Chapter 19
Beach Management Practices and Occupation Dynamics: An Agent-Based Modeling Study for the Coastal Town of Nags Head, NC, USA

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Abstract The analysis of interactions between human and natural systems is crucial for sound beach management practices. Those interactions can be simulated via agent-based modeling. Nevertheless, more work is needed to identify and understand model capabilities prior to societal implementations. This study presents the application of an agent-based model in the coastal town of Nags Head, NC USA. The case study focuses on the influence of storm arrival patterns and soft-engineering design alternatives on town occupation dynamics. The agent-based model consists of three interactive sub-models: (1) Natural Processes and Coastal Landforms, (2) Beach Management, and (3) Household Decisions. Modeling results indicate that sea level rise will exacerbate storm damages and could lead to a declining town

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population. In addition, analysis of occupancy with soft-engineering design alternatives suggests that population in Nags Head maximizes when economic benefits and protection from both, dunes and beaches, are balanced. Our results serve to exemplify the usage and capabilities of an agent-based model for beach management practices in coastal towns subjected to storms and sea level rise. Application of the model provides valuable insights of the system that can ultimately be used by decision-makers and town managers.

Keywords Human-nature interaction • Coastal population • Coupled human-physical systems • Community attractiveness • Soft-engineering • Storm-arrival patterns

19.1 Introduction

Human population increases within coastal areas has led to challenges between natural and anthropic systems. As shorelines retreat landward because of changes in storminess (Slott et al. 2006; Barnard et al. 2015) and sea level rise (Nicholls and Cazenave 2010; Cazenave and Le Cozannet 2014; Church et al. 2013; and many others), flooding risks of coastal properties are heightened and economies are impacted (Gopalakrishnan et al. 2011; Pendleton et al. 2011). Estimates for the U.S. predict that by 2060 25% of properties within 150 m of the coast could be lost to erosion, roughly costing $530 million per year in property losses (Heinz Center 2000). To mitigate erosional impacts, coastal communities often adopt engineering solutions such as seawall construction, beach nourishment, and dune replenishment (e.g. Hamm et al. 2002; Dean and Dalrymple 2004). Communities may also employ policy actions (e.g. land-use restriction and zoning practices) in an attempt to adapt to shoreline retreat (Kousky 2014).

Beach management should rely upon an understanding of feedbacks between natural and human-induced processes that influence the coastal system (Murray et al. 2013; Chin et al. 2014). This knowledge is usually gained by means of observations and modelling studies (e.g. conceptual, statistical, numerical, and mathematical). Despite feedbacks between human and the coastal environment (Vitousek et al. 1997) each component is often considered as operating independently. Until recently, models for coastal systems tend to focus on natural processes alone, such as beach profile changes (Dean 1991), shoreline evolution (Reeve and Fleming 1997) and coastal area models (Lesser et al. 2004, Luettich and Westerink 2004; Roelvink et al. 2009) disregarding human-nature interactions. Similarly, models analyzing economics and policy (Franck 2009a; Filatova et al. 2011) do not typically consider modifications to the nearshore environment as a fundamental part of coastal evolution analysis.

In the last two decades, research integrating human and natural systems within a coupled framework has increasingly appeared in coastal management (Yohe 1991; West et al. 2001; Werner and McNamara 2007; Lazarus et al. 2016). Previous

studies indicate that coupling of human actions and natural processes can reveal concepts such as appearance of a storm-induced tipping point in the long term growth of a community (Franck 2009a), boom and bust cycles in tourist-driven development on barrier islands (McNamara and Werner 2008); and the manifestation of chaotic shoreline evolution spurred by sea level rise and resource allocation challenges among neighboring towns (Lazarus et al. 2011). These emergent trends can provide insight into management activities outcomes (Smith et al. 2009; Magliocca et al. 2011). However, changes in land occupation dynamics due to specific management practices within a coastal community subject to storms, sea level rise, and shoreline retreat are not well understood. Thus, our main goal is to investigate occupation dynamics in a coastal community using soft-engineered beach management practices and the aforementioned natural processes.

To attain our goal, we used an agent-based model (ABM) (Gilbert 2008) coupling natural processes, human activities and beach management solutions in a case study on the coastal town of Nags Head, NC, USA. The ABM was used as a tool to explore the following questions: (1) Do storm arrival patterns have any effect on occupation dynamics in the town? (2) How do design alternatives of beach nourishment and dune replenishment projects affect the community's occupation dynamics? Insights gained from these questions are of particular interest for decision makers working on strategies toward medium- to long-term flourishing and sustainable development of coastal communities (Elko et al. 2016).

19.2   Agent-Based Model for a Coastal Community

Coastal morphodynamics occur over a broad range of spatial and temporal scales. Coastal landforms span from ripples at centimeter scales to continental shelves at scales of hundreds of kilometers. Morphologic features within this range include beach cusps, nearshore bars, beach ridges, and sand banks to identify only some examples. Similarly, these features exhibit time dependence that links to the temporal scale of their governing oceanographic phenomena. Processes with variations of seconds (e.g., short gravity waves) control small-scale features, whereas larger landforms depend on long-term geological processes (e.g. sea level oscillations and isostatic response) (Cowell and Thom, 1994). Present work deals with spatial scales from kilometers to tens of kilometers and temporal scales from years to decades (Fig. 19.1), corresponding to the scale of interactions among social dynamics and morphology of coastal towns.

