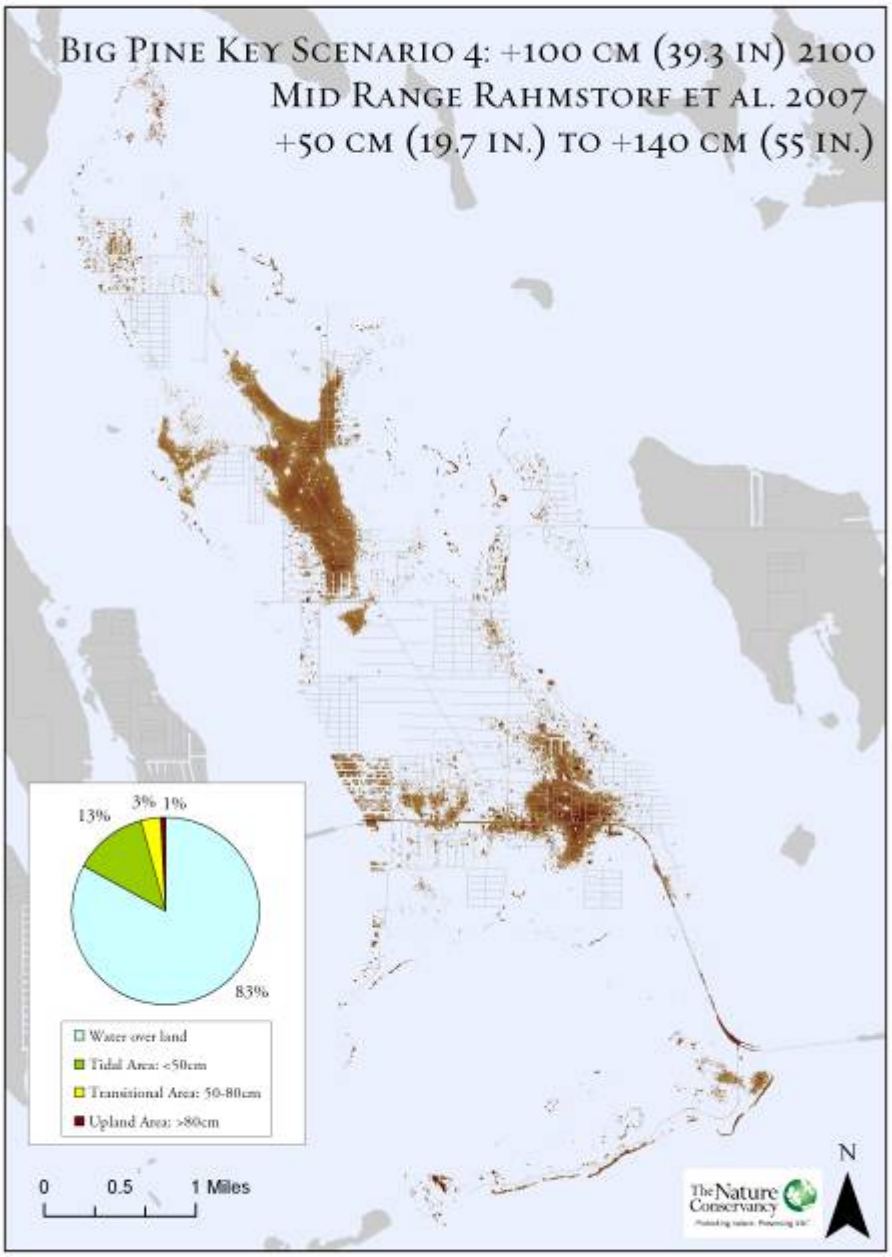


Figure 12. Big Pine Key Scenario 4: +100 cm (39.3 in.) 2040, 2070, 2100 Time Series

