SIMULATION MODELING AS DECISION SUPPORT FOR ADAPTIVE MANAGEMENT: A CASE STUDY IN MANAGING HUMAN DISTURBANCE OF COASTAL NESTING HABITAT WITHIN AN ECOLOGICAL RESILIENCE FRAMEWORK

By

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To my wife, Regina

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ACE BASIN	The Ashepoo-Combahee-Edisto Basin Reserve, the estuary where the study site is located.
BBP	Botany Bay Plantation, the study site.
QND	Question and Decision: The java-based simulation modeling platform used to develop this project's object-oriented simulation.
QND BBP	The QnD model specifically designed for Botany Bay Plantation.
SC DNR	The South Carolina Department of Natural Resources.
SLAMM	The Sea Level Affecting Marsh Model.

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This dissertation presents three stand-alone papers that address resilience, simulation modeling and adaptive management in a coastal social-ecological system. Paper One uses a panarchy/resilience framework to examine coastal resilience in the region surrounding South Carolina's Ashepoo-Combahee-Edisto (ACE) Basin Reserve and locally at Botany Bay Plantation (BBP), a nesting site within the ACE Basin used by least terns (*Sternula antillarum*) and other coastal species targeted for conservation efforts. It evaluates changes to demographics at the regional scale using census data and changes in human activity at the local scale using survey data. It examines the projected effects of sea level rise at regional and local scales using the Sea Level Affecting Marsh Model (SLAMM). It evaluates the implications of current and future system changes by applying the concept of adaptive cycles and matching them to system structure and functions at the regional and local scale.

Paper Two reports on simulation modeling as an adaptive management tool at the local scale. It focuses on managing human disturbance of critical nesting habitat for least terns at Botany Bay. The simulation model uses the Question and Decision (QnD)

system framework. A qualitative conceptual model of least tern nesting serves as the blueprint for developing the model in an iterative process. QnD BBP is designed so that all key variables can be easily adjusted within the code. Monte Carlo simulations are run for the model exploring management scenarios, with nesting productivity as the key output. Simulation results suggest that nesting productivity is at significant risk from human disturbance, and a sensitivity analysis identifies the variables that appear to have the greatest effect on productivity. Paper Three uses the QnD BBP simulation model for exploring potential management actions. Monte Carlo simulations are run for different management options involving scheduled beach closures and restricted access to spatial units. Simulation results suggest that closing off one spatial unit in particular would result in a significant increase in productivity while minimizing disruption to recreational uses of the beach. The dissertation ends with a discussion of how this model can be used going forward to build a successful local adaptive management program.

CHAPTER 1
INTRODUCTION

Coastal systems are tightly coupled social-ecological systems that have significant vulnerability to external threats, including increasing human population, sea level rise and aging infrastructure. In the case of coastal South Carolina, two major drivers force changes at regional and local scales: coastal development and sea level rise (Van Dolah et al, 2008; Scavia et al., 2002). Coastal development alters beach morphology, introduces human activity into previously undisturbed ecological systems, causes habitat loss and fragmentation, and disrupts wildlife populations. Sea level rise speeds up coastal erosion, converts tidal marshes to open water, forces migration of barrier islands, and leaves human infrastructure and ecological systems more vulnerable to storm surges.

Given the significant anthropogenic and climatic forces exerting pressure on coastal systems, the twin concepts of panarchy (Gunderson and Holling, 2002) and resilience (Walker and Salt, 2006) offer a useful theoretical framework for understanding major changes in the identity, structure, and function of social-ecological systems. Complementing these theoretical approaches is the adaptive management of natural resources (Allan and Stankey, 2009). Adaptive management recognizes that uncertainty is a major factor in any given system and that ecological surprises and unknown thresholds are the rule rather than the exception in managed systems. Adaptive management incorporates learning and hypothesis testing into the management process in order to better understand system structure, behavior and changes. Simulation modeling and decision support tools are increasingly used in this process to more effectively address high levels of complexity and uncertainty (Ascough et al., 2008).

In South Carolina, coastal development and population growth have degraded and reduced habitat for estuarine and marine species (Van Dolah et al., 2008; Allen and Lu, 2003). Coastal development frequently results in the loss of sandy beach habitats (Crain et al., 2009; Schlacher et al., 2008; Schlacher et al., 2007). Many species depend on these beaches for nesting habitat, and conservation of remaining natural nesting sites is a priority for natural resource managers (Wenner et al., 2001). These managers face numerous challenges, including:

- Uncertainty about species demographics, migration dynamics, and shifting baselines.
- Stochastic events such as hurricanes, flooding, and prolonged heat waves.
- Global system changes such as sea level rise and climate change.
- Limited resources for protecting species of concern and managing human activity in nesting areas.

Botany Bay Plantation Wildlife Management Area and Heritage Preserve, in South Carolina's Ashepoo-Combahee-Edisto (ACE) Basin, is one such undeveloped nesting site. It is located along a portion of South Carolina coast that has experienced significant development pressures over the last half century, resulting in a major loss of habitat for coastal species given the highest priority for conservation by the S.C. Department of Natural Resources (2011). Botany Bay Plantation encompasses 4,687 acres on Edisto Island, on the northeastern edge of the ACE Basin Reserve Study Area. It comprises important habitats for fauna and flora, including beach and dune nesting habitat for sea birds, shore birds, and loggerhead turtles (*Caretta caretta*). The beach at

Botany Bay is one of only four known natural sites for least tern (*Sternula antillarum*) colonies in the state (Felicia Sanders, personal communication).

Understanding the effects of human disturbance on least tern nesting and productivity at Botany Bay poses a number of challenges:

- Baseline data are lacking.
- Least terns are notoriously difficult to survey.
- The hammock island that anchors the beach is undergoing severe erosion.
- The South Carolina Department of Natural Resources (SC DNR) employs minimal staff on site and relies on volunteers for duties such as visitor check-in at the entrance gate and monitoring visitor activity on the beach.

Given the high level of uncertainty surrounding the effects of human disturbance on least tern nesting, a management strategy needs to be put in place for learning about the system over time and responding to new disturbances and ecological surprises. This dissertation investigates the ecological resilience of nesting habitat at Botany Bay Plantation and develops a computer simulation model for use in adaptive management of human disturbance at the local scale.

The Problem

Coastal development has reduced available habitat for a number of resident and migratory species along South Carolina's shoreline. The ACE Basin gets some protection from development pressures by its inclusion in the National Estuarine Research Reserve System. However, the estuary bears a greater burden for supporting wildlife than in the past as the result of development-driven habitat loss directly north and south of the site. Undeveloped coastal areas also hold strong appeal for tourists and local residents. Botany Bay Plantation is one of the few such places remaining, and the site has attracted a high volume of visitors since first opening to the public in July

2008. More than 50,000 people now visit this 3-mile stretch of beach each nesting season, representing a significant shock to the beach system and posing an ongoing source of stress and disturbance to the species that nest and feed there. Of particular concern to resource managers are the effects of human disturbance on least terns, which are listed as a threatened species by the state of South Carolina, and loggerhead turtles, which are federally listed as threatened.

Of the two species, least terns are more directly affected by human disturbance at Botany Bay. The site is closed at dusk, minimizing disturbance to female loggerheads as they crawl out of the surf to dig nests and lay eggs. During loggerhead nesting season, SC DNR employs a full-time staffer dedicated to monitoring and protecting loggerhead nests at Botany Bay. Least tern colonies, on the other hand, are demarcated by signs, wooden stakes and string to keep visitors from stepping on eggs. These barriers provide minimal protection and can easily become obsolete as terns shift locations in response to overwash flooding, erosion, predation, and human disturbance.

Least terns are known to have high rates of year-to-year fidelity to colony sites and a significant tendency to nest at their natal site (Atwood and Massey 1988). This makes protection of existing colony sites important, and management efforts have been shown to help restore population levels that have declined because of habitat loss, predation and human disturbance (Burger 1989).

Human disturbance can be seriously disruptive to the productivity of nesting sea birds and shore birds (Liley and Sutherland, 2007; Lafferty, 2001; Anderson and Keith, 1980; Robert and Ralph, 1975). The optimal spatial distribution of beach visitors near sea bird colonies depends on factors such as the sensitivity of the species to disturbance and overall visitor pressure (Beale, 2007; Blumstein et al., 2005; West et al., 2002). Management actions restricting access from critical beach areas used by sea birds and shore birds are important for minimizing disruptions (Burger et al., 2004), and reductions in human disturbance can result in higher productivity (Lafferty et al., 2006).

At the landscape scale, features associated with human disturbance can affect the distribution of a particular species (Burton, 2007). In essence, this means that sites attracting large colonies of nesting birds, such as Botany Bay Plantation, must manage human disturbance carefully since least terns and other nesting species are already selecting the site because of its distance from other human-based features on the coastal landscape. A notable exception to this phenomenon is the tendency for least tern colonies to form on tar-and-gravel rooftops of large commercial buildings (Gore and Kinnison, 1991). Approximately 70 percent of least tern nesting in South Carolina occurs on these rooftops, but the productivity and long-term viability of these colonies is not known.

Adaptive Management

Adaptive management has been described as learning by doing. It treats management actions as working hypotheses that require monitoring, analysis and evaluation of outcomes in a structured process of iterative learning (Williams et al., 2009; Argent, 2009). Complex ecosystems and their associated management systems develop increasing uncertainty over time and thus require a process for understanding the system that can be continuously updated and adjusted (Folke et al., 2005). In the face of uncertainty, adaptive management provides a flexible framework that incorporates existing knowledge with new information to develop and modify management objectives (Walters and Holling, 1990; Otter and Capobianco, 2000).

Successful adaptive management programs, however, are rare (Stankey, 2002). Several challenges present themselves when attempting to develop an adaptive management framework, including the additional burden that such activities can impose upon managers and staff (Buckley, 2004a). Implementing adaptive management poses a tremendous challenge to agencies and resource managers. Adaptive management programs are difficult to implement and sustain, and most agencies lack resources for monitoring and evaluation (Koontz and Bodine, 2008; Jacobson et al. 2006; Lee, 1999). Consequently, a gap exists between theoretical approaches to adaptive management and the realities of daily management practice (Medema et al., 2008).

Simulation Modeling

Early efforts to use simulation models in adaptive management initiatives relied on linear system models that were constrained by their underlying assumptions (McLain and Lee, 1996). By contrast, this project uses an object-oriented modeling approach that makes its assumptions explicit and easily accommodates modifications. Object-oriented, agent-based modeling involves a simulation comprising an environment and objects within the environment that act upon one another. It uses formulas for a variety of activities related to decision-making, hierarchical relationships, and communication among agents (Bousquet and Le Page, 2004). Object-oriented models are a subset of individual-based models, which focus on behaviors and interactions such as movement through space; foraging behavior; exploitive species interactions; local competition; and management-related processes (Grimm et al., 2006; DeAngelis and Mooij, 2005).

Simulation models have become an important tool in managing natural resources amid the uncertainties and complexities of social and ecological systems (Otter and Capobianco, 2000). The model becomes a shared representation of the system and a tool for collective learning (Bousquet and Le Page, 2004; Campo et al., 2009). In this respect, the creation and ongoing development of a model becomes an important component of the adaptive management process (McLain and Lee, 1996; Lawson et al., 2003; Lawson 2006). A well constructed model encourages collaboration among management and stakeholders and makes use of available data, theories and other information to represent the interactions among elements in the system of interest. However, many challenges in model development remain, including misunderstandings between resource managers and model developers (e.g., Borowski and Hare, 2007) and onerous data-collection requirements (MacMillan and Marshall, 2006).

Hypotheses and Research Objectives

The primary hypothesis for this study is that proximity to human activity and intensity of human activity are both positively correlated with fewer nests and reduced productivity for least terns (Buckley, 2004b; Buckley and King, 2003). Additional hypotheses that inform development of the simulation model include:

- Overwash threats will increase in intensity from one season to the next as erosion and sea level rise overtake the morphological process of barrier island migration.
- Unknown disturbance thresholds exist that force terns to abandon nesting colonies.
- Human disturbance of tern colonies must be managed effectively in order to maintain productivity levels sufficient for ensuring that nesting pairs return in subsequent years.

This dissertation uses simulation modeling to understand function and structure within a dynamic social-ecological system undergoing significant change. It presents a modeling approach designed to address uncertainty and promote adaptive management at the local scale. The simulation model becomes a central focus of the management strategy by focusing on key indicators as determined by management priorities and establishing a system for monitoring and evaluating those indicators. This approach is designed to create a minimum data-collection burden on resource managers while allowing them to track important system indicators, explore management options and engage site volunteers. The model facilitates decision-making and collaboration through transparency and ease of management input.

The simulation model is built on the Question and Decision (QnD) system framework. QnD allows for iterative development of model components as its users learn more about the system being managed. It is designed for understanding potential ecosystem behaviors and management options for a given social-ecological system. It links spatial components through geographic information system files with selected abiotic and biotic interactions within the system being modeled (Kiker et al., 2006). QnD has two primary elements: a simulation engine and a user-friendly graphical interface that allows users to explore various scenarios and management options. The developer configures the attributes and processes of the simulation's objects through input files written in extensible markup language (XML) that QnD converts into Java objects (Kiker and Thummalapalli, 2009).

Development of a QnD model for Botany Bay Plantation (QnD BBP) requires a comprehensive understanding of ecological systems at Botany Bay and the ways in which human activity affected them. This dissertation breaks down that process into three stand-alone papers:

Panarchy in Coastal South Carolina: Exploring Potential Regime Shifts across Scales in a Coastal Social-Ecological System

This paper uses a panarchy/resilience framework to examine coastal resilience in the region surrounding South Carolina's ACE Basin and locally at Botany Bay

Plantation. It evaluates changes to demographics at the regional scale using census tract data for the three counties in and around the ACE Basin. Changes in human activity at the local scale are determined using survey data from Botany Bay Plantation. It examines the projected effects of sea level rise at regional and local scales using the Sea Level Affecting Marsh Model (SLAMM). It evaluates the implications of current and future system changes by applying the concept of adaptive cycles and matching them to system structure and functions at the regional and local scale. Population and housing structures both show strong growth from 1990 to 2010, fundamentally altering the social-ecological system in and around the ACE Basin. At the local scale, opening Botany Bay to the public in 2008 represented a major disturbance and source of continuing stress for least terns at Botany Bay. At the regional scale, SLAMM shows significant beach loss to coastal areas by 2100. Botany Bay could see significant changes to its beach and marsh system by 2025. Human activity in and around the ACE Basin has lowered resilience to sea level rise and other future threats. Given the tremendous changes to human population and infrastructure over the last two decades, it appears that a shift toward regime shift has occurred in South Carolina's lower coastal counties. The beginnings of regime shift are also seen at the local scale. Resource managers will need to anticipate these changes and have plans in place for proactively responding to them.

Development and Testing of an Object-Oriented, Agent-Based Simulation Model and Decision-Support Tool for Adaptively Managing Human Disturbance of Least Tern Nesting Habitat

This paper reports on simulation modeling as an adaptive management tool at the local scale. It focuses on the use of an object-oriented model for managing human disturbance of critical nesting habitat for least terns at the newly created Botany Bay

Plantation Heritage Preserve/Wildlife Management Area. The simulation model for this project uses the Question and Decision (QnD) system framework. QnD is designed for understanding potential ecosystem behaviors and management options for a given social-ecological system. Developing the QnD model required an examination of how the beach's ecological system functions with respect to least tern nesting, how the introduction of human beach users has affected least tern nesting, and how human disturbance can be managed to minimize adverse effects on nesting productivity. A qualitative conceptual model of least tern nesting serves as the blueprint for developing the simulation model in an iterative process involving surveys and observations of the social-ecological system. QnD BBP is designed so that all key variables for the simulation can be easily adjusted within the code. A unified modeling language diagram of the model is presented, and all relevant algorithms governing object behavior are discussed. System variables are divided into two categories. Level 1 variables represent uncertainties about how key components within the system function and are assigned stochastic probability distributions. Level 2 variables represent assumptions about basic system functions that are made explicit to management and can be changed as necessary. Monte Carlo simulations are run for the model exploring several management scenarios, with nesting productivity as the key output. A sensitivity analysis is conducted on eight Level 1 variables. Simulation results suggest that nesting productivity at Botany Bay Plantation is at significant risk from human disturbance, which wasn't a factor prior to 2008. The sensitivity analysis identifies the variables that have the greatest effect on nesting productivity, namely the length of time that nesting pairs are disturbed by the presence of humans. The paper concludes with a discussion of how uncertainty within the model can be addressed through select monitoring.

Exploring the Use of a Simulation Model for Decision Support in Adaptive Management of Least Tern Nesting Habitat

This paper uses a simulation model for exploring potential management actions and developing an adaptive management program at Botany Bay Plantation. This object-oriented model, built on a java-based platform known as QnD (Question and Decision), is designed to help manage human disturbance of nesting least terns (*Sternula antillarum*) at one of only four known natural sites for least tern colonies on the South Carolina coast. The model measures least tern nesting productivity over the course of a single nesting season in daily time steps as colonies are exposed to human disturbance and flooding from overwash tides. Monte Carlo simulations were run for a number of different management options involving scheduled beach closures and restricted access to spatial units with active colonies. Least tern nesting productivity was compared for scheduled closures of 0 to 3 days per week plus a 7 days per week closure to provide a comparison for nesting habitat with minimal human disturbance. Other simulations looked at the effects on productivity when closing spatial units that contain least tern colonies for the entire nesting season. Simulation results suggest that a successful productivity rate of 0.25 fledglings per breeding adult cannot be achieved under current management conditions and that three of four spatial units are at immediate risk of failure as colony sites. The model shows that closing off the beach would have a significant effect on improving nesting productivity, but the productivity gain from closing the beach for an extra day or two beyond the current management practice of one day closed per week shows no statistical significance. Closing off one spatial unit in particular would result in an increase in global median productivity from 0.08 to 0.36. This suggests that closure of the spatial unit could result in stronger productivity for the entire site while minimizing disruption to recreational uses of the beach. The paper ends with a discussion of how site managers and volunteers could work together to collect data and improve the model.

CHAPTER 2

PANARCHY IN COASTAL SOUTH CAROLINA: EXPLORING POTENTIAL REGIME SHIFTS ACROSS SCALES IN A COASTAL SOCIAL-ECOLOGICAL SYSTEM

Introduction

Coastal systems are tightly coupled social-ecological systems that have significant vulnerability to external threats, including increasing human population, sea level rise and aging infrastructure. Recent climate-related events and oil spills have highlighted these layered vulnerabilities, which contribute to current and future risks (Kiker et al., 2011). In the case of coastal South Carolina, two major drivers force changes at regional and local scales: coastal development and sea level rise (Van Dolah et al, 2008; Scavia et al., 2002). Coastal development alters beach morphology, introduces human activity into previously undisturbed ecological systems, causes habitat loss and fragmentation, and disrupts wildlife populations. Sea level rise speeds up coastal erosion, converts tidal marshes to open water, forces migration of barrier islands, and leaves human infrastructure and ecological systems more vulnerable to storm surges. Salt water marshes in the southeastern U.S. have been projected to decline by 20 to 45 percent, based on simulation models using the IPCC's sea-level-rise scenarios (Craft et al., 2009). As sea levels rise, storm surges from hurricanes and other ocean storms will ride into coastal areas on higher water levels that increase the potential for damage (Scavia et al., 2002). Since the Category IV Hurricane Hugo hit the South Carolina coast in 1989, new construction and development projects have pushed into coastal areas vulnerable to future storms and sea level rise (Allen and Lu, 2003; Van Dolah et al., 2008). This boom in coastal development has reduced system resilience against future disturbances (Bures and Kanapaux, 2011).

A fundamental question for both residents and coastal managers is whether South Carolina's coastal ecosystems and development are resilient to current and future threats. If they are currently resilient, how can this resilience be maintained? If they are not currently resilient, what system elements should be addressed to reduce this vulnerability?

Given the significant anthropogenic and climatic forces exerting pressure on the social-ecological systems in coastal South Carolina, the twin concepts of panarchy (Gunderson and Holling, 2002) and resilience (Gunderson et al., 1995) offer a useful theoretical framework for understanding major changes in the identity, structure, and function of social-ecological systems to both current and potential future events. A panarchy consists of nested cycles that operate on different scales, such as local, regional, and global. This approach is relevant to investigations of system resilience given the influence of human activity on ecological systems at all scales and the potential for global ecological shifts to force changes on systems at lower scales.

Many of today's ecological challenges are so complex and interactive that they require simulation models to explore the potential effects of management strategies given a range of scenarios. But in order to develop a useful model of a system, one must first understand it. This requires knowledge not only of the system at the scale being modeled but of the system at the broader spatial and temporal scales in which it is embedded. This is especially important for identifying key system drivers. Ecological resilience, panarchy and adaptive cycles together form a theoretical framework by which this can be accomplished. A key component of this approach involves a close look at the social-ecological system at different scales.

Ecological resilience can be defined as the magnitude of disturbance a system absorbs before its identity changes. This change, known as a regime shift, results from changes in the variables and processes that control the system's structure and functions (Holling and Gunderson, 2002). The shift occurs rapidly following a period of gradual change (Biggs et al., 2009). Examples include lakes that turn from healthy to eutrophic (e.g., Guttal and Jayaprakash, 2008) and commercial fisheries that suffer collapse (e.g., Biggs et al., 2009).

In resilient systems, shocks and disturbances create opportunities for innovation and development. Stabilizing feedback keeps the system within its stable state (Scheffer et al., 2002). Existing structures and functions recombine into new trajectories while retaining the system's identity. By contrast, even small disturbances can force a system that lacks resilience to switch into a different regime (Folke, 2006). Human impact on ecosystems can exceed long-term sustainable levels well before the effects become noticeable (Biggs et al., 2009). In coastal systems, human populations and infrastructure generally increase at incremental rates. Sandy beaches, marsh systems and maritime forests become more fragmented and disturbed over time. The question is at what point do these disturbances force the system into a different regime?

Because the structuring processes that define natural systems are robust, external disturbances must be extreme and/or persistent in order to push a system into regime shift (Holling et al., 2002a). Coastal development begins as a shock to the affected system and continues as a persistent stress by reducing habitat for plants and wildlife and by interfering with barrier island migration and other morphological changes. Increased coastal development also brings increased human disturbance to undeveloped areas by increasing the number of residents and tourists seeking recreational opportunities. Sea level rise intensifies morphological change by altering existing barrier-island and marsh systems more quickly than the capacity of those systems to respond. A prime example would be the conversion of marsh to open water, which in turn prevents barrier island migration (FitzGerald et al., 2008). Coastal development exacerbates this intensified rate of morphological change through the placement of artificial structures that inhibit and alter the dynamic properties of coastal systems (Bromberg Gedan et al., 2009; Gabriel and Kreutzwiser, 2000).

This paper uses a panarchy/resilience framework to examine coastal resilience in the region surrounding South Carolina's Ashepoo-Combahee-Edisto (ACE) Basin Reserve and locally at Botany Bay Plantation, a nesting site within the ACE Basin used by least terns and other coastal species targeted for conservation efforts. It explores two hypotheses: that population growth and infrastructure development has reduced resilience along the South Carolina coast, and that this reduction in resilience has a direct impact on management of natural resources in South Carolina's ACE Basin Reserve. To examine the viability of these hypotheses, this paper:

- Evaluates changes to demographics at the regional scale and human activity levels at the local scale. At the regional level, it uses census tract data to determine changes in population and physical structures in the three counties in and around the ACE Basin. At the local scale, survey data from Botany Bay Plantation is used to look at beach user profiles and temporal and spatial patterns of beach use.

- Examines the projected effects of sea level rise at regional and local scales using the Sea Level Affecting Marsh Model (SLAMM).

- Uses the panarchy and resilience frameworks to evaluate the implications of current and future system changes by applying the concept of adaptive cycles and matching them to system structure and functions at the regional and local scale.

Examining the relationship between the two scales of the social-ecological system raises a number of questions: How do they fit together? How does the resilience level in one system affect the resilience of the other? What can be learned about the resilience of the South Carolina coast by looking at the interactions between the two scales? What level of control and influence is possible over present and future changes to the social-ecological system? What are the implications of all this for the use of simulation modeling in resource management?

Ecological Resilience and the Role of Adaptive Cycles

Ecological resilience emphasizes non-linear dynamics, thresholds and uncertainty (Carpenter et al., 2001; Holling and Gunderson, 2002; Walker et al., 2004; Folke, 2006; Brand and Jax, 2007). It identifies four phases of ecosystem behavior that taken together make up its adaptive cycle: exploitation (r), conservation (K), release (Ω) and re-organization (α). The first two phases, known as the front loop, involve rapid colonization of disturbed areas that eventually leads to the slow accumulation and storage of energy and material. System structures and functions become more tightly organized over time. The back loop consists of the release and re-organization phases. These phases can bring about major system changes in relatively brief periods (Carpenter et al., 2001; Holling and Gunderson, 2002).

A nested set of adaptive cycles that occur across spatial and temporal scales is known as a panarchy. Adaptive cycles within a panarchy function at different orders of magnitude, and each cycle can be characterized as having a fast, medium or slow speed. The temporal and spatial relationships among the adaptive cycles gives a system its adaptive complexity (Holling et al., 2002b). Slow variables provide the system with stabilizing effects: Each slower level sets the ground rules by which the next faster level responds. Large, unique disturbances combine with changes in slow variables to create the potential for system collapse and regime shift (Carpenter et al., 2002).

Identifying a system's regime shifts and the changes to its adaptive cycle can be accomplished by identifying its structures, functions and processes. In order to model a system, a least three key interacting components must be included (Holling et al., 2002a). Typically there is an order of magnitude difference among each component's variable speed and corresponding spatial scale. The interactions among these variables result in the system's complexity. In addition, a panarchy shows:

- Nonlinear causation and multistable behavior.
- Vulnerability and resilience that change with the slow variables.
- Biota that create structure that reinforces biota.
- Spatial contagion and biotic legacies that self-organize over space and time.

Once a slow-speed component enters the collapse phase of its adaptive cycle, medium-speed and fast components will eventually enter their own collapse phases, bringing the panarchy into alignment for regime shift. The full effects of the slow variable’s collapse become apparent in the reorganization phase of adaptive cycles for medium and fast cycles. The next slowest cycle no longer contains the stored energy upon which the faster cycle would reorganize itself. In coastal systems, this regime shift can occur in a number of ways. Human-built structures designed to mitigate the effects of sea level rise can impede the flow of sediment necessary for renourishing shifting beaches and hammock islands. This in turn prevents the formation of potential habitat that would be colonized by displaced plant and animal species during the reorganization and exploitation phases of the adaptive cycle. These negative effects can occur at local scales (characterized by fast-speed variables) and at landscape and metapopulation levels (medium-speed variables).

Alternative Stable States

Alternative stable states theory offers a related approach to understanding system change. It predicts that ecological systems can exist in contrasting states under the same external environmental conditions (Schröder et al., 2005). Multiple basins of attraction occur within the system so that it is capable of supporting two or more assemblages of species (Suding and Hobbs, 2009). The boundary at which a system changes states is commonly called its ecological threshold (Groffman et al., 2006).

The development of this theory comes at a time when ecologists are seeking ways to anticipate large-scale changes in the systems they study. Probable mechanisms for dramatic regime shifts, such as occurred in the 1990’s when coral reefs in the Caribbean became algae encrusted, currently are detected only in hindsight (Scheffer and Carpenter, 2003). These changes are often the non-linear result of incremental changes rather than one sudden external shock.

Beisner et al. (2003) describe two different contexts in which an ecological community can shift into an alternative stable state. One involves a shift in variables in the form of population changes that directly move the community from one stable state into another. (In adaptive-cycle terms, these would be fast or medium-speed variables.) This perspective assumes that system parameters remain basically constant. A change of states occurs with a change in variables, such as overfishing or the introduction of a new predator. The second context involves a shift in parameters, or environmental drivers (Beisner et al., 2003). In this ecosystem perspective, the parameters change and alter the equilibrium point. The community then arrives at an alternative, locally stable equilibrium point. Climate change (slow speed variable) would be one example of this. Within these two contexts, the variable shift represents fast change, and the parameter shift represents slow change. Variable changes that don't respond to feedback become parameter changes: Examples include continued overfishing despite declining stocks and increased coastal development despite increasing habitat degradation and threats from sea level rise. Variable changes potentially respond quickly to management actions. Parameter changes don't.

Schröder et al. (2005) caution that given the amount of anthropogenic-driven changes in many environments, the presence of alternative stable states can have serious, unexpected consequences. Human activities cause a number of impacts that create new threshold triggers: transforming transient events into persistent disturbances, introducing new disturbances that create chronic stress, and suppressing disturbance events that are important to system function (Suding and Hobbs, 2009).

A catastrophe fold occurs when the stress level within a system reaches a critical threshold, causing the system to switch to an alternative state (Scheffer et al., 2002). The system can be viewed as possessing two alternative stable states represented by an upper and lower branch of a sigmoid response curve. As stress levels increase and the system approaches the ecological threshold, little change is observed in the system. However, once stress levels pass the threshold, a rapid catastrophic transition occurs (Scheffer et al., 2002). The system is said to possess alternative stable states because once it switches to the lower branch, stress levels must be reduced significantly for the system to switch back to the upper branch. This leaves a range of stress levels in which the system can exist at either the upper or lower branch, depending on whether the ecological threshold or return point has been reached.

The ecological threshold corresponds with the Ω phase. The point at which the system enters the lower branch state can be represented by the α phase. At this point, the system can reorganize in one of two ways: If stress levels decline or remain relatively stable, the system can continue to exist in the lower branch state and retain the potential for returning to the upper-branch state once stress levels decline to the return point (depicted by *r* in the adaptive cycle). If stress levels continue to increase beyond the ecological threshold, the system will re-organize into a different state, and the alternative stable state dynamic will have been lost for good. This change corresponds with regime shift. Both approaches point to the same result: a system that undergoes fundamental changes to its identity, structure and functions.

The Ashepoo-Combahee-Edisto (ACE) Basin

The Ashepoo-Combahee-Edisto (ACE) Basin covers 320,000 hectares (790,000 acres) in a relatively undeveloped 40-km-wide tract between the expanding metropolitan areas of Charleston and Beaufort (Figure 2-1). Extending about 72 km (45 mi) inland, the ACE Basin contains saltwater and brackish marshes, maritime forests, upland pines and bottomland hardwoods (Wenner et al., 2001). The basin is one of the most diverse natural areas on the U.S. Atlantic coast and has one of the east coast's most pristine estuaries, St. Helena Sound (Cooperative Conservation America, 2006). The basin is also one of the largest intact coastal ecosystems on the east coast, comprising six distinct habitats that support nine federally endangered species and six threatened species, including the bald eagle (*Haliaeetus leucocephalus*), red-cockaded woodpecker (*Picoides borealis*), and the wood stork (*Mycteria americana*). In addition, it supports some 30 species listed as endangered, threatened, or special by the state of South Carolina, including the least tern (*Sternula antillarum*) (Wenner et al., 2001). Based on estuarine surveys conducted by the U.S. Fish and Wildlife Service and the SC DNR, the ACE Basin's marshes are highly productive nursery grounds for the region's marine life (Harrigal, 2009).

About two-thirds of the ACE Basin lies in Colleton County. While the basin remains largely undeveloped, population pressure continues to intensify along other portions of the South Carolina coast. This growth poses a number of environmental problems for the basin, including nonpoint source pollution from road runoff and other sources; nutrient enrichment from agricultural activities; resource depletion; and habitat loss and fragmentation. The potential for increased development within the basin exists because of the area's mild climate, rural character and affordable land prices (Wenner et al., 2001).

Botany Bay Plantation is located on the northeast edge of Edisto Island (Figure 2-1). It comprises 4,687 acres (1,897 hectares) of beach, tidal marsh, agricultural fields, forest, and ponds. Its ocean-facing beach, about 3 miles long (4.8 km), serves as nesting habitat for least terns, loggerhead turtles (*Caretta caretta*), state listed Wilson's plovers (*Charadrius wilsonia*), American oystercatchers (*Haematopus palliatus*) and a variety of other sea birds and shorebirds. The beach also provides important stopover habitat for migrating shorebirds.

The property was privately owned as a working plantation and hunting reserve until December 2007, when the State of South Carolina assumed full ownership of it. The S.C. Department of Natural Resources took responsibility for the property as a wildlife management area and heritage preserve beginning in June 2008. The site opened to the public in July 2008.

The Beach at Botany Bay Plantation

The beach at Botany Bay Plantation is one of only four known natural sites in South Carolina for least tern nesting (Felicia Sanders, personal communication). It also provides nesting habitat for federally threatened loggerhead turtles. Opening the beach to public access represents a major system change and has created a persistent disturbance within the system.

The beach at Botany Bay ranks as one of the more important beaches in South Carolina as nesting habitat for loggerhead turtles (Harrigal, 2009). It recorded 176 nests in 2010 and 131 nests in 2009 (Chris Salmonson, personal communication). Management goals for Botany Bay include a relatively undisturbed tidal marsh and beach ecosystem that continues to provide habitat for loggerhead turtles and resident and migrating shorebirds. To that end, management focuses on reducing predation and the impact of human disturbance upon nesting loggerheads and nesting and migrating shorebirds (Harrigal, 2009). SC DNR staff and turtle-patrol volunteers conduct daily surveys of loggerhead nesting. Nests at risk from erosion and washover are relocated. Nesting areas for least terns are posted and roped off once colonies begin developing to reduce disturbance by beach users.

Botany Bay Plantation has one entrance gate. An unpaved road takes visitors about 2 miles to a parking area that leads to a half-mile walk through marsh and hammock islands to the beach. The beach itself has no permanent structures or facilities, and unauthorized motor vehicles are not allowed on the marsh path or beach. Several features make the beach notable (Figure 2-2). Northeast of the entrance lies "the boneyard," a large area of dead trees in the intertidal zone. The beach's largest tern colony is found beyond the boneyard in a overwash area at the end of the island's hammock. A dune area that loggerheads frequently use to nest stretches more than a mile past the overwash area.

The beach southwest of the entrance is characterized primarily by overwash and relic marsh mud exposed by the shifting sand. A second tern colony can be found more than a half mile south of the entrance near Townsend's Inlet, which is popular for fishing. This inlet can be crossed on foot at low tide to an area known as Interlude Beach. This stretch of beach, about 0.75 miles long, is essentially unmanaged except for signs and rope to designate nesting areas. Both of the colony areas south of the entrance are more susceptible to overwash, and Interlude Beach is vulnerable to unmanaged human disturbance. Frampton's Inlet lies at the southern end of Interlude Beach. People cross this inlet at low tide from a private beach to the south. They also access Interlude Beach by boat and kayak. These visitors do not sign in and are for the most part unmonitored.

The small hammock that anchors the beach at Botany Bay, known as Pockoy Island, is currently undergoing severe erosion (Figures 2-3 and 2-4). The dune system protecting the hammock has disappeared, and the beach experiences frequent overwash. These overwash events flood the hammock, leaving ponds of salt water that kill its stand of mature maritime forest. On either side of the hammock, overwash deposits sand along the backside of the beach, overrunning the cordgrass (Figure 2-5). As long as these overwash sands are deposited on the marsh platform, Pockoy will remain a hammock island. But as the erosion process intensifies as a result of sea level rise, marsh will convert to open water. This conversion disrupts food webs and eliminates important nesting habitat for loggerhead turtles, sea birds and shore birds.

Least Tern Nesting

The least tern is listed as a threatened species in South Carolina. In the early 20th Century, the bird was overhunted for its plumage. In recent decades, loss of habitat resulting from coastal development has posed the biggest threat. Predation and overwash also threaten nesting success (Wenner et al., 2001). Since the 1970s, least terns in South Carolina have taken to nesting on pebbled rooftops in greater numbers. Currently, about 70 percent of least terns nest on roofs (SC Department of Natural Resources, 2006).

Of the four known natural sites for least tern colonies, the two sites with the largest colonies are found in Cape Romain National Wildlife Refuge, about 60 miles to the north of Botany Bay. An additional colony resides on Kiawah Island, a resort development about 10 miles north of Botany Bay. The least tern appears on South Carolina's shore in late April for the breeding season and stays through August. Least terns usually begin breeding at two years old. They are monogamous and usually produce one brood of one to three eggs per year. Renesting can occur after loss of eggs or chicks from predation or overwash (Massey and Atwood, 1981; Massey and Fancher, 1989). Both adults incubate the eggs for approximately 20 days. The chicks fledge about three weeks after hatching.

Terns nest in colonies on beaches and sandbars. They prefer bare overwash areas with shells and other litter. They make small depressions in the sand for their nests and actively protect the nests from predators and perceived predators such as humans (Wenner et al., 2001). Overwash during spring tides poses a constant threat to colony productivity. Least terns are also vulnerable to human disturbance and predators, both of which provoke an intense defensive response from the entire colony (Elliott et al., 2007). These responses expose tern eggs to direct sunlight, potentially reducing their viability through heat exposure. Protection of least terns from human disturbance and predators has been shown to increase productivity over time (Burger, 1989).

Least terns show strong fidelity to natal colony sites (Atwood and Massey, 1988). Not much is known about the migratory behavior of least terns, except that they migrate to wintering grounds in Central and South America. This contributes to uncertainty about inter-annual fluctuations in nesting populations.

Effects of Disturbance on Least Terns

Stress and disturbance both work in different ways to reduce tern populations. The primary stress factor affecting least tern nesting at Botany Bay is human activity, which creates daily disturbance events. The main stochastic disturbance is wave action in the form of storm surges and tide overwash.

Stress reduces overall productivity and makes ecosystems less resilient to disturbances (Grime, 1973). By contrast, disturbances play a vital role in maintaining a system's biodiversity. They create environmental heterogeneity by interrupting ecological succession sequences and opening niches for random colonization by opportunistic species (Levin and Paine, 1974). A continual process of localized and random disturbances creates patchiness and opens up evolutionary opportunities (Levin, 1999). For least terns, the same overwash events that disrupt nesting and displace colonies also open up new nesting habitat and expose mud flats for foraging.

Hurricanes and other strong storms represent the most dramatic disturbance regime for the South Carolina coast. Hurricane Hugo, the last major storm to strike the coast, had maximum sustained winds of 217 km per hour and a maximum storm surge of 6 m. The hurricane caused overwash; storm surge; storm surge ebb; beach and dune erosion; and shoreline retreat. These effects were intensified in areas with shoreline development (Hall et al., 1990). In the decades since Hugo, development has proliferated throughout coastal South Carolina, reducing habitat for coastal species. In this way, a major disturbance event opened a niche within the social-ecological system for intensified coastal development, which then became an ongoing stressor that affects barrier island systems supporting least tern colonies. Increased development along the coast frequently increases human activity levels in adjacent undeveloped areas. The additional stress placed on undeveloped areas by increased human activity reduces resilience for systems within those areas, thus making them more vulnerable to future disturbances.

Botany Bay Plantation remains relatively untouched, and Edisto Island has relatively low levels of coastal development. But the region from Savannah to Georgetown, S.C., has undergone tremendous development in the last two decades. This has brought an increase in habitat fragmentation and a proliferation of impervious surfaces. This represents wide-scale habitat loss and negates the role of natural disturbance regimes, which act to renew the limiting resource of space by initiating progressions of species invasion and occupancy (Paine and Levin, 1981).

