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*Review*

# A Review of Climate Adaptation Impacts and Strategies in Coastal Communities: From Agent-Based Modeling towards a System of Systems Approach

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**Abstract:** Global warming and climate variations are expected to alter hydrologic conditions and exacerbate flooding, primarily through increasingly frequent and intense storm events and sea-level rise. The interactions between coastlines and their inhabitants around the world are highly diverse, making them challenging to model due to the non-homogeneous, nonlinear, and complex nature of human decision-making. Agent-based modeling has proven valuable in various fields, enabling researchers to explore various social phenomena and emergent patterns under different institutional frameworks, including climate change scenarios and policy decisions, particularly at local scales. This approach is particularly useful in providing insights into possible outcomes and feedback resulting from the convergence of individual- and community-level adaptation decisions, and it has increasingly been used to model coastal systems. However, there are a limited number of studies that examine the effects of climate adaptation decisions on coastal tourism systems. This paper aims to address this gap by first providing an overview of the current state of agent-based modeling literature that explores coastal community adaptation responses to climate change. Subsequently, the paper argues for the application of these methods to simulate the effects of adaptation on coastal tourism dynamics. To better capture the interactions within subsystems and potential redistributed effects inherent in multi-scale and multi-stakeholder decision-making processes within these systems, we propose integrating agent-based modeling with a novel system of socio-environmental systems (SoSES) approach. This integration aims to assist city planners, policymakers, stakeholders, and attraction managers in effectively assessing adaptation options to safeguard their communities from the multifaceted impacts of climate change.

**Keywords:** climate change; coastal community; flood; agent-based modeling; system of systems; tourism

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## 1. Introduction

Climate change has and will continue to affect the hydrologic cycle by way of altered precipitation event frequency and intensity, wreaking havoc on infrastructure as well as both ecological and social systems [1–3]. These changes, coupled with rising global temperatures, are amplifying the frequency and severity of extreme weather events, such as hurricanes, floods, droughts, and wildfires. For example, studies have indicated that warmer temperatures are associated with a higher likelihood of extreme rainfall events, resulting in more frequent and intense floods in various regions [4,5]. Moreover, climate change-induced alterations in the hydrologic cycle can also exacerbate drought conditions and water scarcity in certain areas, impacting agriculture, water supply, and ecosystems [6,7]. The increasing understanding of these interconnections between climate change, the hydrologic cycle, and natural disasters is crucial for effective disaster risk reduction, water resource management, and climate adaptation strategies.

Coastal systems, in particular, will be disproportionately affected by our warming planet, now facing these exacerbated risks coupled with sea-level rise and increasingly severe storm surge. The warming climate has implications for glacial melt and sea-level rise, which could lead to coastal inundation and increased vulnerability to storm surges [3,5,8]. Coastal property damage will cause physical risks and financial losses for individuals, as well as pose threats to local economies and cultural landscapes by way of environmental degradation. According to the United States Global Change Research Program's 2017 summary of the Fourth National Climate Assessment, the extent of future climate change effects is heavily dependent on the choices our world makes today, and over half of the presently anticipated coastal property damages are avoidable through adaptation measures [3].

Coastal adaptation has many forms, from artificial dune construction, seawalls, surge barriers, flood hazard mapping, early-warning systems, insurance programs, and the formation of disaster management committees, to community retreat [9]. With there being no one-size-fits-all solution for coastal communities, each with their own increasingly complex and interconnected economic, social, and biophysical systems, it is of growing importance that we understand the outcomes and possible redistributed effects of our adaptation decisions [10]. Responses are often dictated by individual actions and beliefs that widely vary across communities facing unique geographies and priorities, in addition to differing social, economic, and cultural circumstances.

For example, surveys conducted in small island communities of Tubigon in the Philippines found that most residents prefer in situ adaptation strategies to relocation, even after the local government devised a program that would give them permanent new homes on the mainland [11]. Alternately, homeowners in Staten Island's Oakwood Beach neighborhood successfully lobbied to have their waterfront homes demolished and bought out following Hurricane Sandy so they could move further inland and bar the flooded areas from future development [12]. Alaska's Shishmaref, known for its houses falling into the sea as a result of permafrost loss and rapid erosion, voted to relocate their community in both 2002 and 2016, and still have not done so [13] due to funding restraints and fear surrounding both cultural and livelihood preservation [14]. System-level outcomes for each of these communities vary, including but not limited to maladaptive in situ strategies in Tubigon, such as unsustainable coral mining for the purpose of home elevation, making the island communities more vulnerable to storm surge in the future [11,15]. Buyouts for Oakwood Beach's predominantly white and wealthy residents created climate justice tensions, while Shishmaref's decision to relocate almost two decades ago has caused a cease in new housing development, resulting in an outward migration of younger residents. The individuals, societal rules, and available resources within these scenarios each play a role in deciding adaptation recourse and the consequent effects on their environment, working to either reduce or exacerbate vulnerability at the community level.

The occurrence of emergence, or emergent properties, describes the event in which system-wide behaviors, patterns, or structures are brought about by but not explicitly programmed within a system's individual components [16]. Although these are not modeled scenarios, emergence is depicted by the increased physical vulnerability of Tubigon, newly fueled social tensions across Oakwood Beach, and unintended outmigration from the Shishmaref community, as these each describe system-level consequences of diverse beliefs and decisions which did not individually or explicitly account for these outcomes but arose from the interactions of the decisions of many. Upon discovery, emergent properties such as these have and will continue to shape the future, affecting decisions ranging from infrastructure installation to climate policy.

In addition to emergence, the importance of incorporating big data in natural disaster monitoring and modeling cannot be overstated [17]. With the increasing frequency and severity of natural disasters, traditional modeling approaches may fall short in providing accurate and timely insights to mitigate and respond to emergencies [18]. Big data, including satellite imagery, sensor networks, social media data, and historical records, offer a wealth of real-time and historical information, enabling researchers and decision-makers to gain a deeper understanding of disaster patterns, impacts, and vulnerabilities [19]. By integrating this vast and diverse dataset into modeling frameworks, we can enhance the precision of forecasting, early-warning systems, and emergency response strategies. Additionally, big data-driven models enable more comprehensive risk assessments, aiding in the formulation of proactive and targeted disaster preparedness measures to protect lives and minimize economic losses, ultimately fostering more resilient communities in the face of natural disasters.

The goals of this review study are as follows:

1. Explore agent-based modeling (ABM) applications which examine the effects of various climate change adaptation strategies on coastal communities.
2. Accentuate and underscore the potential of filling a gap in the ABM space pertaining to the integration of possible effects of climate change adaptation decisions and coastal tourism.
3. Introduce a novel system of socio-environmental systems (SoSES) approach as well as a case for the integration of SoSES and ABM methods for the purpose of better-informing decision-makers and institutions at all levels within coastal systems about possible outcomes and feedbacks following adaptation choices.

A general overview and explanation of ABM and its components will be provided as well as advocation for its use to simulate dynamic and complex systems. Adaptation will be defined largely in the context of common practices in coastal settings. A non-systematic review of the existing literature regarding the use of ABM to observe potential outcomes of climate change response will follow, in which their employed adaptation strategies and individual case studies will be, if applicable, placed into the following categories: accommodation, protection, and retreat. Following this review, a gap in the coastal agent-based modeling space will be presented, pertaining to the limited ABM studies which explore interactions between climate change adaptation decisions and the coastal tourism sector. The potential and importance of exploring the extension of adaptation ABMs into this area is discussed, as is the role of systems dynamics in adequately capturing the interconnectedness of our physical, economic, and social systems within these models. Imitations of ABM and associated practices will be mentioned, followed by suggestions for future work.

## 2. Agent-Based Modeling

Agent-based modeling (ABM) is a means of simulating behaviors, relationships, and interactions among autonomous actors within an environment, allowing the modeler to observe and explain system-wide collective and emergent behavior [16], as well as to test hypotheses concerning relationships among individual attributes, behaviors, environmental features, and macroscopic regularities [20]. An agent can be defined as an entity, object, or software abstraction that bundles chosen methods (i.e., actions, behaviors) and attributes within a single entity, which often seeks to achieve a certain goal [21,22]. A user-specified topology which defines agent relationships and interaction rules dictates how agents may interact with one another and their environment depending on their assigned attributes, such as their individual goals, memories, experiences, economic status, or location, allowing for the representation of virtually any system under investigation [16]. An example model structure is illustrated in Figure 1. ABM is particularly suited to aid in the study of local–global interactions, self-organized systems, decentralized decision-making, and the effects of many complexity features (e.g., heterogeneity and nonlinearity) on emergence [23]. It allows for testing hypotheses or performing "what-if" scenario analysis under various conditions [24–26], as well as the integration of data, knowledge, and models across temporal, spatial, and organizational scales or across disciplines [27,28].

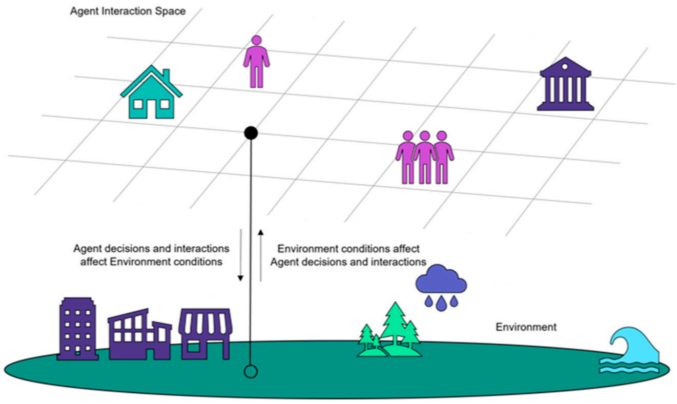

**Figure 1.** Agent-based model structure.

Due to this, ABM has been used in a range of fields and studies, from logistics optimization [29] and economics [30] to social sciences [31], ecological and biophysical sciences [32,33], complex human–environmental science [27,34,35], and urban planning [36]. While applications for water resources' planning and management are still relatively limited [37], the long- and short-term outcomes of ecological, environmental, economic, and social changes are all important aspects of the water resource system planning and management process [38] that have the potential to be observed, modeled, and understood through ABM.

Additionally, scenarios in which agents with diverse characteristics and abilities can change their behaviors based on previous decisions and interactions, in turn changing the characteristics of the system, the system's archetype, and emergent outcomes through feedback, have been referred to as complex adaptive systems (CASs) [39,40]. CASs can be reasonably simulated using ABM [37] and system dynamics. Socio-ecological systems (SESs) are among the CASs with high complexity and adaptivity levels [41]. SESs are characterized by their complex feedback between social and biophysical subsystems, strategic human behavior, and policies, which influence the status of ecosystems that, in turn, affect the social system in terms of its quality of life and future welfare of the system's inhabitants, as well as adjacent and distant systems. It can be argued that coastal communities as we know them fit this description as they are endangered by a confluence of factors, including climate change, subsidence, sea-level rise, and other human-induced changes.

It should also be noted that a significant limitation that researchers often encounter is the lack of data required to accurately calibrate and validate the ABM models. This scarcity of data can impede the model's ability to reflect real-world conditions and may lead to less reliable predictions and insights. To address this challenge, researchers have explored various approaches. One common strategy is to incorporate synthetic data generated from statistical methods or data imputation techniques to supplement the missing or incomplete data [42]. Additionally, sensitivity analyses and scenario-based simulations are employed to assess the model's robustness and examine its behavior under different input conditions, providing a more comprehensive understanding of the system's dynamics despite the data limitations [28].