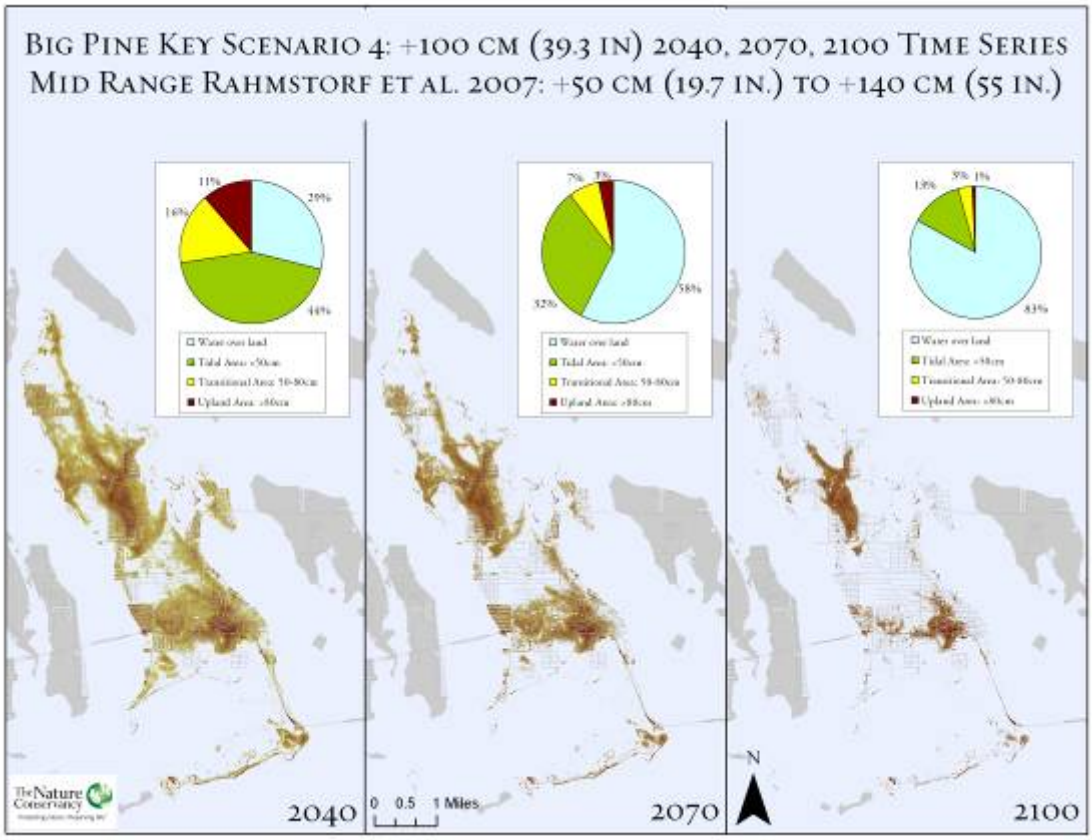


Figure 13. Big Pine Key Scenario 5 +140 cm (55 in.) 2100

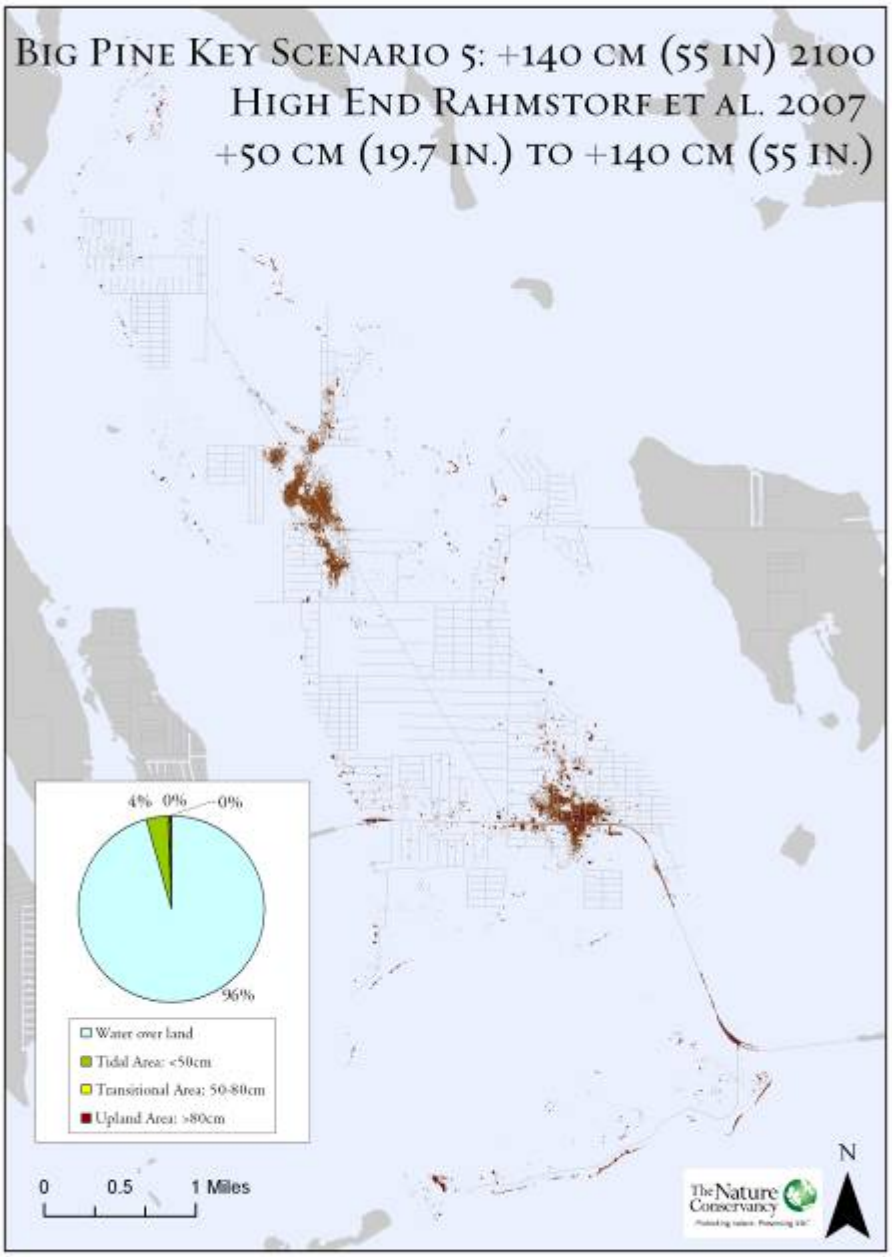


Figure 14. Big Pine Key Scenario 5: +140 cm (55 in.) 2040, 2070, 2100 Time Series