Overwash and other morphological changes to barrier island beaches represent the back loop (release and reorganization) of the system. Beach lost to morphological changes remains within the adaptive cycle as the sand migrates into the marsh or circulates with the currents to create sandbars and/or accrete on other sections of beach. Natural beach lost to coastal development lacks the stored memory for reorganization, thus increasing the possibility of regime shift. Sea walls, hardened shores, paved roads and buildings inhibit the adaptive cycle and increase the likelihood of marsh systems converting to open water, resulting in loss of migrating sand.

The beach at Botany Bay Plantation serves as an important undeveloped habitat for a variety of fauna and flora. However, its beach is in the midst of an erosion regime, characterized by frequent overwashes during spring tides. Overwash at Botany Bay has a strong negative impact on nesting success for least terns. Accretion also serves as a disturbance on Botany Bay's beach. Sand from nearby Deveaux Bank washes onto certain sections of the beach and raises sand levels to a height that smothers intertidal mud patches that provide invertebrates for shorebirds. However, these sands also wash into the marsh behind the island, resulting in expanded overwash habitat as the island migrates inland. These disturbance regimes are in part driven by climate change and associated sea level rise by thermal expansion (FitzGerald et al., 2008) and are expected to increase in intensity over time.

Changes to slow variables within coastal systems pose major challenges to natural resource managers trying to enhance the resilience of nesting tern colonies. These challenges are evident at Botany Bay Plantation, where an infusion of beach users delivered an initial shock to the beach system that then became an ongoing source of stress for nesting least terns and other species. The long-term effects of human disturbance on Botany Bay's least tern colonies are not known and are made more uncertain by the morphological changes occurring to the beach and hammock island.

Methods

Demographics

This paper evaluates changes in resilience to the social-ecological system at the regional scale through the use of demographic data (Bures and Kanapaux, 2011). Data from the U.S. Census of Population for the years 1990-2010 are used to describe population characteristics and change. Tract-level data for the three coastal counties in and around the ACE Basin (Beaufort, Charleston and Colleton Counties) are used to examine changes in population and in housing units, which are used as an indicator for changes in disturbance levels, overall infrastructure, and potential loss of nesting habitat for the metapopulation of least terns. These data come from the Longitudinal Tract Database, which adjusts census data from previous decades to 2010 census tract boundaries (Logan et al., 2011). These data are imported into ArcGIS 9.2 for spatial representation of growth in coastal development, with a focus on those tracts containing barrier island sandy beaches that would provide nesting habitat to least terns and other species in undisturbed conditions.

Beach Users

Botany Bay is open to the public six days a week (closed Tuesdays) from dawn until dusk. Three approaches were used to understand the potential impact of humans on least tern nesting at Botany Bay: a visitor-use survey, a causeway count of people entering and exiting, and a spatial distribution survey on the beach itself. All three of these were conducted during peak hours of beach use: 10am to 5pm. The visitor-use survey was conducted from June 26 to August 13, 2009 to provide a snapshot of beach user characteristics and behaviors. Surveys were conducted over the course of two hours once or twice a day at randomly selected times. Beach users were approached as they entered the causeway (marsh path) to return to the parking lot. Respondents provided information on personal demographics, composition of their group, visits to Edisto Island and Botany Bay, activities while on the beach, and perceptions of the beach. Surveys lasted approximately 10 minutes and concluded prior to the end of the marsh walk. The next available respondent was approached once the interviewer achieved sufficient distance from the parking lot for conducting a new survey along the marsh path. Choice of male or female respondent, when applicable, was determined in advance by random selection. In all, 120 beach users were interviewed.

Causeway counts were conducted on 14 randomly selected occasions between July 11 and August 13, 2009. Each count lasted approximately two hours. Individuals and groups were tallied on a time sheet as they entered and exited the beach. These counts were then divided into one-hour blocks to determine the rate of overall causeway foot traffic as well as rates entering and exiting the beach. These counts were done to calculate disturbance potential on the beach. Spatial distribution beach surveys were conducted on 19 occasions at randomly selected times between June 25 and September 7, 2009. These surveys began at one end of the beach and counted the number of people in each area of the beach. These counts were conducted in order to characterize spatial patterns of beach use by humans.

In addition, semi-structured interviews were conducted with management and staff of the S.C. Department of Natural Resources and with volunteers who worked the beach and entrance gate at Botany Bay Plantation. Field observations of human behavior, wildlife responses and morphological changes at Botany Bay were conducted throughout the 2009 and 2010 nesting seasons (May – August) as well as during other times of the year. These interviews and observations helped inform this paper's perspective on the broader social-ecological system and the challenges faced at Botany Bay in particular.

Sea Level Rise

The interactive online version of the Sea Level Affecting Marshes Model (SLAMM), known as SLAMM-View 2.0, was used to examine potential changes to barrier island beaches along the southern portion of South Carolina's coast, including the beach at Botany Bay. SLAMM uses the Intergovernmental Panel on Climate Change's (IPCC's) three sea level rise (SLR) scenarios for the year 2100: a global SLR average of 0.4 m, 0.7 m, and 1.0 m.

SLAMM-View 2.0 offers geospatial data results from SLAMM simulations for three regional projects and three site-specific projects (Image Matters, 2011). Runs for this paper are based on the Georgia / South Carolina Region Project (Craft et al., 2009). Base conditions for the simulation runs use the 1999 National Wetland Inventory maps from the U.S. Fish and Wildlife Service. Each sea level rise scenario is adjusted for local conditions.

Most of the barrier islands were selected in their entirety using the polygon tool to define an area that including ocean beach and back marsh. Due to the size of Edisto Island, only the southern portion of the island was selected. The area directly surrounding the beach at Botany Bay Plantation was also selected. Each selection was then analyzed for changes to coverage classes under the three SLR scenarios. Given the prospects for sea level rise about the IPCC projections (Rahmstorf, 2007; Nicholls and Cazenave, 2010), this paper focuses on the effects of the maximum IPCC projection, 1m by 2100.

Results

Demographics

Population and housing structures both show strong growth from 1990 to 2010, fundamentally altering the social-ecological system in and around the ACE Basin.

Figure 2-6 shows the percentage change for human populations in the study area's census tracts. In aggregate, all three counties have experience strong growth over the two decades and are projected to continue that trend at least through 2030 (Table 2-1). From 1990 to 2010, population grew 102 percent in Beaufort County, 37 percent in Charleston County, and 33 percent in Colleton County. If population growth from 1990 to 2030 matches current projections, Beaufort County will have increased 280 percent, and Charleston and Colleton will have increased 79 percent each.

The southernmost section of the coastal counties, located inland of Hilton Head Island in Beaufort County, shows the highest growth rate. Much of this was undeveloped land prior to 1990, and most of the growth has occurred away from the sandy beach habitats of Hilton Head. However, the change represents significant pressure on the tidal marsh system, affecting marine nurseries that ultimately support the energy needs of nesting birds and other species. Further, this influx of humans adds greater potential for disturbance across the ecological system through daily activities and recreational pursuits. A similar process occurs on the southern boundary of the ACE Basin, where the city of Beaufort is located. This growth potentially represents a far greater threat as populations move deeper into the estuary and along its coastal boundary.

Just north of ACE Basin, the islands of Seabrook, Kiawah, and Folly all show significant growth over 20 years. These were developed areas in 1990, and additional growth suggests these barrier islands are at or near their saturation points. The growth in census tracts just northwest of these islands suggests that demand remains strong for continued growth and development in these marsh systems.

The census tracts within the ACE Basin show the least amount of population growth. This is to be expected, given the number of conserved areas and private hunting properties. However, the highway cutting through the ACE Basin (Hwy. 17) is currently being expanded to four lanes for safety reasons, and this opening up more opportunities for expanded development within the ACE Basin boundaries.

Changes in percentage of housing units show strong growth as well (Figure 2-7). In some coastal areas, housing units increased significantly while populations held steady or declined slightly. This indicates an increase in rental units and vacation homes. Given that these housing units are most likely at full occupancy during the nesting season, housing units provide a better indicator of potential disturbance and disruption to nesting habitat than does population. A close look at the census tracts containing sandy beach habitat show rapid growth in housing units from 1990 to 2010 (Table 2-2). Established upper-class enclaves show only modest growth in housing units. Most of Hilton Head grew by less than 20 percent. Sullivan's Island saw only a 10 percent increase. Other areas show major exploitation of remaining undeveloped coastal habitat. The remote Daufuskie Island, which faces the ocean but has no beach, saw a proliferation of housing (1,200 % increase) as it transitioned to a resort destination. Other resort areas also saw rapid increases in housing units, including

Kiawah Island (250%) and Seabrook Island (115%), which are located just north of Botany Bay Plantation.

Beach Users

According to visitor sign-in data, more than 56,000 people visited Botany Bay Plantation in 2009. In 2010, more than 47,000 people visited the site. During the height of the least tern nesting season (May 1 – July 31), Botany Bay had 23,375 visitors in 2009 and 20,667 visitors in 2010 (Figure 2-8). Prior to 2009, least terns nested on a relatively undisturbed beach. Public access began late in the nesting season in 2008, resulting in slightly more than 2,000 visitors. The 2009 season in particular represented a major disturbance and source of continuing stress for least terns at Botany Bay. For the first time they encountered large numbers of humans as they established colonies and attempted to reproduce. Staff at Botany Bay roped off the largest colonies each year near the beginning of the nesting season, but these roped areas have been placed close to active nests, resulting in disturbances as beach users walk by or approach the warning signs. Late-arriving terns also have nested outside the roped areas, increasing the chance of being exposed to higher levels of human disturbance.

The survey shows that the number of visitors to the beach at Botany Bay are primarily vacationers on Edisto Island (Table 2-3). A majority of visitors have vacationed on Edisto at least once before, with 41 percent reporting 10 or more visits. Of all survey respondents, a vast majority said they planned on visiting Botany Bay within the next year (options ranged from again the same week to the next summer). These results show a strong fidelity to Edisto as a summer destination and suggest that Botany Bay's popularity will remain closely tied to annual fluctuations in visits to Edisto Island. Given the ongoing development in the general area, the potential for human disturbance is likely to remain a management challenge for years to come.

The percent of respondents wanting facilities on the beach (33%), versus keeping the site in its natural state, suggests potential pressure on making Botany Bay more park-like in the future. This change would likely bring even higher traffic levels to the beach through the presence of a wheelchair-friendly walkway, restrooms, and shaded areas on the beach. However, this preference could be balanced out by the number of respondents who vacation frequently on Edisto (41%), assuming that people who are most familiar with the barrier island value preserving the site in a relatively undisturbed state. But even beach users who value the natural state of Botany Bay pose a disturbance threat. While survey respondents reported an average stay on the beach of 1.5 hours, a number of respondents reported spending as long as seven hours on the beach (Figure 2-9).

The causeway count shows visitor traffic to and from the beach (Table 2-4). Each beach user represents two potential disturbance events: one for walking past a tern colony and a second when returning to exit the beach. The total number of people entering and leaving the beach per hour gives the high range of potential disturbance if a least tern colony were to be located at the beach entrance. Given that least terns at Botany Bay nested in a relatively undisturbed setting prior to July 2008, this measure gives an indicator of how human disturbance has changed nesting behavior at Botany Bay. Looking only at the rate at which people enter the beach gives a low range of potential disturbance that is probably more accurate for current conditions in which least tern colonies are located at either end of the beach. Under these conditions, most beach users would approach the colony and then turn around, representing a single disturbance event. The number of clusters and average cluster size show group behavior as perceived by the enumerator. It remains to be determined whether larger groups with fewer disturbances are less harmful than smaller groups with more frequent disturbances.

The spatial distribution survey shows where people go once they arrive on the beach (Table 2-5). Most beach users (about 40%) don't stray too far from the entrance, and this is consistent with the survey's finding that half of respondents (52%) had children with them. However, about 60 percent of all beach users disperse to either end of the beach, approaching the areas colonized by least terns. The survey found 17.7 percent of all beach users in colony areas. That represents about 4,000 users approaching least tern colonies during the 2009 nesting season and about 3,700 beach users in the 2010 nesting season.

Sea Level Rise

Salt water marshes in the southeastern U.S. have been projected to decline by 20 to 45 percent, based on simulation models using the IPCC’s sea-level-rise scenarios (Craft et al., 2009). As sea levels rise, storm surges from hurricanes and other ocean storms will ride into coastal areas on higher water levels that increase the potential for damage (Scavia et al., 2002). Since the IPCC issued its SLR scenarios, additional studies have found a likelihood for sea level rise by 2100 above 1 m (Rahmstorf, 2007; Nicholls and Cazenave, 2010). This means that all projections by SLAMM potentially under-predict the impact of sea level rise in future years.

The SLAMM-View data outputs suggest that the overall trend will be for significant beach loss under the 1m sea level rise scenario (Table 2-6). Of the nine islands examined under SLAMM-View simulations, only one shows an increase in ocean beach, Hilton Head Island. The others show non-linear losses and gains that result in significant beach loss by 2100. While these results are not guaranteed by SLAMM developers for accuracy, correctness, or completeness, they do capture the dynamic nature of morphological changes to barrier island beaches. Salt-water marshes on the backside of the barrier islands all show consistent, significant losses under SLAMM-View (Table 2-7). These losses suggest that barrier islands will have difficulty migrating landward as marsh is lost to open water. The beaches that do remain under such conditions will most likely be vulnerable to overwash tides and storm surges, threatening both human infrastructure and nesting habitat.

Under all three IPCC scenarios, SLAMM-View shows changes to the beach and marsh system at Botany Bay Plantation by 2025 that could represent regime shift (Figure 2-10 and Table 2-8). Salt-water marsh, which currently covers about 50 percent of the simulated area, shows reductions up to 16 percent. At the same time, riverine tidal open water shows an increase of up to 100 percent. For the base year, open water covered about 8 percent of the area. SLAMM doesn't show the marsh system flipping to open water by 2025 but does show the beginnings of that process. Under all three scenarios, ocean beach loses about 16 percent of its area, while tidal flats increase between 60 and 100 percent. These results suggest that under all scenarios, Pockoy will continue to lose its hammock, and the beach will be increasingly vulnerable to overwash.

If sea levels were to decrease beyond 2025, areas of open water would likely once again be colonized by oysters and cord grass, entering the reorganization and growth phases for rebuilding the marsh. But if sea levels continue to rise, or storm surges are persistent enough, positive feedbacks would favor open water. At some point, the ability of the system to revert to marsh would be lost entirely.

Discussion

Nested adaptive cycles co-exist at spatial and temporal scales that are separated by orders of magnitude (Figure 2-11). ACE Basin and Botany Bay Plantation face similar threats, but the manifestation of those threats are scale-specific. Human activity in and around the ACE Basin has lowered its resilience to sea level rise and other future threats. The economic forces that drove recovery of the social system during Hurricane Hugo, the area's last major natural disturbance, is unlikely to occur again as financial incentives to rebuild in vulnerable areas disappear (Bures and Kanapaux, 2011). Degradation, fragmentation, and loss of barrier-island ecosystems to development and human activity reduce the ability for the ACE Basin to resist regime shift under the persistent disturbance of sea level rise.

Management of least terns provides one entry point into the panarchy. The panarchy for least terns occurs in three adaptive cycles at the local, meso-, and global scales (Tables 2-9 and 2-10). The global level of the panarchy involves slow variables such as sea level rise, which poses the greatest threat to nesting sites by converting marsh into open water. The meso-level adaptive cycle involves the metapopulation of least terns that nest along the South Carolina coast. At this scale, the two events that can cause collapse within the adaptive cycle are increases in human population and in development of coastal infrastructure (houses, roads, etc.). Changes in human population density and housing density can result in extirpation of least terns from previous colony sites. These changes work in two ways: Locally, the thresholds at which human population density, structure density, and disturbance frequency result in permanent loss of nesting sites will be unique to each site. Some colony sites will be more resilient than others to these disturbances and regime shifts. At the meso level, each loss of a local nesting site represents reduced resilience for the metapopulation.

Given undisturbed conditions, the adaptive cycle of a local nesting site can be categorized as follows:

- Reorganization (*α*): in-migration to a potential nesting site.
- Exploitation (*r*): pairing, breeding, and nesting on site.
- Conservation (*K*): established colony raising and fledging chicks.
- Release / Collapse (*Ω*): out-migration at end of nesting season, or colony abandonment during the nesting season.

Since site fidelity is strong among least terns, this adaptive cycle repeats itself for productive colony sites with each new season. However, least tern colonies on the South Carolina coast will rarely if ever experience undisturbed conditions. Overwash tides and storm surges can push a colony into complete collapse (Ω) if their magnitude or frequency exceed a certain threshold. Least terns will respond to these disturbances by moving to nearby sites to establish new colonies. Floods below the threshold will result in reorganization of the colony (α) at the site as least tern pairs that lost eggs begin renesting and the colony continues to attract migrating terns.

Other disturbances become factors at this point, most notably human disturbances, which as previously noted occur at all scales in the panarchy. At the local scale, least tern colonies have thresholds for human disturbance that determine whether the site remains colonized following a natural disturbance such as overwash and whether other sites are viable for colonizing. Human disturbance also can independently reach a threshold at which a colony collapses and reorganizes. The ongoing level of human disturbance will then determine whether the colony reorganizes on its original site or least terns abandon the site to nest elsewhere. This suggests that colonies have two thresholds for each form of disturbance: one that determines when the colony collapses and another that determines whether the colony reorganizes or abandons the site altogether.

Climate change and its consequences will be the key drivers of future changes to the physical and biological processes of coastal habitats. Sea level rise threatens to increase overwash events and ultimately overwhelm barrier islands, resulting in coastlines retreating inland (Schlacher et al., 2008). Zhang et al. (2004) found a highly multiplicative association between long-term erosion of sandy beaches and sea level rise. Consequently, erosion problems are projected to worsen throughout this century.

Given the tremendous changes to human population and infrastructure over the last two decades, it appears that a shift toward regime shift has occurred in South Carolina's lower coastal counties. The social-ecological system in place in 2010 is dominated by human presence, and undisturbed natural areas are few and far between. At the local scale, opening Botany Bay Plantation to the public also signals the beginning of regime shift. Humans there now create persistent disturbances and chronic stress during the nesting season and throughout the year. The long-term effects of this are not yet known, but it clearly has an impact on nesting behavior and colony productivity.

As one of only four known natural sites for nesting least terns, Botany Bay Plantation is an important resource. Human disturbance must be managed effectively so that colonies remain productive and site fidelity is maintained. As sea level rise becomes a larger problem, least terns are likely to have fewer options for nesting sites, regardless of how human populations respond to shoreline retreat. Resource managers will need to anticipate those changes and have plans in place for proactively providing least terns with nesting habitat in the face of significant morphological changes. A first step would to find a way to effectively protect least tern colonies at Botany Bay from human disturbance and detect changes in the system that signal pending regime shift.

Table 2-1. Actual and projected population for coastal counties in and around ACE Basin.

County	1990	2000	2010	2020	2030
Beaufort	86,427	120,938	162,233	185,220	215,270
Charleston	289,567	310,350	350,209	366,380	386,660
Colleton	34,385	38,274	38,892	43,080	46,250

Sources: U.S. Census Bureau; Office of Research & Statistics, S.C. State Budget & Control Board

Table 2-2. Change in number of housing units in coastal census tracts that contain ocean-facing sandy beaches. Islands are listed north to south from north of Charleston Harbor to the Georgia state line.

Name	Census tract	1990	2010	Pct. Diff.
Isle of Palms	49.02	1,615	2,874	78
	49.01	1,448	1,400	- 3
Sullivan's Island	48	954	1,054	10
Folly Beach	20.04	1,149	1,918	67
Kiawah Island	21.04	961	3,368	250
Seabrook Island	21.05	1,037	2,235	115
Edisto Island	23	529	1,145	116
Edisto Beach*	9708	2,098	3,110	48
Fripp Island	12	1,211	2,087	72
Hilton Head	110	1,178	3,332	183
	112	697	1,809	160
	113	2,590	3,005	16
	101	3,004	3,260	9
	109	1,065	1,272	19
	111	3,334	4,401	32

* The census tract for the town of Edisto Beach includes interior sections of the ACE Basin.

Table 2-3. Beach user profile based on Botany Bay visitor survey (n=120, except where noted)

Variable		Mean / Percent
Average age of respondent		45.2
Average time spent on beach (hrs.)		1.5
Average group size		4.8
Cars In group:	Percent with one	72.0
	Percent with two	24.0
	Percent with three or more	4.0
Percent wanting facilities or improved beach access		33.0
Percent with children under 16		52.0
- Average number of children in groups with children		2.0
Percent of visitors who live in South Carolina		60.0
Percent of visitors vacationing on Edisto Island		78.0
Percent visiting Edisto for first time (n=66)		21.0
Percent with 10 or more visits to Edisto (n=66)		41.0
Percent planning to visit Botany Bay again in future		85.0

Avg. age (std error 1.1, median 44); time spent on beach (std. error 0.1, median 1.0); avg group size (std. error 0.3, median 4.0)

Table 2-4. Number of people entering and leaving the beach on marsh walk causeway (n=23)

Variable	Mean	Standard Error	Median	95% LCL	95% UCL
Number of people entering beach per hour	31.3	3.9	26.0	23.3	39.2
Total number entering and leaving per hour	65.6	8.3	56.0	48.3	82.9
Clusters entering beach per hour	7.3	0.9	6	4.0	10.0
Total clusters entering and leaving per hour	15.7	2.0	13.0	11.6	19.8
Cluster size per hour	4.4	0.4	4.1	3.6	5.1

Table 2-5. Probability that beach users will enter a section of beach from the adjacent section nearest the entrance (Center Beach).

Beach area	Mean	Variance	Percent of Total Beach Users
South colony (from south section)	0.28	0.08	7.5
South section (from center beach)	0.28	0.02	29.2
Center beach	1.00	0.00	100.0
Boneyard (from center beach)	0.32	0.03	33.8
North colony (from boneyard)	0.35	0.08	10.2
Turtle nesting area (from north colony)	0.48	0.13	4.8

Table 2-6. Projections from SLAMM-View simulations for loss or gain of sandy beaches on South Carolina barrier islands under the IPCC scenario of 1m sea level rise by 2100.

	Percent beach loss / gain			
Barrier island(s)	2025	2050	2075	2100
Sullivan's Island / Isle of Palms	-5.96	-13.36	16.24	-50.00
Folly Island	-6.56	-9.58	0.74	-79.58
Kiawah Island / Seabrook Island	-13.52	0.23	25.55	-44.28
Edisto Island (southern portion)	-6.97	33.26	-1.85	-93.59
Hunting Island / Fripp Island	-12.47	-0.67	-4.04	-85.10
Hilton Head	21.80	32.53	16.08	81.87

Table 2-7. Projections from SLAMM-View simulations for loss of salt water marsh on South Carolina barrier islands under the IPCC scenario of 1m sea level rise by 2100.

	Percent marsh loss			
Barrier island(s)	2025	2050	2075	2100
Sullivan's Island / Isle of Palms	-17.36	-50.29	-78.37	-77.67
Folly Island	-18.62	-51.14	-78.54	-89.57
Kiawah Island / Seabrook Island	-17.79	-50.94	-77.41	-74.63
Edisto Island (southern portion)	-17.24	-44.91	-73.30	-62.78
Hunting Island / Fripp Island	-17.60	-49.60	-84.93	-90.25
Hilton Head	-9.61	-29.43	-62.10	-71.16

Table 2-8. Results from SLAMM-View showing changes to selected coverage classes for the beach at Botany Bay Plantation given three sea level rise scenarios.

Coverage class	Base coverage percent (1999)	Percent decrease / increase by 2025		
		0.4 m SLR	0.7 m SLR	1.0 m SLR
Regularly flooded marsh	49.02	-6.42	-10.2	-15.73
Tidal flat	1.08	79.12	61.24	97.66
Ocean beach	3.51	-15.35	-15.38	-16.08
Riverine tidal open water	7.66	49.17	75.82	104.15

Table 2-9. Basic elements of the panarchy comprising least tern nesting at Botany Bay.

Key elements	Speed	Disturbance - ecological	Disturbance – social
Habitat	Slow	Sea level, currents	Coastal development
Least tern colony	Medium	Population declines, habitat loss	Human activity levels
Nesting pairs	Fast	Overwash, storms, heat	Daily disturbances

Table 2-10. Two examples of adaptive cycles fitting within the alternative stable state model.

Adaptive cycle phase	Example 1: Least tern colony / human disturbance	Example 2: Barrier island beach / overwash
K	Active nesting	Marsh, hammock, dune system
Ω	Colony abandonment	Persistent overwash eliminates vegetation
α	Nesting pairs return	Migration of sand
r	Colony re-established	New marsh and dune configuration
r-alt	No new colony	Open water

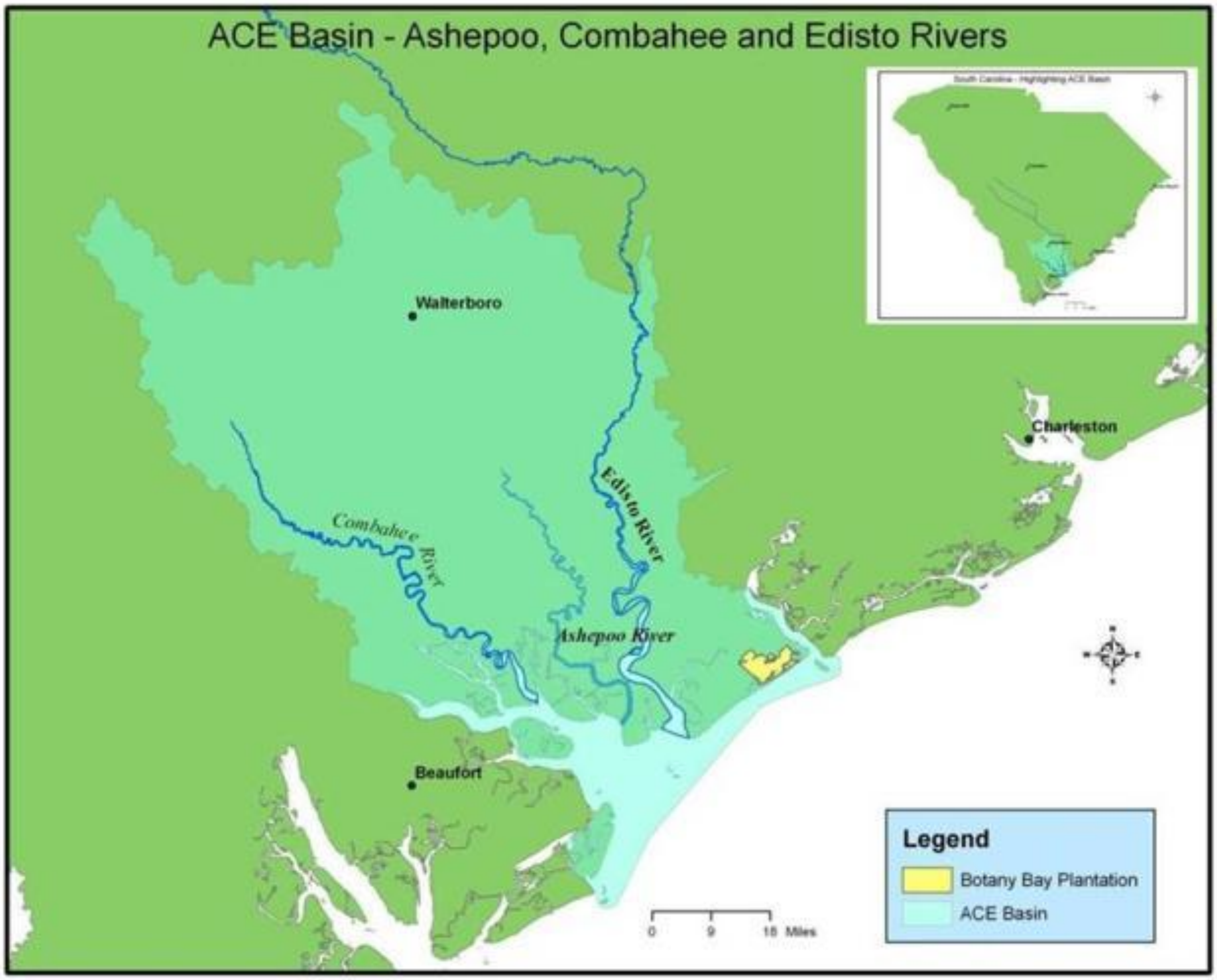

Figure 2-1. The location of Botany Bay Plantation within South Carolina's ACE Basin.

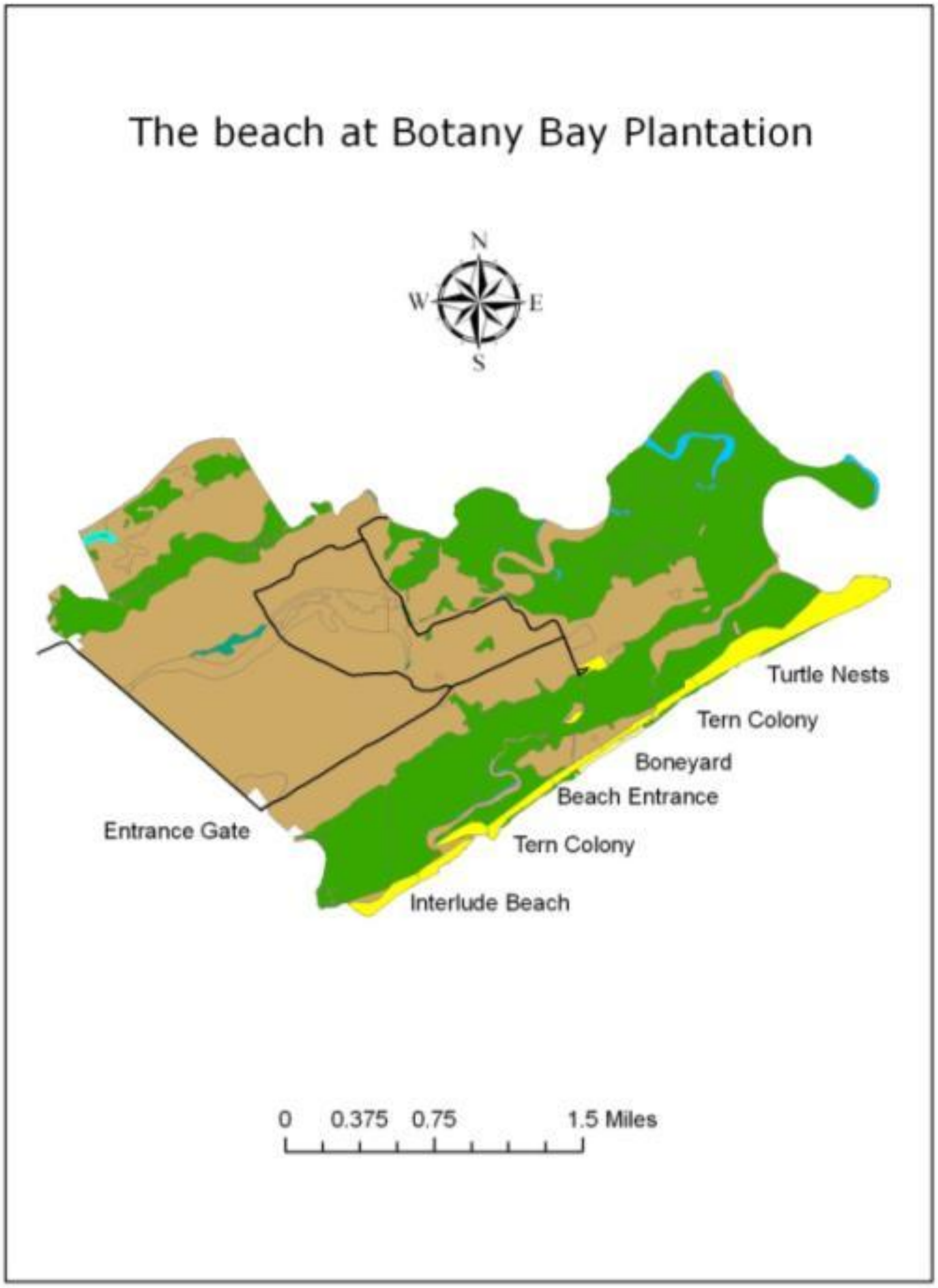

Figure 2-2. The beach at Botany Bay Plantation, showing the key areas.

Figure 2-3. Erosion on the beach at Botany Bay Plantation near the entrance on Pockoy Island.

Figure 2-4. Dead trees litter the beach in the area known as the boneyard.

Figure 2-5. An overwash area on Botany Bay's beach where least terns nest shows sand migrating into the marsh platform.

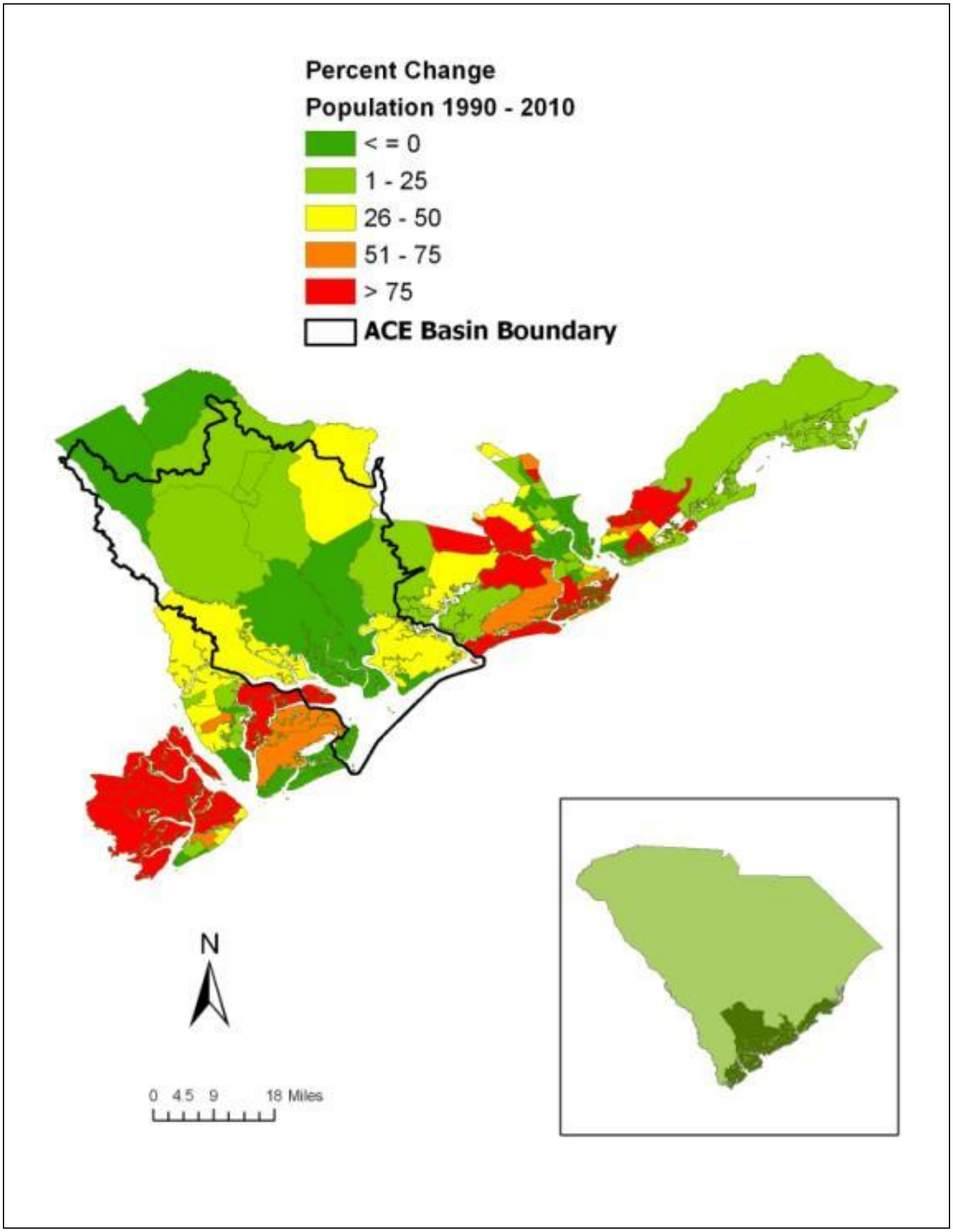

Figure 2-6. Percent changes in human population for census tracts in Beaufort, Charleston and Colleton Counties from 1990 to 2010.

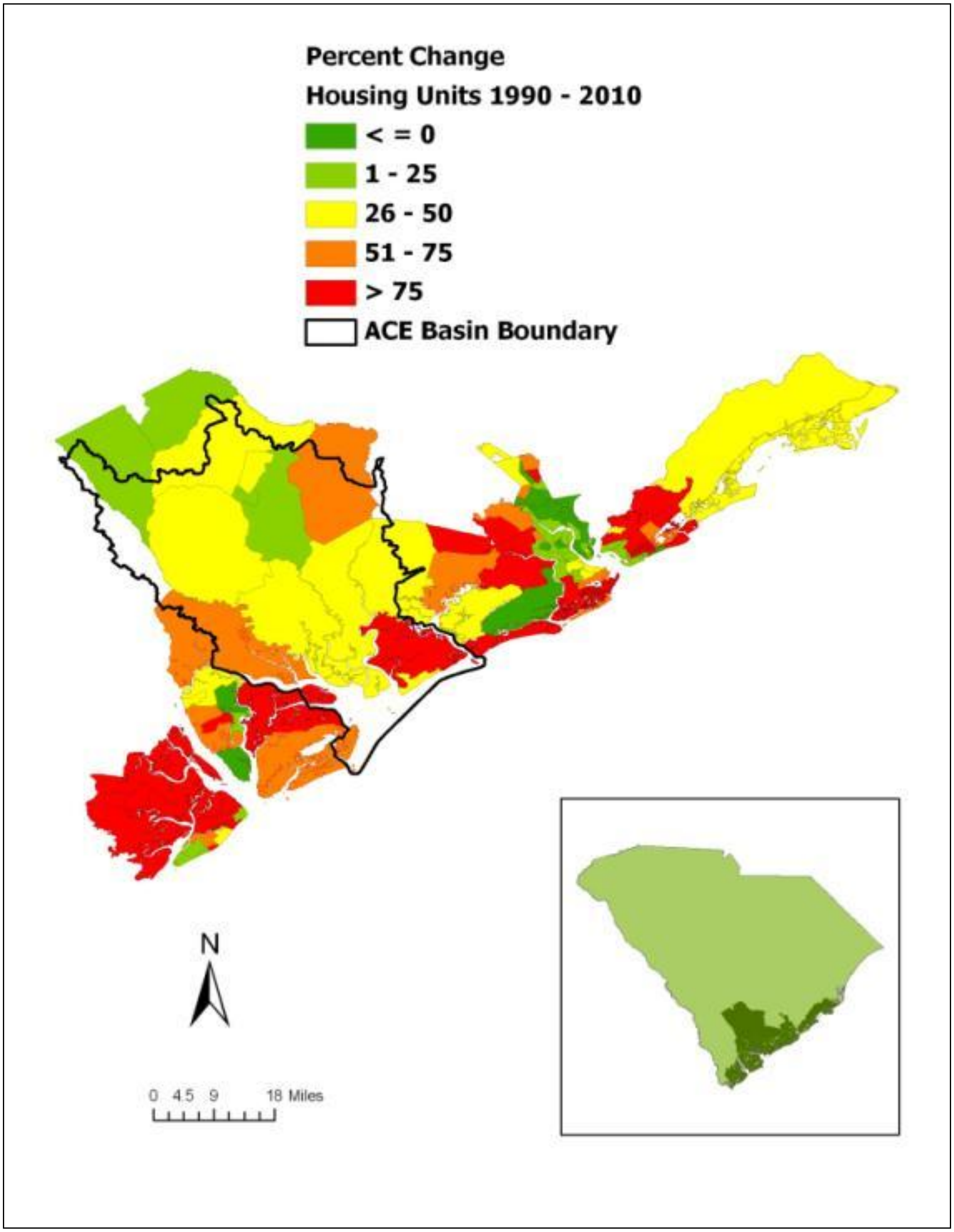

Figure 2-7. Percent changes in the number of housing units for census tracts in Beaufort, Charleston and Colleton Counties from 1990 to 2010.