Moreover, researchers have sought to integrate other sources of data, such as remote sensing data, social media data, and crowdsourced data, to complement traditional data sources and enhance the model's representation of real-world complexities [43]. These additional data streams offer valuable insights into human behavior, spatial interactions, and environmental changes that contribute to refining the ABM's accuracy. Furthermore, researchers have started to promote data-sharing initiatives and open-access repositories, encouraging collaboration and data exchange among the scientific community, which can collectively contribute to building more robust and data-rich ABM models [44]. The following section will discuss ABM case studies which simulate employment of coastal adaptation strategies in response to individual- and community-level risks exacerbated by climate change.

## 3. Climate Change and Coastal Adaptation

Climate change has impacted human and natural systems all over the world at every level of development. These impacts are not evenly distributed, both exacerbating existing vulnerabilities and creating new ones for both human and natural systems [5]. The Intergovernmental Panel on Climate Change's (IPCC) 2014 Climate Change Synthesis Report predicts that, among other things, storms, extreme precipitation, inland and coastal flooding, storm surges, and sea-level rise will continue to erode habitats, increase coastline vulnerability, and degrade both fisheries and tourism. Coastal systems and low-lying areas will be subject to an escalating amount of submergence, flooding, erosion, and displacement of people. Property and life vulnerable to these coastal risks, as well as the pressures these place on coastal ecosystems, will significantly increase in the foreseeable future due to population growth, economic development, and urbanization. While adaptation strategies are context-specific and limited in their ability to eradicate the effects of or slow climate change itself, the report states that if adaptation strategies are considered in the context of long-term sustainable development, they can work to make communities more protected in both present and future climate scenarios, promoting the integration of adaptation into planning, policy design, and decision-making.

Adaptation in terms of climate change response refers to a community's planning for climate impacts and reacting to them before they occur and lead to risk and harm, as the costs following an event or disaster often far exceed those of precautionary measures [9]. Coastal communities can choose to prepare for a combination of increased storm intensity, frequency, storm surge, and sea-level rise effects in a number of ways, from community-wide measures such as seawalls to individual measures such as home elevation. The ways in which individuals choose to respond to climate change, presumably to reduce vulnerability, have the potential to unwillingly redistribute this vulnerability to others [10], as in the previously mentioned cases of Tubigon and Shishmaref. Both adaptation and possible maladaptation will vary by geographical, social, and economic conditions.

Numerous studies highlight the escalating risks posed by rising sea levels, intensified storm events, and changing hydrological patterns, which threaten coastal communities and ecosystems. Scholars have investigated various adaptation measures, including nature-based solutions such as coastal wetland restoration and dune stabilization, engineering interventions such as sea walls and tidal barriers, and community-based approaches, to enhance resilience through capacity building and stakeholder engagement. For instance, the authors of [45] emphasize the importance of integrating social and ecological considerations in adaptation planning, while those of [46] underscore the critical role of interdisciplinary research in addressing complex coastal challenges. Additionally, the work in [47] demonstrates the cost-effectiveness of proactive adaptation strategies compared to reactive responses to climate-induced coastal hazards.

Through ABM, researchers have aimed to provide insights surrounding possible outcomes for new or alternate climate policies, greening initiatives, development restrictions, and so forth, that will aid city planners, stakeholders, and residents alike in making safe, sustainable, and effective adaptation choices. Overall, the literature emphasizes the importance of comprehensive, context-specific approaches to coastal adaptation, and it provides valuable insights to guide policymakers and practitioners in developing adaptive measures that can protect coastal regions and their inhabitants in the face of climate change.

### *3.1. Background*

The aim of this review is to assess the extent to which ABM has been used to determine possible outcomes of climate change adaptation decisions in coastal communities. Adaptation types include three overarching categories: accommodation, protection, and retreat, which are essentially behaviors of agents (e.g., people, households, governments) or changes in the environment in response to climate change. These and their respective subcategories, presented in Table 1, have been put forth and defined by the Intergovernmental Panel on Climate Change (IPCC) [9,48]. The IPCC states that coastal systems are made up of human and natural systems, with the latter including rocky coasts, beaches, barriers, and sand dunes, estuaries and lagoons, deltas, river mouths, wetlands, and coral reefs [9]. Therefore, the authors deemed it appropriate and useful to include studies in the presented review which explore adaptation to climate change challenges within reasonable proximity of both ocean and river shorelines.

To provide an overview of ABM applications for climate change adaptation outcomes in coastal areas, the following steps were taken. First, potential publications were identified through a search using standard research databases. Keywords included various forms and combinations of the following terms: climate change, adaptation, agent-based model, flood, flood-proofing, coast, managed retreat, household, green infrastructure, and policy. Publications were initially filtered for relevance by title, and further by cross-checking the abstract contents. The full texts for the selected studies were then examined and the 38 publications for this review were hand-picked using the following criteria.

The scope of selected works was limited to studies which present ABMs with mechanisms in place which allow agents within the model to put forth at least one of the presented adaptation strategies in a coastal setting in response to climate change impacts. Studies were not limited to peer-reviewed publications and excluded studies which solely present adaptation types not reasonably within those provided in the accommodation, protection, and retreat categories (i.e., fishery management), as well as studies which observe decision-making in coastal areas but do not allow agents to employ adaptation measures. For a working paper which offers a comprehensive review on integrated-assessment ABMs on climate change adaptation in coastal zones with alternate criteria (exclusion of consideration for riverine flooding and non-peer-reviewed papers, alternate categorization, and inclusion of adaptation types, etc.), readers are referred to [49].

The organization of the selected literature by adaptation type is valuable in its ability to highlight understudied climate change adaptation outcomes in the agent-based modeling space. Moreover, some studies are repeated in the table, indicating that they exhibit multiple adaptation strategy types. From this, we can deduct potential novel and lesser explored combinations of these strategies for future works. The remainder of this section will define the presented adaptation types and discuss ABM case study findings from each category.

**Table 1.** Types of coastal adaptation strategies and associated studies which utilize ABM. Adaptation types and secondary categories are as determined by the IPCC [9,50]. Asterisked secondary categories and example strategies were added at the discretion of the authors (i.e., green infrastructure has been categorized as a flood-proofing strategy).

| Adaptation Type | Secondary Categories | Example Strategies | ABM Studies |
|---|---|---|---|
| Accommodation | Land use changes | Flood-resistant agriculture | [50–52] |
| | | Replacement of armored with living shorelines | |
| | | Adjusted land use planning | |
| | Flood-proofing | Building retrofits | [51,53–70] |
| | | Building and contents' elevation * | |
| | | Elevation of low-lying infrastructure | |
| | | Green infrastructure * | |
| | Evacuation planning | Improved evacuation routes * | [71] |
| | | Improved flood shelters | |

**Table 1.** *Cont.*

| **Adaptation Type** | **Secondary Categories** | **Example Strategies** | **ABM Studies** |
|---|---|---|---|
| | Flood forecasting and projection | Flood hazard mapping | [54–67,70,72–77] |
| | | Flood warning systems | |
| | | Flood insurance | |
| | | Government subsidies * | |
| | | Flood information campaigns * | |
| Protection | Hard structures | Seawalls | [51,55–57,59,60,67,68,72,75] |
| | | Dikes | |
| | | Storm surge barriers | |
| | Coastal management | Beach and dune nourishment | [68,72,74,76,78] |
| | | Artificial dunes | |
| | | Removal of invasive and restoration of native species | |
| | | Enhancement of coastal vegetation | |
| Retreat | Land reclamation | Allow wetlands to migrate inland | [51,78,79] |
| | | Shoreline setbacks | |
| | | Deny development approval in flood-prone areas * | |
| | Climate migration * | Managed community retreat | [57–60,66,74,76–86] |
| | | Sale of property in flood-prone areas * | |

### Agent-Based Modeling and Accommodation Practices

In the context of coastal adaptation, to accommodate is to increase flexibility through modified human activity and infrastructure [9]. In this paper, accommodation practices have been further categorized into land use changes, flood-proofing, evacuation planning, and flood forecasting and projection (Table 1). Strategies at the household level include but are not limited to home and home content elevation to minimize flood damages, green infrastructure installation to aid in stormwater capture, and participation in flood insurance programs [9,48,87]. Government agencies can practice accommodation through, for example, flood hazard mapping, sustainable land use planning, ensuring emergency storm shelter space [9], flood information campaigns, and subsidy initiatives that encourage households to take part in mitigation practices. These strategies are defensive rather than offensive, and do not consider physically removing life or property from vulnerable areas. The following will detail outcomes and adaptation recommendations provided from several works which explore accommodation scenarios through ABM.

While ABMs are not expected to act as reliable predictive tools at local scales, they are useful for investigating possible outcomes and emergent responses at higher scales, allowing for observation of, for example, possible impacts to systems or communities following implementation of various climate, flood, subsidy, and policy scenarios, which are commonly explored in the literature [27,88]. For example, an ABM was developed to assist with agricultural land use policy development in North Canterbury, New Zealand, by considering greenhouse gas price effects on net emissions and land use spatial arrangements [50], and another to gain insight concerning what policies could be put forth to simulate emergent patterns of green infrastructure investment in urban tropical environments [53]. Public–private flood insurance partnerships in London have been simulated with the goal of better-incentivizing surface flood risk reduction while keeping insurance premiums affordable, with results calling for an overall stronger policy approach to flood risk management and further collaboration between all levels of government as well as developers and planners [89].

Additionally, ABMs have been paired with flood modeling software to investigate the influences of policy on individual behavior and flood damages in coastal areas. For example, the authors of [63] coupled a flood model and an ABM framework, the Coupled fLood-Agent-Institution Modelling (CLAIM) [62], to observe human–flood interactions on the river island of Wilhelmsburg, Germany. They found that household adaptation behavior is heavily defined by the interval between the flood events they experience, and that government mitigation subsidies increase household participation in flood-proofing measures, in one scenario decreasing building damage costs by 130%. Modeled household–authority interactions allowed the researchers to recommend that Wilhelmsburg authorities provide more mitigation subsidies as an effective motivation tactic and to demonstrate that coupled ABM and flood models can be used as a decision support tool for flood risk mitigation.

Aside from policy, ABM also allows the user to simulate individual responses to environmental changes and test disaster warning and evacuation procedures. An ABM was developed for the Netherlands neighborhood of Heijplaat, which incorporated human decision-making in flood risk analysis, demonstrating that flood risk assessment estimates fail to accurately portray future flood risk when they do not consider the effects of decentralized human behavior [54]. The authors found that accounting for adaptive dynamic household behavior in response to flood risks over time reduced the estimated flood risk by up to 56%, offering insight as to how shifting the risk reduction responsibility to the individual can affect the overall community risk.

Similarly, an ABM was used to simulate individual flood-proofing responses to an early flood warning system in the Ng Tung River basin of Hong Kong [61]. Rather than flood risk assessment changes, this study examined behavior effects on flood loss assessments, and found it less costly and more effective for households to invest in preventative rather than reactive flood-proofing. The model also tested responses to storm warnings with varying lead times and frequencies and found that lead times have a significant effect on flood losses, which are minimized when messages are accurate and more frequent, in one scenario prompting a 40% loss reduction. This allowed modelers to suggest an increased focus on improving rain warning systems with longer lead times. In the same vein of accommodation by way of evacuation planning, a coupled ABM–flood model for Towyn, Wales, investigated the vulnerability of individuals to different storm surge, defense breach, warning time, and evacuation scenarios [71]. The methodology put forth in this paper could serve as an appraisal tool for flood managers and policymakers concerned with flood defense investment, floodplain occupancy, and optimal shelter locations. The results provide insight on commonly congested evacuation routes, an emergent outcome otherwise unavailable through alternate modeling methods.