ABM is a simulation tool that enables the exploration of interactions between the natural environment and social systems by explicitly modeling the behavior of individual agents over a heterogeneous landscape (Filatova et al. 2011). Individual agents' behaviors are combined to reveal the behavior of the whole system. Our ABM couples changes in the coastal landscape with housing market dynamics to explore feedbacks between soft-engineered protection projects and occupation trends. The coupled coastal community model consists of three sub-models: 1. natu-
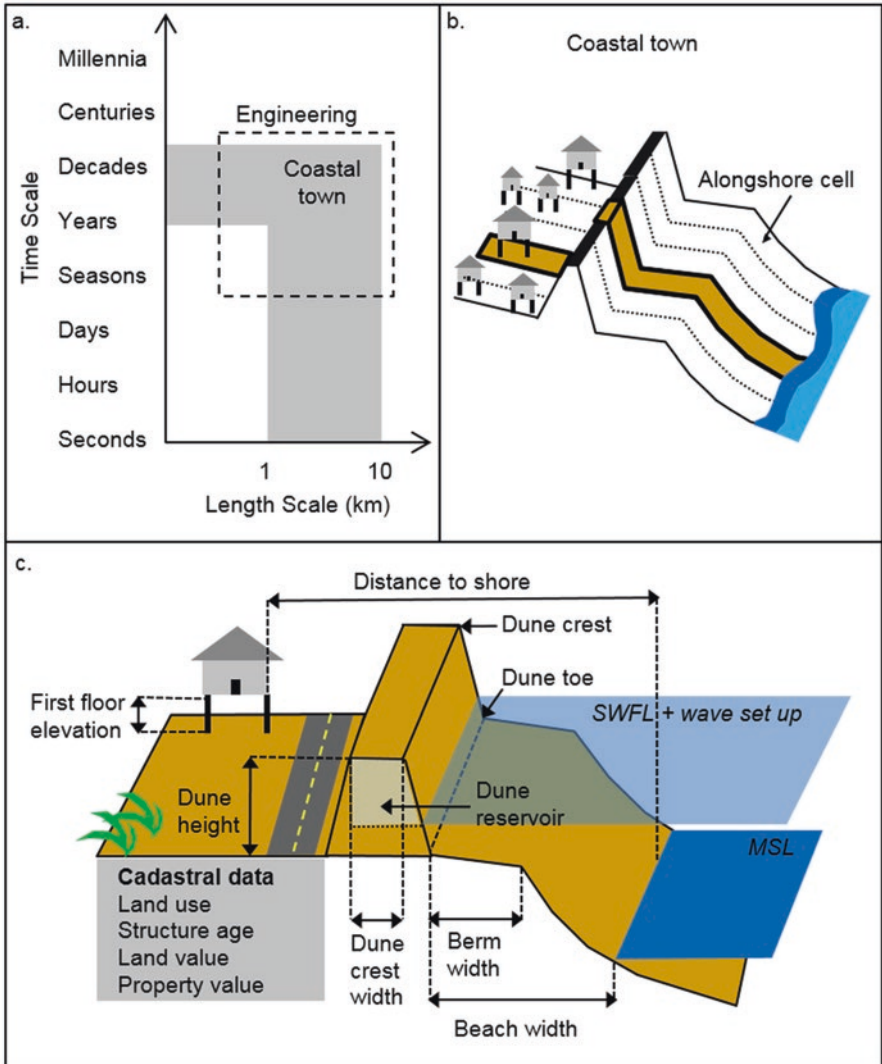
Fig. 19.1 Scales and spatial sketch of the ABM. (**a**) Spatial and temporal scales of application of the ABM (modified from Cowell and Thom, 1994). (**b**) Coastal town model composed by alongshore cells. (**c**) Alongshore cell and its relevant physical and cadastral parameters

ral processes and coastal landforms; 2. household decisions; and 3. beach management. Figure 19.2 depicts the generalized structure of the model components and flow of information among the components.

The components of the ABM interact through feedback links while storms and sea level rise are the exogenous drivers. When a storm occurs, it causes flood damage
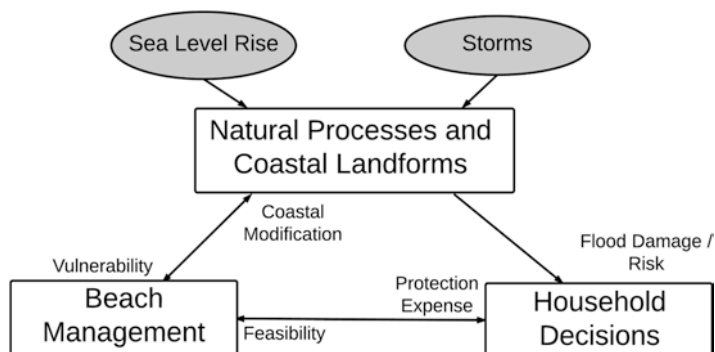
Fig. 19.2 ABM overview, including sub-models and flow of information

and influences the risk perception of households. Changes in the coastal landforms such as shoreline retreat also affect risk perception.

Vulnerabilities due to changes in beach morphology by natural processes are evaluated by coastal managers. Using information from the households, managers then determine the feasibility of pursuing a management measure: if a given project is feasible the beach morphology is altered. When a project is undertaken, the cost of the project is passed on to the households through taxes that increase the expenses of the homeowners and influence their occupation decisions. Conversely, wider beaches, resulting from the decision to nourish, increase the recreation potential, tourism income and property values in the community.

In the model the coastal community is defined as a series of alongshore cells that accounts for the spatial variability of beach morphology and structural/household development (Fig.19.1 b and c). Each alongshore cell consists of a subaerial beach specified by beach width, beach slope, and the height and width of a trapezoidal-shaped dune. Alongshore cells also contain a hinterland formed by cadastral parcels and buildings. Time advances through increments of 1 year during which beach profiles are modified by long-term erosion, sea level rise, storms and protective measures. Damage to buildings, household insurance and housing investment decisions are also simulated within the one-year time step.

19.2.1 Natural Processes and Coastal Landforms Sub-Model

The natural processes and coastal landforms sub-model simulates morphological changes by modifying the physical properties of each alongshore cell. The processes considered in this sub-model are summarized in Fig. 19.3.

