Alternative Futures Under Climate Change for the Florida Key's Benthic and Coral Systems

Final Report

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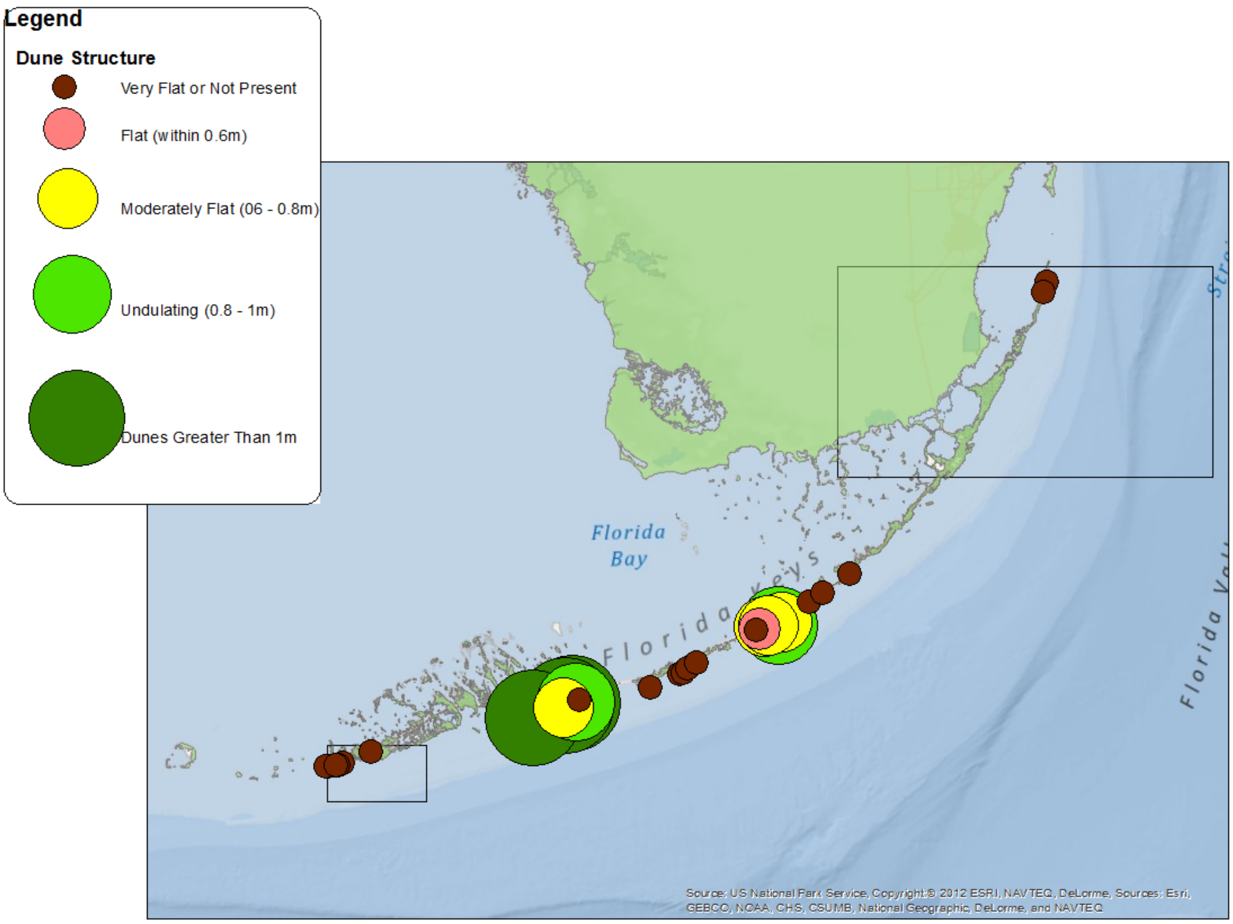

Modeling the beaches available for turtle nesting in the KeysMAP project.

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Abstract

Climate change is portending an unsettling future for coastal communities, their economies and the environments upon which they depend. Yet, developing planning approaches that address those changes remains a daunting challenge due to the uncertainty inherent in the climate models, future patterns of human demography, political vicissitudes, and economic conditions. A number of tools have been developed to address climate change and to help plan for the effects. These include vulnerability analyses and climate adaptation strategies. Yet, uncertainty makes planning difficult and, therefore, approaches that incorporate uncertainty are valuable for anticipating the effects and the possible adaption approaches that mitigate effects from a changing climate. One method that is gaining particular interest is the use of alternative future scenarios (AFS). This approach examines a suite of potential scenarios that can constructed to include variability related to climate but also include social, political, economic and other dimensions. This tool enables users to visualize the effects of a wide set of changes and to visualize the outcomes. Managers can then use these anticipated outcomes to develop scenarios from which adaptation strategies can be constructed to manage the resources under their jurisdiction.

AFS approaches have gained traction in the terrestrial environment; yet, its use in the coastal and marine environments is nascent. In a series of workshops, we applied this approach to examine the potential impacts to mangroves, coral reefs, and beaches in the Florida Keys and extended the results to anticipate the effects on spiny lobsters, loggerhead turtles, and Goliath grouper. Scenarios were tied to management-relevant IPCC emissions scenarios and regional projections related to sea level rise and changes to sea surface temperature. A suite of adaptation strategies was developed and prioritized, and monitoring programs were coupled to the strategies.

Introduction

Climate change is one of the most pernicious threats facing coastal communities and the resources upon which they depend. Sea levels are rising (IPCC 2013), sea surface temperatures are exceeding critical life-supporting thresholds (Hoegh-Guldberg et al. 2007), oceans are becoming more acidic (Raven et al. 2005), ocean circulation patterns are modifying (Wood et al. 1999), coastal upwelling is becoming more pronounced (Bakun 1990), and tropical cyclone intensity is predicted to increase (Webster et al. 2005). In response, species ranges are shifting (Nye et al.2009), species' phenologies are adjusting (e.g., Philippart et al., 2003), and community composition is changing (Doney et al. 2012). To cope with the changing realities and to conserve biodiversity, societies must adapt. However, the shear enormity of the problem, coupled with the uncertainties associated with the future climate landscape, leave managers and policy-makers without a clear vision on how to prepare for the changing conditions. Even the United Nations Intergovernmental Panel on Climate Change (IPCC) is unsure of the trajectory of future carbon emissions and, since these emissions drive impacts (e.g., sea level rise, ocean acidification), a number of scenarios were developed to bracket possible future conditions (Figure 1). These scenarios can have dramatically different outcomes relative to sea level rise (IPCC, Table 1), sea surface temperatures (Figure 2), and other conditions. Methods that deal with uncertainty in ways that stakeholders can understand are necessary to prepare for an uncertain future.

Alternative future scenario planning provides a compelling way to deal with uncertainty (Peterson et al. 2002). The anticipated futures are only as good as the information that is used to initialize the models. This, too, is an issue, especially when study areas are at a finer scale than the resolution provided by available models. We ran models that address both sea level rise and sea surface temperature and examined the habitat succession that is likely under each scenario.

The objectives of this project were to 1) determine the effects of climate change scenarios on critical habitats within the Florida Keys coral reef ecosystem, 2) examine how changes to those habitats may impact different life-history stages of 3 sentinel SGCN, 3) develop a scenario planning tool that can be applied in Florida marine environments, and 4) provide a framework for manager's to understand the effects of a changing climate on Florida's critical marine resources.

The fourth objective is perhaps the most important given that ultimately understanding impact from climate change is valuable only if it informs the development of approaches for enhancing resilience, or facilitating recovery, of ecosystems. To achieve this, a stepwise approach is proposed for the development of adaptation strategies.

This report provides a brief overview of the effects of a changing climate on coastal resources in the Florida Keys, the models that are used to forecast and understand the effects in the coastal zone, and approaches that have been used to develop adaptation strategies to address those changes.

Methods

Impact Modeling

A number of approaches were used to model the changes that may occur in the coastal zone as a result of a changing climate. The models overall are rapidly evolving and becoming more versatile with respect to 1) the confidence in the data that is used to initialize them and 2) the broad applicability of the model outputs. These models are often tied to IPCC scenarios thus providing a common framework.

Because sea level rise (SLR) is one of the most consequential impacts of climate change, a great deal of effort has been focused on modeling the processes and forecasted impact to habitats. The most commonly used approach is a simple eustatic model in which sea level is visualized as rising uniformly across the coastal zone similar to rising water in a bathtub. This is over-simplistic due in part to changes in the localized underlying geo-morphological processes (subsidence and accretion); therefore, several other models have been developed to estimate sea level rise at a more local scale.

One of the more popular SLR models is the Sea Levels Affecting Marshes Model (SLAMM). This model has been used to estimate local SLR and to forecast the changes that may occur to habitats in coastal areas upon inundation. The model uses a rule-based approach to forecast habitat succession. SLAMM is initialized based on measurements of accretion, subsidence, available data from sea level gauges, and other relevant parameters (Supplemental Table S-1). In tropical locations, inundated coastal habitats often turn to mangroves. The model predicts beach migration and was used in this respect in the Florida Keys to visualize the effect on sea turtle nesting habitat.