By observing possible emergent outcomes brought about by primarily decentralized forms of accommodation practice, researchers have been able to provide insights concerning policy and subsidy implementation, effects of individual behavior on risk at the community level, as well as ways in which storm warnings affect household response, losses, and vulnerability. While any recommendations made are not reflective of the ability of ABM to predict the future or events which are most likely to occur, they do provide a means of observing possible future responses to new developments within a system [90] as well as their key factors and drivers [91]. In studies where protection measure effects are observed, ABM offers a look at how community-level decisions can affect those made at the individual level.

### 3.2. Agent-Based Modeling and Protection Practices

Protection measures, typically put in place at the community or government level, are primarily concerned with advancing or holding existing lines of defense from flood hazards [9]. Protection practices can be "hard" measures or structures such as seawalls, dikes, and other built infrastructure, or "soft" coastal management measures that aim to enhance our coastlines as barriers, such as implementation of artificial dunes or enhancement of coastal vegetation (Table 1). Notable examples of coastal protection projects include the Dutch Maeslant storm surge barrier [92], the Venice MOSE flood barrier [93], and the Army Corps of Engineers' Long Island Beach widening project [94]. While the study outcomes described in the previous section were from studies which only considered accommodation practices in their ABMs, there were no studies found that matched our search criteria which only considered protection measures. Protection measures are generally put forth at the community or government level, so insights are provided concerning government mitigation attempts and their effects on adaptation choices at the household level and how these jointly affect the overall actual and perceived risk.

Abebe et al. [51] put forth a coupled ABM–flood model to observe behavioral responses to building development and various flood mitigation policies on the island state of Sint Maarten. The model allows households with different compliance thresholds to react to various accommodation requirements, including one which restricts new home building within 50 m of the coastline, one that requires homes be elevated if located within a flood zone, and another that requires all homes be elevated regardless of coast proximity. In addition, a government actor may institute protection measures through dike construction and widened channel cross-sections if a flooded household threshold is exceeded. Results show that higher policy compliance results in lower community vulnerability, again highlighting the importance of individual mitigation participation [51]. However, results also suggest that structural protection measures are the most important factor in reducing community flood risk, something not currently commonly practiced in Sint Maarten due to community consensus that hard measures have the potential to detract from the beauty of the island's beaches and consequently, the tourism economy [51]. Unintended decreases in tourism business due to protection measure installation would, arguably, be a form of maladaptation. Another form of maladaptation which has only recently been modeled using ABM is the levee effect, or the safe development paradox.

The safe development paradox (SDP) describes situations in which individuals fail to perceive the actual flood risk following the implementation of government-level protection measures, creating consequent catastrophe hotspots [95,96]. Haer et al. [56] developed an ABM to provide the first quantification of the economic effects of the SDP, observing extreme flood event impacts on the European Union. The model observes SDP effects on population growth, property values, individual accommodation choices in response to public protection measures, and potential flood damage increases. The study found that the population in flood-prone regions increased following the government raising the height of an existing dike. The SDP is observed in the consequent increased household vulnerability as well as their failure to participate in home elevation or other flood-proofing precautions, as perceived flood risk decreases with the implementation of public safety measures. Modelers suggest not only the introduction of policy for regulating household accommodation measures in case of a dike failure, but also that SDP-induced population growth be included in future risk assessments. Overall, this study quantified how proactive government measures can result in a lower yearly flood risk, but higher extreme event impacts due to a lower individual inclination to protect their homes, a finding echoed in a previous ABM study by Haer et al. [55], which found that proactive government measures are less influential on losses than household accommodation practices in the short term.

Similarly, a coupled ABM–flood model was developed for Boretto, Italy, to investigate the combined use of individual flood-proofing measures and community-level infrastructure improvement, as well as the effects of levee failure and individual risk perception on government decision-making [68]. Household agents protected by a levee system have options to move into low-risk areas, take part in accommodation measures, or complain to the government agent in hopes of them imposing protection measures by raising the height of their existing levee system. In addition to reinforcing the notion that individual adaptation actions play a significant role in flood-risk dynamics, the model explores population growth in the context of the SDP and demonstrates increased household risk perception following flood events. The impact of stochasticity, for example on household parameters including the risk perception threshold and the coping appraisal threshold, was significant, enforcing that the heterogeneities among individuals are important for flood risk evaluation. The advantage of using ABM is that these heterogeneities can be incorporated for each household in the model, and flood risk is simulated over both time and space. It is important that these characteristics also be incorporated into individual decision-making surrounding inward and outward movements from at-risk coastal areas.

### *3.3. Agent-Based Modeling and Retreat Practices*

Retreat, also coined Climigration [97], is the permanent displacement of a community brought about by gradual biophysical changes and extreme weather events [97,98]. This strategy is unique in its aim to not only relocate a group of people, but to also allow the eradicated area to completely return to nature [97,99]. Sea-level rise and worsening storm events present physical and economic issues for coastal communities that can contribute to making them unlivable, particularly in small island states [100], including infiltration of freshwater aquifers, saline-rich soil, and consequent crop yield losses. Highly contested and often seen as a last resort, migration from coastal zones is both costly and a source of severe disruption for the at-risk community [101]. For some, migration may pose a feasible adaptation option in terms of resident safety but threaten cultural ties and a way of life passed on for generations, as in the cases of Louisiana's Isle de Jean Charles [102] and Alaska's Kivalina [103]. Though often presented as a passive or defeatist route [99], it has also been argued that retreat is a truer form of adaptation than accommodation or protection strategies, as it seeks to truly change human activity to suit the environment rather than resisting environmental change to preserve human activity [104].

Retreat has been broken into the following categories: climate migration, which includes the resettlement of communities and the sale of flood-prone properties, and land reclamation by way of, for example, shoreline setbacks (Table 1). Understanding interactions between the rising sea levels, policy, and human mobility is key to informing national decision-makers, planners, and the populations facing this extreme adaptation option [105]. ABMs offer the ability to observe retreat responses to climate change scenarios and have been used to explore climate-induced agricultural labor migration in the United States [91] as well as to support the need for migration policy in response to climate and demographic changes in Burkina Faso, Africa [106]. The remainder of this section will discuss takeaways from several ABMs, which observe outcomes of implemented retreat strategies in coastal communities.

Hassani-Mahmooei and Parris [81] developed an ABM to explore emergent patterns in climate migration flows between districts in coastal and highly populated Bangladesh by mapping population growth alongside resettlement preferences and interactions between individuals at the household level. Agents relocate depending on their social network and physical vulnerability, with the objective of an improved socioeconomic status. Agents make migration decisions depending on the economic success of previous decisions, property ownership and employment, and the population size of potential resettlement locations. Model results predict that climate change will cause increased movement toward east and northeast districts, away from droughts and floods. Additionally, modelers suggest specific cities which may need to adapt to provide additional manufacturing and commerce jobs for incoming migrants as well as affordable housing and flood controls in hazardous areas [81]. In this way, ABM is shown to be a prospective tool for aiding district planners in future financial decisions.

Alternately, Bell et al. [85] developed the Migration, Intensification, and Diversification as Adaptive Strategies (MIDAS) ABM platform to investigate push, pull, and mooring influences on household migration in Bangladesh. While retreat was investigated as an adaptive choice, results indicate that flood impacts on household income do not lead to net retreat inland from the country's coastal areas. Agents, among other actions, share information and resources across dynamic social networks and make migration decisions based on affordability and which of their potential livelihood portfolios has the highest utility, which consider income opportunities, resource sharing ability, and utility values of places or assets. Agents also have access to credit corresponding to their existing capital, which can be used to migrate or invest in their current livelihoods. Results indicate that migration accelerates towards the coast due to livelihood opportunities, but less so when agents experience sea-level change-induced flood "shocks". Following flood damages, some agents can no longer afford to migrate inland again due to damage costs and a lack of livelihood alternatives [85]. This study emphasizes the difference between financially immobilized households in flood-prone areas and 'moored' households by incorporating attachment to place in decision-making by examining credit investment pathways. Attachment to place is something frequently discussed in coastal adaptation literature [11,107–110] but rarely incorporated in the coastal ABM space. This case study, following Hassani-Mahmooei and Parris [81], is a demonstration of how emergent responses can vary, even when considering the same location and adaptation responses, and stresses the importance of incorporating the agent livelihood context and behavioral responses [85].

There are additional studies which consider retreat practices in conjunction with accommodation and protection strategies. These include the study in [74], which presented an ABM to observe feedback between storm- and sea-level rise, beach nourishment projects, and household accommodation and retreat decisions for Nags Head, North Carolina, and found a strong link between storm intensity and community occupancy. Similarly, the authors of [59] studied the influence of protection, retreat, and household accommodation decisions in Fargo, North Dakota. ABM results reiterate the significant influence that individual movements to and from high-risk areas can have on community flood risk. In another case, the authors of [80] used an ABM to track migration to and from the Arctic community of Old Crow, Yukon, as well as changes in the local economy and resource harvests in response to climate, tourism, and government spending. Migration preference is dependent on past job and harvest shortfall experience, both of which are affected by tourism development, government spending, and climate change effects on subsistence resources and land access. Results provide insights concerning short- and long-term job availability following newly built road access to the community, as well as different levels of ecotourism development. These discussions may allow decision-makers to make better-informed choices concerning possible policy implementation routes for both development and environmental protection.

## 4. Beyond ABM and Towards a System of Systems Approach

Uniquely, the use of ABM in Berman et al.'s [80] study allows for exploration of community and tourism development on in-migration and retreat choices in the face of climate change. While it has been determined that tourism is a prime candidate for ABM applications [111], the integration of the two within mainstream tourism research remains limited [112]. While a few studies have aimed to observe how climate change and adaptation affect ski tourism by way of artificial snowmaking [113–116], studies of this kind are even more scarce in coastal contexts, and rarely incorporate coastal adaptation effects in response to climate change on tourism dynamics. The remainder of this paper makes a case for furthering ABM applications for the purpose of observing interactions among environmental changes, decentralized and community-level adaptation choices, and coastal tourism trends through the integration of ABM and a novel system of socio-environmental systems (SoSES) approach.

### *4.1. Climate Change and Coastal Tourism Interactions*

First, the importance of the tourism industry to communities, coastal and otherwise, should be stressed. Tourism is one of the world's largest global businesses [117], deemed a sector of hope for its potential to "drive inclusive socioeconomic growth, provide sustainable livelihoods, foster peace . . . and help protect our environment" [118]. Maritime and coastal tourism are vital to the economy of many countries, generating income for local communities, and providing seasonal and year-round employment. The United States coastal tourism and recreation sector, for example, makes up nearly 75% of the employment of the country's entire marine economy [119]. Coastal areas are primed for tourist visitation as they often offer a combination of history and natural landscapes that cannot be experienced elsewhere. The effects of increasing environmental changes and flooding events on tourist activities have been explored by multiple studies, illustrating the potential ongoing and future threats to the economic and employment benefits they provide [120–123]. Moreover, human activities and rising carbon dioxide emissions are contributing to increasing ocean temperatures, deoxygenation, and acidification, posing threats to marine ecosystems, contributions to local economies, as well as the numerous individuals and industries that rely on them [117,124]. Many landmarks and cultural heritage sites are now at risk due to climate change impacts, including sea-level rise, coastal erosion, increased flooding, and heavy rain, threatening archaeological resources, historic buildings, and cultural landscapes, while creating complex interactions within and between natural, cultural, economic, and social systems [125–128]. Coastal areas all over the world have much to lose in the way of both economic and natural resources [127,129,130], but the magnitude of these losses has the potential to be offset by participation in adaptation measures. For example, with the tourism industry bringing in just under one-fourth of the sales for the entire Charleston County in 2018 [131], the town's mayor has acknowledged the rising seas as an "existential threat" [132]. The same can be argued for Venice, Italy, whose economy heavily relies on their tourism industry, bringing in over 25 million visitors each year [133,134].