Fig. 19.3 Natural processes and coastal landforms sub-model flowchart
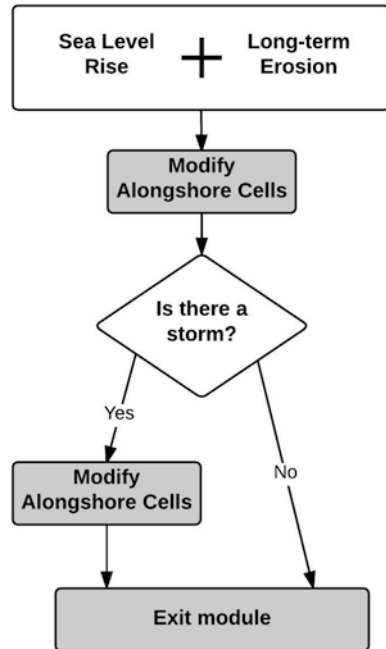
19.2.1.1 Sea Level Rise

When accounting for sea level effects in coastal communities, the appropriate quantity to consider is the local (relative) sea level, which changes according to global sea level change, vertical land movement (i.e., uplift or subsidence), and oceanographic conditions (e.g., variations in ocean temperature and ocean circulation) (Pirazzoli 1997). In this model, the historical combined effect of vertical land movement and oceanographic processes are isolated by differencing the historical global sea level rise rates from local sea level rise rates observed at local tide gauges. For simplicity, the isostatic effects are assumed to be constant in the near future. Assuming steady cross-shore and alongshore constant sediment flux (e.g., Wolinsky 2009), the Bruun Rule (Bruun 1962) is used to determine the shoreline change resulting from a set quantity of sea level rise. The Bruun Rule uses sea level rise rate, the cross-shore and the vertical extent of the active profile to calculate landward recession of the shoreline due to sea level rise. At the start of each time step the segment of the representative profile from berm to the depth of closure is moved landward by calculated recession and moved upward by the local sea level rise according to the Brunn Rule.

19.2.1.2   Erosion Rates

Sediment transport along the coast is controlled largely by wave-driven currents. For this simple model, a long-term averaged erosion/accretion rate (e.g., Dolan et al. 1991) is assigned to each alongshore cell according to historical annual rates for the corresponding geographical location, and assumed to remain steady over the simulation period. Shoreline change rates are then adjusted to remove the recession due to sea level rise, as the model accounts for this component separately (described above). In each time step, the beach profile from berm to depth of closure, is moved horizontally by the amount representing shoreline changes (erosion/accretion).

19.2.1.3   Storms

Storms with different recurrence intervals are used to represent storm arrival to the community in the model. The recurrence intervals are used to assign storm surge heights and significant wave heights from historical observations (Gōda 2010). Storm-induced changes in the subaerial profile are calculated using the empirical method adopted by The U.S. Federal Emergency Management Agency (FEMA) for flood mapping studies (Hallermeier and Rhodes 1988). The overall response of the dune is classified as either dune retreat or removal. Dune retreat is defined as any frontal dune escarpment created by a storm where there is no evidence of landward sediment transport. Dune removal is specified as the complete eradication of a dune by a storm. To predict the overall dune response against a storm, the storm-induced dune erosion is calculated using the storm recurrence interval as (Hallermeier and Rhodes 1988). The amount of erosion calculated from this relationship is then compared to the primary frontal dune reservoir to determine the retreat or removal of the dune. The primary frontal dune reservoir is defined as the cross-sectional area above the Still Water Flood Level (SWFL) and the landward side of the dune crest. FEMA (2013) also included the wave setup in determination of flood level datum above which the dune reservoir is calculated (Fig. 19.1c). In accordance with FEMA methods, wave setup calculations are based on the 1984 Shore Protection Manual (USACE 1984; Dean et al. 2005).

For a dune retreat case, the profile is altered such that the eroded material is relocated from the seaward portion of the dune profile (above the flood level datum) and deposited on the beach and the nearshore with uniform thickness. Dune removal is represented by removing material from the dune above a 1:50 seaward-dipping slope through the dune toe. In this case, it is assumed that the sand is removed from the profile.

19.2.2   Beach Management Sub-Model

The beach management sub-model imitates decision-making, planning and implementing beach nourishment and dune replenishment projects using economic and physical analyses (Fig. 19.4). Each year the beach management sub-model assesses
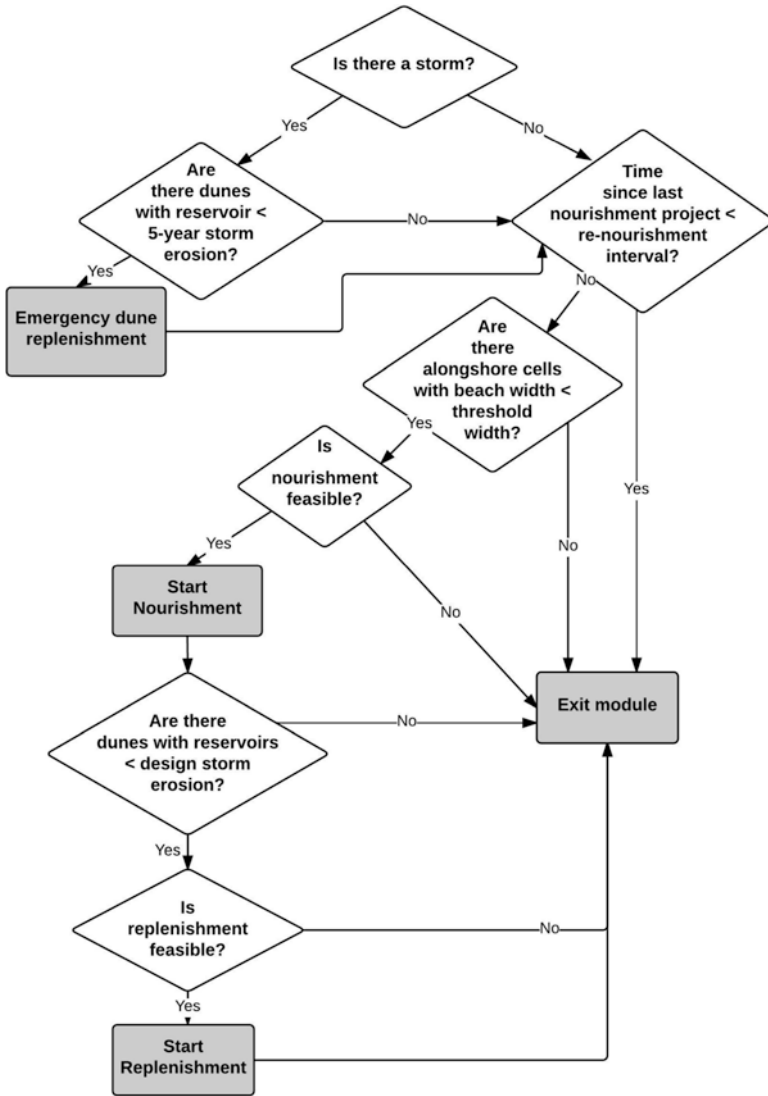
Fig. 19.4 Beach protection decisions diagram

the subaerial morphology to locate areas with narrow beaches and small dune reservoirs (thresholds defined by users). After identifying vulnerable locations, the submodel makes a decision on feasibility of dune replenishment and beach nourishment projects. If it is found feasible, the sub-model executes the project.