SLR is not the only variable associated with climate change that will drive resource persistence and health. Warming sea surface temperatures (SST) are increasingly damaging coral reef environments. In 2005, an unprecedented SST event occurred in the eastern Caribbean in which the thermal tolerance of boulder-forming corals was exceeded for an extended period thus resulting in a large-scale mortality event (Eakin et al., 2010). Satellite imagery has been able to identify these events as they occur; however, predictive models are necessary for planning for an uncertain future.

Accordingly, the National Oceanic and Atmospheric Administration has developed a dynamically downscaled model to predict SST under different IPCC scenarios. The model is relatively new but, as it develops, there will be numerous applications for its use. NOAA researchers already have examined the effects of forecasted SSTs on bluefin tuna larvae in the Gulf of Mexico (Muhling et al., 2011).

Sea Level and Habitat-Succession Modeling (SLAMM)

Selection of Sea Level Rise Scenarios

We based our sea level rise scenario selection on the generally accepted range of sea level rise predictions for south Florida (Southeast Florida Regional Compact 2011; SFRC; Figure 3). Using that yardstick, we then selected the IPCC predicted eustatic sea level rise estimates under the different AR4 emissions scenarios (http://www.ipcc.ch/ipccreports/tar/wg1/553.htm) to select the AR4 scenario(s) that most closely corresponded with the SFRC predictions. The time horizon for this study was 2060 which corresponded approximately with the 50 year planning horizon relevant for land use managers.

The minimum sea level rise scenario evaluated during this study was the mean of the IPCC A1FI emissions scenario from the IPCC Fourth Assessment Report (AR4). When the fourth assessment was completed, the A1FI scenario was generally viewed as an aggressive scenario ("a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology": http://www.ipcc-data.org/sres/ddc_sres_emissions.html); a scenario that is looking increasingly conservative (Nicholls and Cazenave 2010).

The maximum sea level rise scenario we selected was based on a trajectory predicted by a model calibrated to 1-m SLR by 2100. This was a scenario explicitly defined within the Southeast Florida Regional Compact sea level rise document (Southeast Florida Regional Compact 2011) and corresponds to the upper trajectory in their model.

SLAMM Modeling

Sea level rise and the consequent changes to coastal habitats were modeled by Brian Beneke and Beth Stys of the Florida Fish and Wildlife Conservation Commission, Tallahassee, Florida. We selected the Sea Level Affecting Marshes Model (SLAMM 6.0.1) developed by Warren Pinnacle Consulting, Inc because earlier versions were used in the Florida Keys region by the U.S. Fish and Wildlife Service to examine sea level changes within the wildlife refuges. Furthermore, it controls a number of parameters instrumental in determining how sea level will change and for which data was available.

The Florida Keys were split into three sites due to the different initialization parameters associated with different geographies throughout the Keys. The sites slightly overlap with adjacent sites in order to create seamless data from one site to another.

Each of the sites (site 1=Lower Keys, site 2=Middle Keys, site 3=Upper Keys; Figure 4) were subdivided into two polygonal sub-sites. Sub-sites on the northern portion (Gulf side) of the map were identified as sub-site A and sub-sites on the southern portion (Atlantic side) of the map were identified as sub-site B.

SLAMM version 6.0.1 was run with the minimum data requirements including land cover (Florida Cooperative Land Cover map, FNAI 2010), and high resolution elevation data (NOAA LiDAR 2011). The elevation data were also used to calculate slope, another required data parameter required for SLAMM modeling.

The data were pre-processed in ArcGIS to create raster files with identical spatial dimensions, projections, size, and cell numbers. Each site was then converted to an ASCII.txt format for input into SLAMM. Original data were provided in img format in geographic coordinates (NAD83) and vertically referenced to NAVD88. Vertical units for all data are in meters. Each file was added to a geodatabase, projected, converted to integer, resampled, converted to a float grid and reprojected. The Spatial Analyst math toolbox was then used (with the cell size set at 10m) to multiply the data by a value of 1. This approach used the "nearest" resampling method and preserved the original data values and range.

The Florida Cooperative Land Cover (CLC) map (FNAI 2010) was used as the base land cover map. The CLC is a raster data set with a resolution of 15m. Land cover classes in the CLC map were cross-walked to the SLAMM land cover categories; however, because SLAMM uses a rules-based approach with a limited set of fixed habitat classes (Supplemental Table S-2), a number of adjustments were needed. Visual inspections of the cross-walked categories were conducted using Google Earth and Bing maps in ArcMap; when necessary, ground-truthing and consultations with experts were conducted. Errors due to land use change and inconsistencies in the actual vegetation types and the cross-walk schema were corrected. The majority of the edits addressed issues with missing areas of mangroves, changing the predicted estuarine water habitat to open water from the Middle and Lower Keys, editing the Rocky Intertidal category (Category 14), Transitional Marsh/Scrub Shrub (Category 7), Regularly Flooded Marsh (Category 8) and Irregularly Flooded Marsh (Category 20). The SLAMM Transitional Marsh/Scrub Shrub and Irregularly Flooded Marsh categories had no corresponding direct cross-walked CLC classes. Areas were identified as Transitional Marsh/Scrub Shrub and Irregularly Flooded Marsh based on expert input/comment and recoded based on current imagery.

Expert input for habitat designations was provided in three meetings with local land managers and by on-the-ground observations of habitats in question. The meetings were held in the lower Keys, Upper Keys, and mainland south Florida and included representatives of the State, Local, Federal, and NGO communities. Based on the cross-walk schema, areas of Irregularly flooded Marsh were typically cross-walked to Regularly Flooded Marsh and Rocky Intertidal, and to a lesser extent Mangrove (Category 9) and Tidal Flat (Category 11). Areas edited to the Transitional Marsh/Scrub Shrub category were originally cross-walked to Mangrove, Regularly Flooded Marsh, Rocky Intertidal, and Undeveloped Dry Land (Category 2) based on the schema. Additional areas of Ocean Beach (Category 12) were added during the editing process based on expert input. Once the cross-walked land cover map was finalized, the converted Roads (Nav-tech) raster file was merged with the cross-walked raster in order to select any missed developed land not found in the CLC map. The final SLAMM category land cover map was resampled to 10m to match other input layers.

When running SLAMM, the "protect developed dry land" option was not used. Using this setting, all land is potentially vulnerable to SLR thus providing the highest probability of capturing impacts to the natural and built environments. Using the soil saturation option caused visible streaking throughout portions of the sampled region in the model outputs; therefore, the soil saturation option was not used. Comprehensive, study area-wide dike data was not available for the Keys; therefore, this option was also not used. The Connectivity Algorithm was used so that dry lands or freshwater wetlands would be subject to saline inundation from low lying sources and/or pathway to estuarine or ocean.

Sea-Surface Temperature Modeling (MOM)

Selection of Sea Surface Temperature scenarios

The sea surface temperature modeling was conducted by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) using the Modular Ocean Model (MOM) described below. This model uses the IPCC AR5 emissions scenarios. Unfortunately SLAMM only has the capabilities to use AR4 scenarios rather than the more current AR5 scenarios to initialize its models. Therefore, we selected the AR5 scenarios which best aligned with the SLAMM sea level rise modeling which we selected. The models that aligned best were the AR5 RCP 4.5 which matched best to the AR4 A1FI scenario, and, the AR5 RCP 8.5 which aligned closest with the 1-meter by 2100 scenario.

The MOM (Griffies et al., 2004; Gnanadesikan et al., 2006) developed at the Geophysical Fluid Dynamics Laboratory (GFDL), was used as the downscaling model. The spatial domain contains the Atlantic Ocean between 100°W and 20°E bounded north and south by 65°N and 20°S, respectively. The regional MOM4 have a fully eddy-resolving horizontal resolution of 0.1° in the Gulf of Mexico region from 10°N to 30°N and from 100°W to 70°W, decreasing linearly to 0.25° in the rest of the model domain. The regional MOM5 has 25 vertical z-coordinates, and is driven by the surface forcing fields obtained from Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset. Again, there were run under the historical RCP4.5, and RCP8.5 scenarios. The initial and boundary conditions were also obtained from CMIP5. The ocean boundaries at 65°N and 20°S were treated as closed, but were outfitted with about 5° of buffer zones in which the temperature and salinity were linearly relaxed toward the corresponding fields obtained CMIP5 dataset. The sea surface salinity (SSS) of the model were also relaxed toward CMIP5 SSS. Two additional buffer zones were located in the northwestern corner over the Labrador Sea, and in the Gulf of Cadiz. The restoring time scale for the northern and southern boundaries were varied linearly from 25 days at the inner edge to 5 days at the walls. The timescale for the Labrador Sea region was 25 days and, for the Mediterranean Sea, 365 days. The MOM4 simulations were conducted under the ensemble-averaged CMIP5 forcing, initial and boundary conditions.