ABM studies which examine climate-induced environmental hazards, adaptation outcomes, and the coastal tourism economy are limited, but have the potential to reveal emergent properties following adaptation decisions. One example is McNamara [72], who put forth dynamically coupled sub-models for natural barrier island processes, tourist resort development, hazard mitigation management decisions, and storm damage, in which economic and policy decisions are simulated through ABM. The model was applied to Ocean City and Assateague Island National Seashore, Maryland. Tourist agents make destination choices, dependent on location familiarity, beach width, and vacation cost. Developer agents build hotels that hotel-owning agents can purchase and set lodging prices to maximize tourism revenue. Policy agents may initiate protection measures including beach replenishment and dune-building projects to widen beaches following beach erosion. Findings indicate that low rates of sea-level rise result in low erosion rates, and therefore, wider beaches and high tourism revenue.

The first model of the coastal tourism system which integrates human–environmental interactions and includes both locally induced environmental problems and global challenges is the ABM Coasting, developed by Student et al. [69]. The model is applied to the Caribbean small island developing state of Curaçao, a tourism destination particularly vulnerable to climate change, with the goal of analyzing socio-ecological vulnerabilities. It employs a dynamic vulnerability approach, also novel in the realm of tourism–climate studies [69]. The model explores coastal tourism users' willingness to collaboratively mitigate tourism-induced pollution and environmental degradation, which lower environmental attractiveness to potential tourists. The ability of environmental agents, such as mangroves and sea turtles, to move, multiply, and die is also influenced by pollution and environmental degradation, which in turn affect tourism operator location selection as well as biodiversity, which affects environmental attractiveness. Additionally, Coasting accounts for several possible environmental changes and accommodation measures, including sea-level rise, environmental shocks, and both infrastructure and beach elevation requirements. Results offer insight into operator and environmental vulnerability over time and indicate that vulnerabilities were introduced, namely, by low tourism returns, increasing pollution levels, and pollution-level influence on environmental attractiveness. Additionally, locally induced pollution management in tandem with sea-level rise has a more significant effect on vulnerability emergence than sudden, extreme events [69].

Studies such as these which aim to integrate climate-induced environmental hazards, adaptation measure implementation, and fluctuations in the coastal tourism economy are limited, and identifying the effects of hazards and adaptation choices on tourist behavior and decision-making remains a challenge. While ABM methods offer the ability to observe tourist behaviors and trends in response to varying climate change event types and frequencies, there is still much to be determined concerning how climate adaptation measures can curb or enforce these responses, as well. This is not without reason—tourism is a "multi-scalar phenomenon" [111] consisting of agents and influences at "local, regional, national, and global levels", with a vast number of agents, ranging from "tourists, residents of destinations, and the industry" [111]. Combinations of influences by and on agents and their environments are immense, and difficulty in adapting these multiple parties' characteristics and decision-making into model parameters and rules [135] may lead to omission of significant system components.

It has been demonstrated that ABM allows us to observe vulnerability and adaptive capacity changes over time and has the means to illuminate possible drivers and outcomes of tourist motivation and behavior, management decisions, planning and development scenarios, and policy and marketing strategies [111]. However, agents affect and are affected by the natural and human landscapes they are placed within, and their interactions with one another and their environments are complex, nonlinear in nature, and produce externalities [111]. The struggle for ABM lies in relaying the flow of causalities among the various subsystems within its modeled environment. To aid in this, we propose an integration of ABM and a novel systems of socio-ecological systems (SoSES) approach to simulate the coastal tourism system, consisting of its highly integrated social, economic, and natural subsystems. This will better-inform managers and administrators about its driving forces [136] and address the following gaps in the present literature, including the need to:

(1) Expand the presently limited integration of ABM applications and tourism in mainstream research [112].
(2) Deepen the understanding of system dynamics and subsystem interactions within the coastal tourism system [135].
(3) Jointly consider private and public climate change adaptation effects on coastal hazard impacts [86].
(4) Determine drivers of possible externalities and redistributed effects of climate adaptation decisions in coastal environments [10,111].
(5) Put forth increasingly robust, innovative adaptation policies based on social and behavioral solutions [111].

### *4.2. Coastal Communities as Systems of Socio-Ecological Systems (SoSES)*

Previously, we stated that coastal communities can be classified as both CASs and SESs. Difficulties in modeling these systems include complex system dynamics as well as externalities, feedback loops, unpredictability, and uncertainties [35]. Coastal systems are facing numerous sorts of additional challenges and risks, such as climate change [137,138], population pressure and urbanization [139], land use change [140], ecological disturbance [141], uncertainties and discrepancies [142], and unsustainable management [143]. Each of these challenges can be the topic of emerging scientific research, which is often rooted in different types of SESs [144].

However, separated analysis of SESs' subsystems overlooks hidden causal forces and compounded inter-connections, calling for a system-of-systems (SoS) approach to adequately capture the complexity, evolution, and feedback of integrated SESs as well as the emergent properties which will appear due to agents' interactions within and among subsystems. We propose a system of socio-environmental systems (SoSES) approach, in which socio-environmental quantitative modeling inputs are dynamically coupled to qualitative outcomes of social system analyses, and vice versa. SoSESs include different hyper-connected socio-environmental systems, where each individual system has its own components, including: (1) environment (natural and constructed), (2) economic (institutions and policies), (3) political (planning, priorities, and strategic behavior), and (4) social (values, perceptions, information, and experience) components, as the long-term sustainability of our coastal communities will be tied to the fully coupled management of these human and natural systems.

ABM methods are particularly well-suited to study the emergent processes of hierarchical interactions between the coastal, social, environmental, and economic subsystems mentioned throughout this paper, as they allow for simulation of heterogeneous agent behavior while encompassing tourism in coastal environments as a complex, adaptive SoSES. Through existing ABM meta-models (i.e., Modeling Agent Systems based on Institutional Analysis (MAIA)) [145], survey and ethnographic data may be translated to ABM inputs (e.g., rules, parameters) to capture diverse and possibly irrational human behavior effects on tourism dynamics and the roles of its intertwined systems on economic feasibility, public interest, and physical vulnerability. Treating the coastal tourism system as a SoSES will aid in identifying areas where institutional mechanisms for cooperation and coordination are needed and will provide a planning framework to sustainably manage the system under future changes.

The SoSES approach supports the mapping and representation of the flow of causalities between SESs. This effort requires integrated quantitative modeling and qualitative analyses of natural–human systems. With ABM, economic and political relations among defined entities can be modeled by the user as agent institutions, social beliefs and perceptions as agent attributes, and the environment of interest through either the ABM program itself (e.g., as pixels or vector objects) or by coupling the ABM with, for example, flood modeling software. Ultimately, ABM is a means of observing the feedback among subsystems and actors of interest in SoSES because it enables the integration of systems across multiple temporal, spatial, and organizational scales [37].

Due to this, the SoSES approach may prove particularly useful in deepening the understanding surrounding possible redistributed vulnerabilities, or maladaptive effects, following adaptation decisions [10] in coastal tourism systems, as well. Development of a maladaptation guidance, which assesses potential side effects and trade-offs of an adaptation initiative before it is enacted upon in any system, is a crucial need [146]. Additionally, the distinction of which actors benefit and suffer from adaptation choices could not only work to "better-support climate-resilient and sustainable development" [147]. Existing ABM study results have indicated maladaptive outcomes following adaptation decisions, including the work of Koning and Filatova [84], whose results indicated market sorting, increased risk of climate gentrification, and increased social vulnerability in flood-prone areas following unmanaged retreat from coastal North Carolina. In another ABM study, it was found that while implementation of backshore protection structures reduced erosion impacts on buildings, building flood exposure was increased, in turn reducing beach accessibility [79]. SoSES will aid in connecting these redistributed effects to connected subsystems, for example allowing for the exploration of coastal gentrification effects on government willingness to institute protection measures, or of reduced beach accessibility effects on tourist influx, average length of stay, nearby hotel income, and so forth.

In coastal environments, interactions between the national government, regional governments and city planners, homeowners, tourism businesses, and environmental organizations are just few examples of interrelationships, feedback, and causalities among the SoSES' components. Possible social forces include economic development, power relations, demographic changes, and investments and management of the coast, all of which can potentially be impacted by physical environmental changes brought about by climate change, storm surge, tropical storms, or land use changes. Decisions, such as investments in technologies and infrastructure, can intensify or dampen the effects of these changes, which often require shared-view management and system-wide (e.g., regional, national) institutional responses for cooperation, coordination, and sustainable planning.

Considering the process and interaction assumptions, ABMs coupled with system dynamics models can be useful and appropriate choices for exploring trajectories of SoSESs and provide insights about individual and aggregated effects of agent choices and environmental changes on each subsystem, while also offering understanding about the overall system's most important features, variables, and actors, and system of systems' archetypes [148]. The extent to and the means through which a system adapts to climate change impacts is an emergent social phenomenon resulting from the joint decision-making of multiple individual decision-makers [90], and the ability of ABM to showcase interactions between the environment and adaptive individuals makes it a suitable strategy for modeling potential climate change adaptation strategy outcomes [149].

### *4.3. Accommodation, Protection, and Retreat within SoSES Context*

A key question which remains and may be further explored through ABM integration with the presented SoSES approach is how different types and combinations of adaptation decisions may interact with the coastal tourism industry, as each strategy has unique potential feedback and outcomes to introduce to the coastal tourism system and its subsystems. For example, accommodation measures, such as policy decisions and government subsidies, have been shown to increase household accommodation participation through flood-proofing measures, leading to decreased household damage costs [63]. Are these results transferable to recreation and commercial buildings facing repeated instances of flood damage, and how would the exacerbation or lessening of this problem affect tourism visitation to these buildings? Are flood-proofing measures only instituted at the individual level providing a significant enough risk reduction to affect the tourism economy? Studies such as these moving forward may explore how shifting adaptation responsibility to the individual tourist-centric businesses, such as restaurants, hotels, and maritime recreation centers, rather than households alone, through policy decisions, government subsidies, or community outreach can work to alter the community-level risk and economy and reduce vulnerability for corresponding subsystems.

Further, we have protection measures, generally instituted at the government or community level. We saw that protection measures were the most effective for flood protection in the tourist-popular Sint Maarten [51], even though they are not currently in use because of the importance of maintaining the aesthetic appeal of the area for tourists. Possible trajectories of tourist influx in response to different protection measures in this area could be explored through the SoSES approach, which would allow for feedback among the existing ABM–flood model and one which encompasses the perceptions and social beliefs of Sint Marteen tourists. Beach replenishment projects have been predicted to reduce the effects of erosion and make beaches more attractive to tourists [72]. Communities highly dependent on tourism revenue may benefit from weighing protection project timelines and their effects on beach accessibility and attractiveness for tourists, and how this may affect surrounding businesses and tourism-related employment opportunities for residents, if at all.