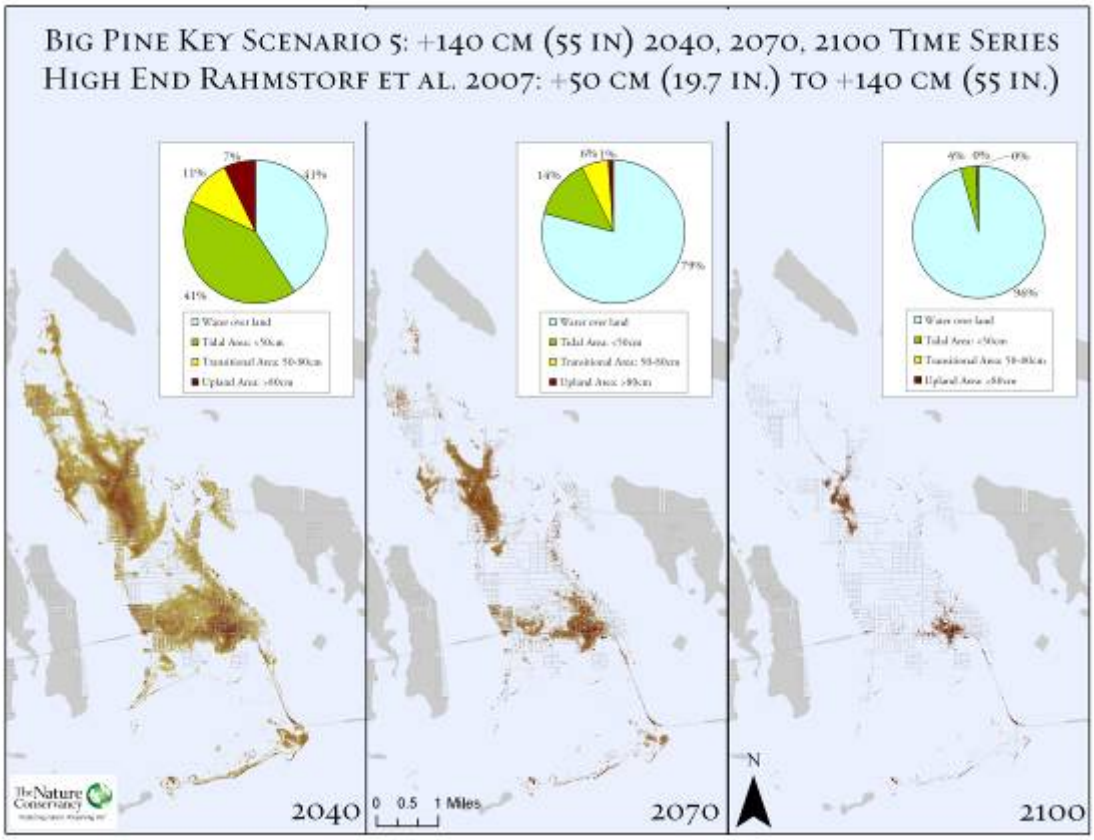


Figure 15. Lower Keys – Parcels at Risk IPCC Scenarios Using 30 m NED

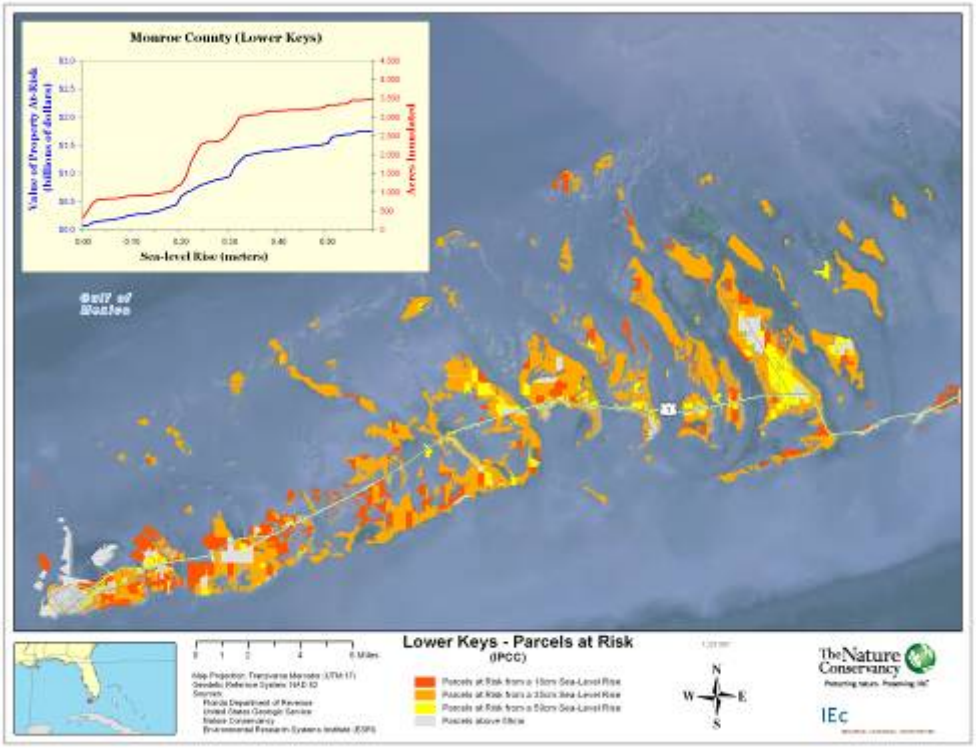


Figure 16. Lower Keys – Parcels at Risk Rahmstorf Using 30 m NED

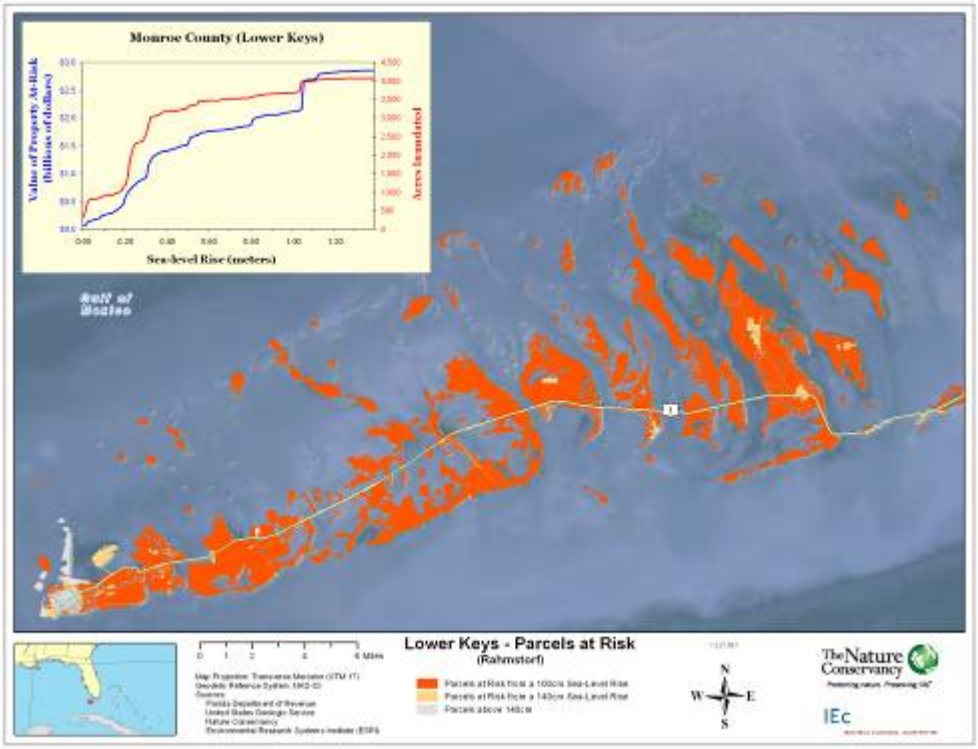


Figure 17. Middle Keys – Parcels at Risk IPCC Scenarios Using 30 m NED

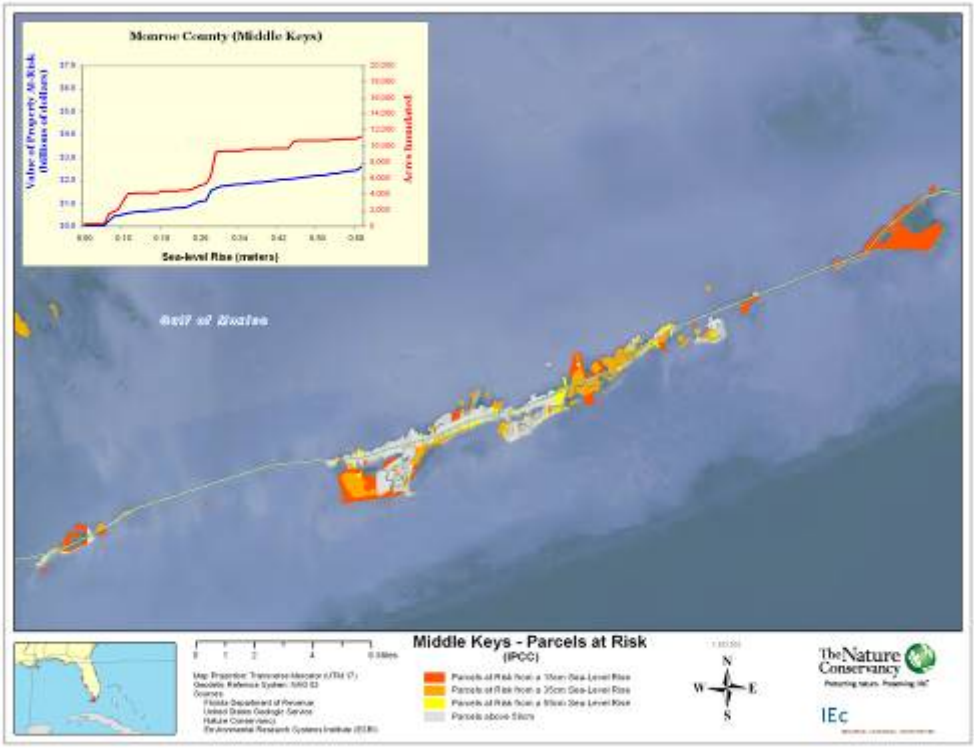


Figure 18. Middle Keys – Parcels at Risk Rahmstorf Using 30 m NED

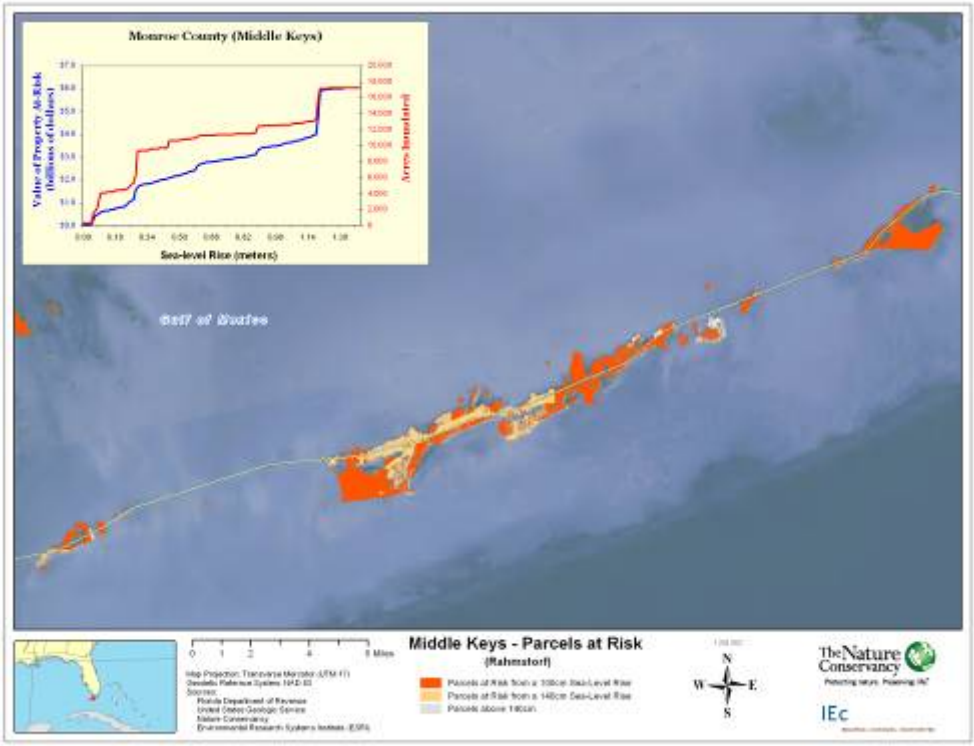


Figure 19. Upper Keys – Parcels at Risk IPCC Scenarios Using 30 m NED

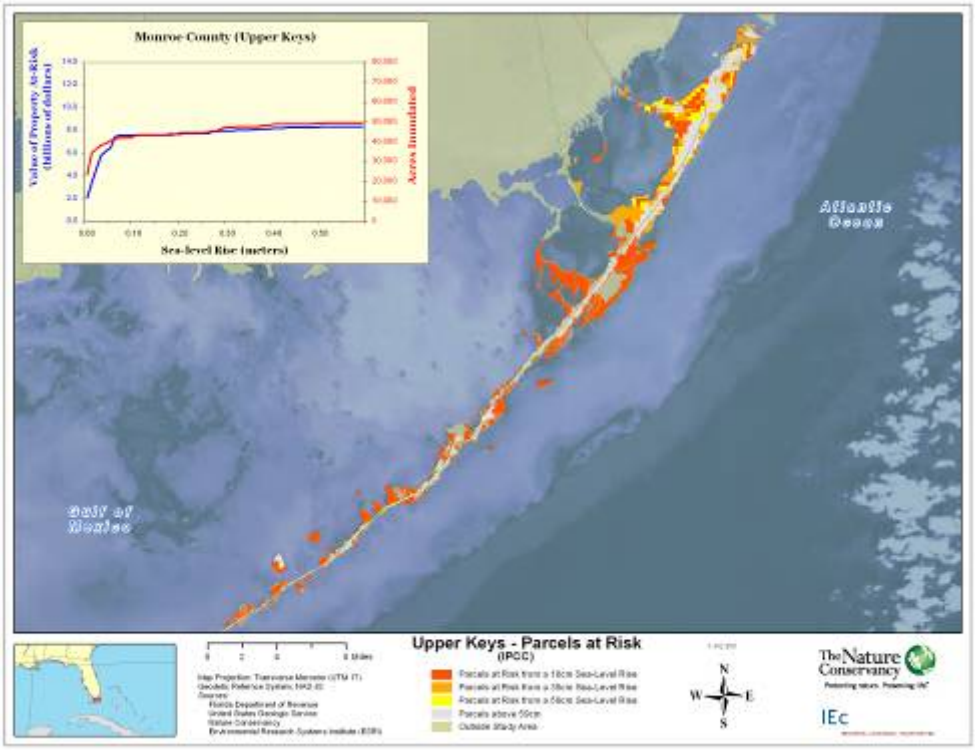
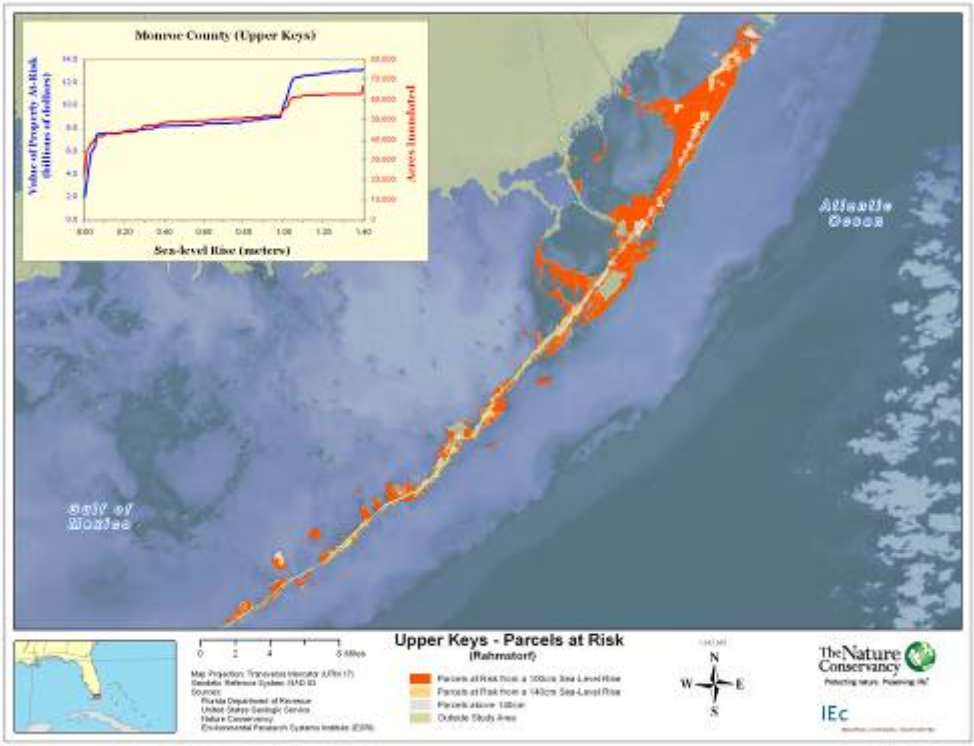


Figure 20. Upper Keys – Parcels at Risk Rahmstorf Using 30 m NED



The area and property value at risk varies under each SLR scenario.

Under the most optimistic IPPC scenario – a rise of 18 cm over the next 100 years – $11 billion in property value and 58,800 acres are at risk of inundation in the Florida Keys. Under the highest Rahmstorf estimate, –a 140 cm rise by 2100 – approximately $35 billion in property value and 142,000 acres are at risk in the same area. Table 1 highlights the