Eighteen CMIP5 models were used to derive the surface forcing fields and initial and boundary conditions (Table 2). These eighteen CMIP5 models were selected because they all showed a realistic Atlantic Meridional Overturning Circulation (AMOC) strength in the 20th century and contain all surface flux variables needed for the model experiments. Each of the eighteen CMIP5 models were ranked and weighted based on the ability to replicate the observed annual mean upper ocean temperature at the surface, 100 m and 200 m in the GoM and Caribbean Sea for the last 30 years of the 20th century (1971–2000), as well as the AMOC at 30N.

Habitats examined

Three habitats were selected to be the focus of this project. These included beaches, mangroves, and coral reefs. Seagrass, despite its importance, was not included because of insufficient resources. The habitats were selected because they represent a diverse set from marine, coastal and terrestrial ecosystems in the study area.

The aerial extent of each terrestrial habitat was originally determined using the Florida Cooperative Land Cover (CLC) map (FNAI 2010) when appropriate within ArcGIS with input from experts and ground-truthing as previously described. The reef habitat extent was determined using the digital atlas Benthic Habitats of the Florida Keys (FWRI 2000).

Integrating Species

We selected three species to integrate into the project. These included the spiny lobster (*Panulirus argus*), the loggerhead turtle (*Caretta caretta*) and Goliath grouper (*Epinepelus itajara*). The species were selected because they represented the following groups: 1) an important commercial species with ties to the reef habitat (i.e., spiny lobster), 2) a species listed in the ESA with habitat requirements that include beaches (i.e., loggerhehad turtles), and 3) a species that was depleted but is now recovering (I.e., Goliath grouper) with requirements that include both reef and mangroves. The intention was to examine how the changing habitat and environmental conditions might impact each species.

Results

The results of the project are extensive and detailed. Therefore, they are presented in the external report from GeoAdaptive, LLC that is attached to this report. That report also includes an overview of the scenario planning process that was used to drive this project.

Achievement of the Objectives

There were four objectives in the project proposal. These are detailed in this section along with the achievements within each objective.

1. *Determine the effects of climate change scenarios on critical habitats within the Florida Keys coral reef ecosystem*

   We examined the effects of sea level rise and changes to sea surface temperature on the three habitats that were encompassed within the proposal (i.e., mangroves, beaches, and coral reefs). The results of these are included within the supplemental document prepared by GeoAdaptive LLC which represents the Results section and is attached to this report.

2. *Examine how changes to those habitats may impact different life-history stages of 3 sentinel SGCN*

   We examined the impacts of the forecasted changes to the habitats on selected SGCN (i.e., loggerhead turtles, spiny lobsters, and Goliath grouper). Again, the results of these are included within the supplemental document prepared by GeoAdaptive LLC which represents the Results section and is attached to this report.

3. *Develop a scenario planning tool that can be applied in Florida marine environments*

   The approach that we developed here is detailed in the Developing Adaptation Approaches section which follows. This approach follows a relatively formulaic and systematic roadmap which is designed to take a manager from the beginning of the project through to the identification of possible adaptation strategies and finally, monitoring programs to identify when those adaptation strategies should be actuated. A specific implementable tool without facilitation from people familiar with scenario planning is not practical but the approach we detail is easily implementable.

4. *Provide a framework for manager's to understand the effects of a changing climate on Florida's critical marine resources*
   This objective ties very closely with number 3. However, rather than defining the approach, this objective was designed to identify the variables, models, and data sources that should be considered when examining climate change in coastal environments. This objective was achieved with a rigorous search for, identification of, and vetting of those items.

Discussion

Our consulting team from the Massachusetts Institute of Technology (MIT), now GeoAdaptive LLC, pioneered the use of spatial modeling of the combined social, political, economic and conservation dimensions in conservation planning. This project extended those ideas and coupled those variables to sea level rise scenarios (see supplemental report prepared by GeoAdaptive LLC). Prior to this project, they worked together with the U.S. Fish and Wildlife Service and the U.S. Geological Survey to develop a set of alternative future scenarios for the Florida peninsula which provided a visualization of the future landscape under a number of different scenarios. The project consisted of a fully participatory process which included managers who developed the priorities based on the conditions of those dimensions that they felt were most important to assess.

The Florida Fish and Wildlife Conservation Commission together with the MIT team, used the results from that project and overlaid species distributions on projected habitat change maps to determine potential conflicts with other resource uses, and to identify areas of high priority for species conservation. Managers who oversee a number of species convened in a series of workshops to synthesize what is known about the effects of climate change in the south Florida environment and to predict the impact to the species. This approach provided an important opportunity for managers and other stakeholders to visualize the impacts to trust resources and to plan accordingly.

The KeysMAP project built on this approach to attempt to duplicate the successful use of scenarios in the terrestrial environment by applying it to the coastal and marine environments. We originally intended to include social and economic data layers in this project. However, after speaking with socio-economists, examining the availability of the datasets, and subsequently examining the data, it became clear that incorporating socio-economic modeling within this project was beyond what was capable given the time constraints and financial resources that were available. Therefore, the numerous available scenarios were reduced to a manageable subset and these were examined within the project.

It has been, and continues to be, a priority of this and future projects to develop scaffolding within which new components can be added to ultimately build out the scenarios. For example, when new data become available or models become refined, their outputs should easily snap into the existing scenarios to better inform the possible future outcomes and, ultimately, refinement of appropriate strategies. Future standalone projects should in part focus in part on developing standalone dimensions so that they can be integrated into the existing results of this project.

Scaling became an issue as this project progressed. The project was built on a scale that, as it turned out, was too fine. Given the species ranges, and the extent of the resources that they use, it will be more optimal to address the priorities more regionally. For example, we looked at very specific and local locations in the range of the species but the true impact will be measure over 100s of kilometers rather than 10's of kilometers. Furthermore, the downscaled models do not provide the sensitivity at highly refined scales and are therefore better suited to more regional approaches. It is our intention to build out future project to more regional scales.

This project, as well as the terrestrial project before it, examined a small number of species. While there is value in this approach, greater value will be achieved when examining a suite of species for which common adaptation strategies are appropriate for their conservation under a changing climate. We intend to use the concept adapted by the Wildlife Conservation Society of surrogate species (*sensu* Coppolillo et al, 2004) as the basis for developing appropriate strategies for suites of species. This aligns well with the FWC approach of Integrated Conservation Strategies which are now being developed for the Imperiled Species Management Plans (ISMPs). Using suites of species allows for a reduction in the number of adaptation strategies that need to be crafted, and identifies broad conservation categories into which new species can be placed.

Developing adaptation approaches

Ultimately, knowing the vulnerabilities of species, habitats, and societies provides little value to managers unless strategies can be developed to address those vulnerabilities. Adaptation planning is one of the emerging fields in climate-change science and management that specifically is designed to address the development of adaptation strategies. This discipline synthesizes the diverse political, social, and environmental sciences into a comprehensive methodology to develop strategies that facilitate resilience. Despite the importance of adaptation planning, developing strategies is often a low priority for community governance and natural resource management because of the uncertainty relative to the outcomes, the massive scope of the issue, the political realities, and the potential costs. Recently, the U.S developed a National Fish, Wildlife and Plants Climate Adaptation Strategy to provide high-level guidance to managers of natural resources. More locally, south Florida has developed a regional plan, and Monroe County (which encompasses the Florida Keys) developed a county-wide plan. The plans all share common visions and are rich with potential actions to address the possible impacts.

Methods to provide specific responses addressing specific resources are now under development. In situations where there is high uncertainly, and potentially high impact to resources, the use of scenario planning (SP) has become a valuable method to visualize potential futures. SP provides a framework within which alternative strategies can be developed. SP was first developed during the cold war by the U.S. military as a method to respond to different potential modes of invasion by the Soviet bloc. The approach has gained in popularity and is now used regularly in the corporate world to prepare for multiple and diverse potential outcomes. It is now an approach that is gaining wider use in natural resources conservation (Peterson et al. 2002).

Applying Adaptation

This section utilizes the lessons learned from this project to build a framework for developing adaptation strategies. The approach is presented in a stepwise fashion although many particular aspects can be applied simultaneously or the sequences can be reversed. The approach is presented within a framework utilizing alternative future scenarios. This approach is best suited as previously described when uncertainly is high, potential impacts are high, and we have very little ability to control the future. Under other conditions, other approaches may be more suitable (Figure 5).

The suggested approach is fully participatory and multidisciplinary from the identification of the scenarios to the identification of the data used for modeling to the implementation of the climate adaptation strategy. The overall approach is presented graphically in Figure 6 in the context of changing environmental conditions.

Despite the fact that the approach detailed below is fairly rigid in its presentation, it is meant to be flexible and adaptable based upon the needs and priorities of the organization/agency conducting the project. The structure is provided in a stepwise approach for the sake of simplicity.

> **Step 1. Define the goals**. In this step, the overall objectives of the project are defined. For example, is the project designed to develop strategies that address an individual species, a commercial fishery, or a community? The scope of the objectives will determine the subsequent steps in the project, the data that is needed, the individuals/organizations that will be involved, potential consultants, and other factors. .
>
> **Step 2. Identify stakeholders who need to be involved.** The stakeholders who are involved in the project will be a directly result of the identification of the goals as defined in Step 1. Depending on the scope of the objectives, different stakeholders and approaches may be warranted.
>
> **Step 3. Develop the scenarios.** The scenarios will include the dimensions to be included (e.g., climate change dimensions, conservations variables, economic conditions, demographic patterns, habitat changes, changes in species distributions.) This is often done based upon the needs of the organization conducting the study. For

example, if fisheries management is a primary concern, one of the dimensions may focus on possible alternative harvest strategies or implementing no-take zones.