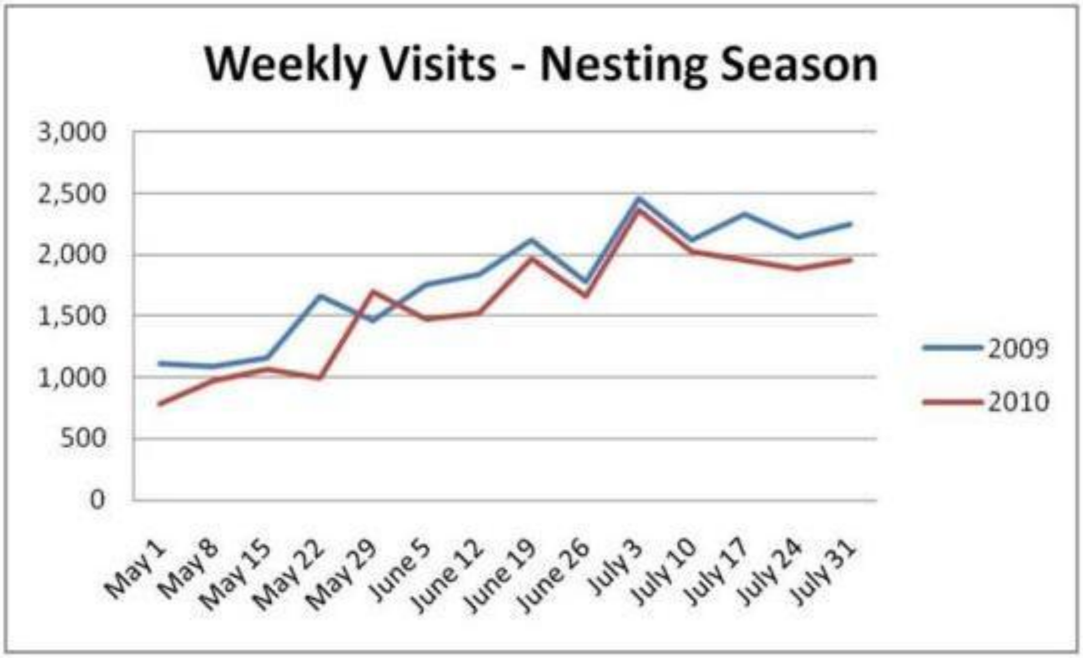

Figure 2-8. The number of visitors to the beach at Botany Bay Plantation during least tern nesting season in 2009 and 2010.

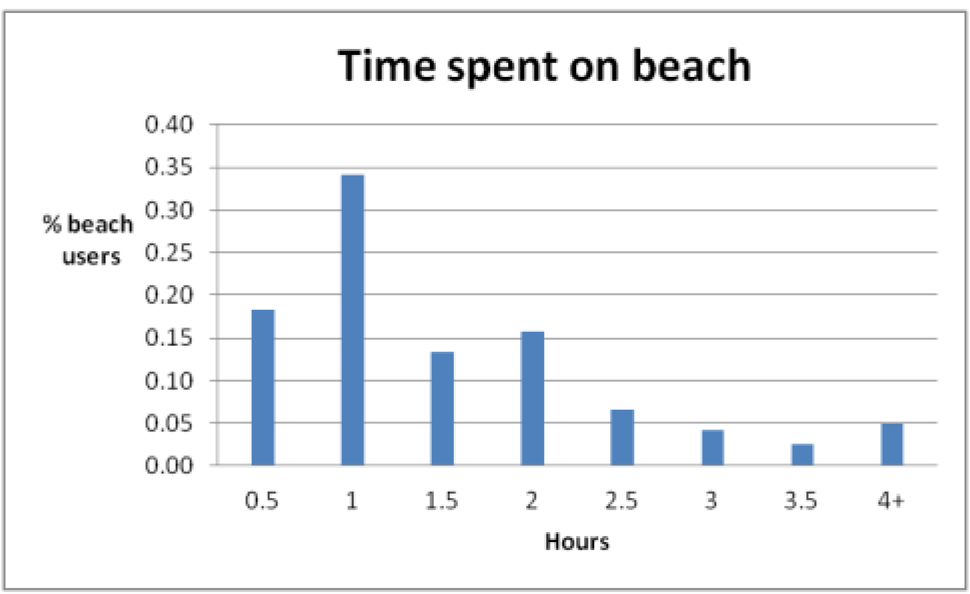

Figure 2-9. Percent of survey respondents (n = 120) reporting time spent on beach in half hour increments.

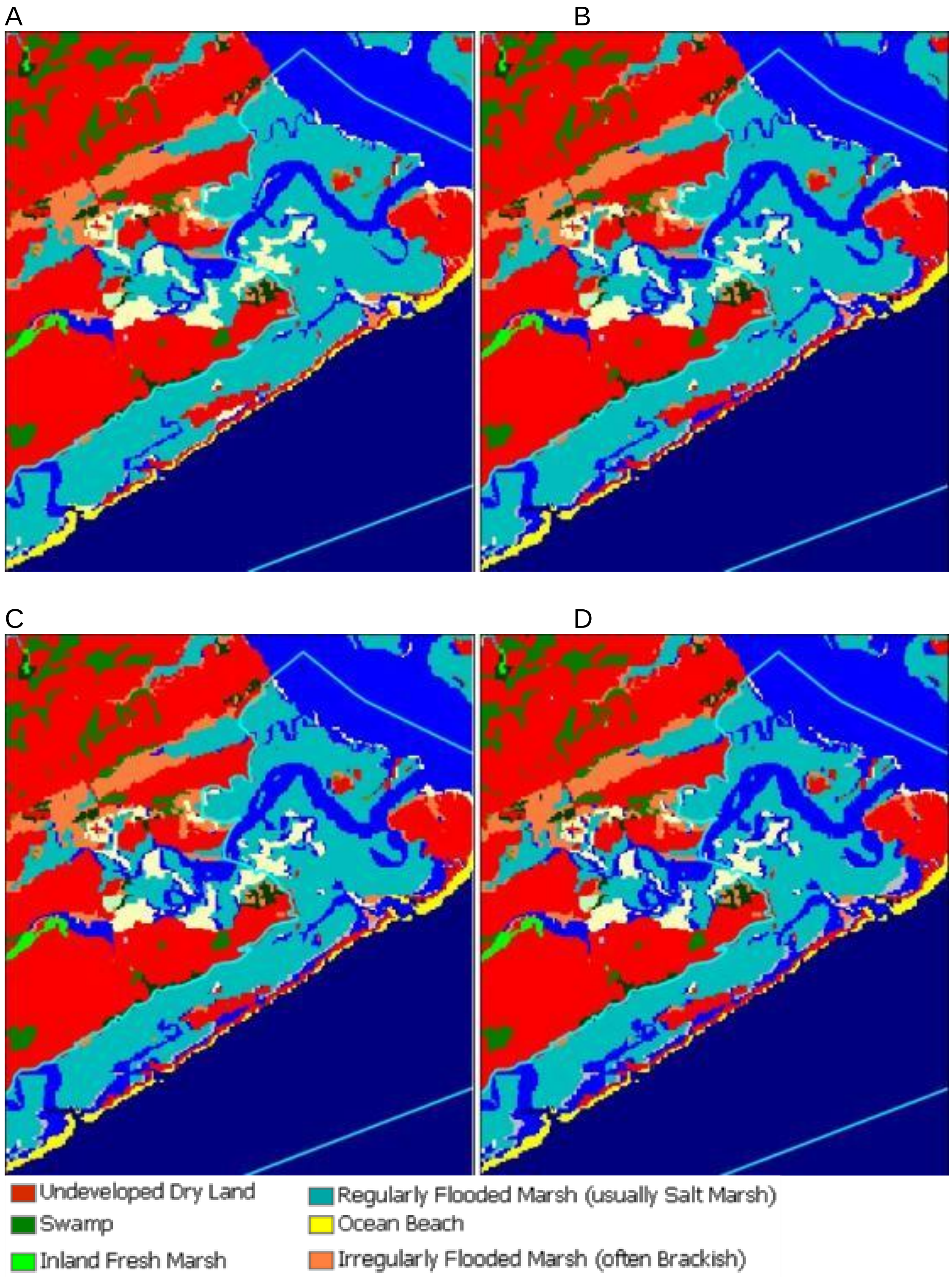

Figure 2-10. SLAMM simulations for the beach at Botany Bay Plantation. The base year 1999 (A) is shown against the effects in the year 2025 of global average sea level rises of 0.4 m (B), 0.7 m (C) and 1.0 m (D) by the year 2100.

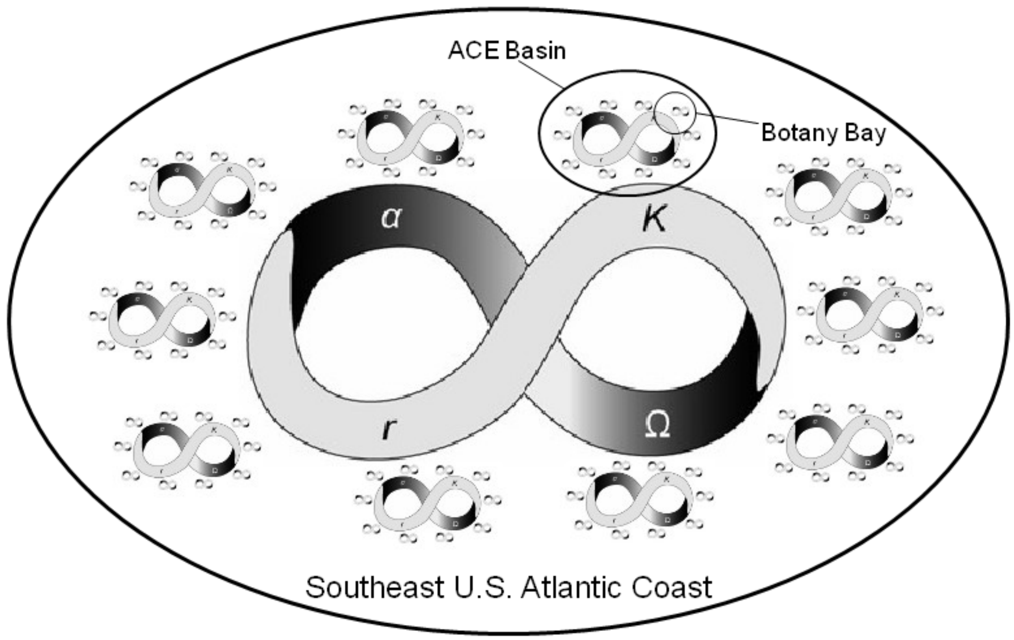

Figure 2-11. Adaptive cycles at three levels of the panarchy can be used to represent spatial and temporal relationships among Botany Bay Plantation, the ACE Basin, and the broader social-ecological system of the Atlantic coast of the southeastern United States.

CHAPTER 3

DEVELOPMENT AND TESTING OF AN OBJECT-ORIENTED, AGENT-BASED SIMULATION MODEL AND DECISION SUPPORT TOOL FOR ADAPTIVELY MANAGING HUMAN DISTURBANCE OF LEAST TERN (*STERNULA ANTILLARUM*) NESTING HABITAT

Introduction

Simulation models can assist in understanding and managing social and ecological systems with a high level of uncertainty surrounding key variables. The act of developing a model requires an immersion into the system being simulated and forces the developer to make choices about how to represent the structures and functions that form system identity. In cases where data is lacking, a simulation model can serve as a structuring mechanism to identify critical areas for reducing uncertainty about system responses. In this way, simulation models can be effective management tools at local and regional scales.

This paper reports on simulation modeling as an adaptive management tool at the local scale. It focuses on the use of an object-oriented model for managing human disturbance of critical nesting habitat for least terns (*Sternula antillarum*) at the newly created Botany Bay Plantation Heritage Preserve/Wildlife Management Area (BBP) in South Carolina's Ashepoo-Combahee-Edisto (ACE) Basin. The BBP site is managed by the South Carolina Department of Natural Resources and was opened to the public in July 2008. Before public access, the site was privately owned. It has few baseline data and lacks management resources for addressing coastal management issues that require immediate attention. This model addresses uncertainty at the site by identifying eight important variables for key responses within the system. Understanding the effects of human disturbance on least tern nesting and productivity at Botany Bay poses a number of challenges:

- Baseline data are lacking.
- Least terns are difficult to survey.
- The hammock island that anchors the beach is undergoing severe erosion.
- The beach is one of only four known natural sites on the South Carolina coast for least tern nesting.

Given the high level of uncertainty surrounding the effects of human disturbance on least tern nesting, a management strategy needs to be put in place for learning about the system over time and responding to new disturbances and ecological surprises. Developing a simulation model that can be used for the purposes of adaptive management at the local scale is a challenge. Viewed through the theoretical framework of ecological resilience, the model should be developed with an understanding of the broader social-ecological system and the adaptive cycles that characterize it (Chapter 2). At the same time, it must account for the system's identity, structure and functions at the local scale. Both are critical to understanding externally driven changes within the system that can cause regime shifts and switches to alternative stable states. This can be a problem for local systems that lack baseline data and the resources for comprehensive monitoring efforts. The model must identify the indicators that are most important to monitor and provide decision support for collecting and analyzing data on these indicators.

The paper describes the steps used for model and decision support system development and how it applies to management of human disturbance on least tern nesting productivity. These steps include:

- Model and decision support system design
- Algorithm structure for key state variables.
- Defining values for key variables.
- Conducting a sensitivity analysis.
- Discussing simulation results.

Model and Decision-Support System Design

Early efforts to use simulation models in adaptive management relied on linear system models that were constrained by their underlying assumptions (McLain and Lee, 1996). By contrast, this project uses an object-oriented, agent-based modeling approach that makes its assumptions explicit and can be quickly modified as new information or management objectives emerge. Agent-based modeling, which uses components that interact among themselves to reveal emergent system properties, has in recent years become a promising method for ecological research, particularly as it pertains to wildlife management and the conservation of critical habitats (McLane et al., 2011). This approach allows for bringing human interactions into wildlife management modeling, which traditionally has focused on density-dependent growth and maximum sustainable yields (Schlüter et al., 2012).

The simulation model for this project uses the Question and Decision (QnD) system framework (Kiker et al. 2006; Kiker and Linkov, 2006; Kiker et al., 2008; Kiker and Thummalapalli, 2009). QnD is designed for understanding potential ecosystem behaviors and management options for a given social-ecological system. It links spatial components through geographic information system files with selected abiotic and biotic interactions within the system being modeled (Kiker et al., 2006). QnD has two primary elements: a simulation engine and a user-friendly graphical interface that allows users to explore various scenarios and management options. The developer configures the attributes and processes of the simulation's objects through input files written in extensible markup language (XML) that QnD converts into Java objects (Kiker and Thummalapalli, 2009). This design allows for iterative development of model components as its users learn more about the system being managed.

Object-oriented and agent-based modeling involves a simulation comprising an environment and objects within the environment that act upon one another. It uses formulas for a variety of activities related to decision-making, hierarchical relationships, and communication among agents (Bousquet and Le Page, 2004). Object-oriented models are a subset of individual-based models, which focus on behaviors and interactions such as movement through space; foraging behavior; exploitive species interactions; local competition; and management-related processes (Grimm et al., 2006; DeAngelis and Mooij, 2005).

Simulation models have become an important tool in managing natural resources amid the uncertainties and complexities of social and ecological systems (Otter and Capobianco, 2000). The model becomes a shared representation of the system and a tool for collective learning (Bousquet and Le Page, 2004; Campo et al., 2009). In this respect, the creation and ongoing development of a model becomes an important component of the adaptive management process (McLain and Lee, 1996; Lawson et al., 2003; Lawson, 2006). A well constructed model encourages collaboration among management and stakeholders and makes use of available data, hypotheses, and other information to represent the interactions among elements in the system of interest.

Many challenges remain, however, especially in regard to misunderstandings between resource managers and model developers from the research community (e.g., Borowski and Hare, 2007). Onerous data-collection requirements can be especially problematic (MacMillan and Marshall, 2006) when modeling in limited resource areas. Qualitative models can help in this regard by clarifying system structure, identifying indicators, and understanding the interactions between ecological and social variables (Dambacher et al., 2009). QnD uses a combination of qualitative and quantitative modeling as the situation requires. The modular structure of QnD (through its object-oriented design) allows for the development of specific agent processes that can be quickly replaced or altered as more information becomes available. Thus, the design, implementation, and testing of QnD objects/agents is an iterative process involving scientific understanding and local conditions. For situations such as Botany Bay Plantation, where few benchmark data exist, qualitative modeling provides a mechanism for decision support and for developing a structural description of the system that helps identify state variables for focused data collection and quantitative model development (Ascough et al., 2008; Salles and Bredeweg, 2006; Poch et al., 2004; Dambacher et al., 2003).

Least Tern Nesting Dynamics

Botany Bay Plantation (Figure 3-1) provides the opportunity for maintaining productive nesting areas for least terns, but this requires an understanding of how disturbance affects colony selection, tenacity, and productivity. Least terns are highly mobile, and standardized surveys are difficult to conduct. A 1988 census of sea birds and shore birds on South Carolina's coast failed to include least terns because of difficulties surveying and monitoring them (Wilkinson, 1997). Colony productivity appears to be restricted by a number of factors, and rates of post-fledgling survival are unknown (Thompson et al., 1997). The species' current breeding distribution is similar to the historic extent of its breeding range, but distribution within that range is far more fragmented than in the past (Thompson et al., 1997). The number of least terns nesting on traditional sand beaches and sand banks in South Carolina has dropped considerably in recent decades. Savereno and Murphy (1995) report that 83 percent of least tern nests in South Carolina occurred on sand beaches before 1960, but only 56 percent of nests occurred there after 1960. Prior to 1960, atypical sites used by least terns were composed of dredged material and fill. After 1960, pea gravel roofs emerged as the most frequently used atypical site, followed by dredge material and gravel fill from construction sites (Savereno and Murphy, 1995).

During the late 1800's and early 1900's, least terns were hunted extensively for their plumage, much of it for women's headwear. This resulted in massive reductions in populations through the species' range. Least terns made a strong comeback along the South Carolina and Georgia coasts during the 1920's and 1930's, with reports of up to 2,500 nesting pairs on an island near the mouth of the Savannah River (Tomkins, 1959). Significant reductions in tern colonies again occurred through the 1950s. This decline was believed to be the result of a number of factors, including predation, storm surges, heavy rains, and vegetation growth (Tomkins, 1959).

Least terns are adapted to change nesting sites frequently in response to environmental changes and disturbances but appear to be most productive at established colony sites (Thompson et al., 1997). Least terns exhibit a high degree of fidelity to particular nesting sites from year to year and show fidelity to their natal colony sites (Atwood and Massey, 1988). Overwash, human disturbance, predation, and presence of vegetation can affect fidelity and result in site abandonment (Kotliar and Burger, 1986). Terns that switch sites from one year to the next have been found to move only a short distance (Atwood and Massey, 1988). These findings suggest that terns encountering disturbance and morphological changes will attempt to colonize areas close to the previous site if appropriate habitat is available. This makes conservation of existing natural sites such as those found at Botany Bay an important management goal.

Colony sites are limited by human activities. Human disturbance has been found to account for more than half of reproductive failures in least tern colonies (Burger, 1984). When predation or disturbance is severe, least terns will abandon a colony site (Burger, 1987). Least terns are among the most defensive of tern species (Burger and Gochfeld, 1988). Burger (1987) observed least terns leaving their nests when humans reached an average distance of 25 to 27 m away. Generally a small group of terns (three to seven) mob an intruder, making an average of 21 to 33 dives per two-minute period. Intensity of defense response increases as nesting progresses (Jackson et al., 1982) Colonies that experience frequent intrusions by humans are much more aggressive toward human disturbance.

Tern colonies usually comprise less than 25 nesting pairs but can contain more than 2,000 pairs (Thompson et al., 1997). The largest colonies are found on man-made sites where predation is limited by major highways and other structures. Jackson and Jackson (1985) report that none of the 20 colonies found on natural sites on Mississippi's barrier island beaches exceeded 30 nests. The limited size may be related to human disturbance. Palacios and Mellink (1996) found that three-quarters of least tern colonies along the Gulf of California coast had 20 or fewer nesting pairs, and only two had more than 100 pairs. Recreational use of the beach with all-terrain vehicles appeared to be the limiting factor.

Sex ratio in colonies is assumed to be 1:1, and nesting pairs are monogamous. Nesting pairs have no more than one successful brood per season, and renesting commonly occurs following the loss of eggs or chicks, for up to three nests per season (Thompson et al., 1997). All of these factors must be taken into account when modeling least tern behavior and assigning values to the variables associated with these behaviors.

Methods

Study Site

The ACE Basin covers 320,000 hectares (790,000 acres) in a relatively undeveloped 40-km-wide tract between the expanding metropolitan areas of Charleston and Beaufort (Figure 3-1). The basin is one of the one of the largest intact coastal ecosystems on the east coast (Wenner et al., 2001). Botany Bay Plantation is located on the southeast edge of the ACE Basin on Edisto Island. It comprises 4,687 acres (1,897 hectares) of beach, tidal marsh, agricultural fields, forest, and ponds. Its ocean-facing beach, about 3 miles long (4.8 km), serves as nesting habitat for least terns, loggerhead turtles (*Caretta caretta*), state listed Wilson's plovers (*Charadrius wilsonia*), American oystercatchers (*Haematopus palliatus*) and a variety of other sea birds and shorebirds. The beach also provides important stopover habitat for migrating shorebirds.

The beach at Botany Bay Plantation is one of only four known natural sites in South Carolina for least tern nesting (Felicia Sanders, personal communication). The site has only one entrance gate. From there, an unpaved road takes visitors about 2 miles to a parking area that leads to a half-mile walk through marsh and hammock islands to the beach. The beach itself has no permanent structures or facilities, and unauthorized motor vehicles are not allowed on the marsh path or beach. Nesting areas for least terns are posted and roped off once colonies begin developing to reduce disturbance by beach users.

Several features make the beach notable (Figure 3-2). Northeast of the entrance lies "the boneyard," a large area of dead trees in the intertidal zone. The beach's largest tern colony is located just north of the boneyard in a overwash area at the end of the island's hammock. A dune area that loggerheads frequently use to nest stretches more than a mile past the overwash area. The beach southwest of the entrance is characterized primarily by overwash and relic marsh mud exposed by the shifting sand. A second tern colony can be found more than a half mile south of the entrance near Townsend's Inlet, which is popular for fishing. This inlet can be crossed on foot at low tide to an area known as Interlude Beach. This stretch of beach, about 0.75 miles long, is essentially unmanaged except for signs and rope to designate nesting areas. Both of the colony areas south of the entrance are more susceptible to overwash, and Interlude Beach is vulnerable to unmanaged human disturbance. Frampton's Inlet lies at the southern end of Interlude Beach. People cross this inlet at low tide from a private beach to the south. They also access Interlude Beach by boat and kayak. These visitors do not sign in and are for the most part unmonitored.

The small hammock that anchors the beach at Botany Bay, known as Pockoy Island, is currently undergoing severe erosion. The dune system protecting the hammock has disappeared, and the beach experiences frequent overwash. These overwash events flood the hammock, leaving ponds of salt water that kill its stand of mature maritime forest. On either side of the hammock, overwash tides deposit sand along the backside of the beach, overrunning the cordgrass. Least terns use these overwash areas for nesting.

Ecological Resilience

Developing the QnD model for adaptive management of human disturbance at Botany Bay Plantation required answering three questions:

- How does the beach's ecological system function with respect to least tern nesting dynamics?
- How has the introduction of human beach users affected least tern nesting ?
- What dimensions of human disturbance can be realistically managed to minimize adverse effects on least tern nesting productivity?

Answers to these questions allow for the translation of management concerns and social ecological system dynamics into the simulation model.

This process requires understanding ecological resilience within the ACE Basin and at Botany Bay Plantation. Ecological resilience can be defined as the magnitude of disturbance a system absorbs before its identity changes. This change, known as a regime shift, results from changes in the variables and processes that control the system’s structure and functions (Holling and Gunderson, 2002). Regime shift can occur rapidly following a period of gradual change (Biggs et al., 2009). Consequently, ecological resilience emphasizes non-linear dynamics, thresholds, and uncertainty

(Carpenter et al., 2001; Holling and Gunderson, 2002; Walker et al., 2004; Folke, 2006; Brand and Jax, 2007).

A social-ecological system can be said to have four phases that taken together make up its adaptive cycle: exploitation (*r*), conservation (*K*), release (Ω) and re-organization (α). The first two phases, known as the front loop, involve rapid colonization of disturbed areas that eventually leads to the slow accumulation and storage of energy and material. System structures and functions become more tightly organized over time. The back loop consists of the release and re-organization phases. These phases can bring about major system changes in relatively brief periods (Carpenter et al., 2001; Holling and Gunderson, 2002).

A nested set of adaptive cycles that occur across spatial and temporal scales is known as a panarchy. Adaptive cycles within a panarchy function at different orders of magnitude, and each cycle can be characterized as having a fast, medium or slow speed. The temporal and spatial relationships among the adaptive cycles gives a system its adaptive complexity (Holling et al., 2002a). Responses from each faster variable is based in part on the stabilizing effects of the system's slower variables. Large, unique disturbances combine with changes in slow variables to create the potential for system collapse and regime shift (Carpenter et al., 2002).

In order to model a system, a least three key interacting components must be included (Holling et al., 2002b). Typically there is an order of magnitude difference among each component's variable speed and corresponding spatial scale. The interactions among these variables result in the system's complexity. QnD BBP simulates a single nesting season and the effects of human disturbance and overwash on least tern nesting productivity during that season. The objects within the QnD BBP model interact with one another at two variables speeds: fast and medium. Slow variables and the disturbances that act upon them are built into the architecture of the model. For instance, as beach morphology changes, values assigned for least tern nesting habitat in each of the model's spatial units can be adjusted to reflect the changes.

Slow- and medium-speed variables affect available habitat and disturbance, and the combination of these two factors determines resilience (Carpenter et al., 2002). In the case of least tern nesting at Botany Bay Plantation and along the South Carolina coast, available habitat is shrinking as disturbance is increasing. This sets up the possibility for future non-linear responses such as regime shift and other ecological surprises. High levels of uncertainty require models that are simple, flexible, and easily understood by non-technical users (Carpenter et al., 2002). QnD provides the ability for its code to be modified on the fly and revised to include unexpected factors. A limited number of Monte Carlo simulations can then be run on the spot using a laptop to produce output data in short time frames. These kinds of models can help resource managers explore possible ways to enhance a system's resilience given a range of potential scenarios (Carpenter et al., 2002).

Management Concerns

Semi-structured interviews were conducted with management and staff of the S.C. Department of Natural Resources and with volunteers who worked the beach and entrance gate at Botany Bay Plantation during the 2009 and 2010 least tern nesting seasons. Interview subjects included the three SC DNR personnel directly responsible for management and operations at Botany Bay Plantation. DNR staff interviews covered ecological changes to Botany Bay Plantation, Edisto Island, and the ACE Basin over time and possible solutions for managing ecological concerns and recreational use of Botany Bay. Discussions with site volunteers who work the entrance gate and the beach provided insights into visitor behavior, patterns of usage, and changes of note in terms of beach morphology, wildlife, and plant community structure. Interviews were also conducted with ecologists and wildlife specialists at SC DNR beginning in 2008 to better understand broad-scale system dynamics on the South Carolina coast.

Development of the model was an iterative process. Field observations and interviews informed model development, which in turn focused further field observations and discussions with staff and management. Input was sought from all ACE Basin management on a preliminary version of this model during a presentation at SC DNR's coastal headquarters in Charleston, S.C., and those responses helped to clarify practical management concerns and build those concerns into the current version of the model.

During initial discussions in 2008, Botany Bay Plantation management identified two species of particular concern: least terns and loggerhead turtles. During the 2009 nesting season, it became apparent that the level of management activities for these two species were quite different. Loggerhead turtle nesting activity remained relatively undisturbed: The beach is closed to the public at night, when turtles are most active in nesting and egg laying activities. Each morning, new nests from the previous night are identified by staff and volunteers and caged against predators. Nests in areas vulnerable to overwash tides and erosion are relocated. Nests are closely monitored, and hatchlings are released with human assistance.

Least tern nesting, on the other hand, is minimally managed. Once a colony has been established, staff and volunteers place small posts in the sand connected by string. Signs alert beach users to the presence of tern nests. Over the course of the season, these colonies may be abandoned or terns may begin nesting outside of the enclosed areas. Baseline data on the effectiveness of these measures are lacking for least terns on the South Carolina coast.

Monitoring of Human Activity and Least Tern Nesting for Model Design

This study uses a qualitative conceptual model of least tern nesting to serve as the blueprint for developing the QnD model, which is designed specifically to identify the key indicators and critical uncertainties necessary to monitor for making informed management choices (Dambacher et al, 2009; Lyons et al., 2008; Dambacher et al., 2003). Figure 3-3 shows the conceptual model that forms the basis of the QnD simulation model and decision support tool. Both the conceptual model and the simulation model were developed in an iterative process involving surveys and observations of the social-ecological system.

Three approaches were used to understand the potential impact of humans on least tern nesting at Botany Bay: (1) a visitor-use survey, (2) a causeway count of people entering and exiting the beach, and (3) a spatial distribution survey on the beach. All three of these were conducted during peak hours of beach use: 10am to 5pm. The visitor-use survey was conducted from June 26 to August 13, 2009 to provide a snapshot of beach user characteristics and behaviors. Causeway counts were conducted on 14 randomly selected occasions between July 11 and August 13, 2009. Each count lasted approximately two hours. Individuals and groups were tallied on a time sheet as they entered and exited the beach. Spatial distribution surveys were conducted on 19 occasions at randomly selected times between June 25 and September 7, 2009. These surveys began at one end of the beach and counted the number of people in each distinct area of the beach. These counts were conducted in order to simulate distribution patterns on the beach based on the number of visitors for each day. These methods were complemented by ongoing observations of beach-user behavior over the course of two nesting seasons.

Field observations occurred on 40 days during the 2009 least tern nesting season and on 33 days during the 2010 nesting season. In order to minimize disturbance and heat stress, least terns were observed with binoculars from the edges of the colonies before 9am and after 5pm. Additional observations at Botany Bay occurred during non-nesting months to observe patterns of human use and morphological changes to the beach, hammock, and marsh systems (14 days in 2009 and 7 days in 2010). All observation days involved overnight stays at the Botany Bay Plantation office, located near the visitor parking lot and marsh walk to the beach.

Field activities during the nesting season included observations of least tern nesting behavior, participation in early morning loggerhead nest monitoring, and general observations about biotic and abiotic structures and functions in the beach, hammock, and marsh systems. Stays at the office allowed for regular contact and interactions with Botany Bay Plantation staff and the dozens of volunteers who work on the beach and at the entrance gate on a daily basis. The office also served as a regular stopover for other SC DNR staff working within the ACE Basin. These interactions allowed for numerous semi-structured and informal interviews on a range of topics regarding conditions on the beach and management concerns. Botany Bay Plantation had been opened to the public for less than a year when this project began, and management priorities were still in the process of being defined.

Simulation Runs

QnD BBP is designed so that all key variables for the simulation can be easily adjusted within the code. These variables are divided into two categories. Level 1 variables represent uncertainties about how key components within the system function. These variables are set as stochastic probability distributions. Level 2 variables represent assumptions about basic system functions that are made explicit to management and can be changed as necessary. Other variables that create the basic architecture and structure of the simulation model are considered Level 3 variables and for the most part are containers for holding data.

For this paper, the simulation is run with all Level 1 variables drawn from their stochastic distributions for 200 runs each of the following scenarios:

- Full Access. The beach is open 7 days a week with no access restrictions to least tern nesting areas.
- Current Management. The beach is closed one day a week, and the least tern nesting areas in two spatial units, BBP02 and BBP06, are roped off to limit access to nesting areas.
- No Access. The beach is closed seven days a week for the entire nesting season.

Least tern nesting productivity is compared across the scenarios.

Sensitivity Analysis

Sensitivity analysis identifies the most important factors that would result in the greatest reduction in variance in a model's output if these values were known. Regression analysis can be used to estimate the coefficient of determination, R^2, for each independent variable when the other independent variables are held constant

(Cariboni et al., 2007; Confalonieri et al., 2010). This one-variable-at-a-time approach is known as local sensitivity analysis. In linear models ($R^2 = 1$), the Standardized Regression Coefficient quantifies the exact amount of output variance explained by the independent variable. For moderately non-linear models ($R_2 > .7$), SRC still gives a qualitative assessment of the independent variable's importance (Cariboni et al., 2007).

This paper uses Monte Carlo simulations to measure the model's sensitivity to each Level 1 variable over its range of uncertainty. Given computational limitations, each simulation was limited to 200 runs. The outputs were:

- Nesting productivity for the whole simulation and for the two spatial units with the largest least tern colonies, BBP02 and BBP06.
- The number of nesting pairs globally and for the two spatial units.

For each of the Monte Carlo simulations in the sensitivity analysis, one of QnD BBP’s Level 1 variables was assigned a random value based on its stochastic probability distribution while the other seven variables were held constant at their mean value. Linear regressions were run for each Level 1 variable to identify the variables whose probability distributions had the greatest effect on the dependent variables, based on R^2 values and Standardized Regression Coefficients.

Results

In Chapter 2, the interactive online version of the Sea Level Affecting Marshes Model (SLAMM) 2.0 is used to examine potential changes to barrier island beaches along the southern portion of South Carolina's coast, including the beach at Botany Bay. SLAMM uses the Intergovernmental Panel on Climate Change's (IPCC's) three sea level rise (SLR) scenarios for the year 2100: a global SLR average of 0.4 m, 0.7 m, and 1.0 m. Under all three IPCC scenarios, SLAMM-View shows changes to the beach and marsh system at Botany Bay Plantation within the next dozen years, by 2025, that could represent regime shift. Salt-water marsh, which currently covers about 50 percent of the simulated area, shows reductions up to nearly 16 percent. At the same time, riverine tidal open water shows an increase of up to 100 percent. Under all three scenarios, ocean beach loses about 16 percent of its area.

The results suggest that under all scenarios, Pockoy will continue to lose its hammock, and the beach will be increasingly vulnerable to overwash. QnD BBP accommodates changes to variables that reflect morphological changes from one season to the next. But the true strength in the model is its ability to explore ways to enhance nesting productivity given the circumstances found on site for any given year.

Humans and Least Terns

QnD BBP simulates human and least tern activity at Botany Bay Plantation. During least tern nesting season (May 1 – July 31), Botany Bay had 23,375 visitors in 2009 and 20,667 visitors in 2010. The distribution of these visitors on Botany Bay's Beach is summarized in Table 3-1. All visitors enter the beach at spatial unit BBP04, with the exception of humans in BBP01, which is accessed primarily from other parts of Edisto Island. The majority of beach users remain in the middle sections, of which only one (BBP03) contains washover habitat that would likely be selected by least terns for nesting in the absence of human disturbance. BBP02 and BBP06, where the main least tern colonies are located, get less than 10 percent of beach users each. But given the number of people who use the beach, these amounts still represent a large number of potential disturbances.

Counts of nesting pairs, chicks, and fledglings were conducted to determine basic colony trends and not intended to be conclusive census counts of tern populations.

Many factors can affect the number of terns seen at any given time, and minimizing disturbance from research activities was a priority throughout this project. Table 3-2 categorizes least tern colonies as small (fewer than 10 nesting pairs spotted), medium (10 to 30 nesting pairs), and large (more than 30 nesting pairs). Up to 100 nesting pairs were counted at various times in the BBP06 colony. Nesting productivity is categorized as light (fewer than 5 chicks spotted), moderate (between 5 and 15 chicks spotted), and robust (more than 15 chicks spotted).

The categorization reveals some fundamental changes in colony composition that could be shaped by the introduction of a large number of humans into that system. BBP02, which is highly susceptible to overwash, appears to have diminished as a preferred location by least terns during 2010 and 2011 after a strong colony was established in 2009, the first full nesting season after Botany Bay Plantation had been opened to the public. The colony at BBP06 has grown as the BBP02 colony has faded away, although initially in 2009 it appeared that terns preferred BBP02 over BBP06, in part perhaps because of predation risks at BBP06 from the nearby hammock. Colonies at BBP01 are something of a wild card. Because the area is remote and lightly managed, the colony there faces a higher risk of human disturbance, including the presence of dogs. The area also is at higher risk of overwash tides, relative to BBP06.

Model Structure

QnD BBP measures least tern nesting productivity over the course of a single nesting season in daily time steps. The model explores potential effects from human disturbance and overwash in order to better understand how terns respond and how to manage these responses in order to enhance productivity and maintain Botany Bay as an active colony site in the years ahead. The model divides the beach into seven spatial units based on morphological and biotic characteristics (Figure 3-4). Nesting pairs migrate into the simulation for a set number of days during the nesting season. The number of nesting pairs per time step is set by random selection from a stochastic probability distribution. Each spatial unit attracts nesting pairs based on its percentage of overwash habitat and level of human disturbance. The simulation divides incoming nesting pairs among spatial units that meet least-tern nesting criteria for overwash habitat and disturbance levels.

Figure 3-5 shows a Unified Modeling Language diagram of the QnD BBP model. Human disturbance by beach users and flooding from overwash tides both reduce tern productivity. Managers can control access to the beach and access to colonies within specific spatial units. The model breaks least tern colonies into separate components that inhabit individual spatial units and interact with one another within the spatial unit. These components are:

- Incoming Nesting Pairs
- Tern Batches (eggs to chicks to fledglings)
- Renesting Pairs
- Departing Nesting Pairs

The model allows for potential colonization in all spatial units. The percentage of overwash habitat within each spatial unit can be measured and changed prior to the start of each nesting season, allowing the simulation to accommodate inter-annual morphological changes. Overwash habitat also can be adjusted through minor modifications to the model if significant changes were to occur in the midst of a nesting season.

Least terns rely on overwash habitat for establishing colonies, but these same areas make colonies vulnerable to overwash tides during nesting season. A major overwash event can wipe out an entire colony's eggs, depending on the beach's morphological characteristics. Each spatial unit in the simulation has a specified tide level at which overwash disturbance occurs. Damage is calculated at a specified rate of loss for every 0.1 foot of flooding. The frequency of overwash events are calculated for each time step by comparing tide heights from NOAA charts with the spatial unit's overwash threshold. Damage to eggs and chicks are recorded in the time step.