The beach nourishment procedure consists of placing sand on the beach from the berm to the depth of closure, to extend the beach width while maintaining the beach slope (Dean and Dalrymple 2004). The sub-model assumes rapid redistribution of the sand, such that the nourished beach profile attains its equilibrium shape

"instantaneously" (by the start of next time step). The volume of sand required for each project depends on the beach width after nourishment, the existing beach width of the alongshore cell and the alongshore cell length.

The model employs a cost-benefit analysis to determine the feasibility of a nourishment project. Costs include fixed costs associated with surveying, planning, mobilizing, dredging and obtaining permits and variable costs, which depend on the volume of sand required for the project.

The community's benefit from widening the beaches is reflected in increased property values. Earlier economic studies employing hedonic models show an inverse relation between coastal property value and its distance from the beach (Pompe and Rinehart 1995; Gopalakrishnan et al. 2011; Landry and Hindsley 2011). To incorporate the relation between property value and beach width, and to address property value changes relevant to beach nourishment, the hedonic pricing model on coastal residential properties discussed by Smith et al. (2009) and McNamara et al. (2015) is used. Employing these constructs, a framework was generated to identify if the beach nourishment project is beneficial. If the benefits are greater than the costs, the town implements the beach nourishment project.

Dunes provide flood protection to coastal communities during storms. Managers identify dunes with insufficient sand in their reservoirs and replenish them. Two replenishment options are defined in the sub-model and differ according to each option's design lifetime and triggers. First option is the emergency replenishment funded by FEMA (FEMA 2009), used as a temporary protection, carried out immediately after storms to provide protection against 5-year storm. The second option is the planned dune replenishment, which is carried alongside the beach nourishment. Due to fixed costs, it is usually favorable to unite planned dune replenishment projects.

The dunes are built to survive a certain design storm. Hallermeier and Rhodes (1988) method is used to derive the amount of sand required in the dune reservoir to the recurrence period of the design storm. It is assumed that the dunes in established coastal communities are constrained landward by development (i.e., highways, houses), thus, as design dunes grow in size, they extend seaward. All designed dunes begin at the heel of the original dune and have a 1:5 frontal slope; 1:3 landward slope, and 8 m crest width (USACE 2008).

As with beach nourishment projects, dune replenishment is undertaken if the project is feasible. The cost of the dune replenishment project depends on the volume of sand required for the project, the fixed costs are included in the beach nourishment project when both are carried out simultaneously. The benefit of a dune replenishment project is assessed by quantifying the protection it provides to the buildings landward of the project as the probability of exceedance of the storm event which will cause the total removal of the dune (Hallermeier and Rhodes 1988) multiplied by the expected damage in U.S. dollars. The sub-model uses a Depth-Damage Curve (Davis and Skaggs 1992) to calculate the potential damage inflicted upon each structure in the alongshore cell based on flood depth, first floor elevation and the value of the building. If the benefits of the project exceed the costs, dunes are replenished.

19.2.3 Household Decisions Sub-Model

The household decisions sub-model consists of cadastral parcels defined by land use, distance to the shoreline, first floor elevation, year structure was built, land value, and property value (Fig. 19.1c). Three types of heterogeneous agents are employed in this sub-model based on households' activities in the real estate market: "homeowners", "homebuyers" and "house sellers". Within the model, these agents interact with each other and the natural environment according to specified rules and goals. The model mimics individual decisions to buy or sell houses and buy insurance. These decisions depend upon economic factors, spatial environment (e.g., vulnerability and amenities) and household's perception of flood risk. The decision framework for each of these agents is shown in Fig. 19.5.
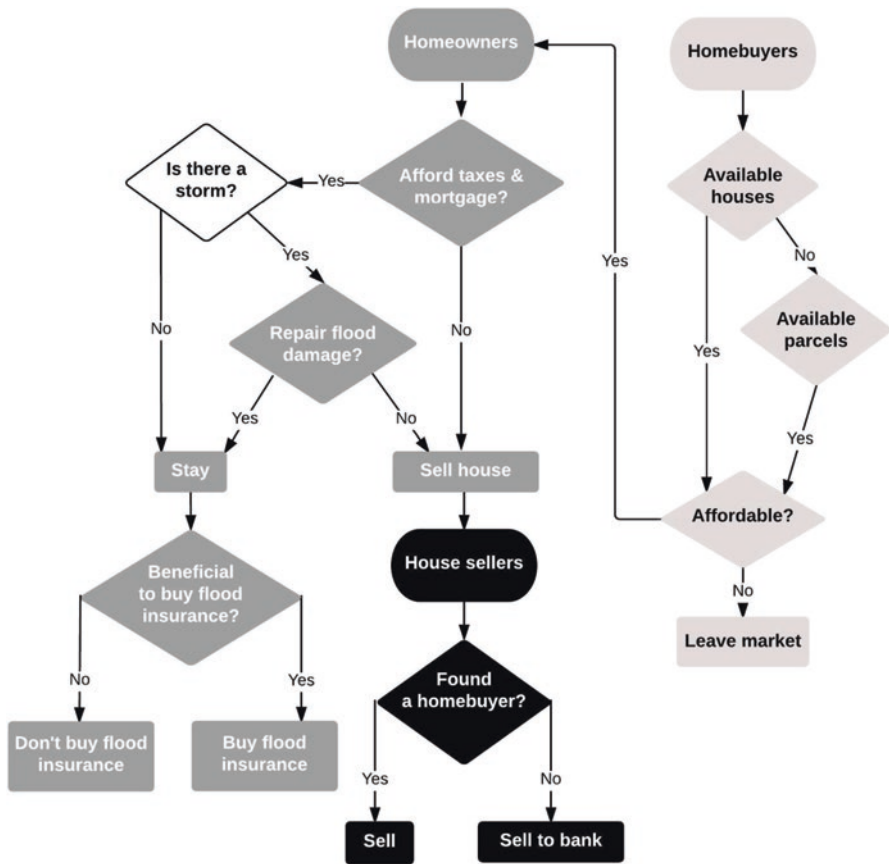

Fig. 19.5 Household decisions diagram. Decisions associated to different agent types are shown in different colors

Homeowners keep their houses based on their ability to pay the monthly mortgage and other fees. As a housing affordability indicator, housing cost to income ratio has the longest history and most wide-spread recognition (Stone 2006). In the model, homeowners are willing to pay up to 50% of their annual income for housing related costs; taxes and mortgage payments (Schwartz and Wilson 2008). Tax calculation is based on the market value of the house and tax rate of the community. If they cannot afford to pay the housing fees, they sell their houses to either a homebuyer or a bank. If a storm occurs, homeowners who cannot afford to fix the damages (computed from Depth-Damage Curves) through their flood insurance or their own funds leave the community.