Step 4. Identify sources of data that are available and begin data collections. The data can be spatial when the planning is geospatial in nature; however, not all data needs to be spatial. For example, management dimensions need not be spatial. Different sources of data may be needed (e.g., socioeconomic, habitat models, species distributions) This is also an important step to identify what data is missing or where there are gaps in knowledge. This step often can be used to develop priorities for future funding.

Step 5. Conduct the modeling to understand the effects on resources or communities. The MIT approach uses well-developed urban-planning models to understand how humans will relocate on the landscape based on a variety of assumption related to planning, funds available for conservation, zoning, and other variables. Similarly, models can be developed to examine how species will redistribute and relocate based on habitat changes (e.g., climate envelope modeling). SLR modeling can inform areas at risk. The models can also be influenced by perceived changes to management. This step often requires capacity beyond that available in-house.

Step 6. Validate the models. The outputs of the models will need to be assessed by individuals and organizations most familiar with the resources. Buy-in for the project will be difficult without an independent assessment of the outcomes. For example, in Florida, SLAMM modeling predicted that a number of habitats in the Florida Keys would change from lowland to estuarine conditions. However, this was nonsensical since there are no freshwater sources from which estuaries can be created. Therefore, in the model output, estuarine was re-coded to open-water. This is a small example of how reviewing the outputs is critical, yet there will be many other results from the modeling which should be interpreted and validated by experts.

Step 7. Identify 'triggerpoints'/thresholds that trigger specific actions. The concept of 'triggerpoints' is very important when identifying when actions should occur. 'Triggerpoints' are points in time when an action should be initiated. The 'triggerpoints' could be very specific (e.g., SST exceeds some value for a period of time). Alternatively, the 'triggerpoint' could be a 'soft-trigger' which would be an indicator of changing conditions which would then actuate a specific response. An example of a 'soft-trigger' could be the shift of an upland ecosystem to one dominated by a more salt-tolerant community.

Step 8. In a relevant forum, develop adaptation strategies. Ultimately, this step is the most important because this is where strategies that address climate impacts are designed and prioritized. This step provides an opportunity for participants in the process to 'think outside the box'. As an example, a specific adaptation strategy may include construction of a dam to address reduction in stream-water flow. A specific 'triggerpoint' associated with this strategy may be when stream flow declines below a pre-defined threshold. This step may also be critical when identifying relevant 'triggerpoints'. In this example, this adaptation strategy (i.e. dam construction) may be identified prior to the identification of relevant 'triggerpoints'.

Step 9. Develop monitoring plans to monitor for 'triggerpoints'. Knowing when to enact a strategy depends upon identifying when a 'triggerpoint' is reached. To know when the triggerpoint is reached, a monitoring plan must be developed. In a coral reef environment, a specific adaptation strategy may be to shade corals that serve as sources of larvae for downstream populations when SST temperatures exceed a certain threshold and when winds are calm. Monitoring buoys that monitor SST and surface winds tied directly to this adaptation strategy will be an effective way to determine when this strategy should be enacted. Importantly, tying monitoring programs to specific adaptation plans is a powerful way to justify the investment in monitoring programs.

Step 10. Identify 'no-regrets' strategies. In some cases, plans must be created and activities must be completed a priori so that the adaptation strategy may be enacted when the 'triggerpoint' is reached. Using the example of a dam as an adaptation strategy for water storage, construction cannot start immediately when the stream flow drops below a pre-defined threshold. Rather, in order to be prepared to begin the construction of the dam, permits must be obtained and engineering plans must be in place. These are examples of 'no-regrets' strategies.

Step 11. Revaluate and adjust the triggers, monitoring plans, and adaptation strategies. The process defined above is dynamic in the sense that it must be continuously reviewed and updated. This is especially critical as the science gets better, more information becomes available, changes in activities occur, priorities change, greater funding becomes available, and other conditions change.

This framework forms the basis for planning for a changing climate. This is a very brief overview of an approach that can be used and that we found useful as the project evolved. Certain parts of this framework can be eliminated as appropriate. In other cases, other steps will need more attention. For example, multiple modeling workshops may be necessary if the activity is based on science, policy, governance, economics and other disciplines.

Conclusions

Climate change has the potential to disrupt societies and ecological communities. Yet, there are approaches that can enhance the resilience of the communities and ecosystems. Planning for adaptation is critical so that communities, ecosystems, and management frameworks can be sufficiently resilient to increase the adaptive capacity of those systems. In the KeysMAP project, a method was presented in which managers can begin planning for a changing climate by implementing a framework within which a comprehensive process can be constructed.

The project was intended to begin development of an approach that could be adapted to a variety of systems and built upon in future iterations. Lessons learned were numerous (Appendix 1) as was expected since this was the first project of its kind attempted in the marine environment. These will need to be addressed in future iterations. Nevertheless, in any multi-dimensional project, there remains the need for continuous review and updating. This, or similar approaches, are required to ensure that we, as societies, are prepared for the changes that are rapidly approaching.

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Table 1. Changes in sea level rise under different IPCC AR4 scenarios. (From the IPCC Fourth Assessment report.)

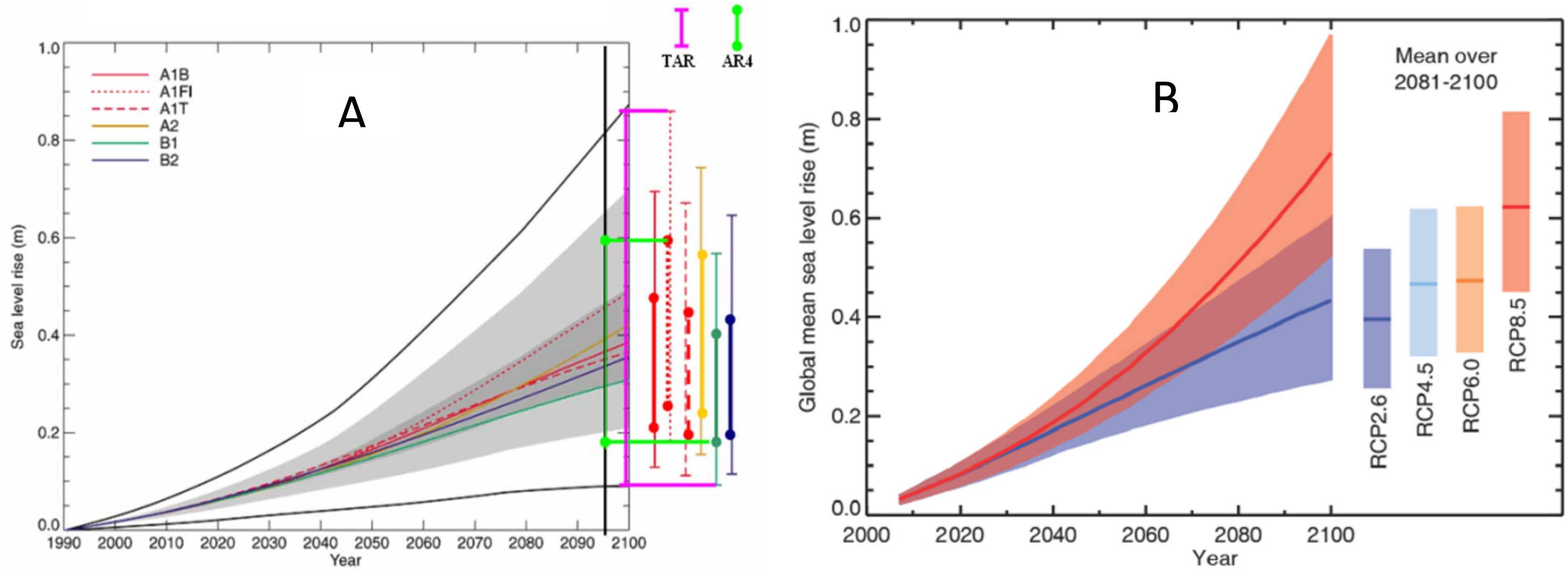
Models average - Total sea level change (mm)						
Year	A1B	A1T	A1FI	A2	B1	B2
1990	0	0	0	0	0	0
2000	17	17	17	17	17	17
2010	37	39	37	38	38	38
2020	61	66	61	61	62	64
2030	91	97	90	88	89	94
2040	127	134	126	120	118	126
2050	167	175	172	157	150	160
2060	210	217	228	201	183	197
2070	256	258	290	250	216	235
2080	301	298	356	304	249	275
2090	345	334	424	362	281	316
2100	387	367	491	424	310	358

Table 2. The list of Global Circulation Models used to model sea surface temperature and the relative weight assigned to each model.