Human disturbance acts as a deterrent to colonization. Changes in management settings that ban human use of the beach during the nesting season would allow colonization to occur in some spatial units that under current management conditions remain empty or sparsely nested. The model can be run with management settings that ban human use during some or all portions of the nesting season to explore the site's potential as undisturbed nesting habitat.

New nesting pairs within each spatial unit are grouped into batches that follow nesting development from egg to chick to fledgling. The model divides the start of nesting season into seven one-week batches per spatial unit. Within each batch, overwash events and human disturbance result in the loss of eggs and chicks, affecting productivity. Time off nest from human disturbance results in cumulative damage to least tern eggs. Human disturbance also affects colony selection and tenacity. The model treats each disturbance as being of equal duration. Disturbance minutes accumulate over the incubation period and result in egg loss.

The model handles human disturbance differently than overwash since least terns can't detect heat damage to eggs. The model determines human disturbance levels based on the number of times people enter or pass through the spatial unit. From this, the model calculates the number of disturbance minutes in which nesting pairs leave the nest and keeps a running count over the course of the incubation period to determine the damage to eggs at the end of the incubation period. The model assumes that nesting pairs losing eggs to human disturbance (heat exposure) do not renest. Chicks are also affected by human disturbance to a lesser degree, and their mortality has no effect on renesting.

The number of fledglings produced by each batch count toward the calculation for productivity of each spatial unit and globally across the site. The total number of nesting pairs on site and in each spatial unit are also recorded.

Algorithms

Nesting pairs

Each spatial unit that meets the criteria for least tern nesting accumulates a pool of available nesting pairs:

$$AP_{t,su} = AP_{t-1,su} + RP_{t,su} + IP_{t,su}$$

where $AP_{t,su}$ is the number of available nesting pairs within the spatial unit in the time step, $RP_{t,su}$ is the number of renesting pairs that remain in the spatial unit, and $IP_{t,su}$ is the number of incoming nesting pairs from the global pool of available nesting pairs.

Global available nesting pairs come from two sources. During the migration period, a random number of nesting pairs enter the simulation in each time step based on a stochastic probability distribution (Level 2 variable). Renesting pairs are created when overwash tides destroy least tern eggs. These renesting pairs join the global available nesting pairs for redistribution among the other spatial units if disturbance-threshold criteria are exceeded in the home spatial unit.

These available nesting pairs are moved into one of seven batches that will track damage to eggs during incubation and chicks during development. When t = start of batch *i*,

$$NP_i = AP_{t,su} – AP_{t-7,su}$$

where B_i is the tern batch and $AP_{t,su} – AP_{t-7,su}$ gives the number of available nesting pairs since the last batch start. These available nesting pairs are converted into the batch's nesting pairs (NP_i), and the number of tern eggs are calculated for the start of the batch:

$$E_i= NP_i * CL$$

where CL is Clutch Size, a Level 2 variable. Until t = end of incubation, all overwash and human disturbance damage is recorded for the eggs in each batch in each spatial unit in each time step:

$$E_{i,t} = E_{i,t-1} – EL_{i,o,t} - ED_{i,h,t}$$

where E_i is the number of eggs in batch *i*, EL_o is the egg loss from overwash in the time step and ED_h is egg damage from human disturbance in the time step. At the end of the incubation period (Level 2 variable), the number of remaining eggs are converted to chicks, and the process continues for calculating damage from overwash and human disturbance of each time step:

$$C_{i,t} = C_{i,t-1} – CD_{o,t} - CD_{h,t}$$

where C_i is the number of chicks in Batch *i*, CD_o is the damage from overwash in the time step and CD_h is damage from human disturbance in the time step. At the end of the growth period (Level 2 variable), the number of surviving chicks are converted to fledglings.

Beach users

QnD BBP moves beach users from one spatial unit to the next during each time step based on a time-series file of sign-in data and observed spatial distributions of human beach users (Chapter 2):

$$H_{t,su} = H_{t,su-1} * P_{su}$$

where $H_{t,su}$ is the number of human beach users in the spatial unit in the time step, $H_{t,su-1}$ is the number of human beach users in the adjacent spatial unit nearest to the beach entrance in the time step, and P_{su} is the probability that beach users in the adjacent spatial unit nearest to the beach entrance will enter the spatial unit. The spatial unit's disturbance level is then calculated by:

$$D_{t,su} = (H_{t,su} + H_{t,su+1})*R_{su}$$

where $D_{t,su}$ is the number human disturbance events in the spatial unit in the time step, $H_{t,su}$ is the number of human beach users in the spatial unit in the time step, and $H_{t,su+1}$ is the number of human beach users in the adjacent spatial unit farthest from the beach entrance in the time step. This algorithm assumes that all human beach users who walk farther down the beach will pass through the spatial unit on their return, representing an additional disturbance. R_{su} is the spatial unit restriction setting. This setting represents access limitations to nesting areas and determines the percentage of human beach users entering the spatial unit that will disturb nesting least terns.

QnD BBP keeps track of minutes of disturbance for each batch in each spatial unit in order to calculate egg damage from human disturbance. Cumulative disturbance minutes are calculated by:

$CD_{t,i} = (D_{t,su} * M_D) + CD_{t-1,i}$

If $CD_{t,i} > XT$

Then $ED_{i,h,t} = (CD_{t,i} / XT) * F_H$

where $CD_{t,i}$ is the cumulative minutes of human disturbance, $D_{t,su}$ is the number of disturbance events in the spatial unit in the time step, and M_D is the minutes per disturbance (Level 1 variable). If the cumulative minutes of human disturbance is greater than the maximum time until egg damage (XT), then the number of eggs lost ($ED_{i,h,t}$) is calculated by dividing cumulative disturbance minutes by maximum time until damage and multiplying by the damage factor F_H, which specifies the percentage of eggs lost in the batch when the cumulative maximum time is reached (Level 1 variable).

Overwash

QnD BBP reads a time series tide table file for Edisto Island and compares high tide height to the overwash threshold for each spatial unit. If the tide is higher than the threshold, the difference is multiplied by a damage factor that takes out a percentage of eggs for each batch with eggs in that spatial unit:

If $T_{n,t} > OT_{SU}$

$D0_t = \sum (T_{n,t} - OT_{SU}) * OF$

$EL_{i,o,t} = E_{i,t} * D0_t$

where $T_{n,t}$ is the first or second high tide in the time step, OT_{SU} is the spatial unit's overwash threshold (Level 2 variable), and OF is the overwash damage factor (Level 1 variable). $D0_t$ is the total percentage of destroyed eggs in the time step. This percentage is multiplied against each batch with eggs in the spatial unit to get $EL_{i,o,t}$, the number of eggs each batch lost to overwash during the time step.

Least terns respond to the loss of eggs by renesting. For each time step with egg loss:

$RP_{i,t} = EL_{i,o,t} / CL$

where $RP_{i,t}$ is the number of renesting pairs in batch *i* for the time step, and CL is the average clutch size.

Productivity

Each spatial unit calculates its productivity after the final tern batch has converted its surviving chicks into fledglings:

$P_{SU} = (\sum F_i / \sum NP_{t=0,i}) / 2$

where P_{SU} is the spatial unit's productivity, F_i is the number of fledglings in batch *i* and $NP_{t=0,i}$ is the number of nesting pairs at the start of batch *i*. The proportion of fledglings to nesting pairs is divided by two to get a proportion of fledglings to individual adult terns.

Level 1 Variables

All key variables in QnD BBP are coded in such a way so that adjustments can be easily made on the fly and appropriate levels of stochasticity are incorporated. QnD allows the developer to define a Level 1 variable's stochastic distribution (Gaussian, Poisson, etc.) and set its values for mean and variance (Table 3-3). Level 2 variables can be adjusted as needed (Table 3-4). This section describes the model's Level 1 variables in detail.

Colony selection disturbance threshold

If the number of human disturbance events is above this threshold, the spatial unit does not receive new nesting pairs. This threshold is also used to determine whether renesting pairs will remain in the spatial unit or join the global supply of available nesting pairs for redistribution to other spatial units (Figure 3-6).

Spatial distribution surveys conducted from June to September 2009 (n=19) provide data for determining initial values for a stochastic probability distribution for disturbance threshold. Values for the distribution were determined from looking at the mean and variance of beach-user numbers in three spatial units. BBP 02 and BBP 06 are both well colonized sites on Botany Bay. BBP 03, which has little to no tern nesting, has similar habitat characteristics but gets more beach-user activity due to its proximity to the beach entrance. The hypothesis here is that since BBP 02 and BBP 03 are adjacent units, the threshold for colony selection based on human disturbance exists somewhere between their two beach-user activity levels.

The disturbance-threshold variable uses a normal distribution based on a weighted mean of a 3:1 ratio for BBP 02 disturbance and BBP 03 disturbance. This ratio has been selected as a hypothesis that colony selection at BBP 02 is closer to the human-disturbance threshold than would be found with a simple averaging of disturbance-event values between the two spatial units.

Colony tenacity distubance threshold

If the number of disturbance events is above this threshold, a percentage of the spatial unit's available nesting pairs will abandon the spatial unit. This threshold uses a lower stochastic probability distribution than for the colony selection threshold. This is based on the hypothesis that increased exposure to human disturbance causes a stronger defensive response and makes it more likely that least terns will relocate prior to nesting.

Colony tenacity response

This sets the percentage of available nesting pairs that leave a spatial unit if the number of disturbance events exceeds the tenacity threshold. This variable has been set at a mean response rate of 25 percent with a normal distribution and variance of 0.0025. This is an estimate based on observations of least tern behavior during disturbances and on published literature.

Tern egg and chick overwash damage

Overwash and storm tides frequently kill eggs and chicks. This becomes a difficult phenomenon to quantify, however, given the variation in morphological features among spatial units and within a given spatial unit over time. For the purposes of this model, it will be assumed that one foot of flood tide would result in a major loss of eggs ranging from 50 to 100 percent. While it is highly unlikely that such losses are incremental, this model calculates losses per 0.1 foot increment (as recorded in NOAA tide charts). Mean percentage reduction and variance are set accordingly. Overwash damage to tern chicks follows the same logic but cuts the mortality in half.

Minutes per disturbance

This variable sets the amount of time that least terns stay off the nest each time they are disturbed. The model assumes that each disturbance lasts an average of two minutes, with a variance of 15 seconds. The model can add more complexity if needed in order to account for temporal variation in defense response: Least terns grow more defensive as eggs near hatching.

Egg damage factor

This determines the percentage of eggs lost in each tern batch when the Maximum Time Until Egg Damage (Level 2 variable) is reached. Eggs can be lost through heat exposure, trampling by beach users, and predation as adult terns abandon the nest in defense response. The value for this variable primarily focuses upon eggs lost to heat exposure but can include enough variance to account for other losses that occur over time from human disturbance. The effects of heat on tern eggs are not well known.

Chick damage factor

This determines the percentage of chicks lost in each tern batch when the Maximum Time Until Chick Damage (Level 2 variable) is reached. Chicks move away from the nest as soon as two days after hatching, and parents brood and feed them within 200 m of the nest (Thompson et al., 1997). Little is known about chick behavior and mortality once it leaves the nest. Older chicks seek shade and shelter while adults feed and are often found in nearby vegetation and debris (Thompson et al., 1997). Some studies have found least tern chicks to be very effective at thermoregulation under extreme heat conditions for nearly 40 minutes, while other studies have found chick deaths to occur after 15 to 20 minutes of exposure to hot sun (Thompson et al, 1997). QnD BBP assumes that a positive correlation exists between factors affecting egg viability and those affecting chick survival. Chick damage relates to accidental killing of chicks through crushing them, exposing them to predation threats, and heat exposure. This variable takes the same approach as the variable for chick damage from overwash: half the damage that occurs in eggs.

Assumptions

This model makes assumptions designed to streamline the simulation and contains a number of assumptions that strive to strike the correct balance between simplicity and complexity. These assumptions simplify data demands on resource managers and can be changed if the need arises for greater complexity within the model.

- Tern migration occurs at the same probability throughout the migration period. In all likelihood, tern migration has a temporal dimension to its distribution. However, in the absence of data that shows temporal variation in migration numbers, QnD BBP assigns the same stochastic probability distribution to the entire migration period.

- Clutch size remains constant throughout the nesting season. There is some evidence that clutch sizes near the end of nesting season are smaller than early-season clutches, but the impact of this on a colony's reproductive success is probably minimal compared to other factors such as human disturbance and overwash.

- The effects of human disturbance remain constant throughout incubation. QnD BBP assigns the same defensive response to human disturbance regardless of how long nesting pairs have been incubating their clutch or how frequently humans have disturbed the colony. This complexity could be added over time with additional data and improved knowledge about the system.

- All spatial units that meet the basic nesting criteria have an equal chance of being selected by incoming terns. This assumption ignores that least terns select larger colonies over smaller ones, especially if those colonies are spaced at wide intervals and contain a mix of nesting pairs and single birds for mate selection (Burger, 1988). QnD BBP can be adjusted to account for these factors if necessary.

- Least terns have an abundant food supply. Least tern nesting season has been found to coincide with a peak in prey fish abundance, and peak hatching coincides with peak availability of fish of an appropriate size for feeding chicks (Zuria and Mellink, 2005). This assumption would need to be revisited if marsh loss from sea level rise were to cause significant disruptions to the coastal food web.

- Predation isn’t a significant problem. Predators can cause colonies to fail, but not to the same extent as human activities (Thompson et al., 1997). Burger (1984) found that smaller colonies suffered greater losses from human disturbance than from predation. Predation is written out of the model in order to avoid unnecessary complexity. However, it must be noted that breeding in large colonies offers least terns protection from predators (Hernández-Matías et al., 2003). Looked at another way, this suggests that disruption of least tern nesting from human disturbance would increase the chances of predation on tern nests by virtue of reducing colony size. In this way, a non-linear response to disturbance may result, with terns potentially showing precipitous declines in productivity following moderate human disturbance levels. If this were the case, predation would need to be written into the model.

Simulation Results

Stochastic runs of QnD BBP for different weekly closure scenarios (200 each) show no significant difference in global productivity for scheduled closures of zero to three days (Table 3-5, Figure 3-7). The management options result in means ranging from 0.10 to 0.16 fledglings per breeding adult, with median productivity ranging from 0.05 to 0.09. Closing the beach completely (seven days a week) would result in a mean productivity of 0.38 fledglings per breeding adult (median of 0.35). Productivity in the 7-days-per-week closure scenario remains limited by overwash damage and human disturbance on BBP01.

Table 3-6 and Figures 3-8 through 3-10 show the effects on productivity per spatial unit for zero, one and seven scheduled closed days per week. BBP01 shows no significant change because of its remote location and off-site access by the public. The other three spatial units show significant changes in productivity between 1 day and 7 days per week closed, as would be expected. Productivity in BBP02 remains limited by overwash, while BBP03 shows strong productivity gains given its lack of higher volume of beach use by humans relative to BBP02 and its lack of access restrictions for potential nesting areas. BBP06 also shows strong productivity gains from its relative protection from overwash and lack of human disturbance under the closed-beach scenario.

Sensitivity Analysis

This model is designed for continued development and looks at all variables in which $R^2 > 0.33$. This is done with the understanding that R^2 values less than 0.70 are at best a crude indicator of factors that may emerge as important variables to monitor once the uncertainty inherent in the other variables (i.e., R^2 >0.70), has been reduced through monitoring and analysis. Tables 3-7 and 3-8 show results of the linear regressions for all Monte Carlo simulations (200 runs), with the R^2 and Standardized Regression Coefficient (SRC) values of interest highlighted in bold. Table 3-7 shows values for the effects of each Level 1 variable on least tern nesting productivity for the entire beach area and individually for spatial units BBP02 and BBP06, which represent the two primary colony areas on the main beach. Table 3-8 shows values for the effects of each Level 1 variable on the number of least tern nesting pairs in each of the two primary colonies.

Variance for the value of one Level 1 variable in particular, Minutes Per Disturbance, has the greatest effect on least tern productivity. R^2 values for global nesting productivity and productivity in BBP02 and BBP06 are all around 0.90, with SRC's of -0.94 or greater. Figures 3-11 through 3-13 show scatter plots of productivity values for all three productivity measures based on the range of values for Minutes per Disturbance. This variable also appears to have an effect on the number of nesting pairs in BBP02 (Figure 3-14).

Variance In the value for the Colony Selection Disturbance Threshold variable also may have an effect on global nesting productivity (R^2 0.36, SRC 0.60) and on nesting productivity in BBP06 (R^2 0.40, SRC -0.63) (Figures 3-15 and 3-16). It also appears to affect the number of nesting pairs in BBP06 (R^2 0.54, SRC 0.73) (Figure 3-17). Global productivity showed a response to the Colony Tenacity Disturbance Threshold (Figure 3-18), as did the number of nesting pairs in BBP06 (Figure 3-19). The number of nesting pairs in BBP02 showed a response to values for Colony Tenacity Response

(Figure 3-20). The higher the values for selection and tenacity thresholds, the less effect human disturbance has on nesting behavior.

Discussion

In general, least terns show strong site fidelity and have been found to return to sites in subsequent years that were moderately successful, defined as producing between 0.25 and 0.49 fledglings per breeding pair (Burger, 1984). This translates to productivity of between 0.13 and 0.25 per breeding adult. Other studies have found that in order to maintain population levels, a colony must achieve breeding success of between 0.51 fledglings per breeding pair (Kirsch and Sidle, 1999) and 0.66 fledglings per breeding pair (Lombard et al., 2010).

Despite the differences in defining reproductive success, productivity provides the most useful metric for determining whether Botany Bay Plantation is in danger of losing its colonies in future years. Reproductive success of least tern colonies can show wide variation among colonies and among years within a single colony (Burger, 1984). Studies have found estimations of reproductive success to include:

- 0.59 fledgling / breeding adult on Gulf Coast from 1979 to 1981 (Thompson et al., 1997).
- 0.24 fledgling / breeding adult in New Jersey from 1975 – 1982 (Burger, 1984).
- 0.24 fledgling / breeding adult on lower Platte River from 1987 – 1990 (Thompson et al., 1997).
- Averages ranging from 0.14 - 0.64 fledglings per breeding adult along the lower Mississippi River (Szell and Woodrey, 2003).

For initial assessments, colonies simulated in QnD BBP can be considered successful at 0.25 fledglings per breeding adult or higher, and at immediate risk of failure if productivity falls below 0.13 fledglings per breeding adult (Burger, 1989).

Of all the Monte Carlo simulations of Botany Bay Plantation under current management conditions with different day-closure scenarios, only closing the beach seven days a week achieved a productivity level that would be considered sufficient for maintaining colony viability in future years, at 0.38 fledglings per breeding adult. These results are on the low side of productivity and, if validated, suggest that the colonies are in peril of not returning to Botany Bay Plantation over the long run. It is also possible that the stochastic values for Level 1 variables overestimate the effects of human disturbance and need to be adjusted.

This modeling approach is designed specifically to identify those variables for which ongoing monitoring and data collection would provide the greatest insight into system behavior. The sensitivity analysis shows that at the very least Minutes Per Disturbance must be measured in order to reduce uncertainty for that value. The same holds true to a lesser extent for the Colony Selection and Colony Tenacity thresholds. The range of values for the threshold variables may be more difficult to measure given the number of potential confounds in determining why least terns might forego or abandon a colony site (flooding, predators, through-migration, etc.). However, data collected on least tern numbers before, during and after busy beach days could help narrow the range of values for these variables.

One curious feature found in the Colony Selection and Colony Tenacity simulation runs is that productivity decreases with higher tolerance for human disturbance (i.e., a higher threshold level for colony selection and a lower percentage of terns leaving a colony in response to human disturbance). At face value, this may seem counter-intuitive, but it makes sense in terms of how the model is constructed: Nesting pairs that avoid or flee disturbance are less likely to expose eggs and chicks to harmful levels of disturbance. If this hold true, it suggests that having a large colony isn't necessarily a good thing. If the colony has strong tenacity but also a strong defensive response, the number of nesting pairs could mask the problem of unseen egg and chick damage from thermal stress and other defense-related problems.

This sensitivity analysis shows that investigation into least tern defense responses to human disturbance is of the greatest importance in understanding the effects of human disturbance on least tern productivity. From a management perspective, this is good news because minutes per disturbance is easier to measure than a variable such as the effects of thermal stress on egg viability. A careful analysis of data regarding disturbance minutes also can result in refinements to the model once temporal variations in disturbance response become clear.

Table 3-1. Probability that beach users will enter a section of beach from the adjacent section nearest the entrance (Center Beach).

Spatial Unit	Mean	Variance	Percent of total beach users
BBP02	0.28	0.08	7.5
BBP03	0.28	0.02	29.2
BBP04	1.00	0.00	100
BBP05	0.32	0.03	33.8
BBP06	0.35	0.08	10.2
BBP07	0.48	0.13	4.8

Table 3-2. General characteristics of least terns colonies observed at Botany Bay Plantation over three years.

	Interlude colony (BBP01)		South colony (BBP02)		North colony (BBP06)	
Year	Size	Productivity	Size	Productivity	Size	Productivity
2009	Small	Moderate	Large	Robust	Medium	Moderate
2010	Medium	Moderate	Medium to small	Light	Large	Moderate
2011	Medium	Moderate	Small to none	None	Large	Moderate

Table 3-3. Values for Level 1 variables used to simulate least terns colonies. QnD uses mean and variance for calculating stochastic probability distributions.

Category	Level 1 variable	Mean	Variance
Nesting pairs	Migrating nesting pairs (per time step)	7.0	16.0
	Colony selection disturbance threshold (# of events)	30.0	100.0
	Colony tenacity disturbance threshold (# of events)	20.0	100.0
	Colony tenacity response (proportion leaving colony)	0.25	0.0025
Overwash damage	Tern egg overwash damage (loss per 0.1 feet overwash)	0.05	0.0006
	Tern chick overwash damage (loss per 0.1 feet overwash)	0.025	0.0002
Human disturbance	Minutes per disturbance	2.0	0.25
	Egg damage factor (proportion eggs lost per max time)	0.075	0.0009
	Chick damage factor (proportion chicks lost per max time)	0.0375	0.0002

Table 3-4. Level 2 variables represent basic assumptions of how the system functions.

Category	Level 2 variable		Value
Nesting pairs	Migrating tern end		45 days
	Tern clutch size		2.0 eggs
	Tern egg incubation		21 days
	Tern chick growth		21 days
	Tern batch start	Batch 1	Day 8
		Batch 2	Day 15
		Batch 3	Day 22
		Batch 4	Day 29
		Batch 5	Day 36
		Batch 6	Day 43
		Batch 7	Day 50
Overwash damage	Overwash threshold (feet with decimal per NOAA tide chart)	BBP01	6.8 feet
		BBP02	6.6 feet
		BBP03	6.7 feet
		BBP04	6.6 feet
		BBP05	6.6 feet
		BBP06	7.1 feet
		BBP07	7.1 feet
	Minimum overwash habitat for colony formation		0.19
	Overwash habitat coverage	BBP01	0.20
		BBP02	0.40
		BBP03	0.50
		BBP04	0.20
		BBP05	0.05
		BBP06	0.60
		BBP07	0.05
Human disturbance	Daily visitors		Time series file – 2009 sign-in data
	Visit probabilities from adjacent spatial unit (values can be stochastic: variance in parenthesis)	BBP01	0.05 (0.0009)
		BBP02	0.28 (0.08)
		BBP03	0.28 (0.02)
		BBP04	1.00 (0.00)
		BBP05	0.32 (0.03)
		BBP06	0.35 (0.08)
		BBP07	0.48 (0.13)
	Max time until egg damage		40 minutes
	Max time until chick damage		40 minutes

Table 3-5. QnD BBP results for global least tern nesting productivity under various beach-closure scenarios (200 runs each; productivity = fledglings / breeding adult).

Days closed per week	Global productivity Median	Mean	Std. dev.
0	0.05	0.10	0.12
1	0.08	0.14	0.15
2	0.09	0.15	0.16
3	0.09	0.16	0.17
7	0.35	0.38	0.16

Table 3-6. QnD BBP results showing median productivity for all spatial units with sufficient nesting habitat under various beach-closure scenarios.

Days closed per week	Median productivity BBP01	BBP02	BBP03	BBP06
0	0.14	0.04	0.00	0.04
1	0.12	0.11	0.00	0.15
2	0.13	0.17	0.01	0.18
3	0.12	0.17	0.01	0.18
7	0.10	0.33	0.43	0.70

Table 3-7. Results of linear regressions for each variable in sensitivity analysis, looking at productivity as the dependent variable for entire simulation and for the two spatial units with the largest colonies.

	Global productivity		BBP02 productivity		BBP06 productivity	
Variable	R^2	SRC*	R^2	SRC	R^2	SRC
Colony selection	0.36	0.60	0.05	0.23	0.40	- 0.63
Colony tenacity	0.47	0.68	0.00	- 0.01	0.08	0.28
Tenacity response	0.07	- 0.26	0.04	0.20	0.02	0.14
Overwash egg damage	0.01	0.11	0.01	0.07	0.02	0.13
Overwash chick damage	0.01	- 0.01	0.01	- 0.10	0.01	- 0.10
Minutes per disturbance	0.89	- 0.94	0.92	- 0.96	0.91	- 0.96
Human dist. egg damage	0.00	0.04	0.00	0.05	0.00	0.04
Human dist. chick damage	0.00	0.00	0.00	0.02	0.00	0.02

*Standardized regression coefficient

Table 3-8. Results of linear regressions for each variable in sensitivity analysis, looking at the number of nesting pairs as the dependent variable for the two spatial units with the largest colonies.

	BBP02 nesting pairs		BBP06 nesting pairs	
Variable	R^2	SRC*	R^2	SRC
Colony selection	0.01	0.09	0.54	0.73
Colony tenacity	0.13	-0.36	0.44	0.66
Tenacity response	0.38	0.61	0.22	-0.46
Overwash egg damage	0.01	0.11	0.00	0.04
Overwash chick damage	0.00	0.01	0.00	0.04
Minutes per disturbance	0.49	0.70	0.02	0.14
Human dist. egg damage	0.00	-0.05	0.01	-0.08
Human dist. chick damage	0.01	-0.09	0.01	-0.08

*Standardized regression coefficient

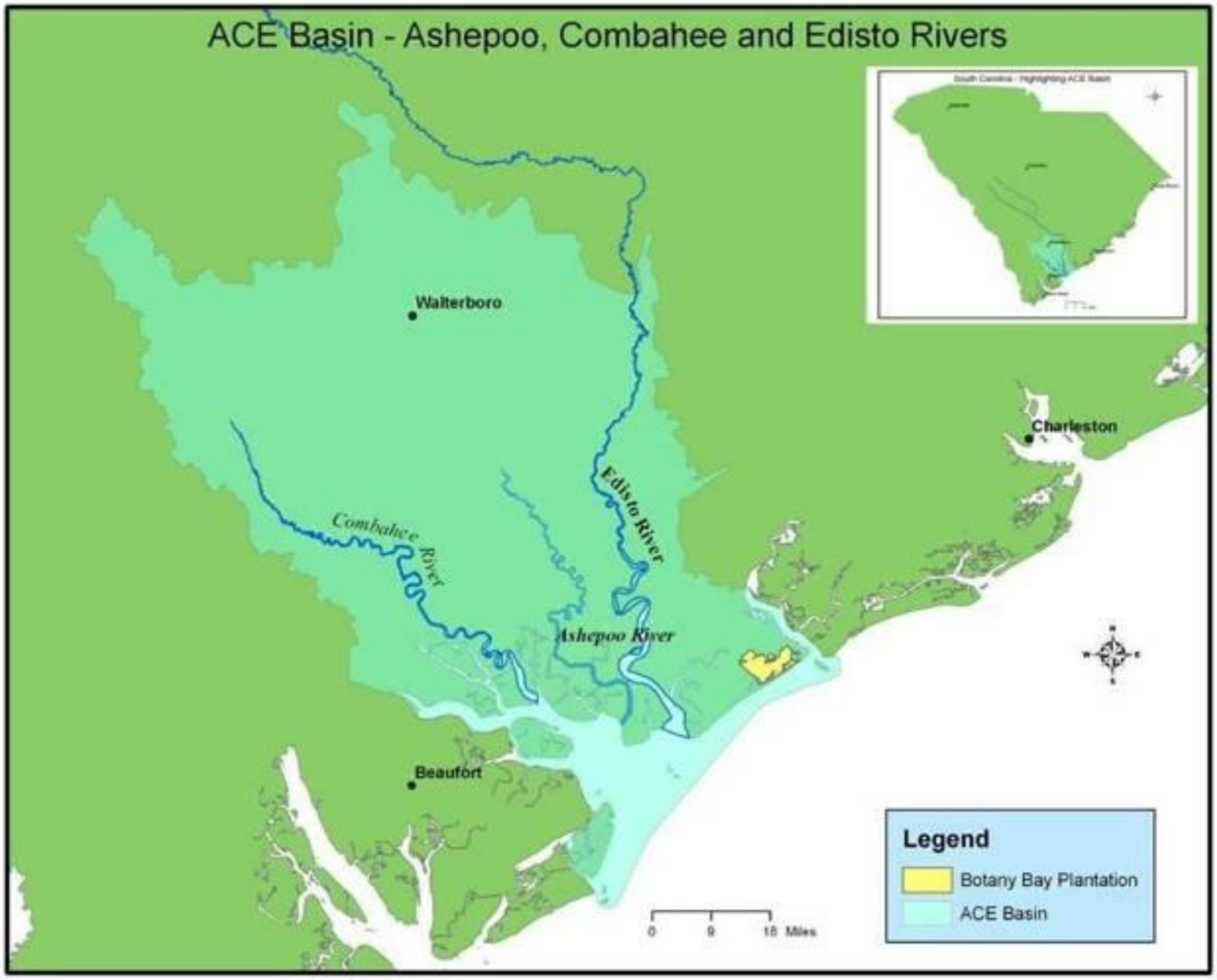

Figure 3-1. The location of Botany Bay Plantation within South Carolina's ACE Basin.

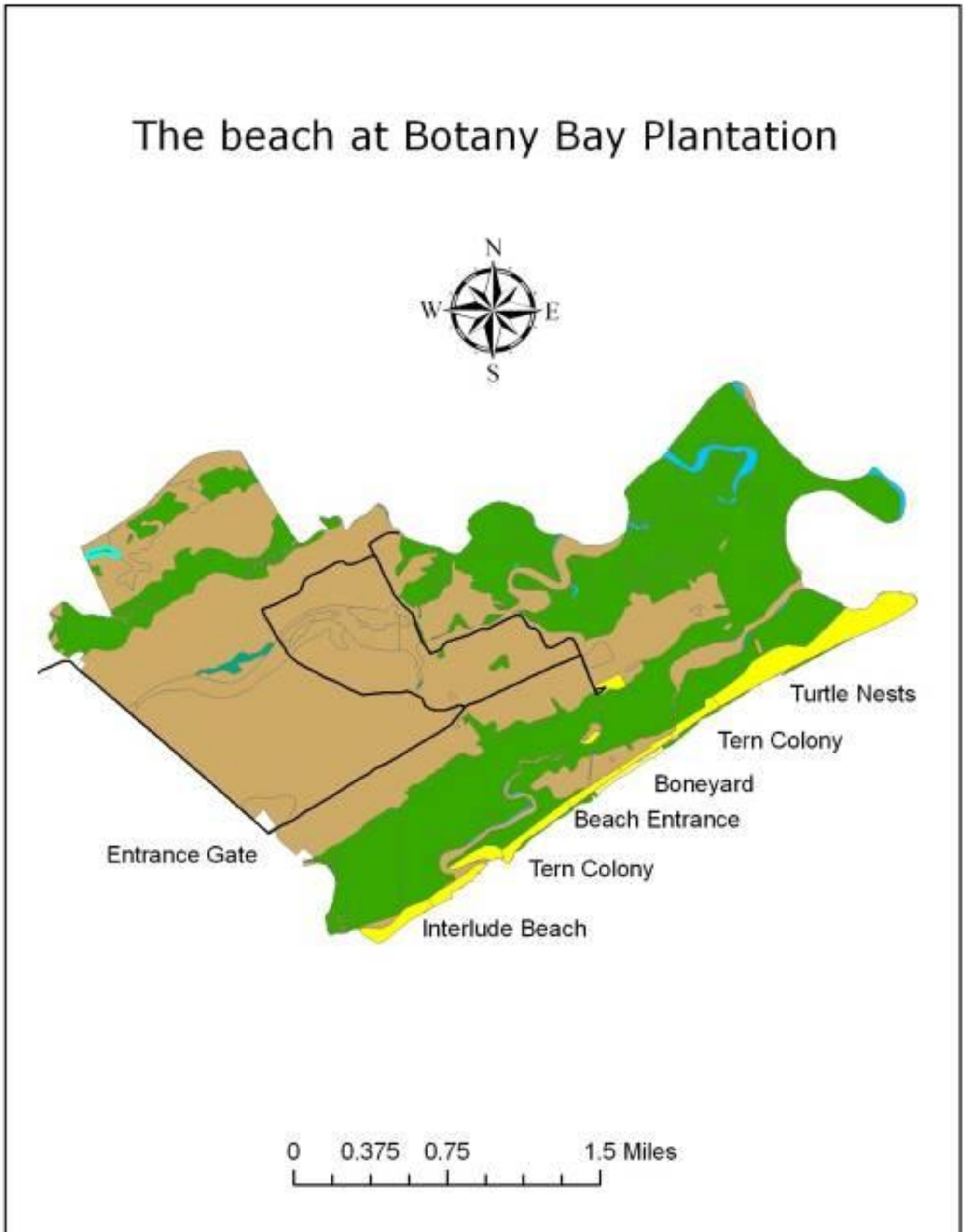

Figure 3-2. The beach at Botany Bay Plantation, showing the key areas.

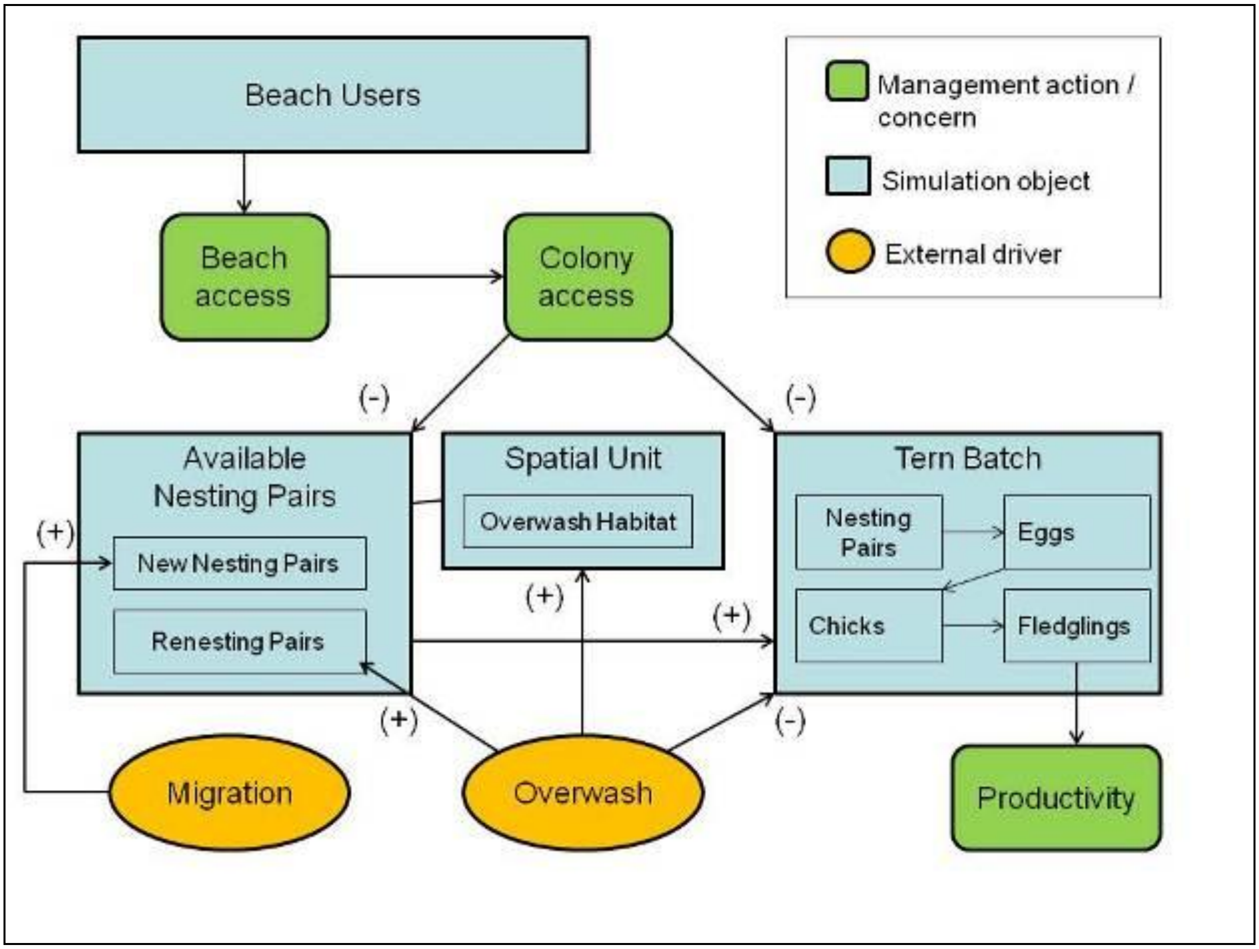

Figure 3-3. A conceptual model for QnD BBP showing relationships among the major components within the system being managed.

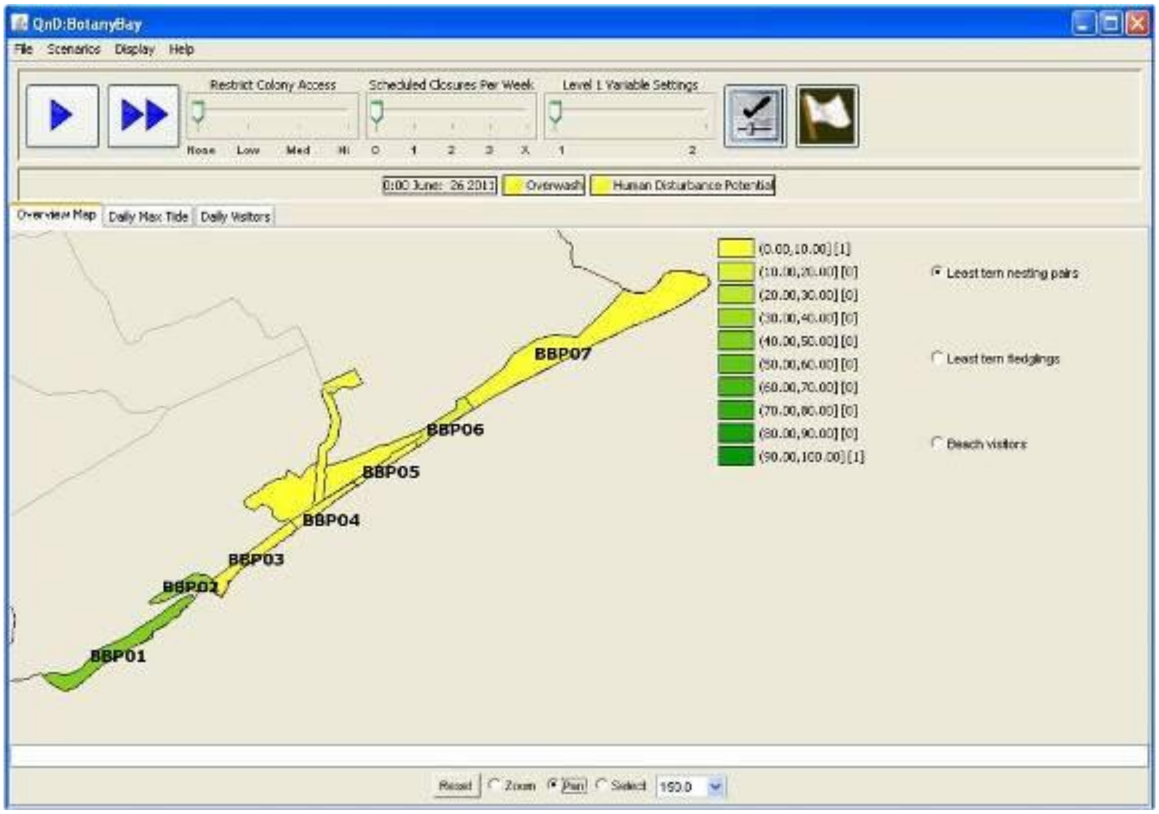

Figure 3-4. A screen shot of the simulation model's graphic user interface and the sections of front beach designated as spatial units. Labels added to show spatial units.