Homeowners buy flood insurance if the expected damage from flooding exceeds insurance premiums. Premiums are calculated based on building occupancy, flooding risk, location of the lowest floor in relation to elevation requirement on the flood map, foundation type, and housing value. The storm damage expected by homeowners is calculated by adding the product of the probability of a storm category, the corresponding fraction of damage due to the storm, and the perceived frequency of storms. The perception of storm frequency changes with time and each storm event experienced (Franck 2009b).

The life quality and attractiveness of the community changes over time. For example, properties could be damaged, recreation opportunities might grow or decline, and social dynamics can change. In the sub-model, three feedbacks represent the community dynamics: housing density, expenses, and perception of flood risk. Towns outside the community of interest are assumed to have a steady attractiveness. Housing conditions are an important consideration for people when choosing a town to inhabit. Space and available housing can be an important incentive for people to relocate or stay in a community (Fujita 1989). To capture this feedback, the model uses housing density, which reflects the ratio of occupied parcels to total number of available parcels (Franck 2009b). If the members of the coastal community have high expenses due to higher tax rates, flood damage, and high insurance premiums, homebuyers will be less likely to move in. To represent the effect of expenses on community attractiveness, the model compares average income in the community to average household expense. The expected averaged storm damage of the community is then averaged and compared to the inital expected storm damage of the community at the start of the simulation to find the relative expected damage from storms. Expected storm damage, housing density, and town expenses are multiplied to quantify the attractiveness of the community.

The number of potential buyers, homebuyer agents, is determined by the community attractiveness and the rate of historical immigration. Homebuyers initially look for available structures. If there are no structures available, they seek empty parcels (Putra et al. 2015). When homebuyers decide on the affordability of structures or parcels, their expected annual payment for housing must not exceed 30% of their annual income (Wilson and Callis 2013).

19.3   A Case Study: Nags Head, NC, USA

The ABM was tested with a case study in the coastal community of Nags Head, NC. The aim of this ABM application is to explore the influence of storm arrival patterns and design alternatives of beach nourishment and dune replenishment projects on occupation dynamics. Nags Head is located in the Outer Banks of North Carolina, a barrier island chain between the Albemarle-Pamlico Sound and the Atlantic Ocean (Fig. 19.6). The town extends for approximately 18 km alongshore with an area of 17.2 km². It is a popular vacation destination for families, with tourism activities generally dependent on its natural environment (Esnard et al. 2001). The town represents a suitable test area of study because: (1) it has been subjected to storms during last century; (2) it is affected by coastal erosion and sea level rise, (3) it has implemented a mitigation plan by incorporating restrictive building standards and providing incentives (Bush et al. 1996; Esnard et al. 2001), and (4) it has had a locally funded beach nourishment and dune replenishment project (Kana and Kaczkowski 2012). The town is also located 25 km south of the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) with over 30 years of historical wave and water level data available (Fig. 19.6).

The community experiences semidiurnal tides with a mean range of 0.97 m and a spring tidal range of 1.3 m on the ocean side. The predominant wave direction is from the northeast, exposing Nags Head to some of the highest wave energy along the east coast of U.S. (Leffler et al. 1996) with mean significant wave heights exceeding 1.3 m at 17 m depth (1985–2015, FRF pier). The mean wave heights from September to April typically range between 1.03 and 1.19 m. Wave heights are usually smaller from May to August (0.6–0.92 m) when dominant southwesterly winds are directed offshore (CSE 2011; USACE-FRF 1985–2015). Net shoreline change in the area ranges between 0.23 m/yr. (accretion) at the north to 2.18 m/yr.
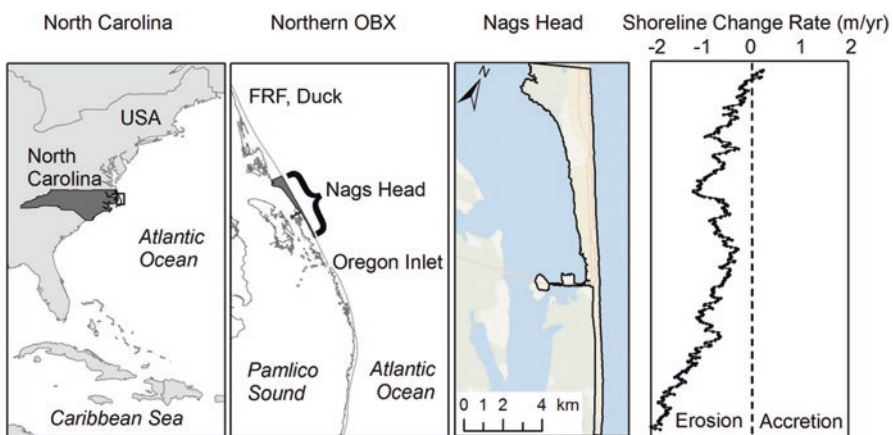

Fig. 19.6 Nags Head location relative to U.S. and to the Outer Banks of North Carolina. Right: Atlantic Ocean shoreline change rates along Nags Head

(erosion) at the southernmost part of the town (Fig. 19.6 - right) (Kana and Kaczkowski 2012; NCDENR 2012).