Rank	Model	Weight
1	NCAR-CCSM4	2.38
2	IPSL-CM5A-LR	2.1
3	BCC-CSM1-1	1.9
4	MRI-CGCM3	1.52
5	IPSL-CM5A-MR	1.48
6	CSIRO-Mk3-6-0	1.43
7	GFDL-ESM2G	1.16
8	GISS-E2-R	1.09
9	HadGEM2-CC	0.93
10	GFDL-ESM2M	0.68
11	HadGEM2-ES	0.65
12	CanESM2	0.55
13	MIROC-ESM	0.53
14	MIROC-ESM-CHEM	0.52
15	MIROC5	0.36
16	GFDL-CM3	0.35
17	CNRM-CM5	0.33
18	NorESM1-M	0.02

List of Figures

Figure 1


A
A1B
A1FI
A1T
A2
B1
B2
TAR
AR4
Sea level rise (m)
Year
1.0
0.8
0.6
0.4
0.2
0.0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
B
Mean over
2081-2100
Global mean sea level rise (m)
Year
2000
2020
2040
2060
2080
2100
RCP2.6
RCP4.5
RCP6.0
RCP8.5

.

Figure 2.

October RCP 4.5 2050 **RCP 8.5 October 2050**

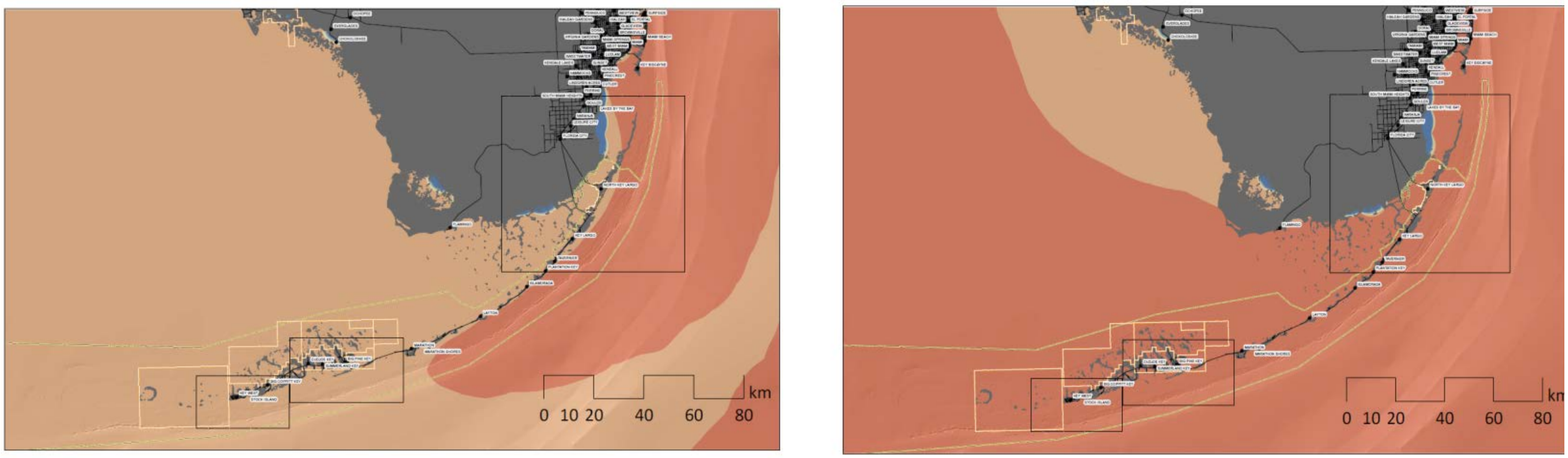


Figure 3.

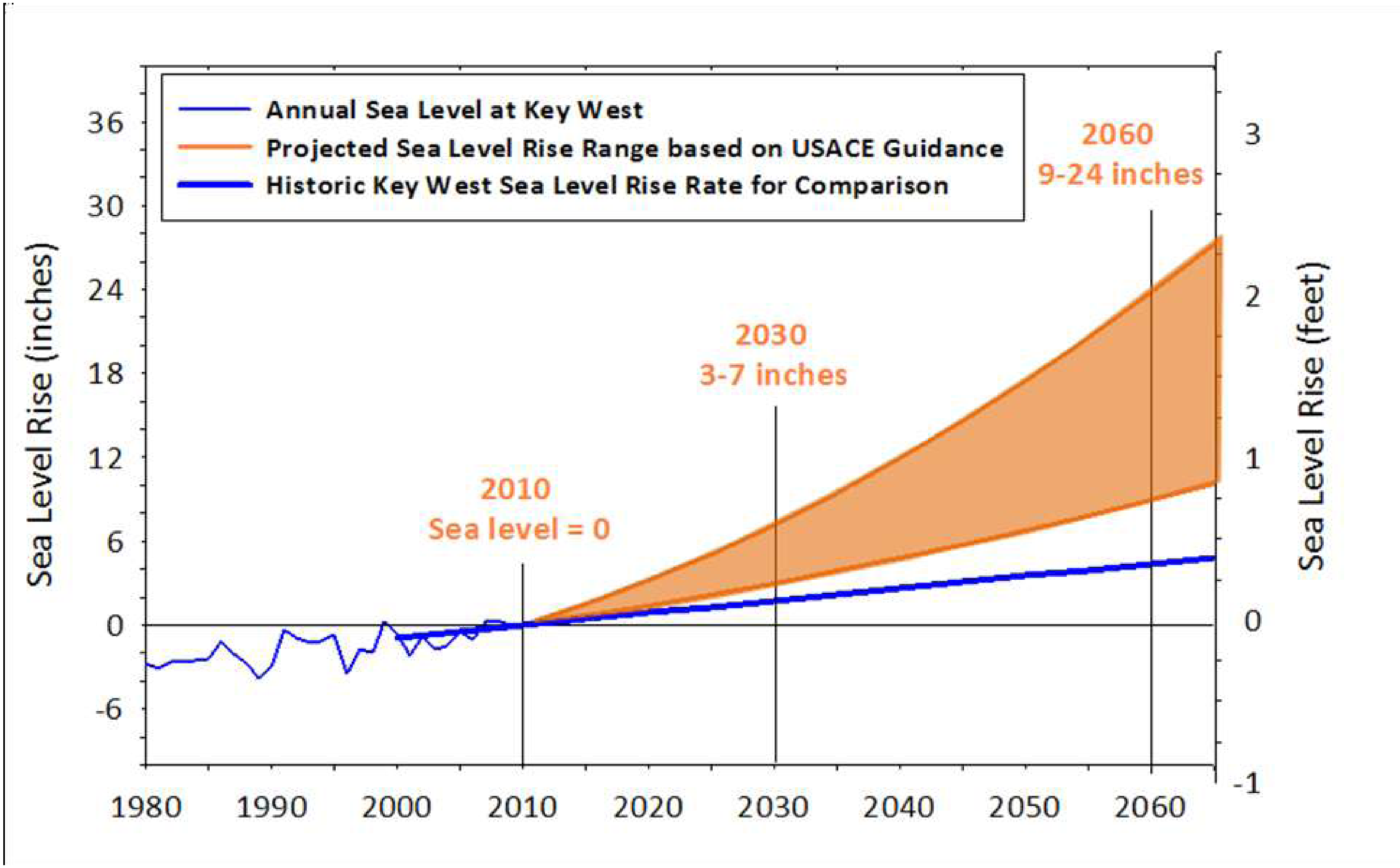

Annual Sea Level at Key West
Projected Sea Level Rise Range based on USACE Guidance
Historic Key West Sea Level Rise Rate for Comparison
2060
9-24 inches
2030
3-7 inches
2010
Sea level = 0
Sea Level Rise (inches)
Sea Level Rise (feet)
36
30
24
18
12
6
0
-6
3
2
1
0
-1
1980
1990
2000
2010
2020
2030
2040
2050
2060

Figure 4.