estimated market value and acreage at risk for all SLR scenarios considered for Monroe County based on the 30 m NED data. Table 2 highlights the market value and acreage at risk for all SLR scenarios considered for Big Pine Key based on the 1 m LIDAR data.

Two important caveats must be taken into consideration when reviewing these estimates of SLR-driven property value change.

1. The Monroe County GIS parcel data contains parcels that are already entirely submerged and others that contain both submerged and unsubmerged area. Many of these coastal properties with both submerged and unsubmerged area are very valuable and their center point elevations may be below, at or only slightly above zero today. Millions of dollars worth of property in Monroe County is already assumed to be at risk using this simplified modeling approach. This causes some overestimation of property values at risk from SLR in the Florida Keys.
2. The IPCC and Rahmstorf scenarios do not incorporate local subsidence — geological "sinking" of the land — which is estimated to be 1 mm per year for the Florida Keys (Mendolsohn and Neuman 1999). In one century this would amount to 10 cm (about 4 in.) of apparent SLR. This causes underestimation of property values at risk from SLR in the Florida Keys.

Table 1. Property Value and Acreage at Risk Under Various SLR Scenarios (Monroe County, 30m NED)

	LOWER KEYS		MIDDLE KEYS		UPPER KEYS		FLORIDA KEYS	
SLR Scenario	PROPERTY VALUE AT RISK	ACRES	PROPERTY VALUE AT RISK	ACRES	PROPERTY VALUE AT RISK	ACRES	PROPERTY VALUE AT RISK	ACRES
IPCC 18cm	$2,610,000,000	11,000	$753,000,000	4,430	$7,670,000,000	43,300	$11,000,000,000	58,800
IPCC 35cm	$8,790,000,000	49,400	$1,850,000,000	9,500	$8,040,000,000	47,500	$18,700,000,000	106,000
IPCC 59cm	$11,000,000,000	54,400	$2,610,000,000	11,200	$8,330,000,000	49,600	$21,900,000,000	115,000
Rahmstorf 100cm	$13,000,000,000	56,300	$3,530,000,000	12,600	$10,100,000,000	55,600	$26,700,000,000	124,000
Rahmstorf 140cm	$15,800,000,000	58,000	$6,040,000,000	17,300	$13,200,000,000	67,100	$35,100,000,000	142,000
2008 Start Values	$20,900,000,000	60,500	$6,400,000,000	17,500	$15,700,000,000	76,100	$43,000,000,000	154,000

Note: Figures are rounded to 3 significant digits. Entries may not sum to totals due to rounding.