The NOAA tide gauge at the FRF reports a relative sea level rise rate of 4.6 ± 0.8 mm/yr. based on water level records from 1978 to 2013. This local rate exceeds both the 1.7 mm/yr. global SLR reported by Church and White (2011) for the period 1900 to 2009, and the current 3.2 mm/yr. reported by NOAA. This difference has been attributed to the combined effects of the post-glacial isostatic adjustment and oceanographic effects linked to the Atlantic Multi-Decadal Oscillation, the North Atlantic Oscillation and changes in the Gulf Stream (N.C. Coastal Resources Commission Science Panel 2015).

The town is characterized by low-lying areas with elevations lower than 3 m above the North American Vertical Datum of 1988 (NAVD88), excluding the dunes. Preceding the 2011 dune replenishment and beach nourishment project, the town had discontinuous dune lines with dune crest heights ranging from 4 to 8 m (NAVD88). For modeling purposes, morphological properties of the model were obtained from a 2009 LiDAR dataset provided by the USACE.

According to the U.S. Census Bureau, Nags Head's population in 2010 was 2757 occupying 1223 of 4884 available housing units, or 25% of the total capacity. This occupancy rate exhibits a 7.5% increase over the 2000 household occupancy of 1138 (U.S. Census Bureau 2000). Cadastral data indicates the development is most active in the northern section of the community.

19.3.1 Nags Head's ABM Model

The multi-agent modeling environment Netlogo (Wilensky 1999) was used to represent the town of Nags Head consisting of 180 alongshore cells of approximately 100 m length alongshore, each cell including at least five cadastral parcels. The initial household occupancy is assigned as 1223 (U.S Census Bureau 2010). The definitions and values of model parameters and references are specified in Tables 19.1, 19.2 and 19.3. Information regarding cadastral parcel properties, first floor elevation, property and land value, structure age and land use were gathered from previous works by Overton et al. (1999) and Dare Land Records Office (2010). Since the majority of the houses in the town are built on piles, the Beach-fx damage curve (USACE 2000) for structures with wooden piles was used to estimate the flooding damage.

19.3.2 Influence of Storm Arrival Patterns on Community Occupation Dynamics

Decision makers in a coastal town under stress by sea level rise and recurring storms should plan on sound management strategies to enhance present conditions while ensuring a long-lasting community in the future. The effects of predictable variables

Table 19.1 Parameters of the natural processes and coastal landforms sub-model representing the local morphology, shoreline migration, oceanographic processes, and storm conditions

Definition	Value	Reference
Sea level rise rate	4.6 mm/yr	NOAA tide gauge 8,651,370 at Duck, NC (1978–2013)
Width of the active profile	456 m	Kaczkowski and Kana (2012)
Depth of closure	7.3 m (NAVD88)	
Berm height	1.8 m (NAVD88)	
Shoreline change at each alongshore cell	Varies with cell location (+0.23 to −2.18 m/yr)	NCDENR (2012)
SWFL	10-yr. storm = 1.54 m 25 yr. storm = 1.78 m (NAVD88)	FEMA (2006)
Significant wave height at 17 m depth	10-yr. storm = 3.16 m 25 yr. storm = 4.07 m	USACE-FRF, 1985–2015

Table 19.2 Parameters of the beach management sub-model (monetary values are given in U.S. Dollars)

Definition	Value	Reference
Fixed nourishment-replenishment costs	$1,200,000	Coastal Science and Engineering, (2011); Coastal Planning and Engineering of NC (2013)
Variable costs (sand)	16.34 $/m^3	
Re-nourishment interval	5 yr	
Discount rate	0.06%	Smith et al. (2009)
Hedonic price of beach width	0.5	
Base property value excluding beach width influence	$ 100,000	
Threshold beach width for nourishment to prevent run-up exceeding the berm	20 m	Holman (1986)
Design dune reservoir area for emergency replenishment	16 m^2	Hallermeier and Rhodes (1988)

Table 19.3 Parameters of the human decisions sub-model (monetary values are given in U.S. Dollars)

Definition	Value	Reference
Rate of household emigration	30 households/yr	U.S. Census Bureau (2010)
Annual interest rate	0.035%	FHA (2014)
Mortgage duration	30 yr	U.S. HDU (2016)
Principal loan	0.85 * property value	Putra et al. (2015)
National Flood Insurance Program coverage	$250,000	FEMA (2016)
Storm recall time interval	5 yr	Atreya et al. (2013)

on occupation dynamics in a community can be gathered from historical records (e.g. established local sea level rise rates, mortality rates, etc.). On the other hand, stochastic events like storms may produce abrupt changes on occupation dynamics that require extensive evaluation of potential scenarios. To tackle this issue, we explored the influence of storm arrival patterns on occupation dynamics by creating scenarios spanning 50 years using historical storm surges.

To create a more compelling storm time history window including at least a 25-year storm, the water levels of storms observed at the NOAA FRF Duck station were magnified by a factor of 1.1. The storms were categorized according to their recurrence intervals, and the mean and variance of time intervals between storms in each category were determined from historical storms. 200[1] different storm arrival scenarios were produced by randomly choosing time intervals between the storms. In the simulations the design width for nourishment and design storm for dune replenishment projects were specified as 35 m and 40-year, respectively (Gopalakrishnan et al. 2011; Magliocca et al. 2011). Results of these scenarios include substantial variability in number of households at the end of each 50-year simulation ranging from 957 to 1384 with a standard deviation of 73.7.

The influence of storm patterns in occupation dynamics was further explored by inspecting the simulated progression of community attractiveness, coastal morphology and occupancy. The temporal evolution of these parameters in two simulations, which had the minimum and maximum household occupations at the end of the simulation period, are presented in Fig. 19.7. At the start of the first scenario, the community grew in size until a 25-year storm arrived at year 9. The storm diminished dune reservoir areas, and damages incurred caused some households to leave. Repair costs and increased risk perception significantly reduced the community attractiveness. Although the community did not grow from years 15 to 28, it had sufficient resources to replenish dunes and was able to withstand the following four 10-year storms without encountering overwhelming damages. After year 28 households' memory of storms started to fade, and community attractiveness flourished as they experienced 12 years without storms with recurrence periods higher or equal to 10 years. When a 10-year storm arrived in year 41 it caused some abandonment but did not change the community attractiveness drastically and in 2 years the community started to grow again. With more households paying tax the available funds grew and a large nourishment project became more appealing as the number of properties that will benefit from wide beaches increased. The community funded a large project at year 47 and nourished the beaches to a mean width of 34 m. At the end of the simulation, the community gained 161 households relative to the initial 1223 occupied households.