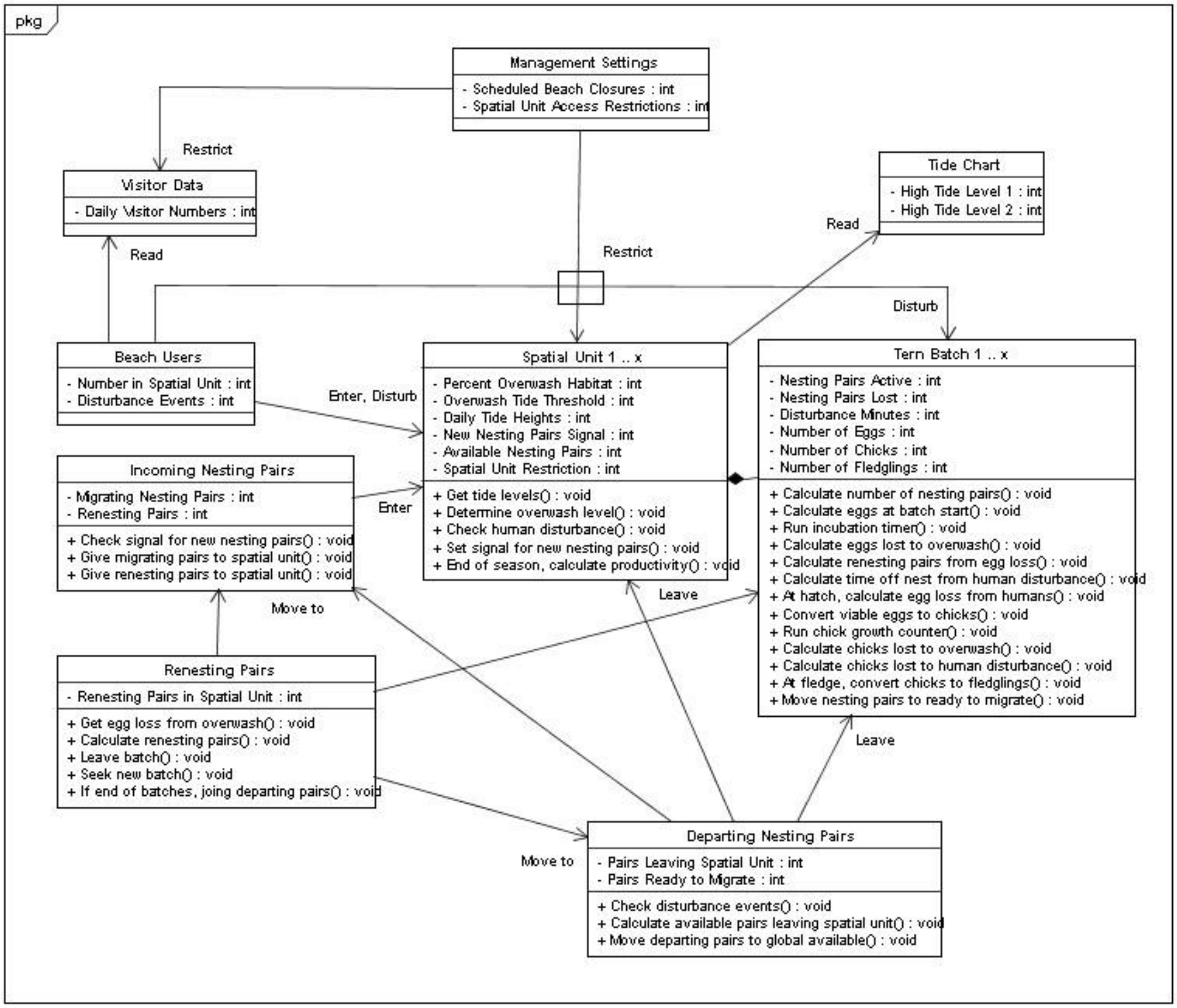

Figure 3-5. A Unified Modeling Language diagram showing the interactions among the objects within QnD BBP.

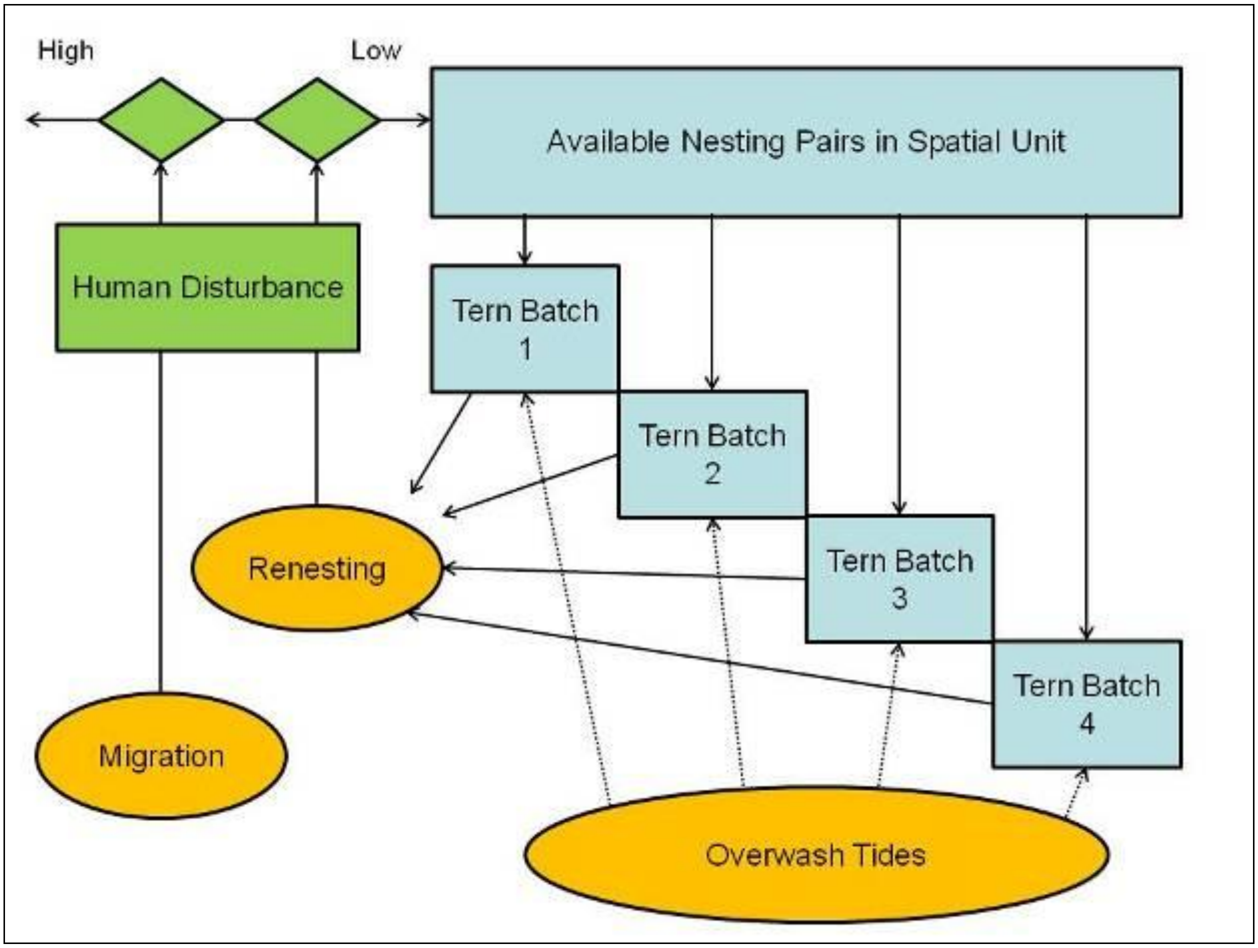

Figure 3-6. Renesting pairs result from overwash damage to eggs. If human disturbance is too high, they leave the system to join a global pool of available nesting pairs. Otherwise, they remain within the spatial unit and join the next batch of nesting pairs.

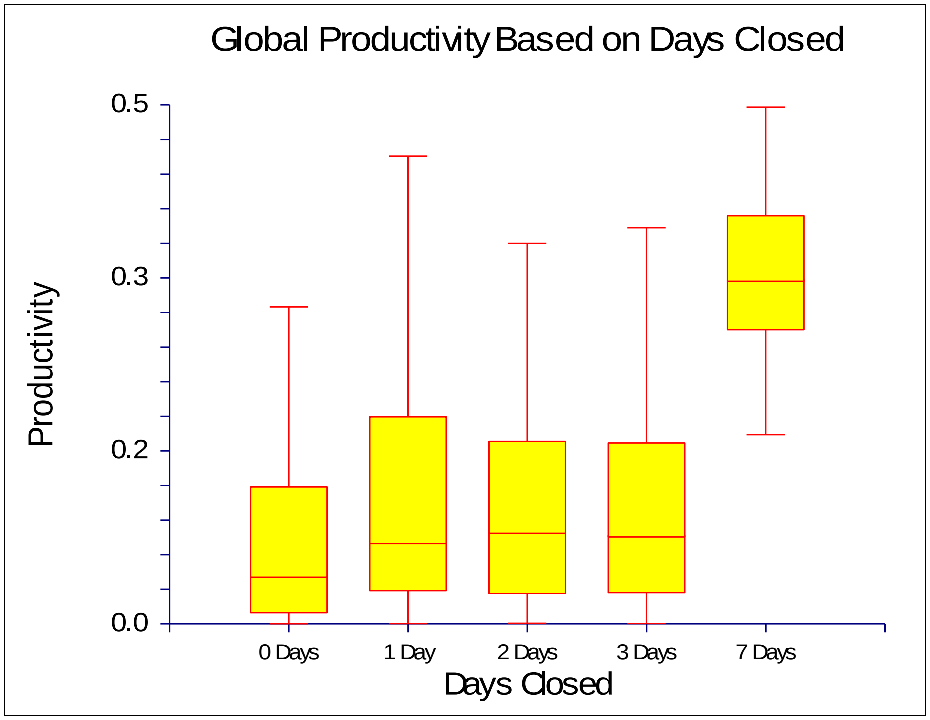

Figure 3-7. Simulation results for nesting productivity for all spatial units based on number of scheduled days per week that the beach at Botany Bay is closed.

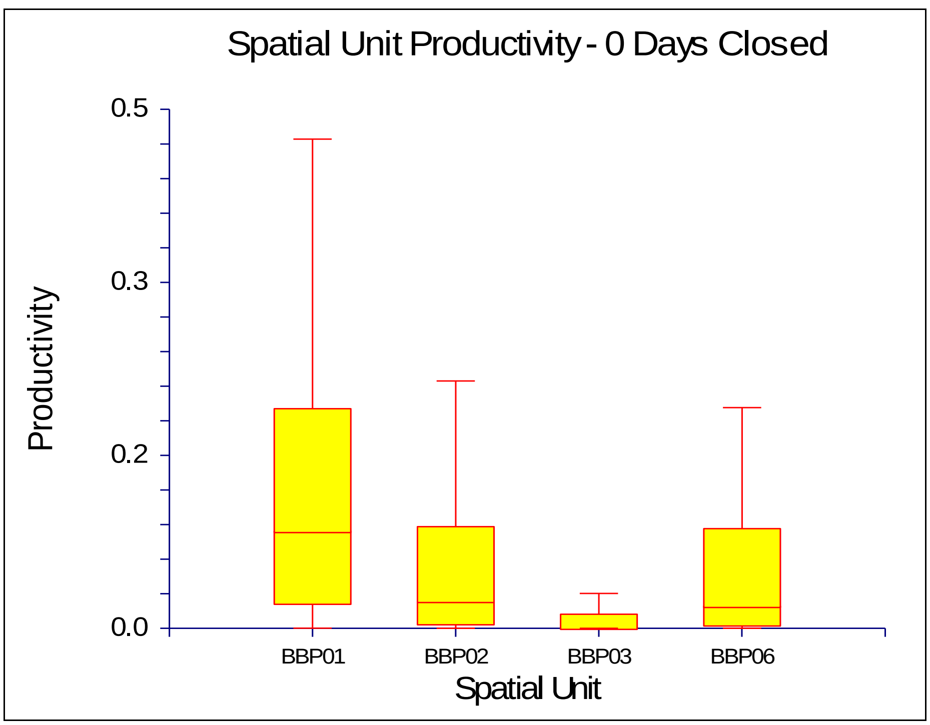

Figure 3-8. Simulation results for nesting productivity in each spatial unit with sufficient overwash habitat if beach at Botany Bay is open 7 days a week.

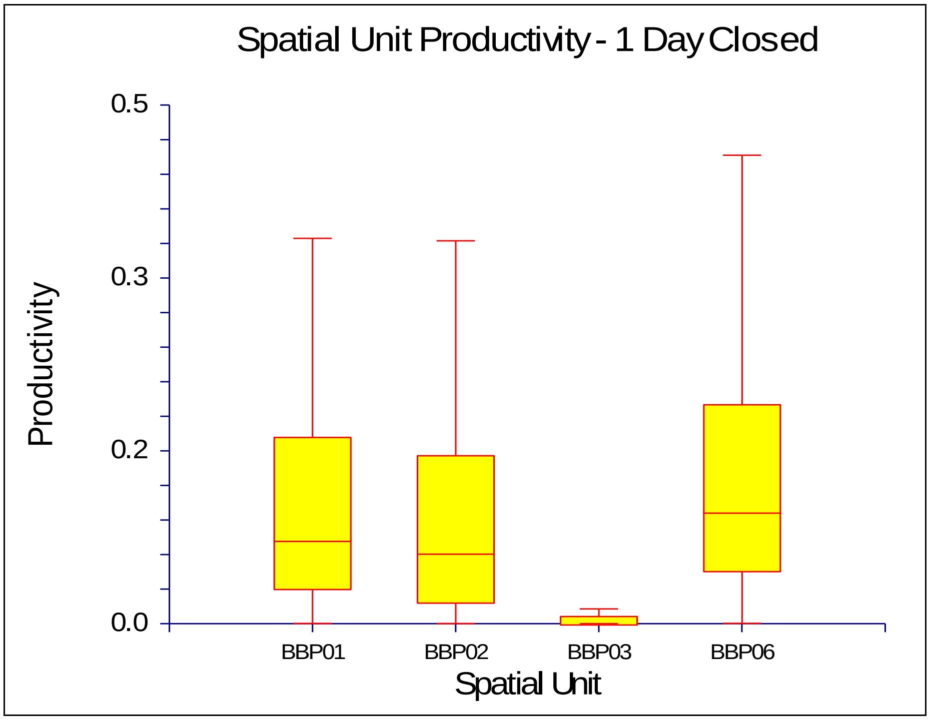

Figure 3-9. Simulation results for nesting productivity in each spatial unit with sufficient overwash habitat under current management restrictions: One day closed per week and colonies roped off.

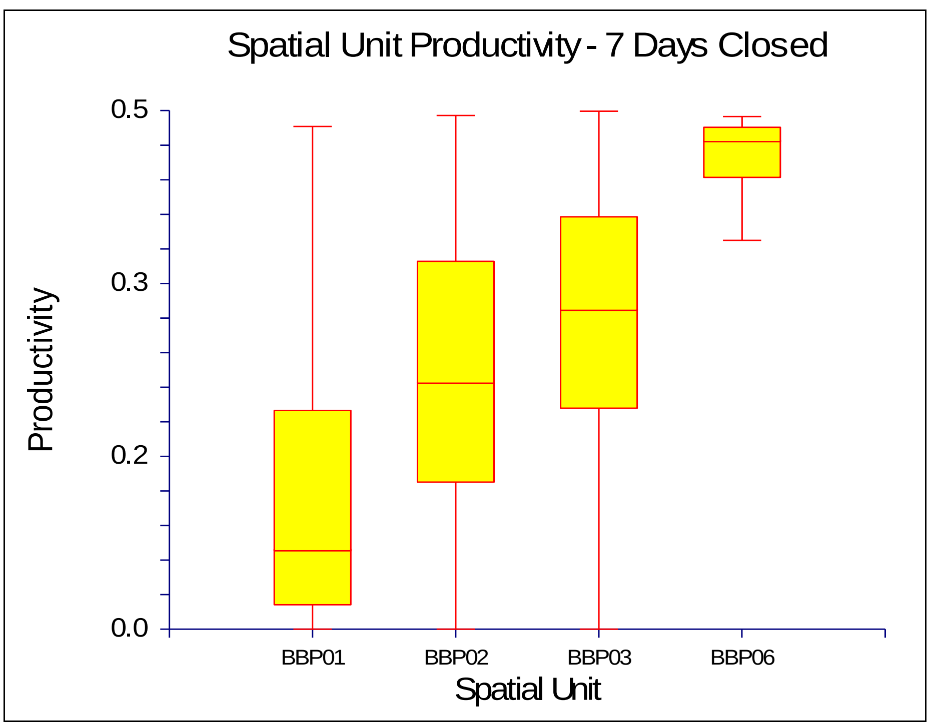

Figure 3-10. Simulation results for nesting productivity in each spatial unit with sufficient overwash habitat if the beach at Botany Bay were closed 7 days a week.

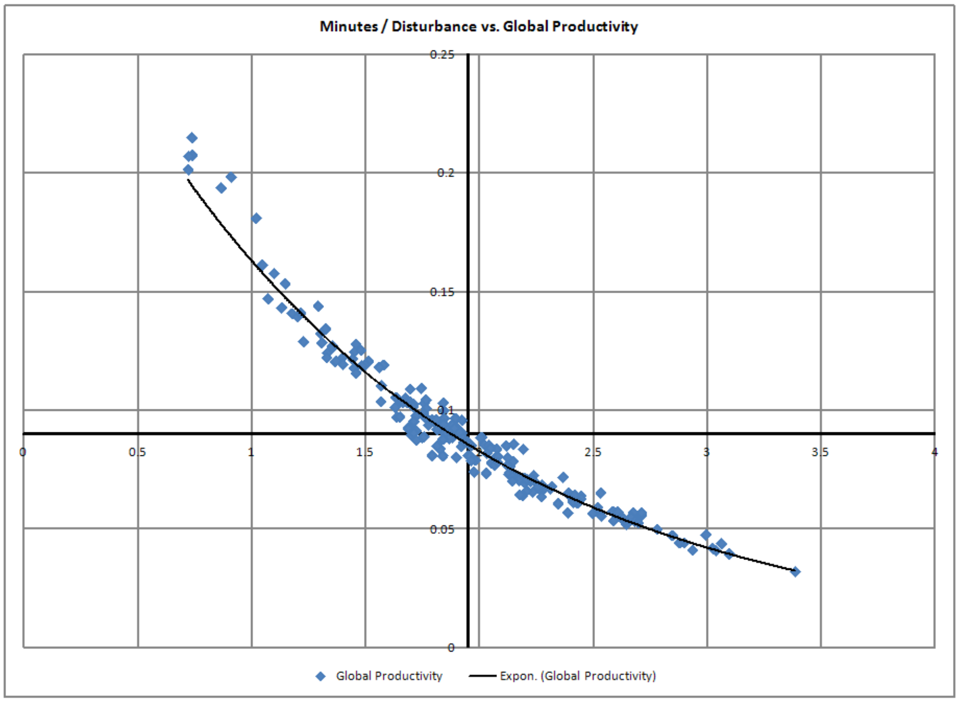

Figure 3-11. A scatter plot showing the effects of Minutes per Disturbance values on total least tern productivity for all spatial units.

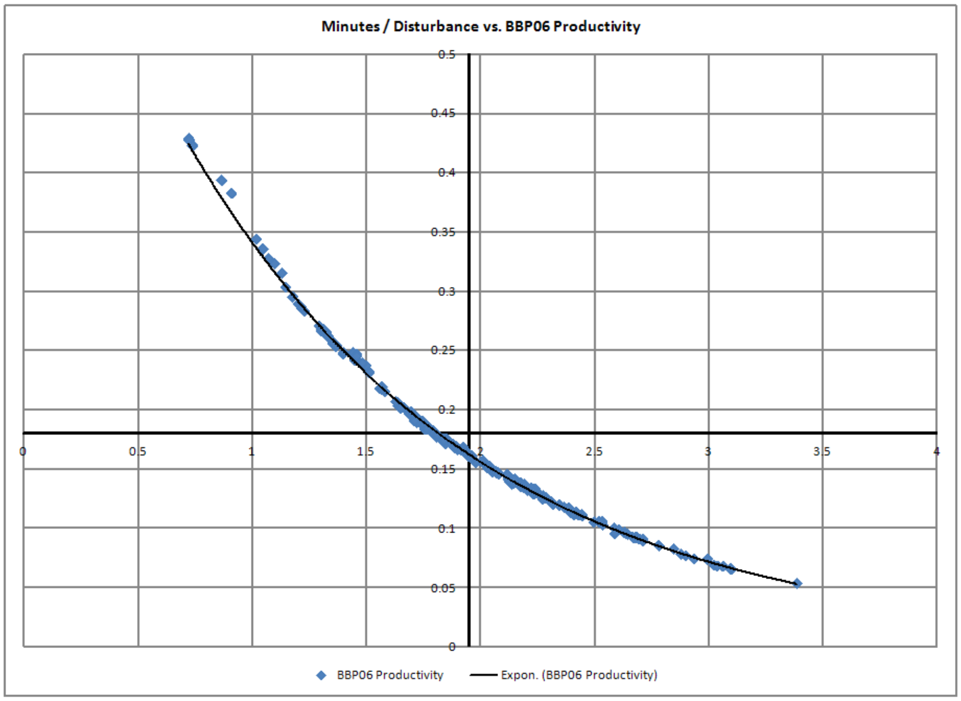

Figure 3-12. A scatter plot showing the effects of Minutes per Disturbance values on least tern productivity for spatial unit BBP06.

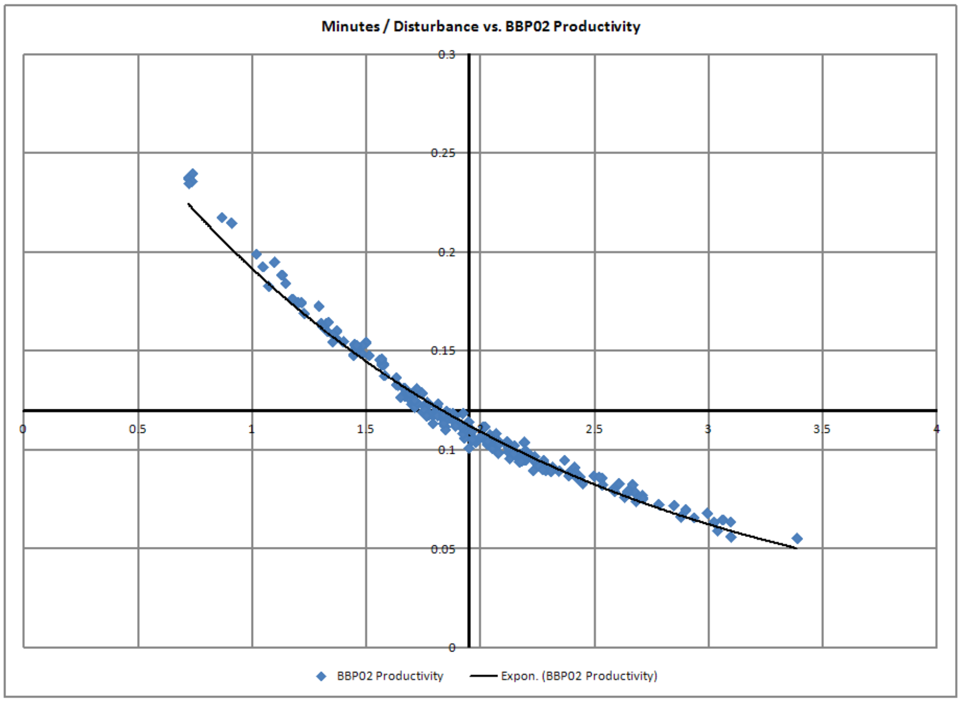

Figure 3-13. A scatter plot showing the effects of Minutes per Disturbance values on least tern productivity for spatial unit BBP02.

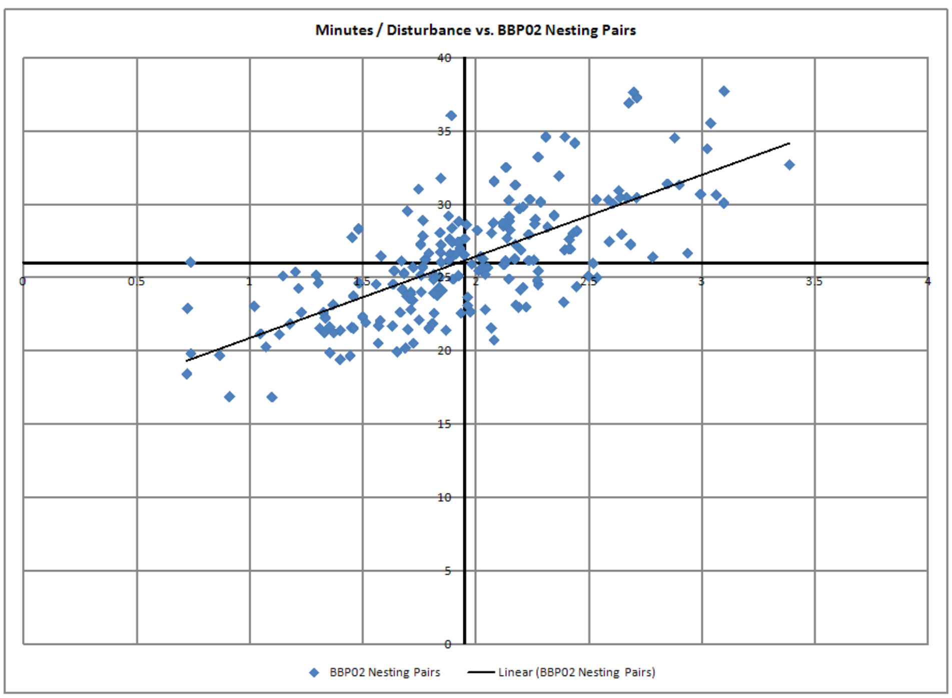

Figure 3-14. A scatter plot showing the effects of Minutes per Disturbance values on the number of nesting pairs in BBP02.

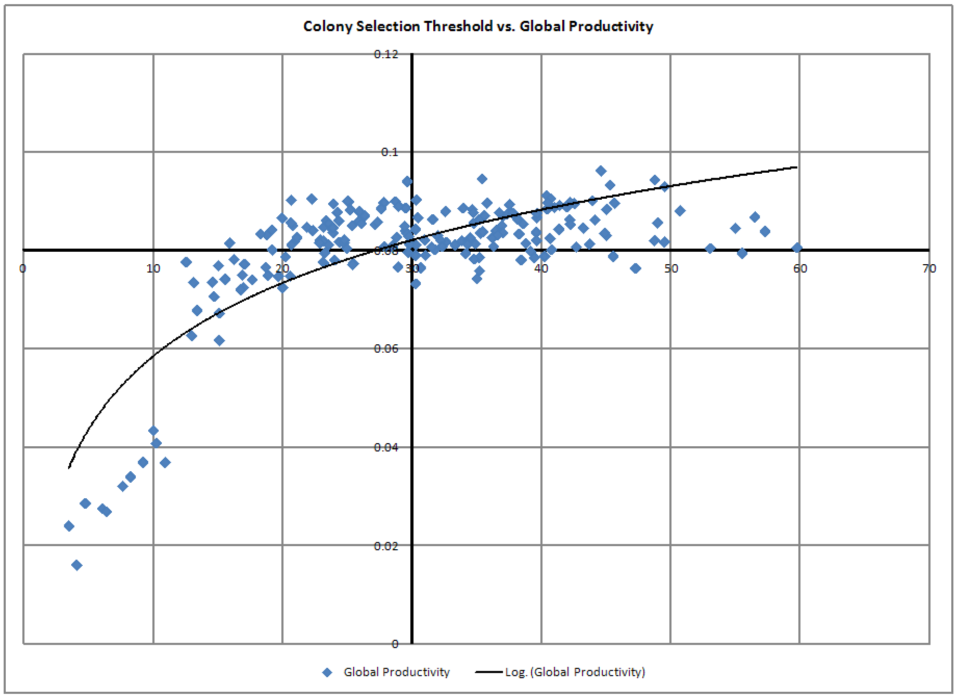

Figure 3-15. A scatter plot showing the effects of Colony Selection Disturbance Threshold values on total least tern productivity for all spatial units.

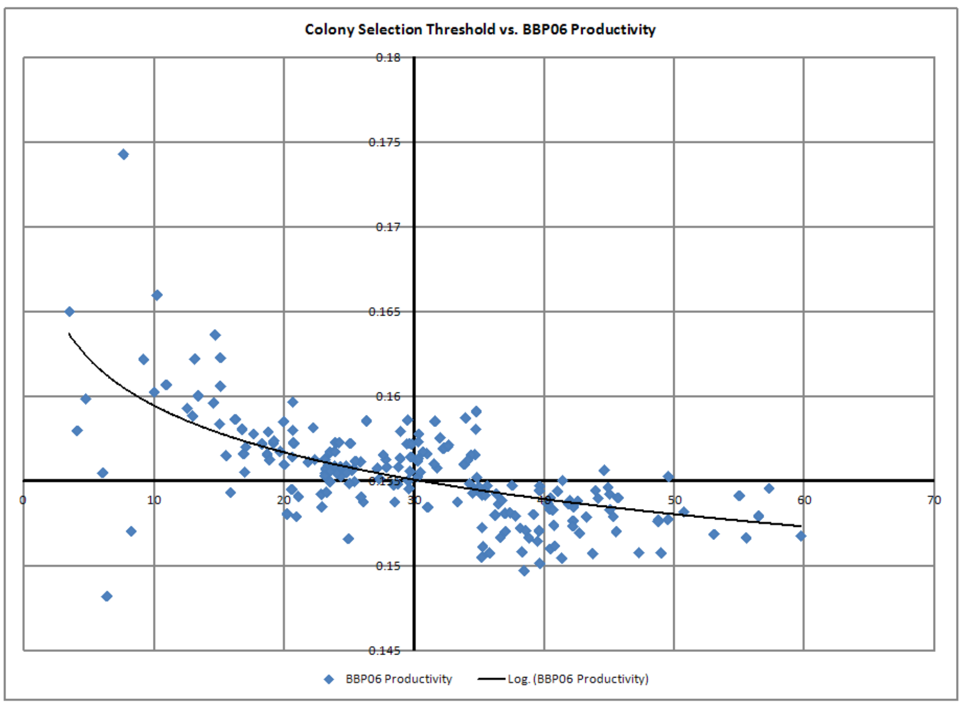

Figure 3-16. A scatter plot showing the effects of Colony Selection Disturbance Threshold values on least tern productivity for spatial unit BBP06.

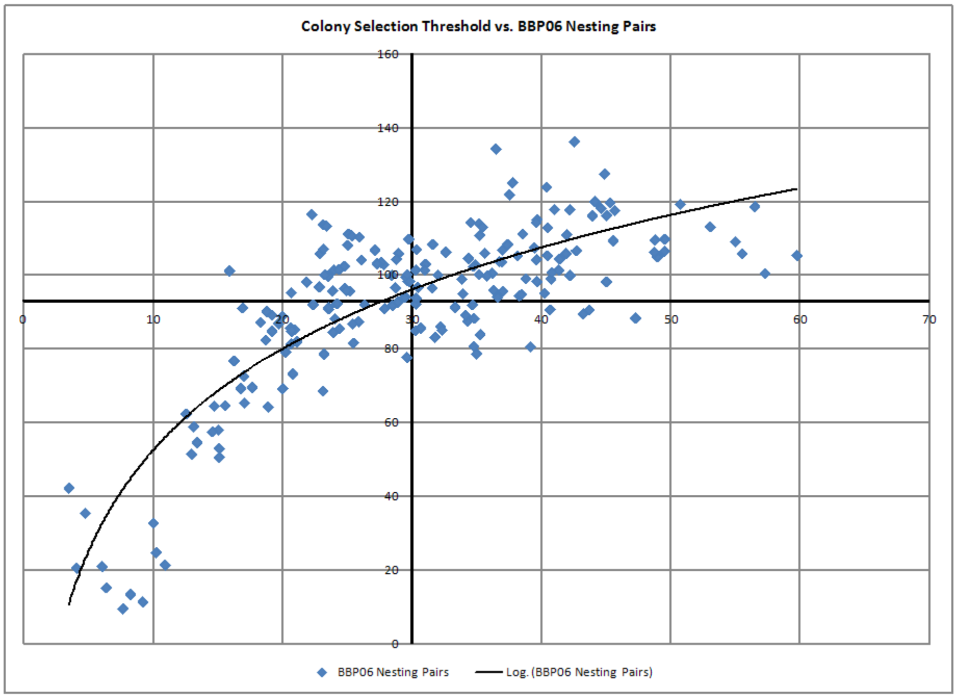

Figure 3-17. A scatter plot showing the effects of Colony Selection Disturbance Threshold values on least tern nesting pairs in spatial unit BBP06.

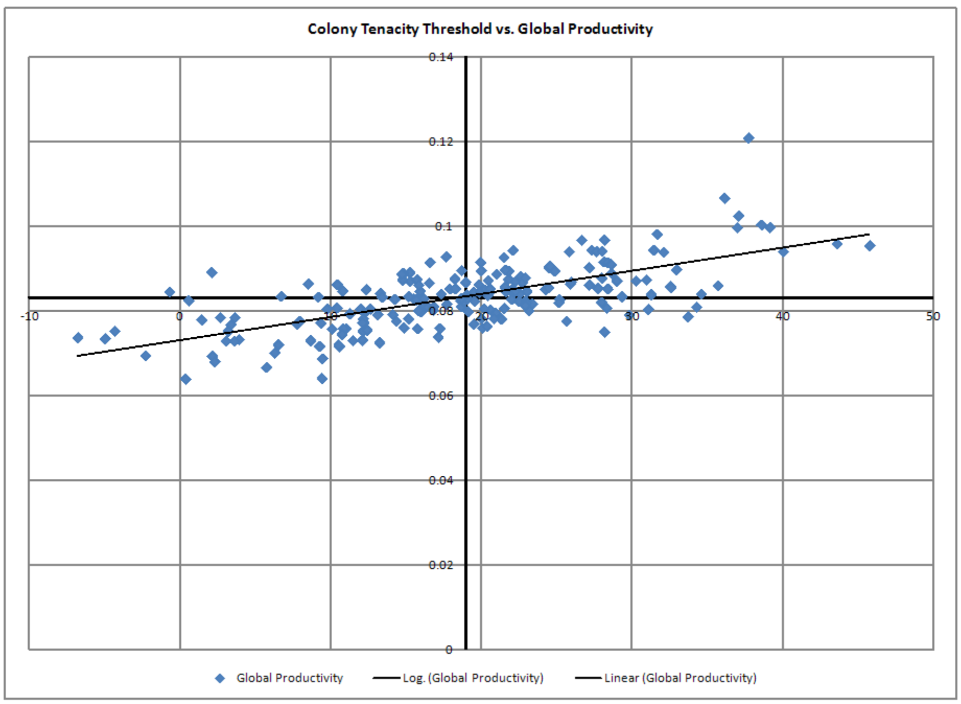

Figure 3-18. A scatter plot showing the effects of Colony Tenacity Threshold values on total least tern productivity for all spatial units.

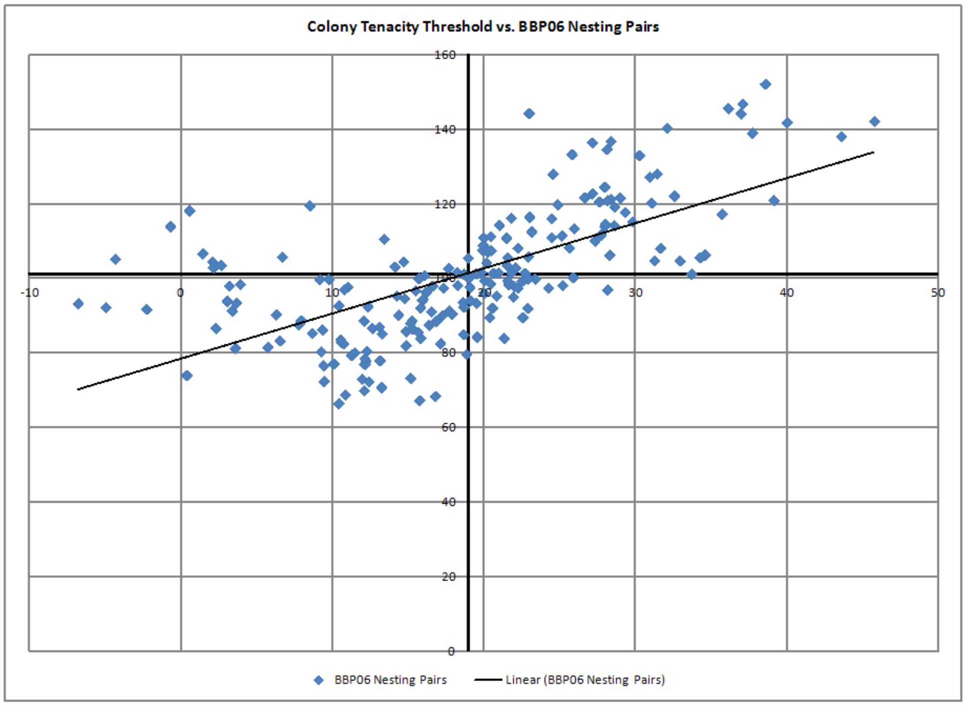

Figure 3-19. A scatter plot showing the effects of Colony Tenacity Threshold values on least tern nesting pairs in spatial unit BBP06.