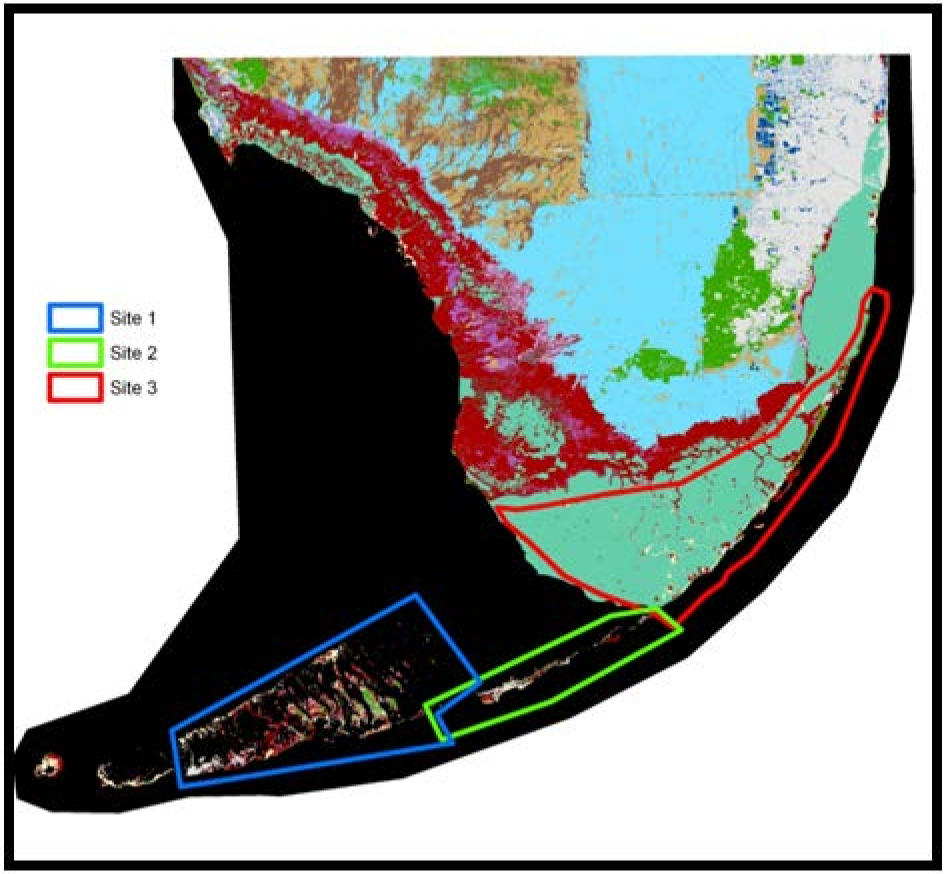


Figure 5.

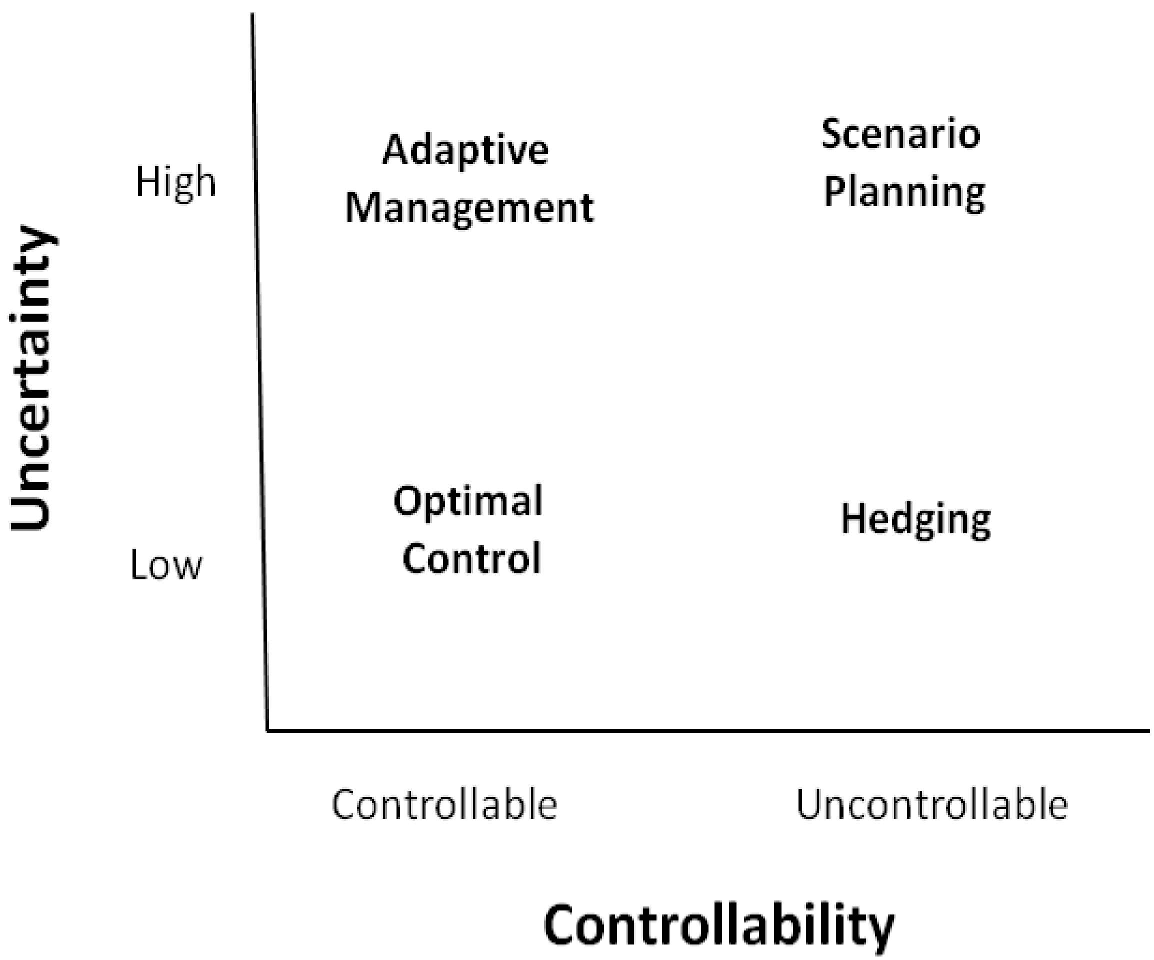
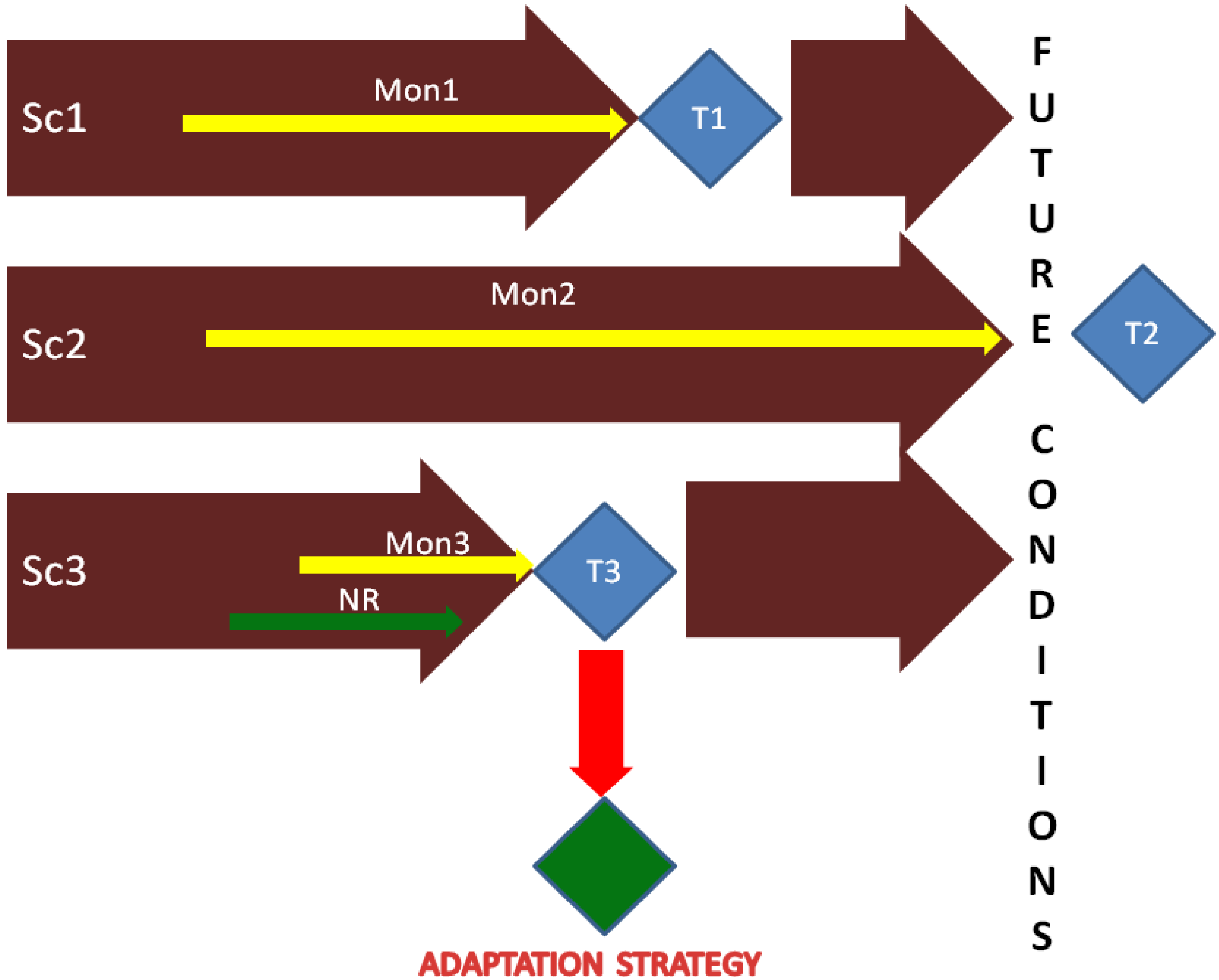

Uncertainty
High
Low
Adaptive Management
Scenario Planning
Optimal Control
Hedging
Controllable
Uncontrollable
Controllability

Figure 6.