It is possible that retreat decisions have the potential for the farthest-reaching cascading effects on surrounding subsystems. With the ability to cause housing market sorting [84], climate gentrification [84,86], and large resettlements of individuals in areas whose existing industry and employment may not support them [81], there are a variety of uncertainties concerning the effects on surrounding businesses and the tourism industry. Gentrification along our coastlines may reduce both affordable housing and property rentals for tourists, increasing social vulnerability, lowering tourist influx, and lowering income and job opportunities at surrounding hotels and restaurants. Alternately, when retreat strategies allow abandoned areas to completely return to nature, a path is cleared for environmental changes, including but not limited to biodiversity adjustments, or eradication of repeat flood damage repair costs for the buildings previously in the retreated area. Understanding possible redistributed effects following the push for or actual retreat in coastal areas through systems analysis and individual preferences programmable through ABM will aid governing bodies in making informed choices for the longevity of their communities, both economically and physically.

This is by no means a comprehensive description of future research questions on this topic but rather a glimpse of how a systems dynamics approach coupled with ABM insights may aid in identifying drivers of climate vulnerability for social, environmental, and economic systems on our coasts, as calls for adaptation grow more urgent. There is also further work to be carried out considering the joint modeling of multiple types of adaptation strategies. It must be taken into consideration that none of the adaptation types presented herein are put forth within a vacuum, and therefore deepened the understanding of how multiple adaptation types and options offered concurrently may affect the coastal tourism system. Many of the studies presented in the review section of this paper [57,59,60,67,68,76] etc. (Table 1) do consider multiple adaptation types within their presented ABMs, but McNamara [72] and Student et al. [69] are the only studies to do so in the context of the coastal tourism system. Perhaps the relocation of historic buildings inland as a form of retreat, and the concurrent sea wall construction as a form of protection, with the goal of reducing flood vulnerability for tourist attractions, could lead to less visitation due to the perceived loss of historical authenticity and the beach aesthetic, or vice versa. The freedom of the ABM user to define and assign agent attributes and rules allows for representation of virtually any social system, and mapping of a great number of possible system-level responses and outcomes to individual and collective actions within the SoSES framework.

## 5. Pros and Cons of ABM and SoSES

While both systems of socio-ecological systems (SoSES) and agent-based modeling (ABM) offer valuable insights and approaches for natural disaster management in coastal communities, here, we examine the pros and cons of each approach based on the previous sections.

### *5.1. Systems of Socio-Ecological Systems (SoSES)*

- Holistic Understanding: SoSES provides a comprehensive and holistic view of the interactions between social and ecological components, allowing researchers and decision-makers to consider the complex and interconnected nature of coastal systems during disaster management.
- Integration of Social and Ecological Factors: SoSES facilitates the integration of human behavior, community dynamics, and ecological responses, leading to a more nuanced understanding of how social decisions and ecological processes interact to influence disaster outcomes.
- Multi-Stakeholder Engagement: SoSES encourages the involvement of various stakeholders, including local communities, governments, and experts, in the decision-making process, promoting collaborative and participatory approaches to disaster management.
- Complexity and Data Requirements: The comprehensive nature of SoSES demands significant data on both social and ecological elements, which can be challenging and resource-intensive to gather, especially in data-scarce regions.
- Limited Predictive Capability: Due to the complexity of SoSES models, predicting specific outcomes of natural disasters can be difficult, making it challenging to develop precise and targeted disaster response plans.

### *5.2. Agent-Based Modeling (ABM)*

- Capturing Individual Behavior: ABM excels at representing individual decision-making and behavior, allowing for a more fine-grained analysis of how individual choices influence disaster preparedness, response, and recovery.
- Adaptive and Dynamic: ABM models are capable of capturing dynamic changes in response to evolving scenarios, making them useful for studying adaptive behavior and resilience in coastal communities facing various natural disasters.

- Scenario Testing: ABM enables the testing of different disaster management strategies and policies in a controlled virtual environment, providing insights into their potential effectiveness and unintended consequences.
- Data Requirements: ABM models rely on detailed data on individual behavior, preferences, and interactions, which may not always be readily available or may be challenging to collect, leading to potential inaccuracies.
- Simplified Representation: ABM often requires simplifications and assumptions about complex social and ecological processes, which might oversimplify the real-world dynamics and limit the model's accuracy.

While this paper has advocated for the use of ABM to observe emergent behavior following climate change adaptation actions for the purpose of mitigating climate variation-induced threats in coastal areas, a major component keeping these models from mainstream use and reliability is the lack of data [51], depending on the questions the modelers are hoping to answer [90]. Most poignant is the lack of data on agents themselves, for the parameterization of their individual behaviors [16,51,68,90], regarding, for example, human response to flood risk [54–56,61], dynamics within the tourist industry [115,150], and migration scenarios [91]. Simplifying assumptions reduce the complexity of these models and impede them from representing wholly real-world scenarios [51,80,151], and lend themselves to compounded uncertainty [152]. In turn, this can make ABM an unreliable predictive tool for both the modeled future scenarios and individual behavior they are conveying, particularly at the local scale [71,91,153]. Additionally, human behavior assumptions compounded with the reported lack of available data make for unsavory model calibration and validation conditions [37,51,54,55,68,115]. Future studies in this area stand to benefit from additional ethnographic data, semi-structured interviews, and attitudinal surveys of individuals for tourists, attraction managers, individuals in coastal areas, policymakers, storm and flood water managers, and decision-makers at every level of government in coastal areas to aid in filling these gaps.

ABM appears more "data-hungry", which results from—at least partially—ABM's greater complexity in comparison with traditional, equation-based models. This is the price ABM developers and users pay for its outstanding flexibility and capacity to capture the corresponding processes or mechanisms. To date, several measures have been adopted or proposed to address this challenge, including but not limited to simplifying assumptions, theoretical representation of processes, and inverse parameterization using sets of observed patterns [154]. Also worthy of mention is the great potential of data science and artificial intelligence in finding appropriate parameter values and functional relationships or rules (readers with interest are referred to the review paper in [154]).

Aside from reducing the physical vulnerability of coastlines for the sake of heritage tourism and beach recreation, we suggest a greater focus of resources on protecting the historical and often culturally significant buildings and landmarks in coastal areas for the sake of cultural and identity preservation for residents. From what standard can we quantify cultural heritage, so there is a common understanding of which historic sites are not only most vulnerable to climate change but most detrimental, economically, or culturally, to the surrounding community if damaged or lost? The decentralized nature of coastal land management, particularly in the United States, makes archaeological site preservation challenging; in response to this, the authors of [155] developed a cultural resource vulnerability (CRV) metric based on elevation and shoreline distance, vulnerability of the nearest shoreline, and the surrounding land use type. As cultural and heritage sites are facing similar threats, development of a comparable metric would be beneficial for setting attraction manager action thresholds within ABMs. Additionally, a dialogue with historic property owners and city managers will have to be opened to discuss which adaptation strategies are appropriate for their sites to set realistic model institutions and adaptation options for specific properties, echoing existing calls for increased collaborations between disciplines and greater involvement of social and psychological sciences in ABM development [156]. This highlights only one of many concerns that must be addressed if we are to better-guide human interactions and interventions within our coastal systems.

Integrating agent-based modeling (ABM) and systems of socio-environmental systems (SoSES) can offer a powerful approach to address the complex issues of climate change and natural disaster impacts on tourism and coastal communities. The combined framework allows for a more comprehensive understanding of the interactions between social, economic, and ecological components within coastal systems, considering the adaptive behaviors of individual agents and the broader system dynamics. The following demonstrates how the integration can be achieved:

- Modeling Individual Behaviors with ABM: ABM excels at representing individual decision-making and behaviors in response to various factors, such as climate change and disaster events. By incorporating individual agents with different attributes, preferences, and adaptive capacities, the ABM captures the heterogeneity of coastal community members, their interactions, and the decisions they make regarding adaptation strategies, tourism activities, and disaster preparedness.
- Capturing System Dynamics with SoSES: SoSES provides a holistic framework that integrates social and ecological systems, including the interactions between human communities and natural environments. It allows for a more nuanced understanding of how social decisions and ecological processes interact to shape the vulnerability and resilience of coastal communities to climate change and natural disasters. SoSES incorporates feedback loops and interdependencies among various components, enabling a deeper analysis of the system's response to different adaptation measures and potential cascading effects on tourism and coastal communities.
- Linking ABM and SoSES: The integration involves linking the individual agents and their decision-making processes from the ABM with the broader socio-ecological dynamics represented in SoSES. The decisions made by individual agents in the ABM, such as investment in tourism infrastructure or participation in adaptation programs, can feed into the larger SoSES framework, influencing community-level resilience and coastal ecosystem health. In turn, the state of the socio-ecological system can feedback to the ABM, shaping the behavior and decisions of individual agents.
- Scenario Testing and Policy Evaluation: The integrated approach enables researchers and policymakers to simulate various scenarios, such as different climate change projections, adaptation strategies, and tourism development plans. By analyzing the outcomes from the ABM and SoSES integration, decision-makers can evaluate the effectiveness of different policy options in reducing disaster impacts on tourism and coastal communities and enhancing their resilience to climate change.
- Stakeholder Engagement and Participatory Modeling: Integrating ABM and SoSES involves engaging stakeholders from various sectors, including local communities, tourism industry representatives, policymakers, and environmental experts. Their inputs and perspectives are vital in calibrating the models, validating the assumptions, and co-creating scenarios to ensure the relevance and applicability of the integrated framework for real-world decision-making.

Overall, the integration of ABM and SoSES offers a powerful tool to address the challenges posed by climate change and natural disasters on tourism and coastal communities. By capturing the complexity of human behavior and its interactions with the environment, this integrated approach can guide the design of adaptive strategies that safeguard coastal regions, promote sustainable tourism, and foster resilient communities in the face of uncertain and evolving environmental conditions.

## 6. Conclusions

Rather than predictions or most likely prescribing scenarios, ABMs produce a means of observing possible future responses to new developments within [90] or beyond [157] a system, as well as changes in key factors and drivers [91]. In this paper, results of ABMs which offered insights concerning emergent responses to varying coastal adaptation strategies to climate change effects were presented. These results may work to promote dialogue across a multitude of disciplines, and aid in decision-making by both stakeholders and community planners. Additionally, they have the potential, upon available data, to map possible sources of maladaptation, wherein adaptation practices have unintended consequences through which they redistribute risk elsewhere in a system [10]. A case has been made for the use of ABM and the presented system dynamics framework, SoSES, to explore interactions within the coastal tourism system more effectively and holistically to aid in preserving local safety, culture, economy, sense of place, and safety.

We know that “no system of modeling can precisely predict the future course of a complex, or complex adaptive, system” [153]. They are filled with uncertainties and are thus highly unpredictable, and both a lack of relevant available data and limited knowledge of quantifiable human behavior can contribute to these challenges [61]. However, whether or not ABM is a useful tool depends on the question being answered, what assumptions can be made for the system [90], whether the model has been well-tested [27,44,88], whether the ABM has been well-documented (e.g., using the ODD protocol) [158,159], and whether it is used for its intended purposes [154,160]. Modelers warn against including too many trivial details within ABM systems to lower the complexity and consequent uncertainty until there is a greater understanding of human decision-making and possible adverse impacts on natural systems [91], but there is potential in combining traditional top-down modeling approaches with the bottom-up techniques used in ABM frameworks to better-allow us to observe and explain emergent human dynamics, including those that occur following adaptation interventions on the coast.