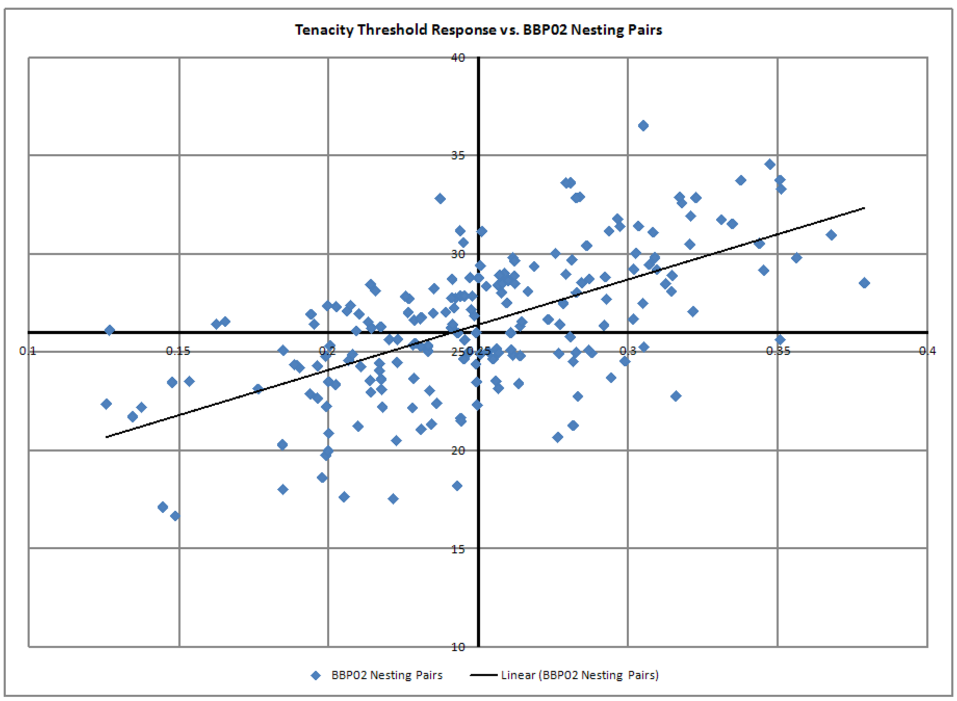

Figure 3-20. A scatter plot showing the effects of Colony Tenacity Response values on least tern nesting pairs in spatial unit BBP02.

CHAPTER 4
EXPLORING THE USE OF A SIMULATION MODEL FOR DECISION SUPPORT IN ADAPTIVE MANAGEMENT OF LEAST TERN (*STERNULA ANTILLARUM*) NESTING HABITAT

Introduction

Coastal managers face major system drivers and key uncertainties when making management decisions to protect habitat and wildlife. Coastal development and sea level rise put pressure on ecosystems being managed for conservation and restoration. Metapopulation dynamics, migratory patterns, and various shocks and disturbances within the social-ecological system all occur beyond the influence of local management, which must anticipate and respond to these changes and their effects at the local level. Adaptive management provides a mechanism for responding to these drivers and uncertainties. It creates a structured system for collecting information that reduces uncertainty and allows managers to identify important changes within the system at their early stages.

Simulation modeling provides an important method for understanding and adaptively managing local systems with a high level of uncertainty. An effective model can identify important system characteristics to monitor and show the potential effects of various management strategies. This in turn allows for the development and exploration of various hypotheses about system functions and behaviors. These hypotheses can be especially important for investigating potential thresholds and alternative stable states. One of the biggest challenges in applying the concept of ecological thresholds to ecosystem management is incorporating decision-making and human behavior into evaluation frameworks and management methods (Groffman et al., 2006). Threshold models used in habitat management are largely heuristic, as the ability to test their underlying assumptions are difficult (Suding and Hobbs, 2009). This gap in theory and practice results from the limited ability for managers to evaluate evidence and uncertainty in a given system (Suding and Hobbs, 2009) Detecting temporal and spatial patterns of change requires an increased emphasis on pattern-based knowledge, the use of system indicators, long-term monitoring, and expert knowledge.

This paper uses a simulation model for exploring potential management actions and developing an adaptive management program at Botany Bay Plantation, in South Carolina's Ashepoo-Combahee-Edisto (ACE) Basin Reserve (Figure 4-1). This object-oriented model, built on a java-based platform known as QnD (Question and Decision), is designed to help manage human disturbance of nesting least terns (*Sternula antillarum*) (Chapter 3). The beach at Botany Bay is one of only four known natural sites for least tern colonies on the South Carolina coast. The site is managed by the South Carolina Department of Natural Resources and was opened to the public in July 2008. Since then, more than 50,000 people have visited the 3-mile stretch of beach each nesting season. This influx of humans represents a significant shock to the beach system and poses an ongoing source of stress and disturbance to least terns and other species that nest and feed there. In addition to human disturbance, the site is also vulnerable to erosion and rising sea levels. This increases the threat of flood tides and storm surges to least tern nesting productivity (Chapter 2).

The effects of human disturbance on least terns, which are listed as a threatened species by the state of South Carolina, are of particular concern to resource managers. However, the site has few baseline data and lacks resources for addressing coastal management issues that require immediate attention. This paper demonstrates how the

QnD model developed specifically for this site (QnD BBP) can be used to help make management decisions and provides a basic blueprint of how this approach can be expanded and replicated at other sites. The following hypotheses form the basis of this investigation:

- Simulation modeling can provide an essential tool for adaptive management at the local scale.
- A customized simulation model can help clarify management choices even under conditions with high uncertainty.
- A simulation model can help define and structure monitoring activities.

The objectives of this research is to use the simulation model to show the effects of management choices involving least tern nesting and to show how the model can be used to structure adaptive management of human disturbance on least tern nesting and guide data collection efforts. It investigates different management options for boosting least tern productivity and then compares the best of those options with current management practices.

Simulation Modeling as Support for Adaptive Management

Modeling provides a process for understanding the system being managed and incorporating new knowledge as acquired over time, both of which are key elements of adaptive management (Stankey, 2003). Figure 4-2 shows a conceptual diagram of how simulation modeling fits into the adaptive management process.

All management policies and actions are essentially experiments or hypotheses put into action. Adaptive management makes this connection explicit and focuses on methodical approaches to measuring and evaluating the results of these hypotheses over the long term (Stankey, 2003; Lee, 1999; Sit and Taylor, 1998; Walters and Holling, 1990). Adaptive management differs from traditional management approaches in that it seeks to adjust to changing circumstances rather than attempt to hold the system in its current state. It accepts that the uncertainty inherent within most systems makes long-term predictions unrealistic (Clark, 2002). Adaptive management emphasizes sequential decision-making in the face of uncertainty and management improvements though knowledge accumulation over time (Williams et al., 2009). It involves structured decision-making that is iterated over time and space, with competing hypotheses about system behavior (Lyons et al., 2008). Management is conducted as an experiment and involves a direct feedback loop between managers and researchers (Reever Morghan et al., 2006). Consequently, successful adaptive management programs require well defined processes for characterizing and solving problems, establishing protocols for documentation and monitoring, defining roles and responsibilities, and determining methods for assessment and evaluation (Stankey et al., 2005).

Adaptive management can take an active or passive form. Active adaptive management employs multiple management solutions and compares their outcomes (Jacobson et al., 2009; Sit and Taylor, 1998). However, many resource managers face limitations in funding and staffing, making active adaptive management difficult to sustain (Lee, 1999). Adaptive management plans also often face expectations that they will show evidence of success in unrealistic time frames (Stankey, 2003). By contrast, passive adaptive management implements a single management policy and evaluates it through a well defined process of data collection and analysis (Walters and Holling, 1990). It offers the possibility of developing a systematic approach to evaluating management actions and policies within existing constraints on budgets and staff time.

This would seem to make passive adaptive management approaches more palatable to policy makers, since they focus on improving knowledge of a system and aligning management practices accordingly, rather than on bold experiments as espoused by proponents of active adaptive management (e.g., Walters, 1997).

Successful adaptive management approaches are hard to find. Program implementation at regional and landscape scales faces numerous challenges, including institutional inflexibility, risk-adverse management cultures and the reluctance to commit large amounts of time, energy and money for long-term support of these programs (Medema et al., 2008; Stankey, 2003). Most proponents of adaptive management call for big, bold experiments that go beyond the functions of existing management structures (Stankey, 2003; Walters, 1997). But the larger the experiment, the greater the reliance on existing management systems that show pathological resilience, i.e., systems that do not change or adapt over time (Gunderson and Light, 2006).

Lee (1999) observes that adaptive management appears primarily to be a top-down tool that is sustainable only when governmental authority has full control over access to the resources being managed. Support from upper management levels is necessary for bottom-up approaches to work, as otherwise they can have difficulty overcoming information deficits and insufficient resources (Evans and Klinger, 2008). Adaptive management programs require institutional capacity and commitment and must involve a meaningful choice among management alternatives (Williams et al., 2009). The process for determining management alternatives should be multi-disciplinary and collaborative and take multiscale responses into account.

One overall advantage of adaptive management is that the approach can begin with a simple plan that adds complexity over time, as knowledge of the system and of its responses to management strategies increases (Reever Morghan et al., 2006). In this way, a passive adaptive management program could begin small, expand its reach over time, and begin to incorporate components of active adaptive management. Adaptive management works in two phases. The set-up phase defines management objectives, identifies potential management actions, and develops predictive models and monitoring plans. The iterative phase focuses on management actions, monitoring, and evaluating the results. Results of this process then inform changes made in the next set-up phase (Williams et al., 2009).

Adaptive management can be helpful in estuarine and coastal restoration projects because of the high level of uncertainty involved (Thom et al., 2005). An effective adaptive management plan must acknowledge uncertainty about system functions and responses to management actions (Williams et al., 2009). Ecological surprises occur frequently enough to require adaptive management approaches that acknowledge the shortcomings of deterministic models of system behavior and anticipate surprises that will have major implications for management strategies (Doak et al., 2008). For instance, a single change in community function, such as an invasion of feral hogs in a sea turtle nesting area, can have ripple effects across the system. Because no static model can account for these effects, adaptive management requires ongoing monitoring and evaluation in order to detect, measure, and interpret such changes over time (S.C. Department of Natural Resources, 2006).

Measurable objectives are a critical component of adaptive management and are what separate it from basic trial and error. Their use focuses and justifies the investigation of management options. Management objectives need to be specific, measurable, achievable, results-oriented, and time-fixed (Williams et al., 2009). Site managers often are already aware of causal relationships between a particular stress and ecological indicators and have no need of studies that re-establish them. Instead, they are more concerned with actually detecting those changes in indicators of interest (Hadwen et al., 2008). Without proper information, resource managers might respond to effects of human disturbance only after the changes have become obvious and possibly irreversible. Human-approach distance to birds is commonly studied, but population-level consequences of flight responses such as individual energy balances, reduction of available habitat, and offspring predation are not often quantified (Buckley and King, 2003). Other effects, such as the impact of disturbance on foraging behavior and ecological effects that work through indirect mechanisms are also difficult to identify. A well designed adaptive management plan can provide a mechanism for identifying which effects are most important to monitor and evaluate.

The Question and Decision (QnD) Model

The simulation model for this project uses the Question and Decision (QnD) system framework (Kiker et al., 2006; Kiker and Linkov, 2006; Kiker et al., 2008; Kiker and Thummalapalli, 2009). QnD is designed for understanding potential ecosystem behaviors and management options for a given social-ecological system. It links spatial components through geographic information system files with selected abiotic and biotic interactions within the system being modeled (Kiker et al., 2006). QnD has two primary elements: a simulation engine and a user-friendly graphical interface that allows users to explore various scenarios and management options. The developer configures the attributes and processes of the simulation's objects through input files written in extensible markup language (XML) that QnD converts into Java objects (Kiker and Thummalapalli, 2009). This design allows for iterative development of model components as its users learn more about the system being managed.

Simulation models have become an important tool in managing natural resources amid the uncertainties and complexities of social and ecological systems (Otter and Capobianco, 2000). The model becomes a shared representation of the system and a tool for collective learning (Bousquet and Le Page, 2004; Campo et al., 2009). In this respect, the creation and ongoing development of a model becomes an important component of the adaptive management process (McLain and Lee, 1996; Lawson et al., 2003; Lawson, 2006). A well constructed model encourages collaboration among management and stakeholders and makes use of available data, hypotheses, and other information to represent the interactions among elements in the system of interest.

The QnD BBP model focuses on local-scale processes, but its fundamental structure can be replicated and customized to meet management needs at other sites while providing the same basic set of indicators and outcomes to facilitate centralized data collection and analysis. In this way, QnD BBP offers a bottom-up method of establishing local adaptive management programs with centralized guidance and support. Organizational capacity for adaptive management can be developed while avoiding some of the pitfalls of top-down approaches.

Local approaches are not without their drawbacks. In particular, the integrated nature of social-ecological systems can get lost in the focus on local specificity

(McFadden, 2008). For this reason, local adaptive management programs must be integrated in a way that accounts for the multiple scales found in coastal and estuarine systems. At the same time, site-specific issues need to be addressed at a scale that allows for customized decision support. Human disturbance of least terns at natural nesting sites appears to play a role in limiting colony size and repeated use of nesting areas (Jackson and Jackson, 1985). Protective measures such as warning signs and fencing are important predictors of nesting success (Medeiros et al., 2007). Resource managers need simulation models that can help them make decisions to get the most out of the measures that they choose to take.

Numerous adaptive management approaches emphasize the need for stakeholder engagement at all levels of development and implementation (e.g., Levrel et al., 2009; Manring and Pearsall, 2006; Habron, 2003; Selin and Chavez, 1995). This project takes a different approach. Given the specific, localized nature of the problem – i.e., managing the effects of human disturbance on least tern nesting productivity – the simulation model was developed with input from resource managers but not other stakeholders. However, Botany Bay has a strong corps of active volunteers who work the beach and front gate on a daily basis and participate in other projects throughout the year. These volunteers would play a key role in data collection and monitoring for the model's key indicators.

Monitoring visitor behavior and spatial distribution is a crucial component in managing visitor impact (Cessford and Muhar, 2003; Sutherland, 2007). Inadequate collection and analysis of visitor data, especially in regards to where visitors go and what they do, has impeded efforts to develop sustainable tourism and recreation in protected areas (Hadwen et al., 2007). Effective monitoring provides the feedback loop for adaptive management and the information that agencies need for making specific management decisions (Lyons et al., 2008). The most impact aspect of monitoring is to record a series of observations at the same place over many years (Buckley and King, 2003). The volunteers at Botany Bay represent a valuable resource for recording these observations over time in a manner consistent with current management activities.

In most cases, management is already collecting some kind of baseline data at local sites, but the potential of this data is not realized in the absence of a structured, sustainable method for using that data to inform management decisions (Nichols and Williams, 2006). In order for that to happen, a strong connection must be made between monitoring design and decision structure, and monitoring programs should focus on critical uncertainties that impede management objectives (Lyons et al., 2008).

Methods

QnD BBP measures least tern nesting productivity over the course of a single nesting season in daily time steps (Chapter 3). Human disturbance by beach users and flooding from overwash tides both reduce tern productivity. The model divides the beach into seven spatial units based on morphological and biotic characteristics (Figures 4-3 and 4-4). Nesting pairs migrate into the simulation for a set number of days during the nesting season, and the simulation divides incoming nesting pairs among spatial units that meet least-tern nesting criteria for overwash habitat and disturbance levels.

Least terns rely on overwash habitat for establishing colonies, but these same areas make colonies vulnerable to overwash tides during the nesting season. A major overwash event can wipe out an entire colony’s eggs, depending on the beach’s morphological characteristics. Each spatial unit in the simulation has a specified tide level at which overwash disturbance occurs. The percentage of overwash habitat within each spatial unit can be measured and changed prior to the start of each nesting season, allowing the simulation to accommodate inter-annual morphological changes. Overwash habitat also can be adjusted through minor modifications to the model if significant changes were to occur in the midst of a nesting season.

QnD BBP looks at the effects of human disturbance on the nesting productivity for least terns. The model does not focus on population dynamics beyond basic movements within the system based on human disturbance patterns. It operates on the hypothesis that since colony productivity is positively correlated with site fidelity, measuring productivity is a useful indicator for predicting the site's success in attracting nesting least terns in subsequent seasons.

Human disturbance acts as a deterrent to colonization. Changes in management settings that ban human use of the beach during the nesting season would allow colonization to occur in some spatial units that under current management conditions remain empty or sparsely nested. The model can be run with management settings that ban human use during some or all portions of the nesting season to explore the site’s potential as undisturbed nesting habitat.

New nesting pairs within each spatial unit are grouped into batches that follow nesting development from egg to chick to fledgling. The model divides the start of nesting season into seven one-week batches per spatial unit. Within each batch, overwash events and human disturbance result in the loss of eggs and chicks, affecting productivity. Time off nest from human disturbance results in cumulative damage to least tern eggs. Human disturbance also affects colony selection and tenacity. The model treats each disturbance as being of equal duration. Disturbance minutes accumulate over the incubation period and result in egg loss.

The model handles human disturbance differently than overwash since least terns can't detect heat damage to eggs. The model determines human disturbance levels based on the number of times people enter or pass through the spatial unit. From this, the model calculates the number of disturbance minutes in which nesting pairs leave the nest and keeps a running count over the course of the incubation period to determine the damage to eggs at the end of the incubation period. The model assumes that nesting pairs losing eggs to human disturbance (heat exposure) do not renest. Chicks are also affected by human disturbance to a lesser degree, and their mortality has no effect on renesting.

The number of fledglings produced by each batch count toward the calculation for productivity of each spatial unit and globally across the site. The total number of nesting pairs on site and in each spatial unit are also recorded.

The model is written with the express purpose of making the simulation easy to use and modify by resource managers in terms of changes to key variables. Development of the simulation model occurred over a two-year span and involved field observations and data collection at Botany Bay Plantation (Chapter 3). Staff with the South Carolina Department of Natural Resources provided information on management priorities and critical input into preliminary versions of the model.

QnD BBP provides an approach to simulation modeling that facilitates decision-making and collaboration. The model is designed for transparency and ease of use. Key variables (known as Level 1 variables) are coded so that input parameters can be easily changed or modified in order to explore outputs based on different hypotheses about system functions (Table 4-1). Examples of Level 1 variables include the number of minutes terns spend off nest in response to human disturbance and the cumulative damage to egg viability from terns leaving the nest in defense response. Level 2 variables represent key assumptions within the model, such as the time range for tern in-migration and the average clutch size for tern nests (Table 4-2). Level 2 variables are also coded to facilitate easy access for making changes as needed.

The model can be run in two ways. Batch mode runs Monte Carlo simulations based on the number of runs specified by the user. Game mode allows the user to explore the effects of different management actions made during a single run by adjusting model settings from one time step to the next through the graphic user interface. Auto-run mode provides output on final data values for each run in the Monte Carlo simulation, while game mode provides an output that shows data for each time step.

Managing Human Disturbance

The model emphasizes a simple design that allows resource managers to explore the effects of potential decisions on a small set of objective measures:

- Productivity (fledglings / total nesting pairs)
- Nesting pairs per spatial unit
- Human disturbance events

At any nesting site, certain factors are beyond management control, namely the fate of migrating terns prior to their arrival at the site, and the frequency and intensity of overwash tides that occur during the nesting season. However, management can control visitor access to the beach and to colonies within individual spatial units. The model's graphic user interface has two management control settings:

- Scheduled beach closings per week.
- Colony access restriction level.

The simulation also has dashboard warning lights in game mode to alert resource managers to the presence of overwash tides and the potential for human disturbance based on the number of beach users (Figure 4-4). Thresholds for these indicator lights are set as Level 2 variables and can be changed based on management objectives.

Access restrictions within a spatial unit, as defined by management setting, determine the area of each spatial unit that is off limits to beach users. This in turn determines the percentage of beach users that cause disturbance events. The percentage for each management setting is defined by a Level 2 variable (Chapter 3).

If a spatial unit's restriction level is set at 1 or 2, the simulation assumes that the actual number of beach users remains the same, and only their impact level changes (Table 4-3). A restriction level of 3 means that beach users have no access to the selected spatial unit and all other spatial units farther from the entrance. In running simulations, resource managers also have the option of closing the entire beach to public access on up to 3 scheduled days per week. An additional option closes the beach on all days until lifted.

Monte Carlo simulations were run 200 times each for a number of different management options:

Number of scheduled closure days for beach

Botany Bay Plantation currently closes one day a week (Tuesday) to give wildlife a break from human activity and to allow staff and volunteers to focus on improvement projects on the 5,000 acre property. QnD BBP allows for a range of management options to explore the effect of beach closures on least tern productivity, from 0 to 3 scheduled closures per week plus an option for 7-days/week closure, which provides a comparison for undisturbed nesting habitat.

Spatial unit restrictions

QnD BBP offers a choice of spatial unit restrictions to limit the effects of human activity on least tern nesting. The default setting for the Monte Carlo simulations is restriction level 1, which assumes that the immediate nesting area is roped off and has warning signs posted. For these runs, the Level 2 variable for restriction level 1 reduces human disturbance within the spatial unit by 50 percent.

Monte Carlo simulations were also run using restriction level 3 (spatial unit closed) on BBP02 and BBP06. These two spatial units generally have the largest nesting colonies and would be the most feasible for prohibiting public access. BBP01 would be nearly impossible to close, as most beach users arrive from outside Botany Bay Plantation via boat and wading over from a private beach to the south. BBP03 is located just south of the beach entrance, and its closure would likely encounter strong opposition from beach users. For all simulation runs, BBP02 and BBP06 are set to have Level 1 restrictions, unless otherwise noted. This reflects current management practice.

Four scenarios are compared to examine the effects of different spatial unit closure actions on global productivity:

- Current management practice (no closures, BBP02 and BBP06 colonies roped off).
- BBP02 closed.
- BBP06 closed

- BBP02 and BBP06 closed.

Differences in productivity globally and within each spatial unit were tested for significance using the non-parametric Mann-Whitney U test. For the scheduled-days closures, this test compares 0-days closure to 1-day closure; 1-day closure to 2-days closure; 2 days-closure to 3-days closure; and 3-days closure to 7-days closure. For the spatial-unit closures, this test compares BBP02 closure to current management; BBP06 closure to current management; BBP02 and BBP06 closure to current management; BBP02 closure to BBP06 closure; BBP02 closure to BBP02 and BBP06 closure; and BBP06 closure to BBP02 and BBP06 closure. The assumption of equal variance for all results is tested using the Modified-Levene Equal Variance Test.

Results

Outputs were checked for statistically significant differences among number of days closed per week, specifically between 0 days and 1 day; 1 day and 2 days; 2 days and 3 days; and 3 days and 7 days. Global productivity show a small significant increase from 0-days to 1-day closure per week, from a median productivity of 0.05 to 0.08 and from a mean productivity of 0.10 to 0.14.The largest gain in productivity occurred at 7-days closure per week: a median productivity of 0.35 and mean productivity of 0.38. Both of these changes were significant when compared to the next lower number of closure days (Table 4-4, Figure 4-5).

Productivity in BBP01 showed no significant differences between closure-day options, as expected given its remote location and off-site access. Its median productivity ranged from 0.10 to 0.14, with mean productivity ranging from 0.21 to 0.24. BBP02 showed a significant difference between 0-days and 1-day closures and from 1-day and 2-days closures. Median productivity increased from 0.04 to 0.11 to 0.17, while mean productivity increased from 0.16 to 0.23 to 0.26. It also showed a significant increase at 7-days closure with a median productivity of 0.33 and a mean productivity of 0.39 (Table 4-5, Figures 4-6 and 4-7).

BBP03, which exists outside of the fenced nesting areas, showed a small significant gain in productivity from 1-day to 2-days closure as median productivity rose from 0.00 to 0.01 and showed a large significant gain at 7-days closure, from a median productivity of 0.01 to 0.43 and mean productivity from 0.11 to 0.47. This result is suggestive of what Botany Bay might look like as a nesting site if it were free from human disturbance. BBP06 showed significant increases at 1-day closure, from a median productivity of 0.04 to 0.15 and mean productivity from 0.15 to 0.25. BBP06 also showed a large significant increase between 3-days and 7-days closure, as this is the spatial unit least likely to be affected by overwash. Median productivity rose from 0.18 to 0.70 and mean productivity rose from 0.28 to 0.71 (Table 4-6, Figures 4-8 and 4-9).

In three instances, the assumption of equal variance was not met: Global productivity for 3-days vs. 7-days closure; BBP03 productivity for 3-days vs. 7-days closure; and BBP06 productivity for 3-days vs. 7-days closure. This may be a result of having a relatively small sample size (200 runs) given the range of variance in the eight Level 1 variables. It also might signal a non-linear response in productivity when removing human disturbance from the system.

Spatial unit closures show a significant difference for increased global productivity for management actions closing BBP06 and closing both BBP02 and BBP06 for the nesting season (Tables 4-7 and 4-8; Figure 4-10). Closing only BBP06 resulted in a gain in median global productivity from 0.08 to 0.36 and an increase in mean global productivity from 0.14 to 0.38. Closing both BBP06 and BBP02 resulted in a gain in median global productivity from 0.08 to 0.37 and an increase in mean global productivity from 0.14 to 0.41. The analysis shows no significant difference in global productivity between the BBP06-only closure and the BBP02-and-BBP06 closure. The assumption of equal variance was met for all T-tests.

Discussion

Nesting productivity is a good predictor of site fidelity (Burger, 1984), and this model focuses on management's ability to enhance productivity in order to ensure that the site remains active for nesting least terns. For these assessments, colonies simulated in QnD BBP are considered successful at 0.25 fledglings per breeding adult or higher, and at immediate risk of failure if productivity falls below 0.13 fledglings per breeding adult (Burger, 1989). Simulation results suggest that a successful productivity rate of 0.25 cannot be achieved under current management conditions and that three of four spatial units are at immediate risk of failure as colony sites. QnD BBP is still in its early stages of development, but its results match observations of least tern colony behavior. The one spatial unit that shows a median productivity above 0.13 under current management conditions, BBP06, is the only one to have consistently shown a stable colony over the 2009 to 2011 nesting seasons.

Closing Botany Bay Plantation for the entire nesting season is not feasible, but the model shows that closing off the beach would have a significant effect on improving nesting productivity. The productivity gain from closing the beach for an extra day or two beyond the current management practice of one day closed per week shows no statistical significance. Increases in global productivity for least tern nesting are significant at 1-day closure and 7-days closure. The current management practice of one scheduled closure per week was initiated during summer 2009 in order to give deer and other wildlife a break from the steady flow of traffic into the site (Dean Harrigal, personal communication). Simulation results suggest that even one scheduled closure per week helps improve productivity for nesting least terns. The 7-day closure option is clearly not viable, given the popularity of Botany Bay Plantation, but provides a comparison for site productivity if human disturbance were drastically reduced. Median global productivity under full closure, at 0.35, would satisfy nesting success requirements for maintaining a viable population with strong site fidelity from year to year. Globally, the other closure options fall well below the threshold needed to keep Botany Bay's colonies viable.

Looking at individual spatial units, the simulation shows that closing any of the three spatial units on the main beach would increase its productivity above the viability threshold. Of these three options, closing off BBP03 is the least likely, as this section of beach is popular among visitors and could prove problematic to enforce. BBP02 would be easier to close off, but the area is vulnerable to overwash tides that have wiped out colonies in the past, and it borders an inlet that is a popular fishing spot (personal observation). BBP06 shows the most dramatic improvement in productivity (from a median of 0.18 to 0.70) because of its greater protection against overwash. This site also would be easier to close off as relatively few beach users venture beyond the colony area to the mile-long stretch of dunes where most of the loggerhead turtles nest.

According to the simulation, closing off BBP06 for the entire nesting season would result in an increase in global median productivity from 0.08 to 0.36. The difference in global productivity between closing only BBP06 and closing both BBP06 and BBP02 is not statistically significant (medians of 0.36 and 0.37 respectively). This suggests that closure of BBP06 could result in stronger productivity for the entire site while minimizing disruption to recreational users of the beach. BBP06 is located about 0.5 miles north of the beach entrance and has the advantage of being removed from most beach traffic during high tide, when access to most of the boneyard (BBP05) is blocked. Generally speaking, the model shows that any nesting area removed from beach crowds and relatively protected from overwash should be protected for maximum productivity gains.

Depending on morphological changes driven by annual fluctuations and sea level rise, the location of prime nesting areas could change from one year to the next. Resource managers have the opportunity to make changes to Level 2 variables, such as which spatial units have suitable habitat, through technical assistance from the developer. The simulation structure itself can be changed as well by the developer with guidance from resource managers and other end users. In this way, QnD BBP contains a built-in process by which a group of managers can collaborate and make decisions through the simulation model. This approach combines the power of simulation modeling with real-time management concerns and is designed to grow stronger with continued use over a number of nesting seasons. The model also can be replicated across sites and customized to address site-specific management concerns while collecting data in a format suitable for aggregation across sites.

Through an iterative process, QnD BBP provides a decision-support structure that identifies indicators in need of monitoring. The monitoring necessary for this simulation model to work long-term is fairly basic and can be performed by beach volunteers with appropriate supervision (Table 4-9). The data feed directly into the model for validation and ongoing refinement. As the uncertainty around key variables is reduced and managers become more confident in the model's results, it can become an important tool for testing potential management actions and responses to storm surges and other shocks to the beach system.

Table 4-1. Users can set the values for nine Level 1 variables as simulation inputs.

Component	Level 1 Variable	Description
Nesting pairs	Migrating nesting pairs	Selection range for random number of nesting pairs per time step that migrate into simulation.
	Colony selection disturbance threshold	If number of disturbance events above this threshold, spatial unit does not receive new nesting pairs.
	Colony tenacity disturbance threshold	If number of disturbance events above this threshold, a percentage of available nesting pairs currently in spatial unit leave spatial unit.
	Colony tenacity response	Percentage of available nesting pairs that leave spatial unit if disturbance events exceed tenacity threshold.
Overwash	Tern egg overwash damage	Percent reduction in tern eggs for every 0.1 foot of flood tide.
	Tern chick overwash damage	Percent reduction in tern chicks for every 0.1 foot of flood tide.
Human disturbance	Minutes per disturbance	The number of minutes least terns stay off nest each time they are disturbed.
	Egg damage factor	Percentage of eggs lost in batch each time max time is reached.
	Chick damage factor	Percentage of chicks lost in batch each time max time is reached.

Table 4-2. Level 2 variables are secondary variables that represent assumptions about the system and are easily modified by the developer.

Component	Level 2 Variable	Description
Nesting pairs	Migrating tern end	The max number of days in which least terns migrate into BBP to nest.
	Tern clutch size	Number of tern eggs per clutch.
	Tern egg incubation	Number of days before eggs hatch out
	Tern chick growth	Number of days before chicks fledge
	Tern batch start	Assigned start date for each batch of nesting pairs.
	Max time until egg damage	The cumulative number of minutes off nest before eggs start to lose viability.
	Max time until chick damage	Number of cumulative disturbance minutes at which chicks become vulnerable.
Overwash	Overwash threshold	Threshold assigned to each individual spatial unit at which tide height results in overwash.
	Minimum overwash habitat for colony	Minimum percentage of overwash habitat necessary for colony to form.
	Overwash habitat percentage	Percent of overwash habitat in each individual spatial unit.
Beach users	Daily visitors	Number of potential beach users per day that arrive at site.
	Visit probabilities	Number of beach users entering each spatial unit based on percentage of beach users in adjacent spatial unit closest to entrance.
Management Settings	Effect of spatial unit restrictions	Percentage of beach users within a spatial unit that will disturb terns based on colony-access restriction levels.
	Day codes	Assignment of day codes for scheduled weekly beach closings.
	Indicator lights	Thresholds at which warning lights in user interface turn from green to yellow to red.

Table 4-3. Management settings for restricting access within each spatial unit, with current values for each setting.

Restriction level	Restricted area	Magnitude of disturbance
0	Open access	100%
1	Colony only	67%
2	Buffer at rack line	25%
3	No visitor access	0%

Table 4-4. Results for all spatial units under different beach-closure scenarios using Monte Carlo simulations (200 runs each).

	Global productivity			
Days closed	Median	Mean	Std. dev.	Probability
0	0.05	0.10	0.13	na
1	0.08*	0.14	0.15	0.00
2	0.09	0.15	0.16	0.40
3	0.09	0.16	0.17	0.24
7	0.35*	0.38	0.16	0.00

*Significant difference from previous management option at p<0.05, Mann-Whitney U-test.

Table 4-5. Nesting productivity under different beach-closure scenarios for BBP01 and BBP02.

	BBP 01 productivity				BBP 02 productivity			
Days closed	Median	Mean	Std. dev.	Prob.	Median	Mean	Std. dev.	Prob.
0	0.14	0.24	0.28	na	0.04	0.16	0.28	na
1	0.12	0.23	0.27	0.52	0.11*	0.23	0.28	0.00
2	0.13	0.21	0.25	0.70	0.17*	0.26	0.27	0.04
3	0.12	0.24	0.28	0.27	0.17	0.29	0.31	0.27
7	0.10	0.21	0.28	0.90	0.33*	0.39	0.28	0.00

*Significant difference from previous management option at p <0.05, Mann-Whitney U-test.

Table 4-6. Nesting productivity under different beach-closure scenarios for BBP03 and BBP06.

	BBP 03 productivity				BBP 06 productivity			
Days closed	Median	Mean	Std. dev.	Prob.	Median	Mean	Std. dev.	Prob.
0	0.00	0.07	0.21	na	0.04	0.15	0.27	na
1	0.00	0.06	0.27	0.70	0.15*	0.25	0.26	0.00
2	0.01*	0.08	0.19	0.00	0.18	0.26	0.25	0.34
3	0.01	0.11	0.26	0.27	0.18	0.28	0.28	0.27
7	0.43*	0.47	0.25	0.00	0.70*	0.71	0.19	0.00

*Significant difference from previous management option at p <0.05, Mann-Whitney U-test.

Table 4-7. Global productivity for different management actions closing spatial units.

Spatial unit closure	Median	Mean	Std.Dev.
None (current mgt)	0.08	0.14	0.15
BBP02	0.10	0.16	0.17
BBP06	0.36	0.38	0.13
BBP02+06	0.37	0.41	0.15

Table 4-8. Results of Mann-Whitney U test comparing global productivity for different spatial-unit closures.

Spatial unit closure	None (current mgt)		BBP 02 and BBP06	
	Z-value	Prob	Z-value	Prob.
BBP02	-1.11	0.13	-12.55	0.00*
BBP06	-13.48	0.00*	-1.64	0.05
BBP02 and BBP06	-13.79	0.00*	na	na

*Significant difference at p <0.05.

Table 4-9. A monitoring plan for reducing uncertainty in simulation variables identified by sensitivity analysis as having the greatest effect on least tern nesting productivity (Chapter 3).

Indicators to monitor	Variable(s)	Frequency
Number of nesting pairs in colony	A,B,C	At least once a week; before and after busy holidays and weekends; before and after overwash tides.
Number of chicks in colony	D	
Number of fledglings in colony	D	
Distance at which defense response occurs	B	At least once a week; after busy holidays and weekends.
Percentage of colony responding	C	
Times off nest per disturbance	E	
Number of overwash occurrences in spatial unit	F	As overwash occurs.
Extent of overwash flooding in spatial unit	F	Day after overwash tide

A. Colony selection disturbance threshold
B. Colony tenacity disturbance threshold
C. Colony tenacity response
D. Productivity
E. Minutes per disturbance
F. Overwash threshold (Level 2 variable specific to each spatial unit)

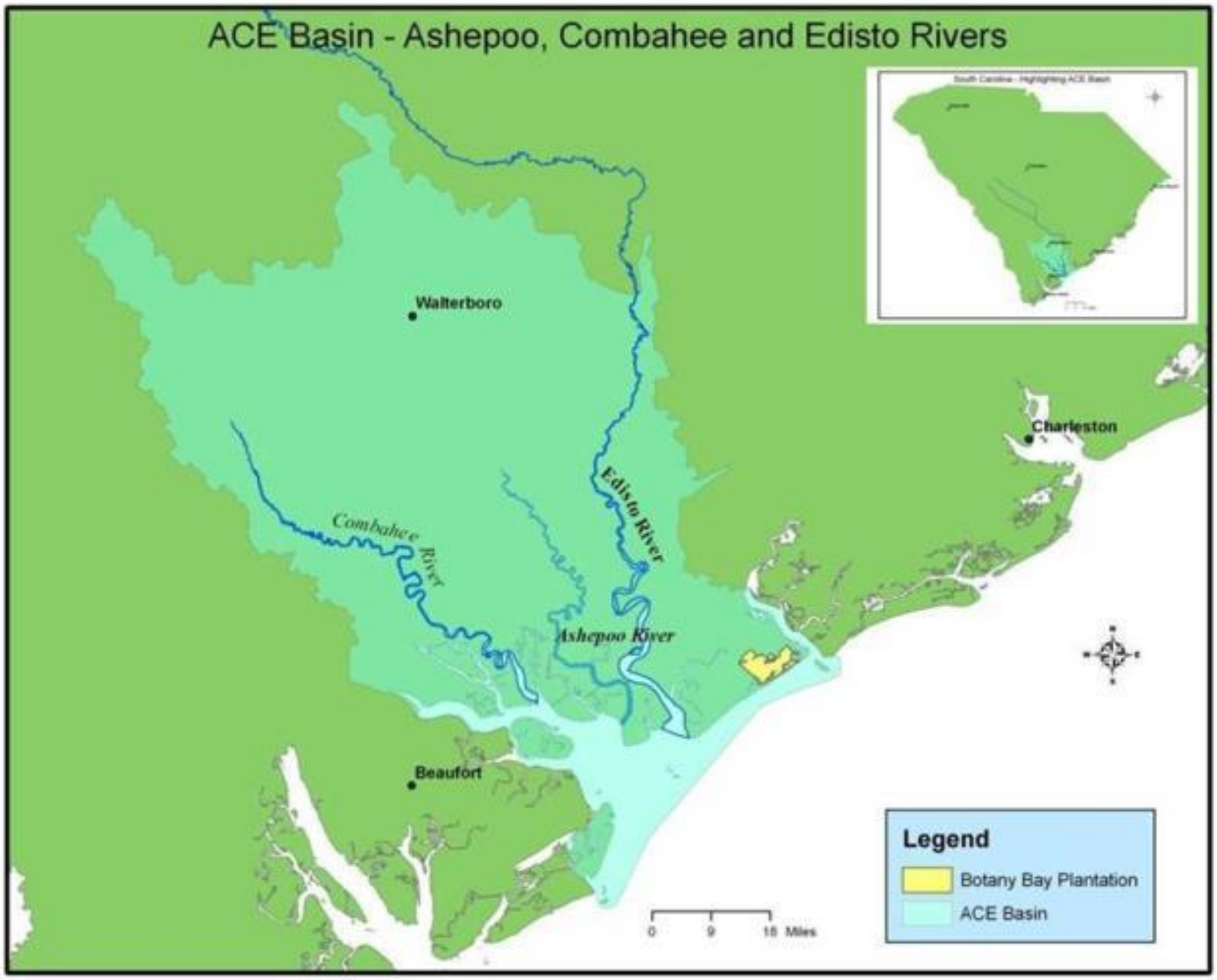

Figure 4-1. The location of Botany Bay Plantation within South Carolina's ACE Basin.