Table 2. Property Value and Acreage at Risk Under Various SLR Scenarios (Big Pine Key; 1 m LIDAR)

SLR Scenario	BIG PINE KEY	
	PROPERTY VALUE AT RISK	ACRES
IPCC 18cm	$39,500,000	1,840
IPCC 35cm	$75,000,000	2,530
IPCC 59cm	$239,000,000	3,410
Rahmstorf 100cm	$993,000,000	4,980
Rahmstorf 140cm	$1,620,000,000	5,950
2008 Start Values	$1,561,809,861	6,235

Note: Figures are rounded to 3 significant digits. Entries may not sum to totals due to rounding.

Discussion

The relatively simple modeling methods used to generate the results could undoubtedly be further refined, and – in a place as vulnerable to SLR as the Florida Keys – it is likely that they will be improved upon, either by The Nature Conservancy or others with a vested interest in understanding how the islands and their inhabitants will change over time. No matter how sophisticated future modeling approaches may be, the fact remains that there are no credible projections that suggest that the sea will stop rising in the decades and centuries to come.

Some will respond to the information in this report with a "come what may" attitude, but The Nature Conservancy's mission and its significant investment in the Florida Keys compel the organization to respond proactively.

Becoming informed — the motivation for the scientific activities reported herein — is the first step in that proactive response and it is an ongoing process. Informing others — the motivation for releasing this report publicly — is the second step. Only informed people and institutions are likely to be able to define the array of problems associated with SLR and then develop strategies to address those problems. Subsequently, only informed people and institutions are likely to support SLR response strategies that may be novel, complex, costly or otherwise challenging to implement.

Response strategies will take two general forms: mitigation and adaptation.

Mitigation of the root causes of climate change and SLR — primarily fossil fuel use and forest loss — must take place at every scale from the global to the local in order for the Florida Keys to experience any appreciable reduction in the local rate of SLR.

International agreements and U.S., State of Florida, Monroe County and Florida Keys municipal laws, regulations and codes do, or will soon, address climate change mitigation. Non-regulatory bodies like the IPCC, the U.S. Mayors Climate Protection Task Force, the Florida Energy and Climate Commission, Monroe County's Green Initiatives Task Force and local government "green teams" for the City of Key West, City of Marathon, City of Key Colony Beach, City of Layton, Islamorada, Village of Islands play an increasing role in developing and tracking mitigation actions. Non-governmental organizations focused on climate change mitigation include the international Local Governments for Sustainability (ICLEI), national Climate Communities, Florida Climate Alliance and the Florida Keys Green Living & Energy Education (GLEE) among many others. Since its creation in 2003, GLEE has been a powerful catalyst for climate change mitigation at the local level.

Mitigation activities notwithstanding, the Florida Keys will experience SLR-driven changes that will incrementally diminish the viability of terrestrial plants, animals and natural communities while creating new marine habitat of uncertain quality.

SLR adaptation strategies are being developed in coastal areas around the world. At one extreme, the Republic of Maldives, a low-lying archipelago nation south of India, is examining options to purchase a new homeland in India, Sri Lanka or Australia for its 386,000 citizens in the event of rapid SLR, while simultaneously going "carbon neutral." The State of Rhode Island is preparing for a sea level rise of 3-5 feet by 2100. Miami-Dade County's Climate Change Advisory Task Force (MDCCATF) has developed specific adaptation recommendations for that county's natural areas and built environment based on a 1.5 foot SLR in 50 years and 3-5 feet in 100 years. The MDCCATF recommends support for the Comprehensive Everglades Restoration Plan based on a belief – shared by the U.S. National Park Service and others including The Nature Conservancy – that a restored Everglades ecosystem will be better able to resist SLR-driven change in general and better able to protect south Florida's freshwater supply in particular (Kimball 2007, Miami-Dade County Climate Change Advisory Task Force 2008).

Examples of SLR adaptation planning by government entities are relatively few in the Florida Keys themselves, but that is changing. In developing its Comprehensive Conservation Plan for the lower Keys National Wildlife Refuges, the U.S. Fish and Wildlife Service is incorporating SLR estimates in its management planning, using site specific modeling work done in collaboration with Florida International University, and Sea Level Affecting Marshes Model (SLAMM) results for the National Key Deer Refuge. In the process of responding to the immediate need to raise the elevation of low-

lying streets that are flooded with seawater by high tides today, the City of Key West is beginning to factor SLR into its engineering and construction decisions.

In the 2009 publication, "Disturbance and the Rising Tide: the Challenge of Biodiversity Conservation in Low-island Ecosystems," Ross et al. lay out a compelling argument for helping natural areas and ecosystems adapt to both the incremental long-term effects of SLR and acute disturbances such as storm surges and forest fires. Their approach calls for:

(1) Identification of "core areas" with the best chances of persistence during SLR,
(2) Intensive management of core areas to minimize loss of biodiversity, and
(3) Ex-situ conservation, including relocation of vulnerable species to less vulnerable areas.

Those with conservation interests in the Florida Keys have long been proponents of identification of core areas for conservation. This began in the early 1990s with the establishment of the original boundaries for the state's land acquisition program, now known as Florida Forever. Adding a thorough understanding of likely SLR impacts to the current conservation land acquisition prioritization process can only help focus acquisition efforts. Current acquisition efforts are characterized by a large amount of land owned by a multitude of individuals, only some of whom are willing sellers. Particularly at present, there is insufficient funding available to purchase land even when landowners are willing to sell to government or private conservation buyers.

Identifying core areas will not be as simple as choosing the highest ground, although elevation will be a critical component of any such analysis. Four other important components include the following.