Looking to the future, both SoSES and ABM offer valuable contributions to natural disaster management in coastal communities. SoSES excels at providing a holistic understanding of the interconnected social-ecological systems, while ABM offers insights into individual behavior and adaptive responses. Combining the strengths of both approaches can potentially enhance the effectiveness of disaster management strategies in coastal areas. However, it is essential to consider the data requirements and limitations of each approach when applying them in real-world scenarios.

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## References

1. Wu, S.; Bates, B.; Zbigniew Kundzewicz, A.W.; Palutikof, J.; Intergovernmental Panel on Climate Change WMO UNEP. Climate Change and Water. 2008. Available online: https://www.ipcc.ch/site/assets/uploads/2018/03/climate-change-water-en.pdfv (accessed on 11 July 2023).
2. *Climate Change Indicators in the United States*, 3rd ed.; U.S. EPA: Washington, DC, USA, 2014. Available online: www.epa.gov/climatechange/indicators (accessed on 11 July 2023).
3. U.S. Global Change Research Program. *Summary Findings Fourth National Climate Assessment*; U.S. Government Publishing Office: Washington, DC, USA, 2017.
4. Hirabayashi, Y.; Mahendran, R.; Koirala, S.; Konoshima, L.; Yamazaki, D.; Watanabe, S.; Kanae, S. Global flood risk under climate change. *Nat. Clim. Chang* **2013**, *3*, 816–821. [CrossRef]
5. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014.
6. Dai, A. Increasing drought under global warming in observations and models. *Nat. Clim. Chang.* **2013**, *3*, 52–58. [CrossRef]
7. WMO. *WMO Statement on the State of the Global Climate in 2018*; World Meteorological Organization: Geneva, Switzerland, 2018.
8. Mimura, N. Sea-level rise caused by climate change and its implications for society. *Proc. Jpn. Acad. Ser. B* **2013**, *89*, 281–301. [CrossRef] [PubMed]

9. Wong, P.P.; Losada, I.J.; Gattuso, J.-P.; Hinkel, J.; Khattabi, A.; McInnes, K.; Saito, Y.; Sallenger, A. Coastal Systems and Low-Lying Areas. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014; pp. 361–409.
10. Atteridge, A.; Remling, E. Is adaptation reducing vulnerability or redistributing it? *Wiley Interdiscip. Rev. Clim. Chang.* **2018**, *9*, e500. [CrossRef]
11. Jamero, M.L.; Onuki, M.; Esteban, M.; Billones-Sensano, X.K.; Tan, N.; Nellas, A.; Takagi, H.; Thao, N.D.; Valenzuela, V.P. Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nat. Clim. Change* **2017**, *7*, 581–586. [CrossRef]
12. Koslov, L. Avoiding Climate Change: "Agnostic Adaptation" and the Politics of Public Silence. *Ann. Assoc. Am. Geogr.* **2019**, *109*, 568–580. [CrossRef]
13. Marino, E.; Lazrus, H. Migration or forced displacement? The complex choices of climate change and disaster migrants in Shishmaref Alaska and Nanumea, Tuvalu. *Hum. Organ.* **2015**, *74*, 341–350. [CrossRef]
14. Fagan, B.M. *The Attacking Ocean: The Past, Present, and Future of Rising Sea Levels*; Bloomsbury Press: London, UK, 2013.
15. Tanim, A.H.; Goharian, E.; Moradkhani, H. Integrated socio-environmental vulnerability assessment of coastal hazards using data-driven and multi-criteria analysis approaches. *Sci. Rep.* **2022**, *12*, 11625. [CrossRef]
16. Macal, C.M.; North, M.J. Tutorial on agent-based modelling and simulation. *J. Sim.* **2010**, *4*, 151–162. [CrossRef]
17. Balti, H.; Abbes, A.B.; Mellouli, N.; Farah, I.R.; Sang, Y.; Lamolle, M. A review of drought monitoring with big data: Issues, methods, challenges and research directions. *Ecol. Inform.* **2020**, *60*, 101136. [CrossRef]
18. Wu, X.; Guo, J.; Wu, X.; Guo, J. A new economic loss assessment system for urban severe rainfall and flooding disasters based on big data fusion. In *Economic Impacts and Emergency Management of Disasters in China*; Springer: Singapore, 2021; pp. 259–287.
19. Lin, A.; Wu, H.; Liang, G.; Cardenas-Tristan, A.; Wu, X.; Zhao, C.; Li, D. A big data-driven dynamic estimation model of relief supplies demand in urban flood disaster. *Int. J. Disaster Risk Reduct.* **2020**, *49*, 101682. [CrossRef]
20. Epstein, J.M.; Axtell, R. *Growing Artificial Societies: Social Science from the Bottom Up*; Brookings Institution Press: Washington, DC, USA, 1996.
21. Abar, S.; Theodoropoulos, G.K.; Lemarinier, P.; O'Hare, G.M.P. Agent Based Modelling and Simulation tools: A review of the state-of-art software. *Comput. Sci. Rev.* **2017**, *24*, 13–33. [CrossRef]
22. An, L.; Grimm, V.; Sullivan, A.; Malleson, B.L.T.N., II; Heppenstall, A.; Vincenot, C.; Robinson, D.; Ye, X.; Liu, J.; Lindkvist, E.; et al. Agent-based modeling in the light of data science and artificial intelligence. *Environ. Model. Softw.* 2023, *in press*.
23. Bandini, S.; Manzoni, S.; Vizzari, G. Agent Based Modeling and Simulation: An Informatics Perspective. *Comput. Complex. Theory Tech. Appl.* **2009**, *12*, 105–117. [CrossRef]
24. DeAngelis, D.L.; Grimm, V. Individual-based models after four decades. *F1000 Prime Rep.* **2014**, *6*, 39. [CrossRef]
25. Schulze, J.; Müller, B.; Groeneveld, J.; Grimm, V. Agent-based modelling of social-ecological systems: Achievements, challenges, and a way forward. *J. Artif. Soc. Soc. Simul.* **2017**, *20*, 8. [CrossRef]
26. An, L.; Mak, J.; Yang, S.; Lewison, R.; Stow, D.A.; Chen, H.L.; Xu, W.; Shi, L.; Tsai, Y.H. Cascading impacts of payments for ecosystem services in complex human-environment systems. *J. Artif. Soc. Soc. Simul.* **2020**, *23*, 5. [CrossRef]
27. An, L.; Linderman, M.; Qi, J.; Shortridge, A.; Liu, J. Exploring complexity in a human-environment system: An agent-based spatial model for multidisciplinary and multiscale integration. *Ann. Assoc. Am. Geogr.* **2005**, *95*, 54–79. [CrossRef]
28. An, L.; Zvoleff, A.; Liu, J.; Axinn, W. Agent based modeling in coupled human and natural systems (CHANS): Lessons from a comparative analysis. *Ann. Assoc. Am. Geogr.* **2014**, *104*, 723–745. [CrossRef]
29. Barbati, M.; Bruno, G.; Genovese, A. Applications of agent-based models for optimization problems: A literature review. *Expert Syst. Appl.* **2012**, *39*, 6020–6028. [CrossRef]
30. Hamill, L.; Gilbert, N. *Agent-Based Modelling in Economics*; Wiley: Hoboken, NJ, USA, 2016.
31. Klein, D.; Marx, J.; Fischbach, K. Agent-Based Modeling in Social Science, History, and Philosophy. An Introduction. *Hist. Soc. Res.* **2018**, *43*, 7–27. [CrossRef]
32. Grimm, V.; Ayllón, D.; Railsback, S.F. Next-generation individual-based models integrate biodiversity and ecosystems: Yes we can, and yes we must. *Ecosystems* **2017**, *20*, 229–236. [CrossRef]
33. Liu, J. ECOLECON: A spatially-explicit model for ECOLogical-ECONomics of species conservation in complex forest landscapes. *Ecol. Modell.* **1993**, *70*, 63–87. [CrossRef]
34. An, L. Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecol. Modell.* **2012**, *229*, 25–36. [CrossRef]
35. Liu, J.; Dietz, T.; Carpenter, S.R.; Alberti, M.; Folke, C.; Moran, E.; Pell, A.N.; Deadman, P.; Kratz, T.; Lubchenco, J.; et al. Complexity of coupled human and natural systems. *Science* **2007**, *317*, 1513–1516. [CrossRef]
36. Zhang, H.; Zeng, Y.; Ling, B.; Xijun, Y. Modelling urban expansion using a multi agent-based model in the city of Changsha. *J. Geogr. Sci.* **2010**, *20*, 540–556. [CrossRef]
37. Berglund, E.Z. Using Agent-Based Modeling for Water Resources Planning and Management. *J. Water Resour.* **2015**, *141*, 04015025. [CrossRef]
38. Loucks, D.P.; van Beek, E. Water Resources Planning and Management: An Overview. In *Water Resource Systems Planning and Management*; Springer: Cham, Switzerland, 2017. [CrossRef]