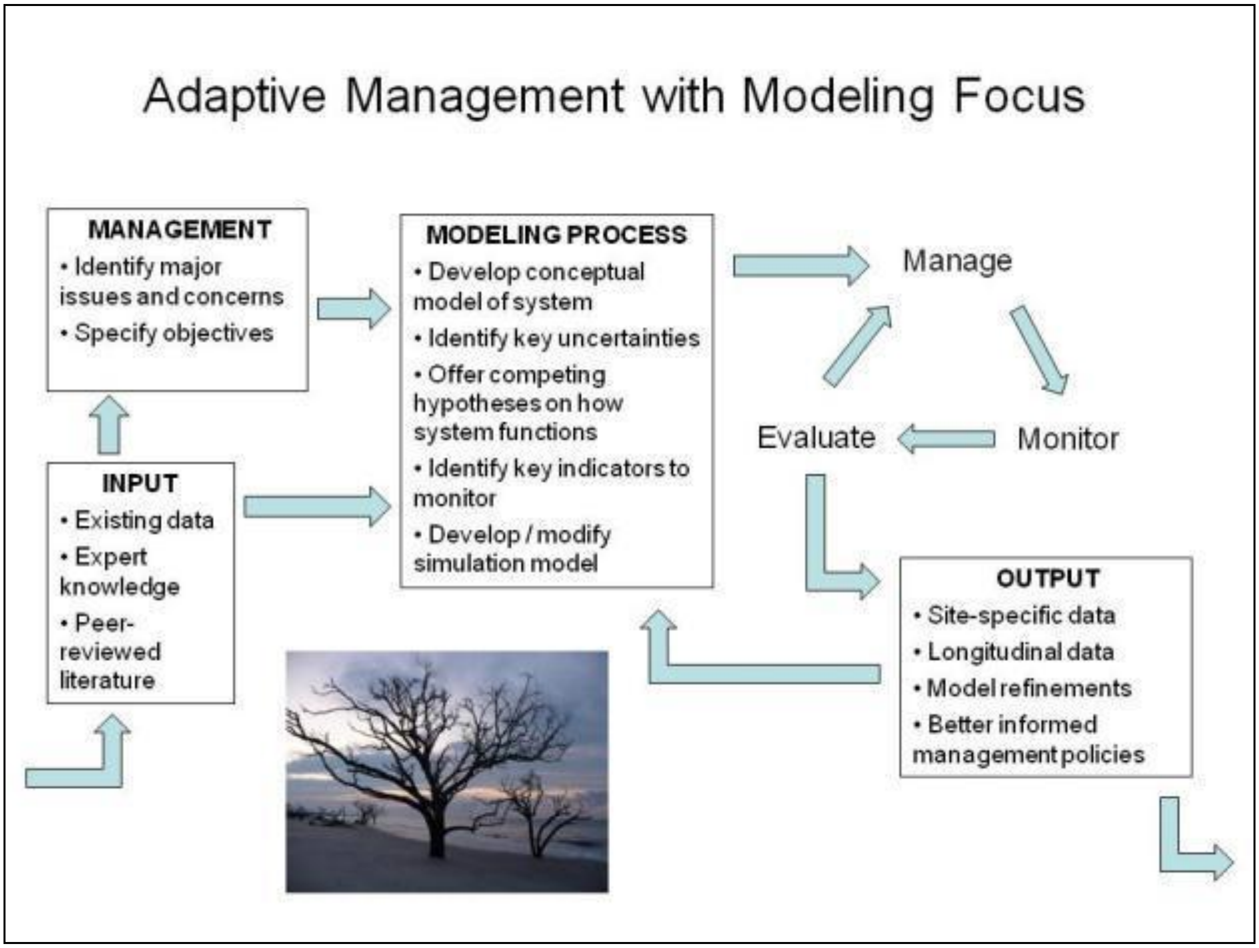

Figure 4-2. A conceptual diagram showing how simulation modeling fits into the adaptive management process.

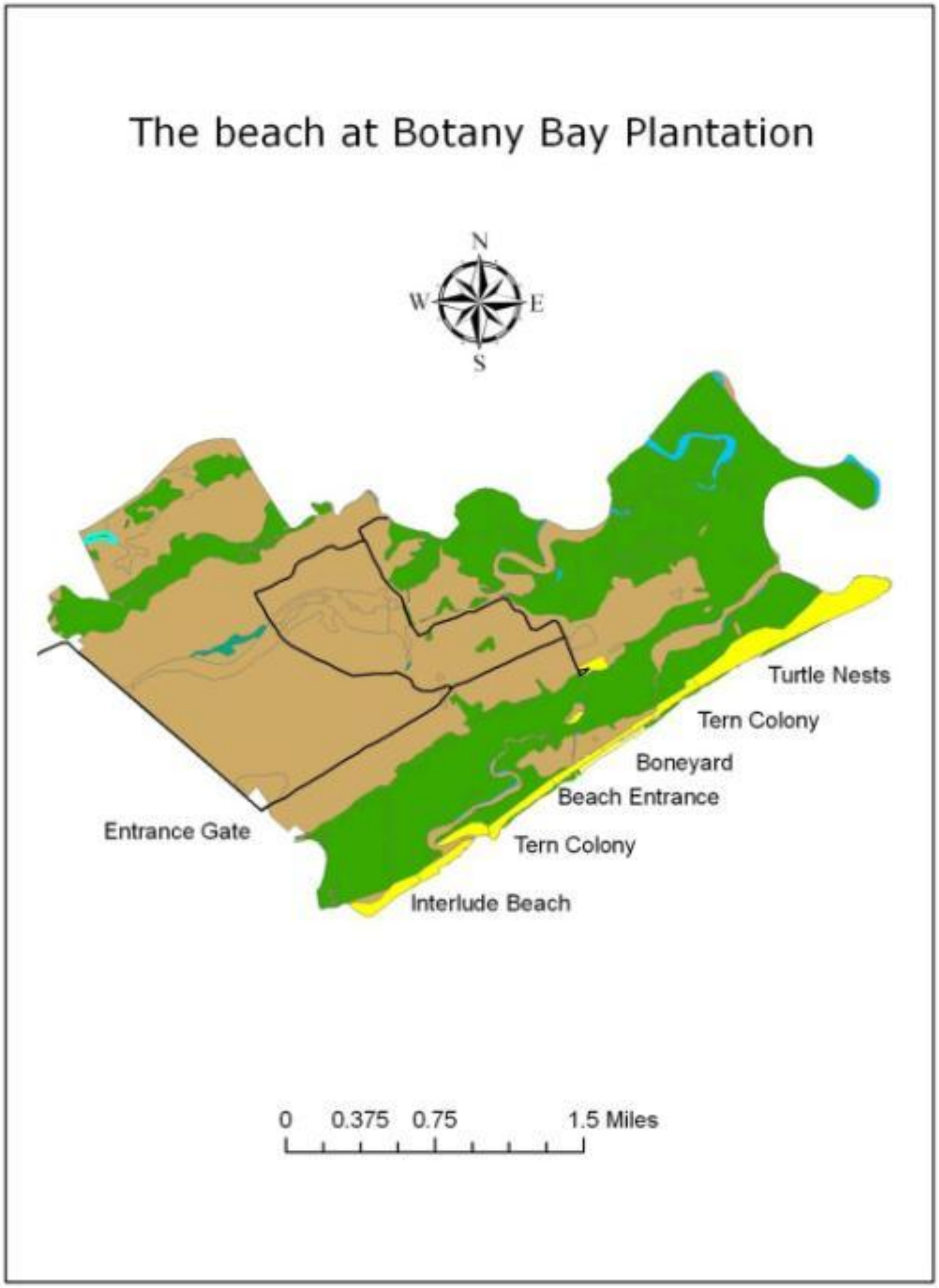

Figure 4-3. The beach at Botany Bay Plantation, showing the key areas.

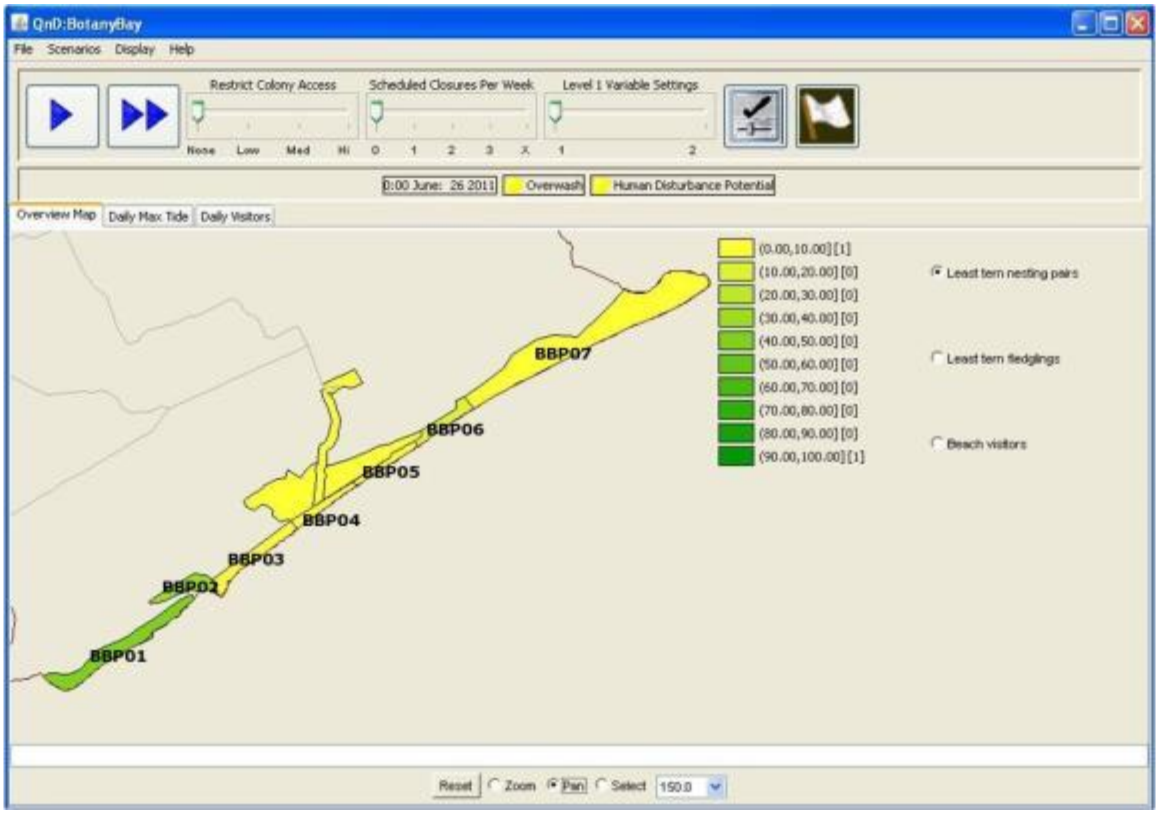

Figure 4-4. A screen shot of the simulation model's graphic user interface and the sections of front beach designated as spatial units. Labels added to show spatial units.

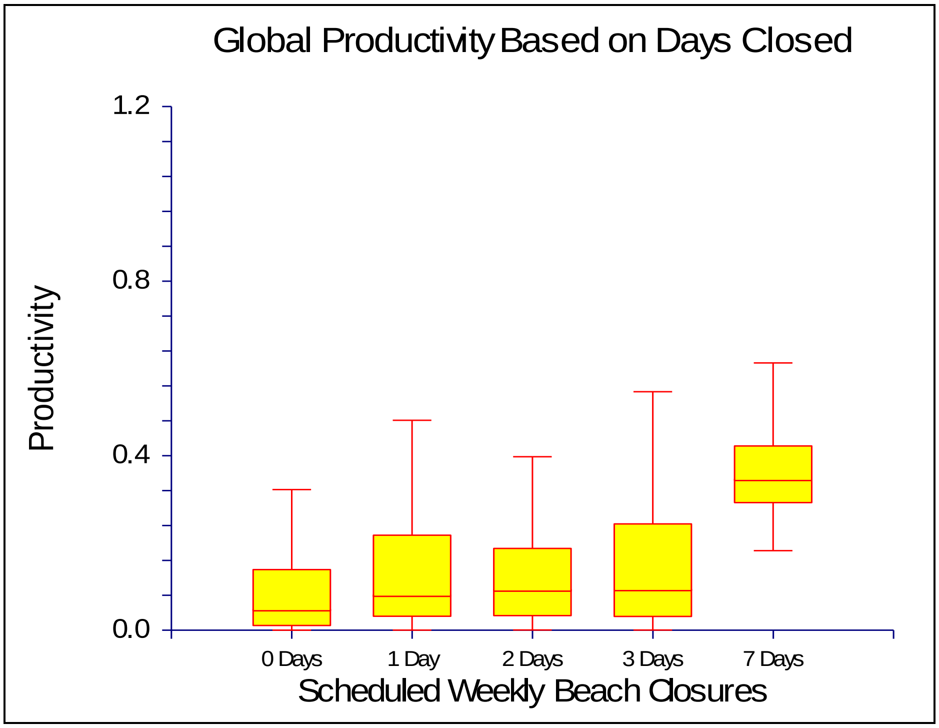

Figure 4-5. Box plots of productivity for least tern nesting in all spatial units.

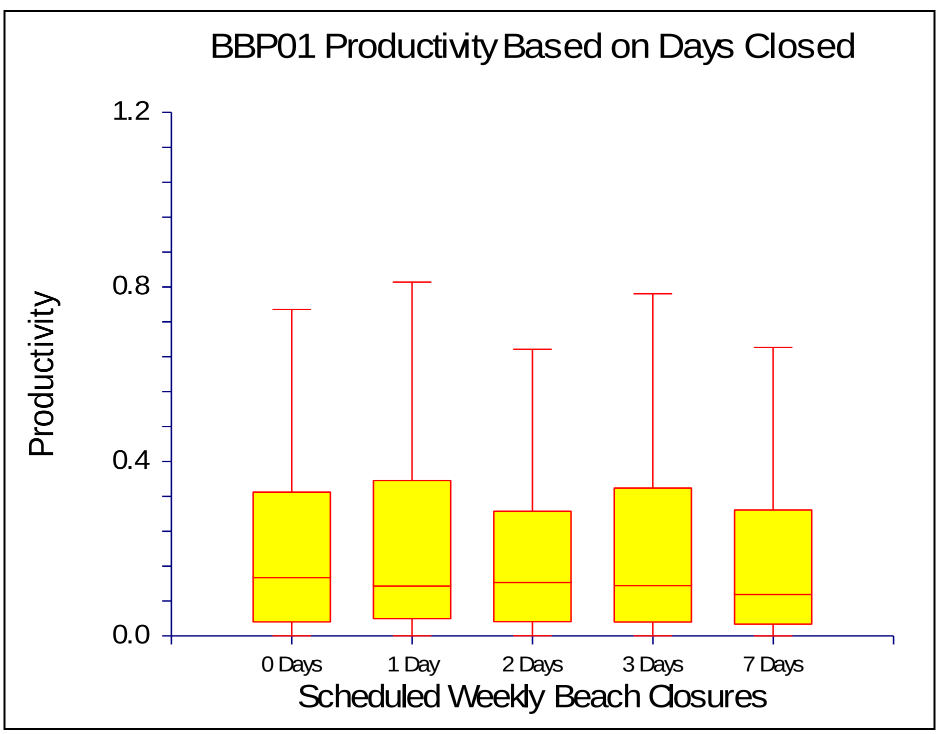

Figure 4-6. Changes in productivity to BBP01 under different beach closure scenarios.

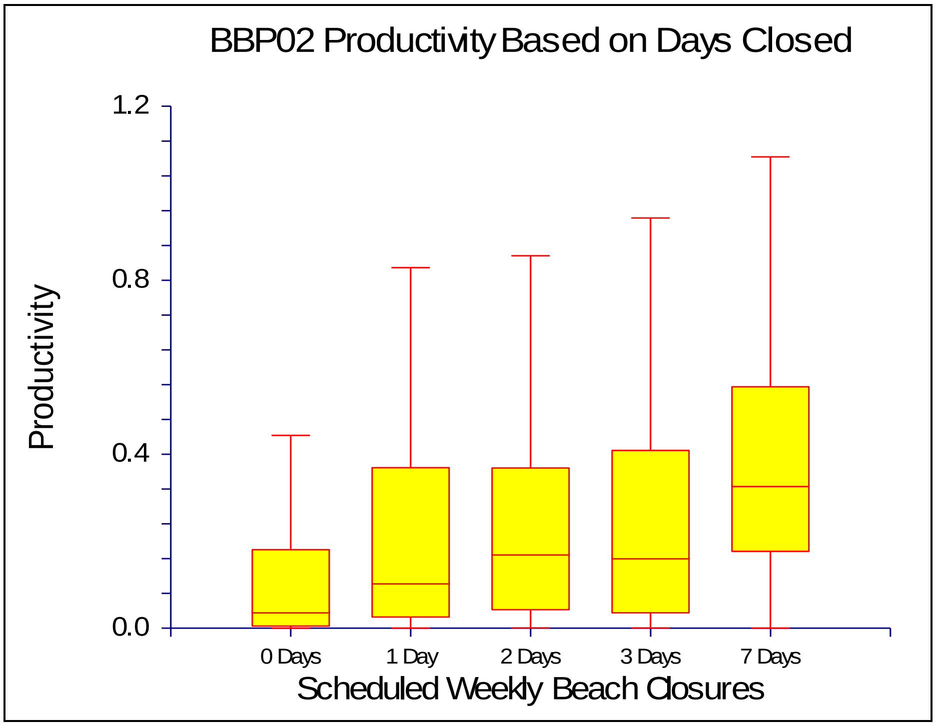

Figure 4-7. Changes in productivity to BBP02 under different beach closure scenarios.

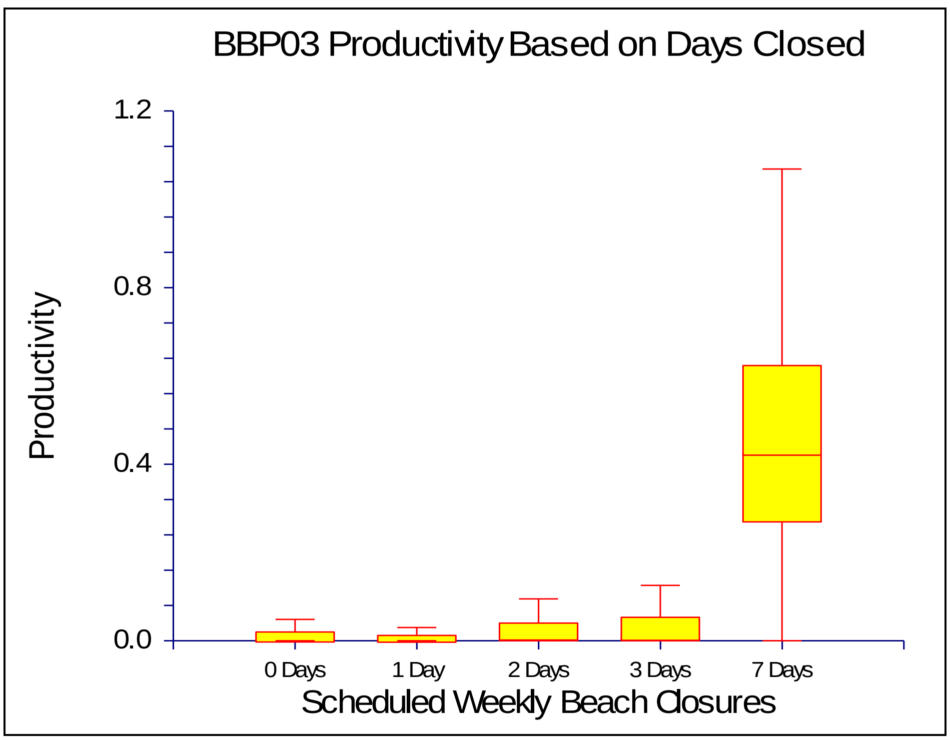

Figure 4-8. Changes in productivity to BBP03 under different beach closure scenarios.

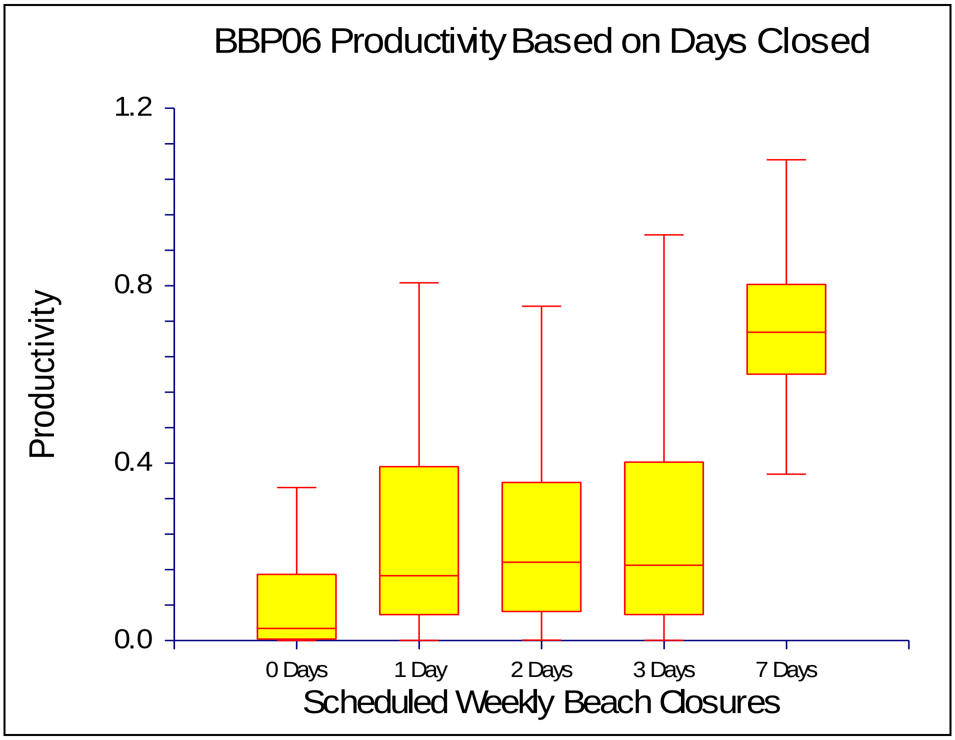

Figure 4-9. Changes in productivity to BBP06 under different beach closure scenarios.

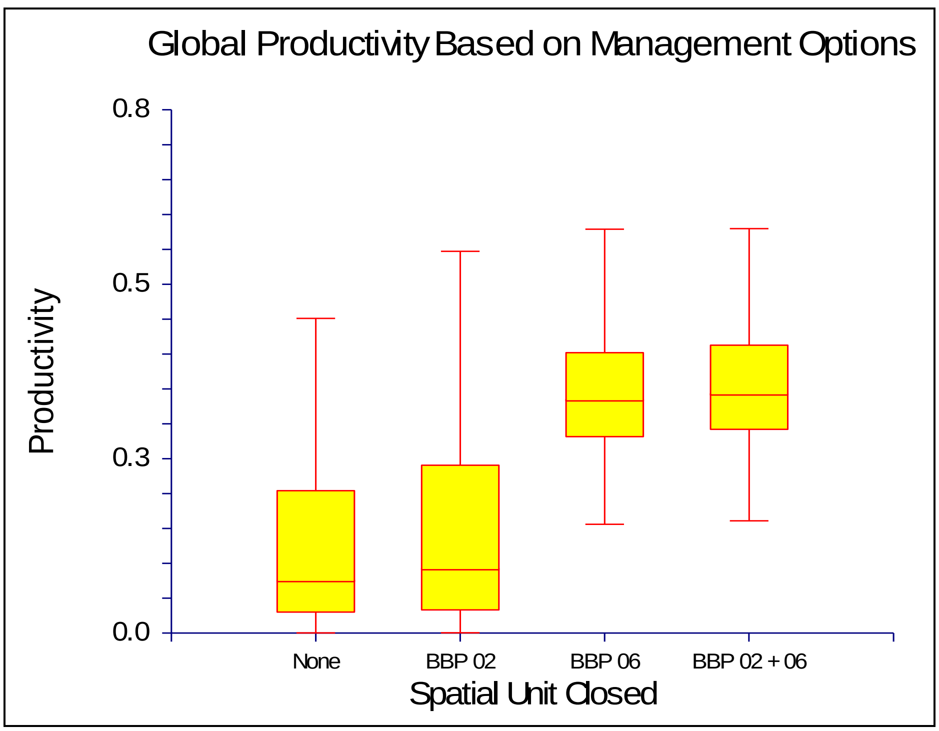

Figure 4-10. Global productivity based on management options for closing access to spatial units or maintaining current practice of roping off colonies.

CHAPTER 5
CONCLUSION

Model development is a process, not an end result. QnD BBP is designed for the long term. This current version of the model is part of an iterative process in which the simulated representations of the system are refined through data collection and analysis; management input; and new literature. A top priority of this project is to provide a practical method of decision support that is inexpensive to implement and replicable across sites. The model is designed to be validated over time through its own data-collection processes and to integrate that data collection into current management activities to avoid adding burdensome requirements.

The broader goal of this project is to develop a mechanism for understanding and responding to high levels of uncertainty and to find ways to incorporate resilience thinking into an object-oriented simulation modeling approach. The next 10 to 20 years are likely to bring a number of ecological surprises to coastal systems. These shocks and disturbances will demand immediate attention, and in many cases baseline data will either be lacking or of limited use. QnD BBP was developed with these future challenges in mind. It combines the power of simulation modeling with real-time management concerns and is designed to grow stronger with continued use. The model can be replicated across sites and customized to address a range of management concerns through adaptive management approaches at the local scale. It can be used to understand potential effects of management actions under scenarios such as storm surges and other major disturbances.

The specifics of this project involve managing human disturbance of least tern nesting. The research site offers a microcosm into the effects of larger system drivers on critical habitat, namely sea level rise and human encroachment. The monitoring necessary for this simulation model to work long-term is fairly basic and can be performed by beach volunteers with appropriate supervision (Chapter 4). As managers become more confident in the model's results, it can become an important tool for testing potential management actions.

An important part of making this a practical management tool will be developing the methods for data collection. Non-intrusive methods for estimating the number of nesting pairs, chicks, and fledglings will need to be tested and standardized. For instance, counting the number of fledglings can result in underestimating least tern productivity since juveniles may leave a colony or otherwise be difficult to detect once they have fledged (Thompson and Slack, 1984). Understanding these kinds of challenges will result in a practical monitoring effort that accounts for its own limitations. The same holds true for monitoring disturbance events and least terns' responses to them. Data collection and monitoring must begin with the basic needs of the simulation model and build upon that only as needed and only when the additional data collection can be reasonably implemented given management constraints.

Expanding the Model

Complexity can be added to the model over time, especially as data reduce uncertainty about the value ranges for key system variables. For example, greater frequency of disturbance by humans is known to provoke a greater defensive response in nesting least terns. A version of the model can be developed to count the number of prior disturbances when calculating defense response, and output results from the two versions can be compared to determine whether the added complexity improves management's decision-making abilities.

As it stands, QnD BBP leaves open the possibility for a number of refinements in its fundamental design. Examples include:

- Currently, the model is essentially a closed system for nesting pairs that enter it. Nesting pairs disappear from the system through two mechanisms. A series of overwash events may prevent renesting pairs from successfully nesting during the season, and nesting pairs that experience damage to eggs from human disturbance never renest. There may be need for processes that allow nesting pairs to explicitly choose not to nest anywhere on Botany Bay as a result of overwash or human disturbance. Currently this process works only for selecting a spatial unit within the site.

- Atwood and Massey (1988) note that abandonment of tern colonies may have more to do with nocturnal predation than with diurnal predation and human disturbance. Nocturnal activities are more difficult to measure, and abandonment may be falsely attributed to daytime disturbance. A well designed adaptive management program can take this kind of question into account and can conduct management experiments to determine which form of disturbance has the greatest impact.

- As currently constructed, the model can account for predation that results from disturbance by adjusting the Egg Damage Factor and Chick Damage Factor for human disturbance. But it may be that the model needs to add a Predator component that acts upon each tern nesting batch with a frequency and intensity determined by Level 1 variables.

These kinds of refinements need to done in coordination with management needs and ongoing data analysis. Adding unnecessary complexity to the model would work against the objective of developing an efficient method of decision support.

Use of the simulation model can also facilitate experiments done through active adaptive management. Examples include:

- The use of decoys and vocalizations to attract least terns to abandoned or unoccupied colony sites (Arnold et al., 2011; Kotliar and Burger, 1984).

- Elevated platforms and other beach modifications to protect nests against flood tides and encourage nesting at sites prone to overwash (Amador et al., 2008).

- Nesting-area monitors to guard active colony sites during times of excessive human activity such as three-day weekends (Burger, 1989).

Next Steps

Ultimately this project has the potential for developing into a replicable method for connecting and coordinating local adaptive management programs that make use of existing resources across a range of concerns at the local scale. As a simple model with modest data-collection needs, it stands the chance of holding up well for long-term management projects. It is a low-cost, low-staff tool designed for long-term use in the field. Developing a scalable local-based approach can help retain the benefits of centralized support for adaptive management while avoiding a number of the problems associated with regional adaptive management programs by engaging smaller management groups with a tighter focus on local programs.

The next step for this project is to begin a pilot effort in the 2012 nesting season to work with Botany Bay staff and volunteers to methodically collect data for the model's Level 1 variables, particularly those identified in the sensitivity analysis as having the greatest effect on least tern nesting productivity (Chapter 3). Implementing this will involve getting approval from management at the South Carolina Department of Natural Resources and developing the method for monitoring and data collection in cooperation with staff and volunteers on site. The initial goal is to run a five-year project with an eye toward collecting 20 years worth of data.

Over time, the collected data can be analyzed for patterns such as those found in adaptive cycles and alternative stable states. The ability to identify ecological thresholds and return points would be important for informing restoration and conservation efforts both on the site and in other coastal areas. The most basic approach would be to consider a simple binary approach to the stable state of a nesting area: It either supports a colony or it doesn't. Whether the primary source of the stress is human disturbance or storm surges and overwash tides, there is likely to be an identifiable threshold at which a colony disappears and a point at which the stress is reduced enough for terns to recolonize the site. Data collected by QnD can help make those determinations and provide decision support for management responses to those conditions.

APPENDIX A
BEACH USER SURVEY

Beach User Survey   Botany Bay Plantation   Summer 2009

Interview # __________

Date __________

Time __________

I. DEMOGRAPHICS

1. Age ____

2. Gender ____

3. Race ____ 1. White ___ 2. Black ___ 3. Asian ___ 4. Hispanic ____ 5. Other

4. Educ ___ 1. H.S. ____ 2. Some college ____ 3. Bachelor's ____ 4. Grad/ Prof

5. Married ___ Yes ___ No

6. # in HH ________

7. Household Income
   1. ___<$25,000
   2. ___ $25,000 - $49,999
   3. ___ $ 50,000 - $74,999
   4. ___ $75,000 - $99,999
   5. ___$100,000 +

8. Occupation ____

9. Hometown ____

10. Home zip code(if US) __________________

II. VISITOR PROFILE

11. How many people including yourself were in the car with you to get here? ____

12. How many of them were younger than 16? ______

13. Were you part of a group in other cars? ___ Total cars in group ___

14. Are you staying overnight away from home on this visit? Yes / No

    15. If Yes, where? ____

    16. For how many nights? ____________

17. How many times have you visited Edisto Beach / Edisto Island (including this time)?

____

____

18. How did you find out about this beach?

____

____

19. How many times, including this time, have you visited this beach?

____

20. When did you last visit?

____

____

III. ACTIVITY PROFILE

21. What activities have you participated in while on the beach today? Main activity?

____

____

22. Where did you go? Boneyard Middle South Stretch All

23. How long did you stay on the beach (hours / minutes)?________________________

How many people were on the beach today?

24. Start: ___ <10 ___ <10-25 ___ 26-50 ___ 51-75 ___ 75+

25. End: ___ <10 ___ <10-25 ___ 26-50 ___ 51-75 ___ 75+

26. Overall was that: ___ Too few ___ Right amount ___ Too many

27. Ideal amount? _____________

28. Do you plan to visit this beach again? Yes / No / Maybe

29. If yes, when do you plant to visit?

30. Do you plan to do anything today on the rest of Botany Bay Plantation?

IV. VISITOR PERCEPTIONS

31. What do you like about this beach?

32. What do you wish were different about this beach?

Thank you for your time.

APPENDIX B
SIMULATION CODE SAMPLES

Incoming Nesting Pairs (Spatial Unit)

```
<!-- ADD INCOMING PAIRS IF BELOW DISTURBANCE THRESHOLD  -->
<PProcess Name = "PAddIncomingNestingPairsIfBelowDisturbanceThreshold"
        PProcessType = "PProcess"  PProcessTiming = "Early" >

        <!-- Check that terns are migrating  -->
        <PSubProcess Name = "PCheckThatTernsAreMigrating"
                PProcessType = "PIfLessThan" >

                <Input SpatialLinkName="GLOBAL"
                        DData="DCounter"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName="GLOBAL"
                        DData="DMigratingTernEnd"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>

        <!-- Check for signal that spatial unit below threshold  -->
        <PSubProcess Name = "PCheckForSpatialUnitSignal"
                PProcessType = "PIfEquals" >

                <Input  SpatialUnitName = "Home"
                        DData="DSpatialUnitNestingPairsSignal"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName = "GLOBAL"
                        DData="DOne"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>

        <!-- Calculate number of incoming nesting pairs  -->
        <PSubProcess Name = "PGetNumberOfIncomingNestingPairs"
                PProcessType = "PDivideValue" >

                <Input SpatialLinkName = "GLOBAL"
                        DData="DNestingPairsForSpatialUnits"
                        DataType="CurrentValue">
                </Input>
```

```
            <Input SpatialLinkName = "GLOBAL"
                    DData="DGlobalCountSpatialUnitsForNestingPairs"
                    DataType="CurrentValue">
            </Input>

            <Output LocalComponentName = "CIncomingNestingPairs"
                    DData="DIncomingNestingPairsCount"
                    DataType="CurrentValue">
            </Output>
        </PSubProcess>

        <!-- Add incoming nesting pairs to spatial unit's available pairs for next batch -->
        <PSubProcess Name = "PMakeIncomingPairsAvailableToBatch"
            PProcessType = "PAddValue" >

            <Input SpatialUnitName = "Home"
                    DData="DAvailableNestingPairsForBatch"
                    DataType="CurrentValue">
            </Input>

            <Input  LocalComponentName = "CIncomingNestingPairs"
                    DData="DIncomingNestingPairsCount"
                    DataType="CurrentValue">
            </Input>

            <Output SpatialUnitName = "Home"
                    DData="DAvailableNestingPairsForBatch"
                    DataType="CurrentValue">
            </Output>
        </PSubProcess>
</PProcess>
```

Human Disturbance Effects on Available Nesting Pairs (Spatial Unit)

```
<!-- CALCULATE NESTING PAIRS LEAVING SPATIAL UNIT IF DISTURBANCE TOO
HIGH -->
<PProcess Name =
"PMoveNestingPairsOutOfSpatialUnitIfHumanDisturbanceHitsThreshold"
        PProcessType = "PProcess"  PProcessTiming = "Late" >

        <!-- Run this process until the start of final batch -->
        <PSubProcess Name = "PCheckDayCounter"
            PProcessType = "PIfLessThan" >

            <Input SpatialLinkName = "GLOBAL"
                    DData="DCounter"
```

```
                DataType="CurrentValue">
        </Input>

        <Output SpatialLinkName = "GLOBAL"
                DData="DEndTernBatches"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Check whether human disturbance exceeds tenacity threshold  -->
<PSubProcess Name = "PCheckForDisturbanceAboveThreshold"
        PProcessType = "PIfGreaterThan" >

        <Input LocalComponentName="CBeachUsers"
                DData="DBeachUserDisturbanceEvents"
                DataType="CurrentValue">
        </Input>

        <Output SpatialLinkName = "GLOBAL"
                DData="DColonyTenacityThresholdA"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Calculate number of nesting pairs leaving spatial unit  -->
<PSubProcess Name = "PCalculateNestingPairsLeavingSpatialUnit"
        PProcessType = "PMultiplyValue" >

        <Input SpatialUnitName="Home"
                DData="DAvailableNestingPairsForBatch"
                DataType="CurrentValue">
        </Input>

        <Input SpatialLinkName = "GLOBAL"
                DData="DColonyTenacityResponse"
                DataType="CurrentValue">
        </Input>

        <Output LocalComponentName = "CDepartingNestingPairs"
                DData="DNestingPairsLeavingSpatialUnit"
                DataType="CurrentValue">
        </Output>
</PSubProcess>
```

```xml
        <!-- Subtract departing pairs from available nesting pairs for next batch -->
        <PSubProcess Name = "PSubtractNestingPairsFromAvailableInSpatialUnit"
                PProcessType = "PSubtractValue" >

                <Input SpatialUnitName="Home"
                        DData="DAvailableNestingPairsForBatch"
                        DataType="CurrentValue">
                </Input>

                <Input LocalComponentName = "CDepartingNestingPairs"
                        DData="DNestingPairsLeavingSpatialUnit"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialUnitName="Home"
                        DData="DAvailableNestingPairsForBatch"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>

        <!-- Add departing nesting pairs to global supply for redistribution -->
        <PSubProcess Name = "PAddDepartingPairsToGlobalSupplyForSpatialUnits"
                PProcessType = "PAddValue" >

                <Input SpatialLinkName="GLOBAL"
                        DData="DGlobalNestingPairsAvailable"
                        DataType="CurrentValue">
                </Input>

                <Input LocalComponentName = "CDepartingNestingPairs"
                        DData="DNestingPairsLeavingSpatialUnit"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName="GLOBAL"
                        DData="DGlobalNestingPairsAvailable"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>
</PProcess>
```