In contrast, the community in scenario 2 encountered one 10-year storm during the first half of the simulation. The community performed beach management proj-

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[1] 200 runs were determined to be a sufficient sample size to achieve a 90% confidence interval computed by $n = Z_\alpha * (s^2/e^2)$ for the estimate of occupation, where n is the sample size, s is the standard deviation, e is the margin of error and Z is the Z-score. Margin of error was set to 1% of initial occupation.
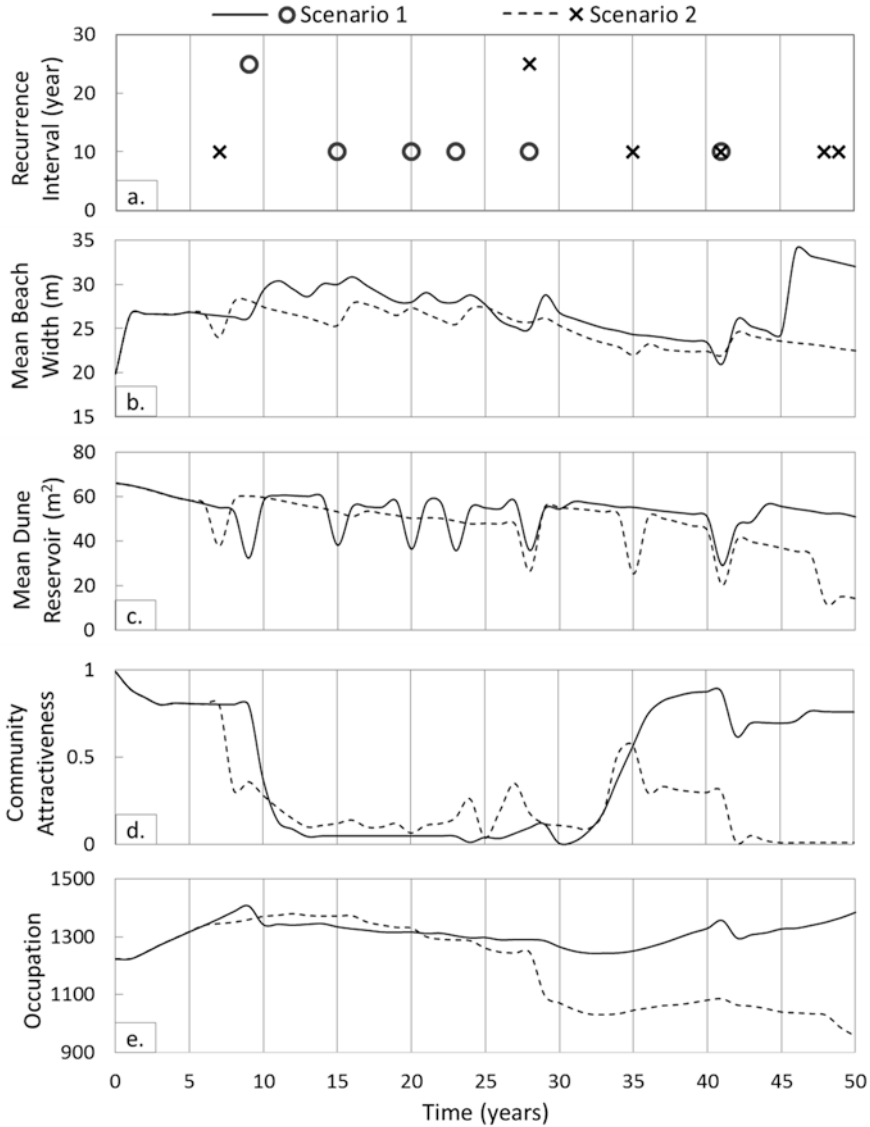
Fig. 19.7 Time series of: (**a**) storm events, (**b**) spatially averaged beach width (BW) over town, (**c**) spatially averaged dune reservoir area (computed over the 10-year storm flood level datum) over town, (**d**) community attractiveness, and (**e**) occupied households in the community

ects to strengthen the dunes and widen the beach and community attractiveness varied with expenses incurred. Occupation increase in community corresponded to more households under risk in case of storm flooding and when a 25-year storm at year 28 hit the community, it caused substantial damage and emigration. Although the community attractiveness improved in the following 5 years, storms in

subsequent years caused it to subside again. Due to rising sea levels, the majority of the homes' first floors were closer to the mean sea level and dunes had less sand in their reservoirs compared to their initial state, thus these storms, induced more damage compared to the storms at the start. Back-to-back storms at the end of the scenario did not let the community to take protection action in between and the diminished dunes were not able to provide protection against the last storm at year 49. Majority of dunes were removed and emergency dunes were constructed by FEMA. In scenario 2 the community had lost 266 households, compared to initial occupancy.

19.3.3   Influence of Beach Management Design Alternatives on Community Occupation Dynamics

Beach nourishment and dune replenishment aim to mitigate flooding, prevent damage to public and private infrastructure, promote tourism and accommodate sustainable development. Ideally, all the benefits from soft-engineered measures could be attained simultaneously, but budget, space and resources constraints generate challenges. Under these circumstances, managers should evaluate beach design alternatives to find practices that lead to a perdurable community. To establish design alternatives which accommodate occupation growth, we investigated the occupation behavior of the agents in Nags Head under varying design alternatives. 72 design combinations were generated by varying the design storm, design storm for dune replenishment (from 20 to 100 years with 10-year time steps) and design beach width for nourishment projects (from 20 to 90 m with 10 m spatial steps). These alternatives were tested by forcing the model with each of the 200 storm arrival scenarios produced for the previous application. This experiment generated 14,400 simulations, producing occupation results after each 50 year simulation.