39. Holland, J.H. *Hidden Order: How Adaptation Builds Complexity*; Basic Books: New York, NY, USA, 1995.
40. Miller, J.H.; Page, S.E. *Complex Adaptive Systems: An Introduction to Computational Models of Social Life*; Levin, S.A., Strogatz, S.H., Eds.; Princeton University Press: Princeton, NJ, USA, 2007.
41. Glaser, M.; Krause, G.; Ratter, B.; Welp, M. Human/Nature Interaction in the Anthropocene: Potential of Social-Ecological Systems Analysis. *Ecol. Perspect. Sci. Soc.* **2017**, *17*, 77–80. [CrossRef]
42. Axelrod, R. Advancing the art of simulation in the social sciences. In *Simulating Social Phenomena*; Springer: Berlin/Heidelberg, Germany, 1997; pp. 21–40.
43. Balbi, S.; Giupponi, C. *Reviewing Agent-Based Modelling of Socio-Ecosystems: A Methodology for the Analysis of Climate Change Adaptation and Sustainability*; Department of Economics Research Paper Series; University Ca'Foscari of Venice: Venice, Italy, 2009.
44. Parker, D.C.; Manson, S.M.; Janssen, M.A.; Hoffmann, M.J.; Deadman, P. Multi-agent systems for the simulation of land-use and land-cover change: A review. *Ann. Assoc. Am. Geogr.* **2003**, *93*, 314–337. [CrossRef]
45. Adger, W.N.; Hughes, T.P.; Folke, C.; Carpenter, S.R.; Rockstrom, J. Social-ecological resilience to coastal disasters. *Science* **2005**, *309*, 1036–1039. [CrossRef]
46. Doney, S.C.; Ruckelshaus, M.; Emmett Duffy, J.; Barry, J.P.; Chan, F.; English, C.A.; Talley, L.D. Climate change impacts on marine ecosystems. *Annu. Rev. Mar. Sci.* **2012**, *4*, 11–37. [CrossRef] [PubMed]
47. Hallengatte, S.; Green, C.; Nicholls, R.J.; Corfee-Morlot, J. Future flood losses in major coastal cities. *Nat. Clim. Chang.* **2013**, *3*, 802–806. [CrossRef]
48. Nicholls, R.J.; Wong, P.P.; Burkett, V.R.; Codignotto, J.O.; Hay, J.E.; McLean, R.F.; Ragoonaden, S.; Woodroffe, C.D. *Climate Change 2007: Impacts, Adaptation and Vulnerability*; Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2007.
49. Di Noia, J. Agent-Based Models for Climate Change Adaptation in Coastal Zones. A Review. *FEEM* **2022**. [CrossRef]
50. Morgan, F.J.; Daigneault, A.J. Estimating impacts of climate change policy on land use: An agent-based modelling approach. *PLoS ONE* **2015**, *10*, e0127317. [CrossRef]
51. Abebe, Y.A.; Ghorbani, A.; Nikolic, I.; Vojinovic, Z.; Sanchez, A. Flood risk management in Sint Maarten—A coupled agent-based and flood modelling method. *J. Environ. Manag.* **2019**, *248*, 109317. [CrossRef] [PubMed]
52. Hoang, B.T. *Land Use, Livelihood, and Legislation: An Agent-Based Model to Investigate the Impacts of a Policy Regime Switch on the Vietnamese Mekong Delta in the Context of Climate Change*; University of Venice: Venice, Italy, 2021.
53. Brown, S.; Ferreira, C. Agent-Based Modeling of Urban Tropical Green Infrastructure Investment. *Alam Cipta* **2013**, *6*, 39–51.
54. Haer, T.; Botzen, W.J.W.; de Moel, H.; Aerts, J.C.J.H. Integrating Household Risk Mitigation Behavior in Flood Risk Analysis: An Agent-Based Model Approach. *Risk Anal.* **2017**, *37*, 1977–1992. [CrossRef] [PubMed]
55. Haer, T.; Wouter Botzen, W.J.; Aerts, J.C.J.H. Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach. *Environ. Res. Lett.* **2019**, *14*, 044022. [CrossRef]
56. Haer, T.; Husby, T.G.; Wouter Botzen, W.J.; Aerts, J.C.J.H. The safe development paradox: An agent-based model for flood risk under climate change in the European Union. *Glob. Environ. Change* **2020**, *60*, 102009. [CrossRef]
57. Löwe, R.; Urich, C.; Domingo, N.S.; Mark, O.; Deletic, A.; Arnbjerg-Nielsen, K. Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations—A new generation of urban planning tools. *J. Hydrol.* **2017**, *550*, 355–367. [CrossRef]
58. Chandra-Putra, H. Real Property Market Responses to Coastal Flooding. Ph.D. Thesis, Rutgers University, New Brunswick, NJ, USA, 2017.
59. Tonn, G.L.; Guikema, S.D. An Agent-Based Model of Evolving Community Flood Risk. *Risk Anal.* **2018**, *38*, 1258–1278. [CrossRef] [PubMed]
60. Tonn, G.; Guikema, S.; Zaitchik, B. Simulating Behavioral Influences on Community Flood Risk under Future Climate Scenarios. *Risk Anal.* **2020**, *40*, 884–898. [CrossRef] [PubMed]
61. Yang, L.E.; Scheffran, J.; Süsser, D.; Dawson, R.; Chen, Y.D. Assessment of Flood Losses with Household Responses: Agent-Based Simulation in an Urban Catchment Area. *Environ. Model. Assess.* **2018**, *23*, 369–388. [CrossRef]
62. Abebe, Y.A.; Ghorbani, A.; Nikolic, I.; Vojinovic, Z.; Sanchez, A. A coupled flood-agent-institution modelling (CLAIM) framework for urban flood risk management. *Environ. Model. Softw.* **2019**, *111*, 483–492. [CrossRef]
63. Abebe, Y.A.; Ghorbani, A.; Nikolic, I.; Manojlovic, N.; Gruhn, A.; Vojinovic, Z. The role of household adaptation measures to reduce vulnerability to flooding: A coupled agent-based and flood modelling approach. *HESS Discuss.* **2020**, 1–40. [CrossRef]
64. Coates, G.; Li, C.; Ahilan, S.; Wright, N.; Alharbi, M. Agent-based modeling and simulation to assess flood preparedness and recovery of manufacturing small and medium-sized enterprises. *Eng. Appl. Artif. Intell.* **2019**, *78*, 195–217. [CrossRef]
65. Han, Y.; Peng, Z.R. The integration of local government, residents, and insurance in coastal adaptation: An agent-based modeling approach. *Comput. Environ. Urban Sys.* **2019**, *76*, 69–79. [CrossRef]
66. Chandra-Putra, H.; Andrews, C.J.; Bloustein, E.J. An integrated model of real estate market responses to coastal flooding. *J. Ind. Ecol.* **2020**, *24*, 424–435. [CrossRef]
67. Han, Y.; Ash, K.; Mao, L.; Peng, Z.R. An agent-based model for community flood adaptation under uncertain sea-level rise. *Clim. Change* **2020**, *162*, 2257–2276. [CrossRef]
68. Michaelis, T.; Brandimarte, L.; Mazzoleni, M.; Archfield, S.; Pande, S. Capturing flood-risk dynamics with a coupled agent-based and hydraulic modelling framework. *Hydrol. Sci. J.* **2020**, *65*, 1458–1473. [CrossRef]

69. Student, J.; Kramer, M.R.; Steinmann, P. Simulating emerging coastal tourism vulnerabilities: An agent-based modelling approach. *Ann. Tour. Res.* **2020**, *85*, 103034. [CrossRef]
70. de Ruig, L.T.; Haer, T.; de Moel, H.; Brody, S.D.; Botzen, W.W.; Czajkowski, J.; Aerts, J.C. Climate-proofing the National Flood Insurance Program. *Nat. Clim. Chang.* **2022**, *12*, 975–976. [CrossRef]
71. Dawson, R.J.; Peppe, R.; Wang, M. An agent based model for risk-based flood incident management. *Nat. Hazards* **2011**, *59*, 167–189. [CrossRef]
72. McNamara, D.E. Emergence in Coupled-Human Landscape Interactions: Combined Numberical and Agent-Based Models for Barrier Island Resorts and Flood Disaster and Response in New Orleans. Ph.D. Thesis, University of California, San Diego, CA, USA, 2006.
73. Lumbroso, D.; Davison, M. Use of an agent-based model and Monte Carlo analysis to estimate the effectiveness of emergency management interventions to reduce loss of life during extreme floods. *J. Flood Risk Manag.* **2016**, *11*, S419–S433. [CrossRef]
74. Karanci, A.; Berglund, E.; Overton, M. An agent-based model to evaluate housing dynamics of coastal communities facing storms and sea level rise. *Coast. Eng.* **2017**, *1*, 23. [CrossRef]
75. Tesfatsion, L.; Rehmann, C.R.; Cardoso, D.S.; Jie, Y.; Gutowski, W.J. An agent-based platform for the study of watersheds as coupled natural and human systems. *Environ. Model. Softw.* **2017**, *89*, 40–60. [CrossRef]
76. Karanci, A.; Velásquez-Montoya, L.; Paniagua-Arroyave, J.F.; Adams, P.N.; Overton, M.F. Beach Management Practices and Occupation Dynamics: An Agent-Based Modeling Study for the Coastal Town of Nags Head, NC, USA. In *Beach Management Tools—Concepts, Methodologies, and Case Studies*; Botero, C.M., Cervantes, O., Finkl, C.W., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2018.
77. Magliocca, N.; Walls, M. Exploring distributional influences on and effects of dynamic adaptive policy pathways for repeated coastal hazards. In Proceedings of the 9th International Congress on Environmental Modelling and Software, Fort Collins, CO, USA, 24–28 June 2018.
78. Mills, A.K.; Ruggiero, P.; Bolte, J.P.; Serafin, K.A.; Lipiec, E. Quantifying Uncertainty in Exposure to Coastal Hazards Associated with Both Climate Change and Adaptation Strategies: A U.S. Pacific Northwest Alternative Coastal Futures Analysis. *Water* **2021**, *13*, 545. [CrossRef]
79. Mills, A.K.; Bolte, J.P.; Ruggiero, P.; Serafin, K.A.; Lipiec, E.; Corcoran, P.; Stevenson, J.; Zanocco, C.; Lach, D. Exploring the impacts of climate and policy changes on coastal community resilience: Simulating alternative future scenarios. *Environ. Model. Softw.* **2018**, *109*, 80–92. [CrossRef]
80. Berman, M.; Nicolson, C.; Kofinas, G.; Tetlichi, J.; Martin, S. Adaptation and Sustainability in a Small Arctic Community: Results of an Agent-Based Simulation Model. *Arctic* **2004**, *57*, 401–414. [CrossRef]
81. Hassani-Mahmooei, B.; Parris, B.W. Climate change and internal migration patterns in Bangladesh: An agent-based model. *J. Dev. Econ.* **2012**, *17*, 763–780. [CrossRef]
82. Milan, A.; Oakes, R.; Campbell, J. *Tuvalu: Climate Change and Migration-Relationships between Household Vulnerability, Human Mobility and Climate Change*; United Nations University Institute for Environment and Human Security: Bonn, Germany, 2016.
83. Walls, M.; Magliocca, N.; McConnell, V. Modeling coastal land and housing markets: Understanding the competing influences of amenities and storm risks. *Ocean Coast. Manag.* **2018**, *157*, 95–110. [CrossRef]
84. Koning, K.; Filatova, T. Repetitive floods intensify outmigration and climate gentrification in coastal cities. *Environ. Res. Lett.* **2020**, *15*, 034008. [CrossRef]
85. Bell, A.R.; Wrathall, D.J.; Mueller, V.; Chen, J.; Oppenheimer, M.; Hauer, M.; Adams, H.; Kulp, S.; Clark, P.U.; Fussell, E.; et al. Migration towards Bangladesh coastlines projected to increase with sea-level rise through 2100. *Environ. Res. Lett.* **2021**, *16*, 024045. [CrossRef] [PubMed]
86. Taberna, A.; Filatova, T.; Roventini, A.; Lamperti, F. Coping with Increasing Tides: Technological Change, Agglomeration Dynamics and Climate Hazards in an Agent-Based Evolutionary Model. LEM Working Paper Series. 2021. Available online: https://www.econstor.eu/handle/10419/259539 (accessed on 11 July 2023).
87. Oppenheimer, M.; Glavovic, B.C.; Hinkel, J.; van de Wal, R.; Magnan, A.K.; Abd-Elgawad, A.; Cai, R.; Cifuentes-Jara, M.; DeConto, T.; Ghosh, J.; et al. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*; Cambridge University Press: Cambridge, UK, 2019. [CrossRef]
88. Manson, S.M. Calibration, verification, and validation. In Proceedings of the Meeting the Challenge of Complexity, Irvine, CA, USA, 2002. Parker, D.C., Berger, T., Eds.; Center for Spatially Integrated Social Science University of California at Santa Barbara: Santa Barbara, CA, USA, 2002; pp. 42–47. Available online: http://www.csiss.org/events/other/agent-based/additional/proceedings.pdf (accessed on 11 July 2023).
89. Crick, F.; Jenkins, K.; Surminski, S. Strengthening insurance partnerships in the face of climate change—Insights from an agent-based model of flood insurance in the UK. *Sci. Total Environ.* **2018**, *636*, 192–204. [CrossRef] [PubMed]
90. Patt, A.; Siebenhüner, B. Agent Based Modeling and Adaptation to Climate Change. *Q. J. Econ. Res.* **2005**, *74*, 310–320. [CrossRef]
91. Ruohong, C.; Oppenheimer, M. An Agent-Based Model of Climate-Induced Agricultural Labor Migration. In Proceedings of the Agricultural & Applied Economics Association's 2013 AAEA Annual Meeting, Washington, DC, USA, 4–6 August 2013.
92. Vrancken, J.; Van den Berg, J.; Dos Santos Soares, M. Human factors in system reliability: Lessons learnt from the Maeslant storm surge barrier in The Netherlands. *Int. J. Crit. Infrastruct.* **2008**, *4*, 418–429. [CrossRef]