Sc1
Mon1
T1
Sc2
Mon2
T2
Sc3
Mon3
NR
T3
FUTURE CONDITIONS
ADAPTATION STRATEGY

Supplemental Materials

Supplemental Table S-1. Initialization parameters and data sources for SLAMM 6.0.1 modeling for the KeysMAP study:

- **Direction offshore**: Decided by professional judgment. Each direction input was indicated by the direction of water from the shoreline.
- **Historic trend for sea level rise**: Estimated for mm / year from NOAA long term SLR gauges. (NOAA Tides and Currents)
- **MTL to NAVD88**: correction (or more generally [any vertical datum] to MTL correction) is utilized to convert the elevation data maps from a fixed vertical datum to a datum based on the Mean Tide Level of the site. It is defined as MTL minus NAV88 based on the data from a NOAA gauge. (NOAA Tides and Currents)
- **GT Great Diurnal Tide Range (GT) (m)**: Difference in height between mean higher high water and mean lower low water. (NOAA Tides and Currents).
- **Salt Elevation** Designates the boundary between wet lands and dry lands or wetlands and fresh water wetlands. Salt Elevation (m above MTL) is derived from inundation from observed data from NOAA gauges. For site 1 and site 2 the value for Salt Elevation was based on the mean values from Clough (2008). Values for subsite A were derived from the mean of subsite A and B; values for subsite B were derived from the mean of subsite C and D; Site 3 used mean values of subsite A and subsite B (from Clough and Larson 2010).
- **Marsh Erosion, Swamp Erosion, Tidal Flat Erosion, Regularly Flooded Marsh Accretion, Irregularly Flooded Marsh Accretion, Tidal-Fresh Marsh Accretion, Inland-Fresh Marsh Accretion, Mangrove Accretion, Tidal Swamp Accretion, and Swamp Accretion:** These parameters were collected from USFWS documented SLAMM studies containing input parameters for SLAMM in the keys (Clough, 2008; Clough and Larson 2010).

Supplemental Table S-2. Crosswalk table from CLC to SLAMM.

SLAMM 6 Category	CLC Category
	1800 - Cultural
	1821 - Low Intensity Urban
	1822 - High Intensity Urban
	1840 - Transportation
	1841 - Roads
	1842 - Rails
	1850 - Communication
	1860 - Utilities
	1870 - Extractive
	1872 - Sand & Gravel Pits
1 - Developed Dry Land	1873 - Rock Quarries
	1875 - Reclaimed Lands
	1877 - Spoil Area
	3240 - Sewage Treatment Pond
	3260 - Industrial Cooling Pond
	18211 - Urban Open Land
	18212 - Low Structure Density
	18221 - Residential, Med. Density
	18222 - Residential, High Density
	18223 - Commercial & Services
	18224 - Industrial
	18225 - Institutional
	182131 - Parks
	182132 - Golf courses
	182134 - Zoos
	1110 - Upland Hardwood Forest
	1123 - Live Oak
	1125 - Cabbage Palm
	1130 - Rockland Hammock
	1131 - Thorn Scrub
	1210 - Scrub
	1214 - Coastal Scrub
	1220 - Upland Mixed Woodland
	1300 - Pine Flatwoods and Dry Prairie
	1311 - Mesic Flatwoods
	1320 - Pine Rockland
	1330 - Dry Prairie

	1340 - Palmetto Prairie
	1400 - Mixed Hardwood-Coniferous
	1500 - Shrub and Brushland
	1610 - Beach Dune
	1620 - Coastal Berm
	1630 - Coastal Grassland
	1640 - Coastal Strand
	1650 - Maritime Hammock
	1740 - Keys Cactus Barren
	1831 - Rural Open
2 - Undeveloped Dry Land	1832 - Agriculture
	1880 - Bare Soil/Clear Cut
	7000 - Exotic Plants
	7100 - Australian Pine
	7200 - Melaleuca
	7300 - Brazilian Pepper
	18331 - Cropland/Pasture
	18332 - Orchards/Groves
	18323 - Tree Plantations
	182111 - Urban Open Forested
	183111 - Oak - Cabbage Palm Forests
	183311 - Row Crops
	183312 - Field Crops
	183313 - Improved Pasture
	183314 - Unimproved/Woodland Pasture
	183321 - Citrus
	183324 - Fallow Orchards
	183331 - Hardwood Plantations
	183341 - Tree Nurseries
	183342 - Sod Farms
	183343 - Ornamentals
	183352 - Specialty Farms
	1833151 - Fallow Cropland
	2112 - Mixed Scrub-Shrub Wetland
	2200 - Freshwater Forested Wetlands
	2230 - Other Hardwood Wetlands
	2233 - Mixed Wetland Hardwoods
	2240 - Other Wetland Forested Mixed
3 - Swamp	2242 - Cypress/Pine/Cabbage Palm
	7400 - Exotic Wetland Hardwoods
	22211 - Hydric Pine Flatwoods

	22212 - Hydric Pine Savanna 22311 - Bay Swamp 22312 - South Florida Bayhead
4 - Cypress Swamp	2210 - Cypress/Tupelo(incl Cy/Tu mixed) 2211 - Cypress 2213 - Isolated Freshwater Swamp 2214 - Strand Swamp
5 - Inland Freshwater Marsh	2111 - Wet Prairie 2120 - Freshwater Marshes 2125 - Glades Marsh 2131 - Sawgrass 2140 - Floating/Emergent Aquatic Vegetation 2300 - Non-vegetated Wetland 5251 - Buttonwood Forest 21211 - Depression Marsh
8 - Regularly Flooded Marsh	5240 - Saltwater Marsh
9 - Mangrove	5250 - Mangrove Swamp
11 - Tidal Flat	5220 - Tidal Flat 9100 - Unconsolidated Substrate
12 - Ocean Beach	1670 - Sand Beach (Dry)
14 - Rocky Intertidal	52111 - Keys Tidal Rock Barren
15 - Inland Open Water	3000 - Lacustrine 3100 - Natural Lakes & Ponds 3200 - Artificial Lakes & Ponds 3211 - Aquacultural Ponds 3220 - Artificial Impoundment/Reservoir

	3230 - Quarry Pond 4200 - Canal/Ditch 4210 - Canal 8000 - Open Water
17 - Estuarine Water	5000 - Estuarine
18 - Tidal Creek	4000 - Riverine 4100 - Natural Rivers & Streams
19 - Open Ocean	6000 - Marine

Appendix 1 – Review and Assessment of the KeysMAP Workshop Process and Results

The following outline are impressions from the KeysMAP project funded jointly by the Florida Fish and Wildlife Conservation Commission and NOAA and conducted by GeoAdaptive, LLC of Boston, Massachusetts. This review is meant to supplement the final report prepared by GeoAdaptive which is included within the reporting package.

This review is meant to serve as an outline of what was learned and what could be improved upon in future efforts that employ scenario planning in multiple dimensions within the marine environment. The details of the process, goals and objectives, and outcomes are in the final report.

The major headings in this review were grouped together based on specific focal points within the project or on significant issues that arose. In some cases, a number of the observations overlapped into other headings; this is intentional. Commercial and recreational fisheries share many of the same characteristics so they were lumped together. In those cases where there are distinct differences between the two activities (e.g., willingness to pay modeling), the fishery is identified in the outline title.

The details in the outline are brief by necessity. They are meant simply to introduce the issue and to provide context for further exploration. The order in which they are presented does not mean to imply significance.

The final section, 'What we would do differently' is a view in the rearview mirror of some deficiencies in how the project was developed. However, many of these deficiencies were a result of inadequate funding which only became apparent as the project progressed. For example, there was a tremendous amount of data available; however, the data was in formats that required extensive processing in order to be usable, especially in a GIS format. Had we know this was going to be the case, we would have changed the approach.

1. **Applications to Commercial Fisheries/Recreational Fisheries.**
    a. <u>Not all species are losers</u>. For example, in this project early life-history stages of spiny lobsters may, in fact, have more recruitment habitat available within Florida Bay as basins experience more overwash due t o increased sea levels. The overwash in turn should 1) decrease sea surface temperatures and salinities to lower than those now present and 2) overcome the physical barriers now present due to emerging banks ringing the basins. Furthermore, as coastal habitats become more dominated by mangroves, species that rely on them during part of their life history will also likely benefit.
    b. <u>Different life-history stages have different vulnerabilities</u>. Each life history state needs to be addressed based on its specific requirements, range, and physiology. One life history stage may benefit under changing climate condition such as the lobster example above; other life-

history stages may be more at risk. Adult lobsters actually may find conditions exceed threshold temperatures during certain times of the year.

c. Different life-history stages may have benefits for one particular factor but more at risk from another factor. In the case of the spiny lobster, larval lobsters may encounter more settlement habitat and therefore have enhanced population resilience; however, increased ocean acidification may buffer this benefit by exposing larvae to conditions that impose physiological stress.
d. Commercial fisheries management is fairly resilient to a changing climate. In general, the structure for policy-making is flexible and responsive enough to make quick changes to harvest quotas and even management plans and is thus fairly robust to changes in environmental conditions, nevertheless, fisheries stock models need to be regularly updated to reflect changing climate conditions
e. Landscape ecological principles should apply to fisheries with respect to climate change. MPA designs for fisheries priorities needs to consider spatial representation of changing conditions and habitats as climate changes and should consider in their spatial design possible changes to
f. Species ranges should not be constrained artificially by project scale. In this project, we a priori determined the spatial scale of the area to be examined. In hindsight, the design may have been better constructed had we defined the area under study based on species range.
g. All life-history stages should be included . This may get very complicated , especially with those species that are broadcast spawners (no broadcast spawners were addressed in this project) with long-lived early life-history phases. This is an important consideration because a species current or projected status will be determined by numerous life-history stages. If this is too unwieldy, the data or models integrated into the project should address all stages.
h. Human behavioral models need to be developed to predict fishing effort changes under changing conditions. Current models don't really project how people will behave differently under changing conditions although this is somewhat better developed in the terrestrial environment. More emphasis needs to be placed on developing human behavioral models related to commercial fishing under changing conditions.
i. Natural resource valuation models need to be developed for non-commercial species. For example, economic models that predict how recreational fishers will respond as access changes with respect to what the recreational enthusiast is willing to pay to conduct activities that may have reduced access. This becomes more of an issue as the encounter with a species may become more restricted, boat ramps become inundated, and access becomes more difficult. This could have the effect of reducing the impact on a species and these models need to be able to forecast those effects.