The influence of design alternatives was explored by analyzing the final community occupancies. Performance of all design alternatives according to final community occupation for each scenario was evaluated by (1) identifying maximum final occupancy among the design alternatives tested with each scenario, and (2) normalizing all occupancy results for each scenario by the maximum occupancy. Then to determine the overall performance of each design alternative across 200 storm arrival scenarios, normalized occupancy results for each alternative were averaged (Fig. 19.8). Results point out the importance of optimizing the use of the funds for management actions on the beach. In essence, the allocation of the community's funds for large beach nourishment and dune replenishment designs reduces the community's ability to undertake other beach management projects that might be required in the future. Figure 19.8 illustrates that trading one option of beach improvement for another will result in a significant decrease in community's occupancy.
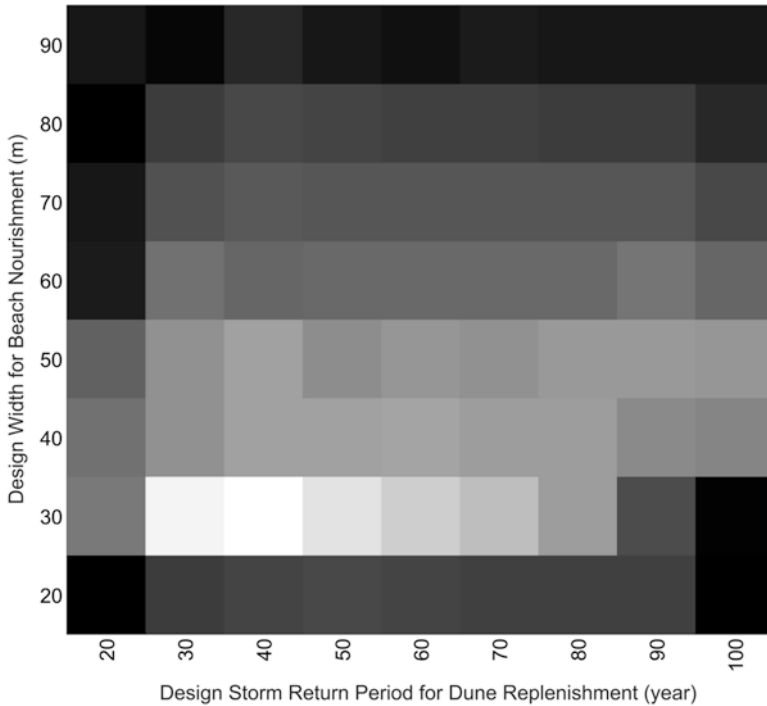
Fig. 19.8 Heat map of the normalized final occupancy averaged over 200 storm arrival scenarios. Rows represent beach nourishment design width options and columns are the design storm used for dune replenishment. Cells are colored based on final number of occupied households at the end of the 50 year simulations. Light colors represent higher occupancy numbers and dark colors indicate lower numbers

For example, dark colors in the top left corner of Fig. 19.8 show that having wide beaches combined with small dune replenishment volumes will result in overall decrease in community's occupancy. Reviewing individual simulations indicate that although wide beaches enhanced tourism and increased property prices, it led to substantial structural damages after storms due to small-sized dune reservoirs. Conversely, having narrow beaches exposed foredunes to chronic erosion or even did not allow its construction due to space constraints. This outcome combined with less attractive beaches diminished community occupancy (dark colors in the bottom right corner of Fig. 19.8). Intending to have big dunes and wide beaches over time was not a sustainable practice due to limited funding. Design beach widths of 30–40 m and design storms of 30–40 years for dune replenishment led to highest occupations among the design alternatives. These alternatives provide enough protection against a 25-year storm and will keep beaches from reaching the threshold beach width for nourishment (20 m) specified in the model during 5-year renourishment period. According to this modeling experiment, the growth of the coastal community requires a balance between optimal economic benefits and adequate protection against storm-driven erosion.

19.4   Summary

An ABM that simulates interactions between human and natural systems has been applied to study occupation dynamics in the coastal community of Nags Head, NC. This model constitutes a novel management tool built to enrich the understanding of human-nature systems by predicting coupled behavior under different forcing scenarios and management strategies. In this study, it was found that storm arrival timing strongly influences the occupation of a coastal town. Availability of funds and sufficient time to undertake protection practices was shown to be essential for recovery of community attractiveness, thus occupation.

The second application explored the influence of design alternatives on occupation. Our results indicate that determining and maintaining a balance between wide beaches that enhance tourism and mitigate erosion impacts and large dunes for storm protection is a crucial challenge. For the storm conditions specified, it was essential to maintain dunes with sufficient sand in their reservoirs to survive the most intense storm in the simulated timeline. The selection of design alternatives which provide beach and dune systems that can endure storms and shoreline retreat in the short-term (e.g. re-nourishment interval) and do not deplete funds so that community can take action against unexpected events (e.g. back-to-back storms), was critical to establish a growing coastal community.

The case study presented served to explore one beach management strategy (soft-engineered coastal protection projects) and humans' response to storm arrival patterns. However, multiple beach management techniques could be investigated together or individually (e.g. zoning practices, managed retreat, use of hard-engineering) furthering the utility of the model. During the simulations the impacts of limited sand resources such as increase in costs and availability of borrow sand material were not considered. Furthermore, a 25-year storm was used as the storm in the case study. Increasing storm intensity and using varying rates for long-term erosion could alter the morphology significantly and would produce different results.

Other limitations of the model include an absence of certain interactions in the human and physical systems such as political influence, environmental degradation of the beach due to human manipulation, irrational decisions by agents, and impacts of neighboring communities. In addition, the morphological processes are accounted in the model by means of empirical formulations, such as: (1) Hallermeier & Rhodes (1988) methodology to estimate the dune response to storms, which includes approximations that do not represent all the physical processes operating in the natural system; and (2) the Bruun Rule to simulate the shoreline migration due to changes in relative sea level (Bruun 1962), which has been widely used (e.g., Leatherman et al. 2000; Zhang et al. 2004), but also highly criticized for some of its assumptions (e.g., Cooper and Pilkey 2004). Therefore, it should be noted that the results presented here are dependent on the formulations and conditions specified (e.g. maximum storm intensity and long-term erosion rates) and should not be used in every case.

Challenges to address the aforementioned limitations in future phases of ABM development include advancement of both the human and physical systems. In future research, the model can be improved by inclusion of different types of agents, processes and interactions in the human system, and the use of morphological models that are able to update morphology with more realistic forcing and response. Examples of such models include Ashton et al. (2001), Roelvink et al. (2009) and Limber et al. (2016). We note, however, that using additional modeling tools with more complexity will involve additional input parameters and will require more advanced computational techniques.

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