(1) Representation: All habitat types and species should be included in protected core areas to the extent possible.
(2) Replication: There should be more than one core area for each habitat type and/or species protected so the impacts of a single unmanageable event, such as a severe storm surge, are less likely to damage all habitat or species occurrences.
(3) Connectivity: Gene flow among core areas is ensured by maintaining biological corridors or, in extreme cases, via direct human intervention (i.e. translocations of organisms or their gametes within the historic range of the species or subspecies). Connectivity also comes into play in assessing the ability of a given habitat patch within a core area patch to migrate from lower to higher ground during the course of SLR.
(4) Effective management: Synonymous with Ross et al.'s "intensive management," it is imperative that core areas are not only identified and protected in a legal sense. Threats to the core areas and the species they support must also be abated, and the natural processes that shape the ecosystem in a given core area must be maintained.

Though incomplete, the present-day system of protected natural areas substantially addresses representation, replication and connectivity. Management is more effective on some protected areas than others, but most core areas are effectively managed.

Managing for resilience and adaptation to SLR.

Effective management increases resilience of natural areas and native species. Resilience may be defined as the ability of something to undergo disturbance or stress and still recover to its former state. Entire ecosystems, core areas, species populations, individual organisms, and even human communities with their built environment and industries all possess a measure of resilience that can be enhanced or degraded.

A local example of resilience-based management may be found in the realm of coral reef conservation. Coral reefs are particularly vulnerable to climate change-induced stresses, such as elevated seawater temperatures that trigger coral bleaching and diseases and ocean acidification that weakens existing coral skeletons and makes it more difficult for new coral structure to grow. In the Keys and southeast Florida, the Florida Reef Resilience Program has been utilizing the concept of resilience since 2005 to identify coral reefs that will be best able to withstand climate change impacts and develop resilience-based reef management and reef use strategies that will maximize protection of resilient reefs and enhance the viability of those that are less resilient. Like SLR, ocean warming and acidification cannot be effectively addressed at the local level alone. However – by minimizing local stresses such as degraded water quality, boat groundings, anchor damage and destructive fishing practices – reef managers and reef users can help make Florida coral reefs and the human communities that depend upon them more resilient to climate change-related stresses.

"No regrets" strategies for managing Florida Keys natural areas for SLR.

Several common natural resource management strategies, which have been practiced in the Keys for decades, increase the resilience of natural areas and native species to SLR. These practices still stand on their own merits, but in light of SLR their importance is amplified. Three "no regrets" strategies are described below.

#1 FIRE MANAGEMENT

Pine rocklands, found only in the lower Keys, southern Miami-Dade County, the Bahamas and Caicos islands, are a fire-dependent forest community that sustains a remarkably rich diversity of flora and fauna. In the absence of periodic fires, fire-sensitive broadleaf plant species invade the pine forest and, if left unchecked, a broadleaf "hammock" becomes established through the process known as succession. In a pine rockland forest, fire is one natural process that counteracts succession, another natural process, to maintain a diverse mix of species across the larger landscape. Sea level rise is

expected to accelerate forest succession, and the careful application of prescribed fire is the only economically viable and ecologically appropriate antidote to that succession. If SLR were not a consideration, prescribed fire would still be necessary to prevent succession to hammock. As such, improving fire management in lower Keys pine rocklands is a no-regrets strategy that should be brought to the forefront of the U.S. Fish and Wildlife Service's habitat management agenda because the Service is the dominant player in pine rockland fire management.

#2 *INVASIVE EXOTIC SPECIES MANAGEMENT*

Another no-regrets strategy is the well-established practice of invasive exotic species management. Invasive exotic species degrade natural areas by directly competing with native species that have life history requirements similar to those of the invader and by degrading habitat of native species that are adapted to feeding on native prey or forage. Invasive exotics plants, most notably Australian pine (several *Casuarina* species), are known to destabilize dunes and other coastal habitats that are the front line of natural defense against storm surges and coastal erosion which will be exacerbated by SLR. Sea level rise will favor some invasive exotics, particularly the salt-tolerant Australian pine, Asiatic colubrina (*Colubrina asiatica*) and scaevola (*Scaevola sericea*) while disfavoring those that are less salt-tolerant. At present, prevention, early detection of and rapid response to new invasive species and long-term control of established invasive species in the Florida Keys is as advanced and effective as almost any place in the world thanks to the efforts of the Florida Keys Invasive Exotics Task Force and its member organizations. Invasive exotic species management must continue to take place in order for natural areas to maintain high habitat values regardless of SLR.

#3 *WETLAND RESTORATION*

Restoration of Florida Keys wetland habitats is a third no-regrets strategy. In the course of developing the Florida Keys people filled many freshwater, brackish and saltwater wetlands, drained others via ditching, and fragmented others in the course of constructing raised roadbeds. It is not uncommon for a single wetland in the Keys to suffer from all three of these problems to some extent. Due to this degradation, inherently limited area, and naturally unfavorable geological conditions in the middle and upper Keys, freshwater wetlands are one of the rarest habitat types in the Keys and they are critically important to many wildlife species. Removing fill from historic wetlands and restoring connectivity in degraded wetlands by strategically filling some ditches, removing obsolete roadbeds and installing culverts under actively-used roads are tried and true methods for recovering lost wetland habitat and improving habitat quality. The National Audubon Society's Keys Environmental Restoration Fund (KERF) has led the way in these activities, utilizing mitigation funds from the Army Corps of Engineers and Florida Department of Environmental Protection to restore wetland habitat on public conservation lands throughout the Keys.

Filling or plugging some ditches may be essential to prevent unnaturally rapid infiltration of interior wetland, transitional, and upland habitats by saltwater. Restoring hydrological connectivity by removing obsolete roadbeds and installing culverts under functional roads takes on added importance in that these actions will enable storm surge waters to rapidly drain off the land in places where they have historically become impounded, causing unnecessary damage to freshwater-dependent habitats and species as they slowly sink into the ground and groundwater. These actions should also slow the shrinkage and salinization of the fresh groundwater lenses present on Big Pine Key and other islands. Freshwater lenses are critical for pine forests, freshwater wetlands, Key deer and other imperiled species.

The problems and the promise of ex-situ conservation approaches.