2. Applications to Endangered Species Research and Species Recovery Planning

a. Within a management areas, adaptation efforts may need to be focused on one life-history stage but, as discussed previously, all life-history stages contribute to a species vulnerability. In this respect, landscapes issues, basic biology, and species' requirements need to be coordinated with other areas to capture other life-history stages.

b. Habitat suitability indices need to be improved. Vulnerable and imperiled species habitat requirements are often poorly known.
c. More pro-active and less 'politically-correct' approaches may need to be considered (Active management). This approach arose in numerous discussions in the breakout groups. For example, several participants suggested that manufactured habitat should be considered such as reducing mangroves and adding sand was suggested as a way to enhance turtle nesting habitat. This is really the case for more
d. Systems view which can translate down to jurisdictional boxes
e. Primary constituent elements
f. Triggerpoints need to be indentified when specific management strategies need to be implemented including abandonment

3. SLAMM modeling /Habitat Succession Modeling

a. New models should be developed for habitat succession in coastal amd marine ecosystems, especially tropical systems SLAMM is not sensitive enough to discern between different species of mangrove (all mangroves are treated as a single habitat type) yet each species of mangrove comprises a distinct habitat. Better-suited models need to be developed that describe habitat succession in tropical environments. The recommendation is that future State Wildlife Grants fund more sensitive models for tropical Florida.
b. There are difficulties with SLAMM in tropical regions and islands due to habitat conversions. A great deal of effort must be made to find the best data, ensure that the results make sense for the region, and that conversions are realistic. Currently, SLAMM reclassifies habitats into mangroves if the current habitat exten of mangroves is >20%. This oversimplifies the true habitat succession. Additionally, SLAMM sometimes has nonsensical outputs. For example, habitats often inundate into estuarine conditions which are obviously wrong for locations such as small islands (e.g., the Florida Keys.)
c. Hindcasting should be used to test succession modeling (statistical and mechanistic)
d. LIDAR coverage needs to be expanded to adequately address critical Keys areas. We benefited from very good LIDAR data; however, unfortunately the Marquesas do not have LIDAR data
e. FWC provided extensive services by validating and running numerous interations of SLAMM. The contribution from the staff in Tallahassee was enormous!

4. Sea Surface Temperature

a. Modeling is in its infancy and needs to be downscaled to be relevant for smaller coastal spatial scales
b. Ideally, changes in temperature at depth should be integrated into studies where species occupy multiple depth strata
c. Changes in ocean currents should also be examined with respect to connectivity and dispersal

5. Ocean Acidification

a. OA is likely far overshadowed by SST within typical planning time horizons. However, when forecasting potential impacts out beyond 50 years, OA becomes more important to consider.

b. Modeling the localized patterns of changes to OA should be prioritized for studies that examine longer time horizons. This is especially important since certain types of marine habitats mitigate the effects of OA (e.g. seagrass) and the extent of these communities in changing seas may provide critical refugia for coastal species at different life-history stages that are susceptible to OA.

6. Process and inclusion

a. Spatial scenario planning should, in certain circumstances, be combined with, or complement non-spatial scenario planning. The non-spatial activities could include concepts such as changes in management strategies that are not necessarily spatial (e.g., harvest-based, life-history based) As was demonstrated in the Florida Fish and Wildlife Commission's terrestrial scenario planning work, integration with vulnerability analyses and conceptual modeling provides a very robust framework for developing adaptation strategies.

b. The formulation including stakeholders was useful as validated by workshop surveys. The workshops included a broad mix of fisheries and ecosystem managers as well as experts in climate science, species, habitat, mapping,, and other disciplines The mix was cross agency and cross sector and this provided a broad perspective on resources, their use, and adaptation options..

7. Developing adaptation strategies

a. The process of alternative future scenarios should be used to develop specific triggerpoints that, when actuated, trigger strategies or actions. More time should be spent on this with the managers up-front so they can visualize the process outcomes as the project progresses.

b. Prioritization of strategies should incorporate other management strategies including adaptive management and structure decision making in order to prioritize activities and strategies

c. Bundles of species may provide opportunities for common strategies. These strategies can have broad applicability.

d. Climate adaptation strategies should be integrated into NOAA planning to be flexible when developing management approaches. As mangers begin developing adaptation strategies, they should be flexible, have specific triggerpoints at which actions are invoked, have well-developed monitoring plans to inform when those triggerpoints are reached, and have pre-identified and implemented 'no-regrets' strategies that provide 'readiness' when the triggers are reached (e.g., permitting, engineering plans).

8. Scale

a. Scale in marine systems needs to be much larger than terrestrial projects when considering habitat and species ranges.

b. Time considerations were constrained to terrestrial planning horizons – we used time horizons attached to planning priorities but longer time responses tied to longer-lived species within extensive metapopulations . The goals of the project should be carefully pre-defined or scoped in order to ensure that the models are calibrated correctly at the beginning and address the expectations of the users of the outputs. For example, in this project, ocean acidification was not considered because it was felt that it would be inconsequential in the 50 year time horizon. However, if we adjusted our horizon to 100 years or longer, OA would likely have much greater impacts.

9. Dimensions, Data, and Modeling

a. Other important data variables need to be integrated into the models. This is especially important for those variables that may have dramatic effects on species persistence, distribution, and metapopulation structure. For this study, Everglades restoration will likely be extremely consequential for the persistence of nearshore habitats and the species they support. Additionally, the willingness of the U.S. Navy to maintain their base in the Florida Keys and therefore contribute to infrastructure support (e.g., roads) will be crucial for understanding socio-economic drivers and, therefore, pressure on the resources. Both of these were beyond the scope of this project and represent particularly ‘wicked’ problems.
b. Little Is known about basic processes and how they affect the distribution and persistence of species and populations. For example, it is not well-known how current patterns may change and these may have immense impacts on dispersal and metapopulation structure. We suggest that these basic questions should be prioritized in future NOAA research.
c. Ecosystem services should be included as dimensions in these studies. For example, how will changes to habitats impact spatially and quantitatively the coastal habitats, the species that depend on them, and the human communities which also drive the persistence of those species and resources.
d. Standardizing data in a format more friendly to stakeholders (especially GIS users) should be a high priority for NOAA. Data standardization and corrections (e.g., cloud free) should be focused (e.g., common usable aggregates of NOAA pathfinder data are needed to model effects of SST on species.) Extensive data transformation was required to process the data and in some cases this was beyond the financial resources available for this project. NOAA should prioritize the standardization of the data in an accessible format for stakeholders. For example, there is a missing link between climate data and biologically relevant drivers and with depth data including salinity and temperatures.
e. Historical records should be in GIS formats
f. Models specific to the marine environment need to be developed. In the terrestrial environment, urban growth is easy to model; but, in the marine environment, use change is more difficult. Future efforts should include allocation models for projected uses.
g. Socio-economic data need to forecast changes. There were extensive databases of socio-economic data; however, they were historically-based rather than forward projections. Models need to be developed to anticipate how behavior and allocation of resources may change under different conditions.

10. What we would do differently

a. Map species life-history prior to developing the project for spatial considerations by, for example, using an expert advisory group
b. Within a broader project, add localized zooms to areas familiar to species experts and managers
c. Major life-history stages need to be included in the studies or else there needs to be bounding conditions/scenarios

d. Include metapopulation dynamic modeling
e. Socio-economics are extremely important but require a much larger dedication of resources
f. Different constructs need to be developed relative to terrestrial land-use mapping
g. Allocate more resources to data processing. There was a tremendous amount of data available but it was in formats that were not friendly for GIS integration.
h. Build out the dimensions of the modeling parameters related to demand, attractiveness, and constraints. Many of these were already detailed above (e.g., willingness to pay) however were difficult to incorporate due to variability in the data, inefficient data, non-spatial nature of the data, and other reasons.