Human Disturbance Damage to Tern Eggs (Tern Batch 1 .. 7)

```
<!—CALCULATE DAILY EGG DAMAGE FROM HUMAN DISTURBANCE -->
<PProcess Name = "PCalculateDisturbanceDamageToTernEggsBatch1"
        PProcessType = "PProcess"  PProcessTiming = "Late" >

        <!-- Check that egg counter has started  -->
        <PSubProcess Name = "PCheckCounterStartedBatch1"
                PProcessType = "PIfGreaterThan" >

                <Input LocalComponentName="CTernBatch1"
                        DData="DBatchEggCounter"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName="GLOBAL"
                        DData="DZero"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>

        <!-- Check that incubation period hasn't ended -->
        <PSubProcess Name = "PCheckIncubationPeriodBatch1"
                PProcessType = "PIfLessThan" >

                <Input LocalComponentName="CTernBatch1"
                        DData="DBatchEggCounter"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName="GLOBAL"
                        DData="DTernEggIncubationDays"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>

        <!-- Check that batch has eggs -->
        <PSubProcess Name = "PCheckForEggsBatch1"
                PProcessType = "PIfGreaterThan" >

                <Input LocalComponentName="CTernBatch1"
                        DData="DTernEggsBatch"
                        DataType="CurrentValue">
                </Input>
```

```xml
        <Output SpatialLinkName="GLOBAL"
                DData="DZero"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Calculate the daily time off nest due to human disturbance -->
<PSubProcess Name = "PCalculateTimeOffNestFromDisturbance"
        PProcessType = "PMultiplyValue" >

        <Input  LocalComponentName="CBeachUsers"
                DData="DBeachUserDisturbanceEvents"
                DataType="CurrentValue">
        </Input>

        <Input SpatialLinkName="GLOBAL"
                DData="DMinutesPerDisturbance"
                DataType="CurrentValue">
        </Input>

        <Output LocalComponentName="CTernBatch1"
                DData="DDailyTimeOffNest"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Calculate egg damage from disturbance in time step -->
<PSubProcess Name = "PCalculateDailyDisturbanceToEggs"
        PProcessType = "PDivideValue" >

        <Input  LocalComponentName = "CTernBatch1"
                DData="DDailyTimeOffNest"
                DataType="CurrentValue">
        </Input>

        <Input  SpatialLinkName="GLOBAL"
                DData="DMaxTimeUntilEggDamage"
                DataType="CurrentValue">
        </Input>

        <Output LocalComponentName="CTernBatch1"
                DData="DDailyEggDamageFromDisturbance"
                DataType="CurrentValue">
        </Output>
</PSubProcess>
```

```
        <!-- Add daily egg damage from disturbance to running total -->
        <PSubProcess Name = "PAddDailyDisturbanceToRunningTotal"
                PProcessType = "PAddValue" >

                <Input  LocalComponentName = "CTernBatch1"
                        DData="DRunningTotalEggDamageFromDisturbance"
                        DataType="CurrentValue">
                </Input>

                <Input  LocalComponentName = "CTernBatch1"
                        DData="DDailyEggDamageFromDisturbance"
                        DataType="CurrentValue">
                </Input>

                <Output LocalComponentName="CTernBatch1"
                        DData="DRunningTotalEggDamageFromDisturbance"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>
</PProcess>

<!—ELIMINATE EGGS ONCE DISTURBANCE THRESHOLD REACHED -->
<PProcess Name = "PCalculateEggLossFromDisturbance"
        PProcessType = "PProcess"  PProcessTiming = "Late" >

        <!-- Check that egg counter has started  -->
        <PSubProcess Name = "PCheckCounterStartedBatch1"
                PProcessType = "PIfGreaterThan" >

                <Input LocalComponentName="CTernBatch1"
                        DData="DBatchEggCounter"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName="GLOBAL"
                        DData="DZero"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>

        <!-- Check that incubation period hasn't ended -->
        <PSubProcess Name = "PCheckIncubationPeriodBatch1"
                PProcessType = "PIfLessThan" >
```

```xml
        <Input LocalComponentName="CTernBatch1"
                DData="DBatchEggCounter"
                DataType="CurrentValue">
        </Input>

        <Output SpatialLinkName="GLOBAL"
                DData="DTernEggIncubationDays"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Check if running total of egg damage is 1.0 or greater -->
<PSubProcess Name = "PCheckEggDamageRunningTotal"
        PProcessType = "PIfGreaterThan" >

        <Input LocalComponentName="CTernBatch1"
                DData="DRunningTotalEggDamageFromDisturbance"
                DataType="CurrentValue">
        </Input>

        <Output SpatialLinkName="GLOBAL"
                DData="DZeroPointNinetyNine"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Calculate percent of batch eggs lost to disturbance -->
<PSubProcess Name = "PCalculatePercentBatchEggsLostToDisturbance"
        PProcessType = "PMultiplyValue" >

        <Input  LocalComponentName = "CTernBatch1"
                DData="DRunningTotalEggDamageFromDisturbance"
                DataType="CurrentValue">
        </Input>

        <Input  SpatialLinkName="GLOBAL"
                DData="DEggDamageFactor"
                DataType="CurrentValue">
        </Input>

        <Output LocalComponentName = "CTernBatch1"
                DData="DPercentEggsLostFromDisturbance"
                DataType="CurrentValue">
        </Output>
</PSubProcess>
```

```
<!-- Calculate number of batch eggs lost to disturbance -->
<PSubProcess Name = "PCalculateNumberBatchEggsLostToDisturbance"
        PProcessType = "PMultiplyValue" >

        <Input  LocalComponentName = "CTernBatch1"
                DData="DTernEggsBatch"
                DataType="CurrentValue">
        </Input>

        <Input  LocalComponentName = "CTernBatch1"
                DData="DPercentEggsLostFromDisturbance"
                DataType="CurrentValue">
        </Input>

        <Output LocalComponentName = "CTernBatch1"
                DData="DDailyDisturbanceBatchEggsLost"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Subtract eggs lost to disturbance from batch total -->
<PSubProcess Name = "PSubtractBatchEggsLostToDisturbance"
        PProcessType = "PSubtractValue" >

        <Input  LocalComponentName = "CTernBatch1"
                DData="DTernEggsBatch"
                DataType="CurrentValue">
        </Input>

        <Input  LocalComponentName = "CTernBatch1"
                DData="DDailyDisturbanceBatchEggsLost"
                DataType="CurrentValue">
        </Input>

        <Output LocalComponentName = "CTernBatch1"
                DData="DTernEggsBatch"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Add batch's eggs lost to spatial unit's total eggs lost for time step  -->
<PSubProcess Name = "PAddBatchEggsLostToSpatialUnitTotal"
        PProcessType = "PAddValue" >
```

```
        <Input  SpatialUnitName="Home"
                DData="DDailyDisturbanceSpatialUnitEggsLost"
                DataType="CurrentValue">
        </Input>

        <Input  LocalComponentName = "CTernBatch1"
                DData="DDailyDisturbanceBatchEggsLost"
                DataType="CurrentValue">
        </Input>

        <Output SpatialUnitName="Home"
                DData="DDailyDisturbanceSpatialUnitEggsLost"
                DataType="CurrentValue">
        </Output>
    </PSubProcess>

    <!-- Zero out batch's running total of egg damage from disturbance -->
    <PSubProcess Name = "PSetRunningBatchTotalToZero"
        PProcessType = "PSetValue" >

        <Input  SpatialLinkName="GLOBAL"
                DData="DZero"
                DataType="CurrentValue">
        </Input>

        <Output LocalComponentName = "CTernBatch1"
                DData="DRunningTotalEggDamageFromDisturbance"
                DataType="CurrentValue">
        </Output>
    </PSubProcess>
</PProcess>
```

Overwash Damage to Tern Eggs (Tern Batch 1 .. 7)

```
<!—CALCULATE DAMAGE TO TERN EGGS FROM OVERWASH2  -->
<PProcess Name = "PCalculateOverwash2DamageToTernEggsBatch1"
    PProcessType = "PProcess"  PProcessTiming = "Late" >

    <!-- Check that egg counter has started  -->
    <PSubProcess Name = "PCheckCounterStartedBatch1"
        PProcessType = "PIfGreaterThan" >
```

```
        <Input  LocalComponentName="CTernBatch1"
                DData="DBatchEggCounter"
                DataType="CurrentValue">
        </Input>

        <Output SpatialLinkName="GLOBAL"
                DData="DZero"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Check that incubation period hasn't ended -->
<PSubProcess Name = "PCheckIncubationPeriodBatch1"
        PProcessType = "PIfLessThan" >

        <Input  LocalComponentName="CTernBatch1"
                DData="DBatchEggCounter"
                DataType="CurrentValue">
        </Input>

        <Output SpatialLinkName="GLOBAL"
                DData="DTernEggIncubationDays"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Check that time step had an overwash2 event -->
<PSubProcess Name = "PCheckForOverwash2Batch1"
        PProcessType = "PIfGreaterThan" >

        <Input  SpatialUnitName="Home"
                DData="DSpatialUnitOverwash2"
                DataType="CurrentValue">
        </Input>

        <Output SpatialLinkName="GLOBAL"
                DData="DZero"
                DataType="CurrentValue">
        </Output>
</PSubProcess>

<!-- Calculate overwash losses to batch's egg count   -->
<PSubProcess Name = "PCalculateOverwash2EggLossBatch1"
        PProcessType = "PMultiplyValue" >
```

```
            <Input  LocalComponentName="CTernBatch1"
                    DData="DTernEggsBatch"
                    DataType="CurrentValue">
            </Input>

            <Input  SpatialUnitName="Home"
                    DData="DSpatialUnitOverwash2"
                    DataType="CurrentValue">
            </Input>

            <Input SpatialLinkName="GLOBAL"
                    DData="DOverwashTernEggDamageFactor"
                    DataType="CurrentValue">
            </Input>

            <Output LocalComponentName="CTernBatch1"
                    DData="DEggsLostOverwash2"
                    DataType="CurrentValue">
            </Output>
        </PSubProcess>
</PProcess>


<!—SUBTRACT EGG LOSSES DUE TO OVERWASH 1 AND 2 -->
<PProcess Name = "PSubtractOverwashDamageFromTernEggsBatch1"
        PProcessType = "PProcess"  PProcessTiming = "Late" >

        <!-- Check that egg counter has started  -->
        <PSubProcess Name = "PCheckCounterStartedBatch1"
                PProcessType = "PIfGreaterThan" >

                <Input  LocalComponentName="CTernBatch1"
                        DData="DBatchEggCounter"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName="GLOBAL"
                        DData="DZero"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>
```

```
        <!-- Check that incubation period hasn't ended -->
        <PSubProcess Name = "PCheckIncubationPeriodBatch1"
                PProcessType = "PIfLessThan" >

                <Input  LocalComponentName="CTernBatch1"
                        DData="DBatchEggCounter"
                        DataType="CurrentValue">
                </Input>

                <Output SpatialLinkName="GLOBAL"
                        DData="DTernEggIncubationDays"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>

        <!-- Subtract both overwash losses from batch's egg count  -->
        <PSubProcess Name = "PSubtractEggLossesFromBatch1"
                PProcessType = "PSubtractValue" >

                <Input  LocalComponentName="CTernBatch1"
                        DData="DTernEggsBatch"
                        DataType="CurrentValue">
                </Input>

                <Input  LocalComponentName="CTernBatch1"
                        DData="DEggsLostOverwash1"
                        DataType="CurrentValue">
                </Input>

                <Input  LocalComponentName="CTernBatch1"
                        DData="DEggsLostOverwash2"
                        DataType="CurrentValue">
                </Input>

                <Output LocalComponentName="CTernBatch1"
                        DData="DTernEggsBatch"
                        DataType="CurrentValue">
                </Output>
        </PSubProcess>
</PProcess>
```

LIST OF REFERENCES

Allan, C., and G.H. Stankey, editors. 2009. *Adaptive Environmental Management: A Practitioner's Guide*. Springer, Amsterdam, the Netherlands.

Allen, J., and K. Lu. 2003. Modeling and Prediction of Future Urban Growth in the Charleston Region of South Carolina: a GIS-based Integrated Approach. *Conservation Ecology* 8(2):2 [online] URL: http://www.consecol.org/vol8/iss2/art2

Amador, E., R.M. Salgado, and E. Palacios. 2008. Nesting site management for Sternula antillarum (Charadriiformes : Laridae) conservation in Baja California Sur, Mexico. *Revista Mexicana de Biodiversidad* 79(1):271-274.

Anderson, D.W., and J.O. Keith. 1980. The Human Influence on Seabird Nesting Success: Conservation Implications. *Biological Conservation* 18:65-80.

Argent, R.M. 2009. Components of Adaptive Management. Pages 11-32 in Allan, C., and G.H. Stankey, editors. *Adaptive Environmental Management: A Practioner's Guide*. Springer, New York, New York, USA.

Arnold, J.M., I.C.T. Nisbet, and R. Veit. 2011. Assessing Aural and Visual Cueing as Tools for Seabird Management. *Journal of Wildlife Management* 75(3):495-500.

Ascough, J.C., H.R. Maier, J.K. Ravalico, and M.W. Strudley. 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecological Modelling* 219:383-399.

Atwood, J.L., and B.W. Massey. 1988. Site Fidelity of Least Terns in California. *The Condor* 90:389-394.

Beale, C.M. 2007. Managing visitor access to seabird colonies: a spatial simulation and empirical observations. *Ibis* 149(Suppl.1):102-111.

Beisner, B.E., D.T. Haydon, and K. Cuddington. 2003. Alternative stable states in ecology. *Frontiers in Ecology and the Environment* 1(7):376-382.

Biggs, R., S. R. Carpenter, and W. A. Brock. 2009. Turning back from the brink: Detecting an impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences* 106(3):826-831.

Blumstein, D.T., E. Fernandez-Juricic, P.A. Zollner, and S.C. Garity. 2005. Inter-specific variation in avian responses to human disturbance. *Journal of Applied Ecology* 42:943-953.

Borowski, I., and M. Hare. 2007. Exploring the Gap Between Water Managers and Researchers: Difficulties of Model-Based Tools to Support Practical Water Management. *Water Resources Management* 21:1049-1074.

Bousquet, F., and C. Le Page. 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling* 176:313-332.

Brand, F. S., and K. Jax. 2007. Focusing the Meaning(s) of Resilience: Resilience as a Descriptive Concept and Boundary Object. *Ecology and Society* 12(1):23 [online] URL: http://www.ecologyandsociety.org/vol12/iss1/art23/

Bromberg Gedan, K., B.R. Silliman, and M.D. Bertness. Centuries of Human-Driven Change in Salt Marsh Ecosystems. *Annual Review of Marine Science* 1:117-141.

Buckley, R.C., and N. King.2003. "Visitor-impact Data in a Land-management Context. Pages 89-99 in R. Buckley, C. Pickering, and D.B. Weaver, editors. *Nature-based tourism, environment, and land management* (Papers presented at the Fenner Conference on Nature Tourism and the Environment, held in Canberra, Australia, 2001). CABI Publishing, Cambridge, Massachusetts, USA.

Buckley, R.C. 2004a.Using Ecological Impact Measurements to Design Visitor Management. Pages 287-296 in R. Buckley, editor. *Environmental Impacts of Tourism*. CABI Publishing, Cambridge, Massachusetts, USA.

Buckley, R.C. 2004b. Impacts of Ecotourism on Birds. Pages 187-209 in R. Buckley, editor. *Environmental Impacts of Tourism*. CABI Publishing, Cambridge, Massachusetts, USA.

Bures, R., and W. Kanapaux. 2011. Historical regimes and social indicators of resilience in an urban system: the case of Charleston, South Carolina. *Ecology and Society* 16(4): 16. http://dx.doi.org/10.5751/ES-04293-160416

Burger, J. 1984. Colony Stability in Least Terns. *The Condor* 86(1):61-67.

Burger, J. 1987. Physical and Social Determinants of Nest-Site Selection in Piping Plover in New Jersey. *The Condor* 89(4):811-818.

Burger, J. 1988. Social Attraction in Nesting Least Terns: Effects of Numbers, Spacing, and Pair Bonds. *The Condor* 90(3):575-582.

Burger, J. 1989. Least Tern Populations in Coastal New Jersey: Monitoring and Management of a Regionally-Endangered Species. *Journal of Coastal Research* 5(4):801-811.

Burger, J., and M. Gochfeld. 1988. Defensive aggression in terns: Effect of species, density, and isolation. *Aggressive Behavior* 14(3):169-178.

Burger, J., C. Jeitner, K. Clark, and L.J. Niles. 2004. The effect of human activities on migrant shorebirds: successful adaptive management. *Environmental Conservation* 31(4):283-288.

Burton, N.H.K. 2007. Landscape approaches to studying the effects of disturbance on waterbirds. *Ibis* 149(Suppl.1):95-101.

Campo, P.C., G.A. Mendoza, P. Guizol, T.R. Villanueva, and F. Bousquet. 2009. Exploring management strategies for community-based forests using multi-agent systems: A case study in Palawan, Philippines. *Journal of Environmental Management* 90:3607-3615.

Cariboni, J., D. Gatelli, R. Liska, and A. Saltelli. 2007. The role of sensitivity analysis in ecological modeling. *Ecological Modelling* 203:167-182.

Carpenter, S., B. Walker, J. M. Anderies, and N. Abel. 2001. From Metaphor to Measurement: Resilience of What to What? *Ecosystems* 4:765-781.

Carpenter, S. R., W. A. Brock, and D. Ludwig. 2002. Collapse, Learning, and Renewal. Pages 173-194 in L. H. Gunderson and C. S. Holling, editors. *Panarchy: Understanding transformation in human and natural systems*. Island Press, Washington, D.C., USA.

Cessford, G., and A. Muhar. 2003. Monitoring options for visitor numbers in national parks and natural areas. *Journal for Nature Conservation* 11:240-250.

Clark, M.J. 2002. Dealing with uncertainty: adaptive approaches to sustainable river management. *Aquatic Conservation: Marine and Freshwater Ecosystems* 12:347-363.

Confalonieri, R., G. Bellocchi, S. Bregaglio, M. Donatelli, and M. Acutis. 2010. Comparison of sensitivity analysis techniques: A case study with the rice model WARM. *Ecological Modelling* 221:1897-1906.

Cooperative Conservation America. 2006. Case Study Database. Accessed November 2011. http://www.cooperativeconservationamerica.org.

Craft, C., J. Clough, J. Ehman, S. Joye, R. Park, S. Pennings, H. Guo, and M. Machmuller. 2009. Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Frontiers in Ecology and the Environment* 7(2):73-78.

Crain, C.M., B.S Halpern, M.W. Beck, and C.V. Kappel. 2009. Understanding and Managing Human Threats to the Coastal Marine Environment. *Annals of the New York Academy of Sciences* 1162:39-62.

Dambacher, J.M., H.W. Li, and P.A. Rossignol. 2003. Qualitative predictions in model ecosystems. *Ecological Modelling* 161:79-93.

Dambacher, J.M., D.J. Gaughan, M. Rochet, P.A. Rossignol, and V.M. Trenkel. 2009. Qualitative modelling and indicators of exploited ecosystems. *Fish and Fisheries* 10:305-322.

DeAngelis, D.L., and W.M. Mooij. 2005. Individual-Based Modeling of Ecological and Evolutionary Processes. *Annual Review of Ecology, Evolution, and Systematics* 36:147-168.

Doak, D.F., J.A. Estes, B.S. Halpern, U. Jacob, D.R. Lindberg, J. Lovvorn, D.H. Monson, M.T. Tinker, T.M. Williams, J.T. Wootton, I. Carroll, M. Emmerson, F. Micheli, and M. Novak. 2008. Understanding and Predicting Ecological Dynamics: Are Major Surprises Inevitable? *Ecology* 89(4):952-961.

Elliott, M.L., R. Hurt, and W.J. Sydeman. 2007. Breeding Biology and Status of the California Least Tern Sterna antillarum browni at Alameda Point, San Francisco Bay, California. *Waterbirds* 30(3):317-325.

Evans, K.E., and T. Klinger. 2008. Obstacles to Bottom-Up Implementation of Marine Ecosystem Management. *Conservation Biology* 22(5):1135-1143.

FitzGerald, D.M., M.S. Fenster, B.A. Argow, and I.V. Buynevich. 2008. Coastal Impacts Due to Sea Level Rise. *Annual Review of Earth and Planetary Sciences* 36:601-674.

Folke, C. 2006. Resilience: The emergence of a perspective for social-ecological systems analysis. *Global Environmental Change* 16:253-267.

Folke, C., T. Hahn, P. Olsson, and J. Norberg. 2005. Adaptive Governance of Social-Ecological Systems. *Annual Review of Environment and Resources* 30:441-473.

Gabriel, A.O., and R.D. Kreutzwiser. 2000. Conceptualizing Environmental Stress: A Stress-Response Model of Coastal Sandy Barriers. *Environmental Management* 25(1):53-69.

Gore, J.A., and M.J. Kinnison. 1991. Hatching Success in Roof and Ground Colonies of Least Terns. *The Condor* 93:759-762.

Grime, J.P. 1973. Competitive Exclusion in Herbaceous Vegetation. *Nature* 242:344-347.

Grimm, V., U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, et al. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198:115-126.

Groffman, P.M., J.S. Baron, T. Blett, A.J. Gold, I. Goodman, L.H. Gunderson, B.M. Levinson, et al. 2006. Ecological Thresholds: The Key to Successful Environmental Management or an Important Concept with No Practical Application? *Ecosystems* 9:1-13.

Gunderson, L.H., and C. S. Holling, editors. 2002. *Panarchy: Understanding transformation in human and natural systems*. Island Press, Washington, D.C., USA.

Gunderson, L., and S.S. Light. 2006. Adaptive management and adaptive governance in the everglades ecosystem. *Policy Sciences* 39:323-334.

Guttal, V., and C. Jayaprakash. 2008. Changing skewness: an early warning signal of regime shifts in ecosystems. *Ecology Letters* 11:450-460.

Habron, G. 2003. Role of Adaptive Management for Watershed Councils. *Environmental Management* 31(1):29-41.

Hadwen, W.L., W. Hill, and C.M. Pickering. 2007. Icons under threat: Why monitoring visitors and their ecological impacts in protected areas matters. *Ecological Management and Restoration* 8(3):177-181.

Hadwen, W.L., W. Hill, and C.M. Pickering. 2008. Linking Visitor Impact Research to Visitor Impact Monitoring in Protected Areas. *Journal of Ecotourism* 7(1):87-93.

Hall, M.J., R.S. Young, E.R. Thieler, and R.D. Priddy. 1990. Shoreline Response to Hurricane Hugo. *Journal of Coastal Research* 6(1):211-221.

Harrigal, D. 2009. *Management Plan for Botany Bay Plantation Wildlife Management Area and Heritage Preserve*. SC Department of Natural Resources: Columbia, South Carolina, USA.

Hernández-Matías, A., L. Jover, and X. Ruiz. 2003. Predation on Common Tern Eggs in Relation to Sub-colony Size, Nest Aggregation and Breeding Synchrony. *Waterbirds* 26(3):280-289.

Holling, C. S. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4:390-405.

Holling, C. S., and L.H. Gunderson. 2002. Resilience and Adaptive Cycles. Pages 25-62 in L. H. Gunderson and C. S. Holling, editors. *Panarchy: Understanding transformation in human and natural systems*. Island Press, Washington, D.C., USA.

Holling, C.S., L.H. Gunderson, and D. Ludwig. 2002a. In Quest of a Theory of Adaptive Change. Pages 3-24 in L. H. Gunderson and C. S. Holling, editors. *Panarchy: Understanding transformation in human and natural systems*. Island Press, Washington, D.C., USA.

Holling, C. S., L. H. Gunderson, and G. D. Peterson. 2002b. Sustainability and Panarchies. Pages 63-102 in L. H. Gunderson and C. S. Holling, editors. *Panarchy: Understanding transformation in human and natural systems*. Island Press, Washington, D.C., USA.

Image Matters LLC. 2011. SLAMM Output for Coastal SC and GA. From: Christopher Craft, et al., *Effect of Sea Level Rise and Climate Variability on Ecosystem Services of Tidal Marshes*. USEPA STAR program grant RD 83222001-0. http://www.slammview.org. Accessed November 2011.

Jackson, J.A., B.E. Rowe, M.S. Hetrick, and B.J. Schardien. 1982. Site-Specific Nest Defense Behavior of Black Skimmers and Least Terns. *The Condor* 84(1):120.

Jackson, J.A., and B.J.S. Jackson. 1985. Status, Dispersion, and Population Changes of the Least Tern in Coastal Mississippi. *Colonial Waterbirds* 8(1):54-62.

Jacobson, S.K., J.K. Morris, J.S. Sanders, E.N. Wiley, M. Brooks, R.E. Bennetts, H.F. Percival, and S. Marynowski. 2006. Understanding Barriers to Implementation of an Adaptive Land Management Program. *Conservation Biology* 20(5):1516-1527.

Jacobson, C., K.F.D. Hughey, W.J. Allen, S. Rixecker, and R.W. Carter. 2009. Toward More Reflexive Use of Adaptive Management. *Society and Natural Resources* 22(5):484-495.

Kiker, G.A., and I. Linkov. 2006. The QnD Model/Game System: Integrating Questions and Decisions for Multiple Stressors. Pages 203-226 in G. Arapis, N., Goncharova, and P. Baveye, editors. *Ecotoxicology, Ecological Risk Assessment and Multiple Stressors*. Springer: Amsterdam, the Netherlands.

Kiker, G.A, N.A. Rivers-Moore, M.K. Kiker, and I. Linkov. 2006. QnD: A modeling game system for integrating environmental processes and practical management decisions. Pages 151-186 in B. Morel, and I. Linkov, editors. *Environmental Security and Environmental Management*. Springer: Amsterdam, the Netherlands.

Kiker, G.A., R. Muñoz-Carpena, P. Wolski, A. Cathey, A. Gaughan, and J. Kim. 2008. Incorporating Uncertainty into Adaptive, Transboundary Water Challenges: a conceptual design for the Okavango River Basin. *International Journal of Risk Assessment and Management* 10(4):312-338.

Kiker, G.A., and R. Thummalapalli. 2009. How2QnD: Design and Construction of a Game-Style, Environmental Simulation Engine and Interface Using UML, XML, and Java. Pages 103-129 in Papajorgji, P.J. and P.M. Pardalos, editors.. *Advances in Modeling Agricultural Systems*, Springer, New York, New York, USA.

Kiker, G.A., R. Muñoz-Carpena, N. Ranger, M. Kiker, and I. Linkov. 2011. Adaptation in Coastal Systems: Vulnerability and Uncertainty Within Complex Socioecological Systems. Pages 375-400 in I. Linkov and T.S. Bridges, editors. *Climate, Global Change and Local Adaptation*. NATO Science for Peace and Security Series C: Environmental Security. Springer, Amsterdam, the Netherlands.

Kirsch, E.M., and J.G. Sidle. 1999. Status of the interior population of Least Tern. *Journal of Wildlife Management* 63(2):470–483.

Koontz, T.M., and J. Bodine. 2008. Implementing Ecosystem Management in Public Agencies: Lessons from the U.S. Bureau of Land Management and the Forest Service. *Conservation Biology* 22(1):60-69.

Kotliar, N.B., and J. Burger. 1984. The Use of Decoys to Attract Least Terns (Sterna antillarum) to Abandoned Colony Sites in New Jersey. *Colonial Waterbirds* 7:134-138

Kotliar, N.B., and J. Burger. 1986. Colony Site Selection and Abandonment by Least Terns *Sterna antillarum* in New Jersey, USA. *Biological Conservation* 37:1-21.

Lafferty, K.D. 2001. Birds at a Southern California beach: seasonality, habitat use and disturbance by human activity. *Biodiversity and Conservation* 10:1949-1962.

Lafferty, K.D., D. Goodman, and C.P. Sandoval. 2006. Restoration of breeding by snowy plovers following protection from disturbance. *Biodiversity and Conservation* 15:2217-2230.

Lawson, S.R. 2006. Computer Simulation as a Tool for Planning and Management of Visitor Use in Protected Natural Areas. *Journal of Sustainable Tourism* 14(6):600-617.

Lawson, S.R., R.E. Manning, W.A. Valliere, and B. Wang. 2003. Proactive monitoring and adaptive management of social carrying capacity in Arches National Park: an application of computer simulation modeling. *Journal of Environmental Management* 68:305-313.

Lee, K. N. 1999. Appraising adaptive management. *Conservation Ecology* 3(2): 3. [online] URL: http://www.consecol.org/vol3/iss2/art3/

Levin, S. 1999. *Fragile Dominion: Complexity and the Commons*. Perseus Publishing, Cambridge, Massachusetts, USA.

Levin, S., and R.T. Paine. 1974. Disturbance, Patch Formation, and Community Structure. *Proceedings of the National Academy of Sciences* 71(7):2744—2747.

Levrel, H., M. Etienne, C. Kerbiriou, C. Le Page, and M. Rouan. 2009. Co-Modeling Process, Negotiations, and Power Relationships: Some Outputs From a MAB Project on the Island of Ouessant. *Society and Natural Resources* 22:172-188.

Liley, D., and W.J. Sutherland. 2007. Predicting the population consequences of human disturbance for Ringed Plovers Charadrius hiaticula: a game theory approach. *Ibis* 149(Suppl.1):82-94.

Logan, J.R., Z. Xu,and B.D. Stults. 2011. Bridging Census Tract Data across Decades Using Interpolation with Population and Areal Weighting. Working paper, Population Studies and Training Center, Brown University.

Lombard, C.D., J.A. Collazo, and D.B. McNair. 2010. Nest and Chick Survival and Colony-Site Dynamics of Least Terns in the U.S. Virgin Islands. *The Condor* 112(1):56-64.

Lyons, J.E., M.C. Runge, H.P. Laskowski, and W.L. Kendall. 2008. Monitoring in the Context of Structured Decisions-Making and Adaptive Management. *The Journal of Wildlife Management* 72(8):1683-1692.

MacMillan, D.C., and K. Marshall. 2006. The Delphi-process - an expert-based approach to ecological modelling in data-poor environments. *Animal Conservation* 9:11-19.

Manring, S.L., and S. Pearsall. 2006. Creating an Adaptive Ecosystem Management Network Among Stakeholders of the Lower Roanoke River, North Carolina, USA. *Ecology and Society* 10(2):16 [online] http://www.ecologyandsociety.org/vol10/iss2/art16/

Massey, B.W., and J.L. Atwood. 1981. Second-Wave Nesting of the California Least Tern: Age Composition and Reproductive Success. *The Auk* 98(3):596-605.

Massey, B.W., and J.M. Fancher. 1989. Renesting by California Least Terns. *Journal of Field Ornithology* 60(3):350-357.

McFadden, L. 2008. Exploring the challenges of integrated coastal zone management and reflecting on contributions to ‘integration’ from geographical thought. *The Geographical Journal* 174(4):299-314.

McLain, R.J., and R.G. Lee. 1996. Adaptive Management: Promises and Pitfalls. *Environmental Management* 20(4):437-448.

McLane, A.J., C. Semeniuk, G.J. McDermid, and D.J. Marceau. 2011. The role of agent-based models in wildlife ecology and management. *Ecological Modelling* 222:1544-1556.

Medeiros, R., J.A. Ramos, V.H. Paiva, A. Almeida, P. Pedro, and S. Antunes. 2007. Signage reduces the impact of human disturbance on little tern nesting success in Portugal. *Biological Conservation* 135:99-106.

Medema, W., B.S. McIntosh, and P.J. Jeffrey. 2008. From premise to practice: a critical assessment of integrated water resources management and adaptive management approaches in the water sector. *Ecology and Society* 13(2): 29. [online] URL: http://www.ecologyandsociety.org/vol13/iss2/art29/

Morghan, K.J.R., R.L. Sheley, and T.J. Svejcar. 2006. Successful Adaptive Management - The Integration of Research and Management. *Rangeland Ecological Management* 59:216-219.

Nicholls, R. J. and A. Cazenave. 2010. Sea-Level Rise and Its Impact on Coastal Zones. *Science* 328:1517-1520.

Otter, H.S., and M. Capobianco. 2000. Uncertainty in integrated coastal zone management. *Journal of Coastal Conservation* 6:23-32.

Pain, R.T., and S.A. Levin. 1981. Intertidal Landscapes: Disturbance and the Dynamics of Pattern. *Ecological Monographs* 51(2):145-178.

Palacios, E., and E. Mellink. 1996. Status of the Least Tern in the Gulf of California. *Journal of Field Ornithology* 67(1):48-58.

Poch, M., J. Comas, I. Rodriguez-Roda, M. Sanchez-Marre, and U. Cortes. 2004. Designing and building real environmental decision support systems. *Environmental Modelling and Software* 19:857-873.

Rahmstorf, S. 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. *Science* 315:368-370.

Reever Morghan, K.J., R.L. Sheley, and T.J. Svejcar. 2006. Successful Adaptive Management—The Integration of Research and Management. *Rangeland Ecology and Management* 59:216-219.

Robert, H.C., and C.J. Ralph. 1975. Effects of Human Disturbance on the Breeding Success of Gulls. *The Condor* 77(4):495-499.

Salles, P., and B. Bredeweg. 2006. Modelling population and community dynamics with qualitative reasoning. *Ecological Modelling* 195:114-128.

Savereno, L.A., and T.M. Murphy. 1995. A Review of Nesting Sites Used by Least Terns in South Carolina. *The Chat* 59(2):41-46.

Scavia, D., J. C. Field, D. F. Boesch, R. W. Buddemeier, V. Burkett, D. R. Cayan, M. Fogarty, M. A. Harwell, R. W. Howarth, C. Mason, D. J. Reed, T. C. Royer, A. H. Sallenger, and J. G. Titus. 2002. Climate Change Impacts on U.S. Coastal and Marine Systems. *Estuaries* 25(2):149-164.

Scheffer, M. 2009. *Critical Transitions in Nature and Society*. Princeton University Press, Princeton, New Jersey, USA.

Scheffer, M., F. Westley, W. A. Brock, and M. Holmgren. 2002. Dynamic Interaction of Societies and Ecosystems – Linking Theories from Ecology, Economy, and Sociology. Pages 195-240 in L. H. Gunderson and C. S. Holling, editors. *Panarchy: Understanding transformation in human and natural systems*. Island Press, Washington, D.C., USA.

Scheffer, M., and S.R. Carpenter. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology and Evolution* 18(12):648-656.

Schlacher, T.A., J. Dugan, D.S. Schoeman, M. Lastra, A. Jones, F. Scapini, A. McLachlan, and O. Defeo. 2007. Sandy beaches at the brink. *Diversity and Distributions* 13:550-560.

Schlacher, T.A., D.S. Schoeman, J. Dugan, M. Lastra, A. Jones, F. Scapini, and A. McLachlan. 2008. Sandy beach ecosystems: key features, sampling issues, management challenges and climate change impacts. *Marine Ecology* 29(Suppl 1):70-90.

Schlüter, M., R.R.J. McAllister, R. Arlinghaus, N. Bunnefeld, K. Eisenack, F. Hölker, E.J. Milner-Gulland, B. Müller, E. Nicholson, M. Quass, and M. Stöven. 2012. New Horizons for Managing the Environment: A Review of Coupled Social-Ecological Systems Modeling. *Natural Resource Modeling* 25(1):219-272.

Schröder, A., L. Persson, and A.M. De Roos. 2005. Direct experimental evidence for alternative stable states: a review. *Oikos* 110:3-19.

Selin, S., and D. Chavez. 1995. Developing a Collaborative Model for Environmental Planning and Management. *Environmental Management* 19(2):189-195.

Sit, V., and B. Taylor, editors. 1998. Statistical Methods for Adaptive Management Studies. *Land Management Handbook No. 42*. Research Branch, British Columbia Ministry of Forests: Victoria, British Columbia, Canada.

South Carolina Department of Natural Resources. 2006. *The 2005 Comprehensive Wildlife Conservation Strategy*. Columbia, SC. http://www.dnr.sc.gov/cwcs/index.html. Last accessed February 2012.

South Carolina Department of Natural Resources. 2011. *Ashepoo-Combahee-Edisto (ACE) Basin National Estuarine Research Reserve Management Plan: 2011-2016*. Charleston, SC. http://www.dnr.sc.gov/marine/NERR/pdf/ACEMP11-16.pdf. Last accessed, December 2011.

Stankey, G.H. 2002. Adaptive Management at the Regional Scale: Breakthrough Innovation or Mission Impossible? A Report on an American Experience. *Fenner Conference on the Environment*. Canberra, Australia, July 30 - Aug. 1.

Stankey, G. H. 2003. Adaptive management at the regional scale: Breakthrough innovation or mission impossible? A report on an American experience. Pages 159–177 in *Proceedings of the 2002 Fenner Conference on the Environment: Agriculture for the Australian Environment*. 24–25 July 2002. Johnstone Center, Charles Stuart University, Canberra, Australia.

Stankey, G.H., R.N. Clark, and B.T. Bormann. 2005. *Adaptive Management of Natural Resources: Theory, Concepts, and Management Institutions*. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, Oregon, USA.

Suding, K.N., and R.J. Hobbs. 2009. Threshold models in restoration and conservation: a developing framework. *Trends in Ecology and Evolution* 24(5):271-279.

Sutherland, W.J. 2007. Future directions in disturbance research. *Ibis* 149(Supp. 1):120-124.

Szell, C.C., and M.S. Woodrey, 2003. Reproductive Ecology of the Least Tern along the Lower Mississippi River. *Waterbirds* 26(1):35-43.

Thom, R.M., G. Williams, A. Borde, J. Southard, S. Sargeant, D. Woodruff, J.C. Laufle, and S. Glasoe. 2005. Adaptively Addressing Uncertainty in Estuarine and Near Coastal Restoration Projects. *Journal of Coastal Research* 40:94-108.

Thompson, B.C., and R.D. Slack. 1984. Post-Fledging Departure from Colonies by Juvenile Least Terns in Texas: Implications for Estimating Production. *The Wilson Bulletin* 96(2):309-313.

Thompson, B.C., J.A. Jackson, J. Burger, L.A. Hill, E.M. Kirsch, and J.L. Atwood. 1997. Least Tern (Sterna antillarum). In A. Poole, editor. *The Birds of North America Online*. Ithaca: Cornell Lab of Ornithology. http://bna.birds.cornell.edu/bna/species/290. Last accessed December 2011.

Tomkins, I.R. 1959. Life History Notes on the Least Tern. *The Wilson Bulletin* 71(4):313-322.

Van Dolah, R. F., G. H. M. Riekerk, D. C. Bergquist, J. Felber, D. E. Chestnut, and A. F. Holland. 2008. Estuarine habitat quality reflects urbanization at large spatial scales in South Carolina's coastal zone. *Science of the Total Environment* 390:142-154.

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, Adaptability and Transformability in Social-ecological Systems. *Ecology and Society* 9(2):5 [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art5/

Walker, B., and D. Salt. 2006. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World.* Island Press, Washington, D.C., USA.

Walters, C. 1997. Challenges in adaptive management of riparian and coastal ecosystems. *Conservation Ecology* [online]1(2):1. URL: http://www.consecol.org/vol1/iss2/art1/

Walters, C.J., and C.S. Holling. 1990. Large-Scale Management Experiments and Learning by Doing. *Ecology* 71(6):2060-2068.

Wenner, E., D. Sanger, S. Upchurch, and M. Thompson. 2001. *Characterization of the Ashepoo-Combahee-Edisto (ACE) Basin, South Carolina*. South Carolina Department of Natural Resources, Marine Resources Division: Charleston, South Carolina. http://www.dnr.sc.gov/marine/mrri/acechar/specgal/leastern.htm. Last accessed November 2011.

West, A.D., J.D. Goss-Custard, R.A. Stillman, R.W.G. Caldow, S.E.A. le V. dit Durell, and S. McGrorty. 2002. Predicting the impacts of disturbance on shorebird mortality using a behaviour-based model. *Biological Conservation* 106:319-328.

Wilkinson, P.M. 1997. Survey and Census of Colonial Nesting Seabirds in South Carolina. *The Chat* 61(4):233-259.

Williams, B.K., R.C. Szaro, and C.D. Shapiro. 2009. *Adaptive Management: The U.S. Department of Interior Technical Guide*. U.S. Department of Interior, Washington, D.C.

Zhang, K., B.C. Douglas, and S.P. Leatherman. 2004. Global Warming and Coastal Erosion. *Climatic Change* 64:41-58.

Zuria, I., and E. Mellink. 2005. Fish Abundance and the 1995 Nesting Season of the Least Tern at Bahia de San Jorge, Northern Gulf of California, Mexico. *Waterbirds* 28(2):172-180.

BIOGRAPHICAL SKETCH

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