Resilience-based planning and management for terrestrial systems and species will not eliminate the eventual need for implementation of "ex-situ" or off-site conservation strategies, but they will help stave off that need. Ex-situ strategies, while perhaps necessary to prevent extinction of species and subspecies endemic to the Florida Keys, are fraught with both uncertainty and risk. Questions about the likelihood of the translocated organism's persistence in the new habitat are difficult to answer, and undesirable impacts of the organism on the new habitat and its suite of native species must be addressed prior to translocation. Long-term monitoring of any translocated species and their impacts on their new habitat and native species must be part of the plan.

Managing today for tomorrow's marine ecosystem.

Intensive management of core areas, while appropriate and necessary, ultimately will not prevent the wholesale transformation of terrestrial habitat into new marine habitat under current SLR projections. The Florida Keys — including core areas which will hold out the longest, particularly if they are intensively managed — will become marine habitat and are likely to remain marine habitat for many millennia thereafter. In light of this, intensive management should not include activities that will result in compromised marine habitat quality in the future. As a hypothetical example, erecting a dike around core habitat may slow the advance of SLR to some extent, but once SLR overcomes both the core habitat and the dike itself, the presence of the submerged dike may disrupt movement or other aspects of some marine organisms' life cycles.

While it is difficult to conceive of many core area habitat management activities that would compromise future marine habitat quality, it is much easier to predict potential negative impacts of the modern built environment on the future marine environment. Landfills, underground storage tanks for petroleum products, soil contaminated by past fuel spills and a multitude of other, less discrete sources of pollutants that could prove toxic to marine life are present in the Florida Keys today. Some forms of pavement and other artificial surfaces may prove inhospitable to the establishment of mangroves, seagrass, or settlement of coral larvae. Inappropriately placed seawalls and other forms of

shoreline hardening may disrupt movement or other aspects of marine species' life cycles. A thorough evaluation of these and other potential future problems is advisable at this time because any warranted mitigation activities will take time and funding to implement. Mitigation of this nature should be factored into future development or redevelopment of the built environment for the sake of efficiency.

Conclusion

The Florida Keys and other low-lying island and coastal communities are faced with a multitude of complex and interrelated issues. Nature conservation, water quality protection, affordable housing, private property rights and other issues have been top priorities in the Keys in recent years. But one thing easily pushes all else to the back-burner: A rapidly approaching hurricane commands undivided attention.

Hurricane contingency plans are in place well before the storm arrives. Prescribed and practiced courses of action are implemented almost mechanically by emergency management authorities once predetermined trigger points are reported by the National Weather Service. To the greatest extent possible, life and property are preserved as a result of forethought and willingness to take necessary action based on scientific evidence.

Compared to a hurricane, even the most rapid SLR will progress very gradually. This makes it easier to relegate it to the list of problems to be dealt with in the future, once SLR becomes more "real" and other, more pressing issues have been settled. But such benign neglect of SLR is likely to prove a costly mistake.

Sea level rise is real now and all indications are that the rate of rise will accelerate in the coming decades. Unlike the acute impacts of a hurricane, which the Florida Keys have historically withstood or recovered from, the impacts wrought by SLR will be permanent. Mitigation of the root causes of climate change and sea level rise may slow or reduce its impact, but significant change is inevitable. Natural areas, native species and human communities will have no choice but to adapt. Decisions made today will influence, sometimes profoundly, the ability of people and nature to adapt to SLR in the future.

Forethought and the willingness to take necessary action – based on scientific evidence – have helped protect the Florida Keys from the impacts of hurricanes. The same principles should guide the islands through their adaptation to sea level rise.

See *Appendix: The Nature Conservancy's SLR resilience and adaptation work plan - 2009-2011,* for the organization's current ideas about the next steps in this process.

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Appendix

The Nature Conservancy's SLR resilience and adaptation work plan - 2009-2011.

Goal 1: Predictive capability for SLR impacts on the Florida Keys is refined based on best available information and shared with partners on an ongoing basis.

> Objective 1.1: Obtain LIDAR data for the entire Florida Keys and improve on the NED-based SLR modeling focused on future shorelines, dominance of generalized habitat types and property values.
>
> Objective 1.2: Complete Sea Level Affecting Marshes Model (SLAMM) or similar analysis of select areas of the Keys to improve predictions of future habitat distributions with and without modeled shoreline hardening as a variable to help determine if large scale shoreline hardening is a viable response to SLR and what the ecological consequences of that response would be.
>
> Objective 1.3: Develop a working understanding of future marine habitat distribution driven by SLR.
>
> Objective 1.4: Remap the freshwater lenses of Big Pine Key to determine if SLR has had a measurable impact on the lenses in the twenty years since the last lens mapping study and install a network of permanent groundwater monitoring wells to help track future SLR-driven changes in lens distribution and water quality.

Goal 2: Demonstration projects in the Florida Keys — linked to others around Florida, the Gulf of Mexico and Caribbean — inform development of resilience and adaptation-based Best Management Practices (BMPs) that may be implemented at landscape-scale in the Keys and similar island and coastal systems.

> Objective 2.1: Host a workshop or workshops to gather input on SLR resilience and adaptation BMPs and a monitoring plan to track BMP effectiveness.
>
> Objective 2.2: Complete a resilience and adaptation BMPs white paper and monitoring plan focused on fire management, invasive exotic species management, wetlands restoration and any other BMPs identified in the workshop.
>
> Objective 2.3: Examine the relationship of SLR-vulnerable species in the Keys to their ranges elsewhere in Florida and around the Gulf of Mexico and wider Caribbean to inform ex-situ conservation approaches.
>
> Objective 2.4: Share relevant BMPs and information with other SLR-vulnerable sites around the Gulf of Mexico and in the wider Caribbean.

Goal 3: Florida Keys decision makers (i.e. natural resource managers and policy makers) know how SLR will impact their respective portfolios, actively implement BMPs and are supported by a well-informed public.

> Objective 3.1: With science support from the Conservancy, Monroe County convenes a climate change/SLR stakeholder engagement process which includes municipalities, non-governmental organizations and other relevant parties and focuses on ongoing emissions reduction efforts, resilience and adaptation BMPs and other priorities to be determined by the participants.