93. Umgiesser, G. The impact of operating the mobile barriers in Venice (MOSE) under climate change. *J. Nat. Conserv.* **2020**, *54*, 125783. [CrossRef]
94. Gaul, G. *The Geography of Risk: Epic Storms, Rising Seas, and the Cost of America's Coast*; Picador: New York, NY, USA, 2019.
95. Tobin, G.A. The levee love affair: A stormy relationship? *J. Am. Water Resour. Assoc.* **1995**, *31*, 359–367. [CrossRef]
96. Burby, R.J. Hurricane Katrina and the Paradoxes of Government Disaster Policy: Bringing About Wise Governmental Decisions for Hazardous Areas. *Ann. Am. Acad. Pol. Soc. Sci.* **2006**, *604*, 171–191. [CrossRef]
97. Bronen, R. Climate-induced community relocations: Creating an adaptive governance framework based in human rights. *NYU Rev. Law Soc. Change* **2011**, *35*, 356–406.
98. Bronen, R. Climate-induced community relocations: Using integrated social-ecological assessments to foster adaptation and resilience. *Ecol. Soc.* **2015**, *20*, 36. [CrossRef]
99. Koslov, L. The case for retreat. *Public Cult.* **2016**, *28*, 359–387. [CrossRef]
100. Goodell, J. *The Water Will Come: Rising Seas, Sinking Cities, and the Remaking of the Civilized World*, 1st ed.; Little, Brown and Company: New York, NY, USA, 2017.
101. Mcgranahan, G.; Balk, D.; Anderson, B. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urban.* **2007**, *19*, 17–37. [CrossRef]
102. Rush, E. *Rising: Dispatches from the New American Shore*, 1st ed.; Milkweed Editions: Minneapolis, MN, USA, 2018.
103. Maldonado, J.K.; Shearer, C.; Bronen, R.; Peterson, K.; Lazrus, H. The impact of climate change on tribal communities in the US: Displacement, relocation, and human rights. *Clim. Chang.* **2013**, *120*, 601–614. [CrossRef]
104. Cooper, J.A.G.; Pile, J. The adaptation-resistance spectrum: A classification of contemporary adaptation approaches to climate-related coastal change. *Ocean. Coast. Manag.* **2014**, *94*, 90–98. [CrossRef]
105. Wrathall, D.J.; Mueller, V.; Clark, P.U.; Bell, A.; Oppenheimer, M.; Hauer, M.; Kulp, S.; Gilmore, E.; Adams, H.; Kopp, R.; et al. Meeting the looming policy challenge of sea-level change and human migration. *Nat. Clim. Change* **2019**, *9*, 898–901. [CrossRef]
106. Kniveton, D.R.; Smith, C.D.; Black, R. Emerging migration flows in a changing climate in dryland Africa. *Nat. Clim. Change* **2012**, *2*, 444–447. [CrossRef]
107. Koch, A. Monitoring, Simulation, and Management of Visitor Landscapes. *J. Artif. Soc. Soc. Simul.* **2008**, *12*.
108. Graham, S.; Barnett, J.; Fincher, R.; Hurlimann, A.; Mortreux, C.; Waters, E. The social values at risk from sea-level rise. *Environ. Impact Asses. Rev.* **2013**, *41*, 45–52. [CrossRef]
109. O'Neill, S.J.; Graham, S. (En)visioning place-based adaptation to sea-level rise. *Geog. Environ.* **2016**, *3*, e00028. [CrossRef]
110. Ajibade, I. Planned retreat in Global South megacities: Disentangling policy, practice, and environmental justice. *Clim. Chang.* **2019**, *157*, 299–317. [CrossRef]
111. Nicholls, S.; Amelung, B.; Student, J. Agent-Based Modeling: A Powerful Tool for Tourism Researchers. *J. Travel Res.* **2017**, *56*, 3–15. [CrossRef]
112. Johnson, P.; Nicholls, S.; Student, J.; Amelung, B.; Baggio, R.; Balbi, S.; Boavida-Portugal, I.; de Jong, E.; Hofstede, G.J.; Lamers, M.; et al. Easing the adoption of agent-based modelling (ABM) in tourism research. *Curr. Issues Tour.* **2017**, *20*, 801–808. [CrossRef]
113. Balbi, S.; Giupponi, C.; Perez, P.; Alberti, M. A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. *Environ. Model. Softw.* **2012**, *45*, 29–51. [CrossRef]
114. Pons-Pons, M.; Johnson, P.A.; Rosas-Casals, M.; Sureda, B.; Jover, È. Modeling climate change effects on winter ski tourism in Andorra. *Clim. Res.* **2012**, *54*, 197–207. [CrossRef]
115. Pons, M.; Johnson, P.A.; Rosas, M.; Jover, E. A georeferenced agent-based model to analyze the climate change impacts on ski tourism at a regional scale. *Int. J. Geogr. Inf. Sci.* **2014**, *28*, 2474–2494. [CrossRef]
116. Scott, D.; Steiger, R.; Rutty, M.; Pons, M.; Johnson, P. Climate Change and Ski Tourism Sustainability: An Integrated Model of the Adaptive Dynamics between Ski Area Operations and Skier Demand. *Sustainability* **2020**, *12*, 10617. [CrossRef]
117. United Nations. *The Potential of the Blue Economy: Increasing Long-Term Benefits of the Sustainable Use of Marine Resources for Small Island Developing States and Coastal Least Developed Countries*; United Nations: San Francisco, CA, USA, 2017.
118. United Nations World Tourism Organization. *United Nations World Tourism Organization Annual Report*; United Nations World Tourism Organization: Madrid, Spain, 2016.
119. Office for Coastal Management. *NOAA Report on the U.S. Marine Economy*; Office for Coastal Management: North Charleston, SC, USA, 2020.
120. Ara, N.; Toubes, D.R.; Antonio, J.; Brea, F. Tourism Industry's Vulnerability upon Risk of Flooding: The Aquis Querquennis Complex. *Environments* **2019**, *6*, 122.
121. Hamzah, J.; Habibah, A.; Buang, A.; Jusoff, K.; Toriman, M.E.; Fuad, M.J.M.; Er, A.C.; Azima, A.M. Flood Disaster, Impacts and the Tourism Providers' Responses: The Kota Tinggi Experience. *Adv. Nat. Appl. Sci.* **2012**, *6*, 26–32.
122. Hino, M.; Belanger, S.T.; Field, C.B.; Davies, A.R.; Mach, K.J. High-tide flooding disrupts local economic activity. *Sci. Adv.* **2019**, *5*, eaau2736. [CrossRef]
123. Peterson, B.; Porter, M. Charleston and the South Carolina Coast Flooded Record 89 Times in 2019. Post and Courier. Available online: https://www.postandcourier.com/news/charleston-and-the-south-carolina-coast-flooded-record-times-in/article_7c18ee5e-2e3b-11ea-8784-23ddbc8d4e0c.html (accessed on 3 January 2020).
124. United Nations. *The Sustainable Development Goals Report*; United Nations: San Francisco, CA, USA, 2021.

125. Hargrove, C. Heritage Tourism. *Cult. Res. Manag.* **2002**, *25*, 10–11. Available online: https://home1.nps.gov/CRMJournal/CRM/v25n1.pdf (accessed on 11 July 2023).
126. Baram, U. Tourism and Archaeology. In *Encyclopedia of Archaeolog*; Pearsall, D.M., Ed.; Academic Press: Cambridge, MA, USA, 2008; pp. 2131–2134. Available online: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/heritage-tourism (accessed on 11 July 2023).
127. Cassar, M.; Young, C.; Weighell, T.; Sheppard, D.; Bomhard, B.; Rosabal, P. *Climate Change and World Heritage: Report on Predicting and Managing the Impacts of Climate Change on World Heritage and Strategy to Assist State Parties to Implement Appropriate Management Responses*; World Heritage Reports; UNESCO World Heritage Centre: Paris, France, 2007; Volume 22.
128. Holtz, D.; Markham, A.; Cell, K.; Ekwurzel, B. *National Landmarks at Risk: How Rising Seas, Floods, and Wildfires Are Threatening the Untied States' Most Cherished Historic Sites*; Union of Concerned Scientists: Washington, DC, USA, 2014.
129. U.S. News & World Repor. *World's Best Places to Visit 2021–2022. Best Vacations Rankings*. 2021. Available online: https://travel.usnews.com/rankings/worlds-best-vacations/ (accessed on 11 July 2023).
130. United Nations Environment Programme & World Tourism Organization. Making Tourism More Sustainable: A Guide for Policy Makers. 2005. Available online: www.unep.frwww.world-tourism.org (accessed on 11 July 2023).
131. Office of Tourism Analysis. *2018–2019 Office of Tourism Analysis Annual Report*; Office of Tourism Analysis: Charleston, SC, USA, 2019.
132. Williams, E.; Moore, T. Rising Tides Take Charleston to the Brim, Threatening Businesses. The Post and Courier. Available online: https://www.postandcourier.com/rising-waters/rising-tides-take-charleston-to-the-brim-threatening-businesses/article_4282b1be-fc28-11ea-891d-07e663e3afed.html (accessed on 19 October 2020).
133. Insurance Journal. Venice Hotels Suffer Nearly $34M in Damages from November's Floods. *Insurance Journal*. 23 December 2019. Available online: https://www.insurancejournal.com/news/international/2019/12/23/552711.htm (accessed on 11 July 2023).
134. Cerini, M. Venice is Flooding—What's the Future of Its Historical Sites? *CNN Style*. 2019. Available online: https://www.cnn.com/style/article/venice-flooding-st-mark-damages/index.html (accessed on 11 July 2023).
135. Boavida-Portugal, I.; Ferreira, C.C.; Rocha, J. Current Issues in Tourism Where to vacation? An agent-based approach to modelling tourist decision-making process. *Curr. Iss. Tour.* **2017**, *20*, 1557–1574. [CrossRef]
136. Farrell, B.H.; Twining-Ward, L. Reconceptualizing tourism. *Ann. Tour. Res.* **2004**, *31*, 274–295. [CrossRef]
137. Barnett, T.P.; Pierce, D.W.; Hidalgo, H.G.; Bonfils, C.; Santer, B.D.; Das, T.; Bala, G.; Wood, A.W.; Nozawa, T.; Mirin, A.A.; et al. Human-Induced Changes in the Hydrology of the Western United States. *Science* **2008**, *319*, 1080–1083. [CrossRef]
138. Gillies, R.R.; Wang, S.-Y.; Booth, M.R. Observational and Synoptic Analyses of the Winter Precipitation Regime Change over Utah. *J. Clim.* **2012**, *25*, 4679–4698. [CrossRef]
139. Gober, P. Desert urbanization and the challenges of water sustainability. Current Opinion in Environmental. *Sustainability* **2010**, *2*, 144–150. [CrossRef]
140. Foley, J.A.; DeFries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Stuart Chapin, F.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; et al. Global Consequences of Land Use. *Science* **2005**, *309*, 570–574. [CrossRef]
141. Melillo, J.M.; Richmond, T.C.; Yohe, G.W. (Eds.) Climate Change Impacts in the United States: The Third National Climate Assessment. 2014. Available online: https://nca2014.globalchange.gov/downloads (accessed on 11 July 2023).
142. Vano, J.A.; Udall, B.; Cayan, D.R.; Overpeck, J.T.; Brekke, L.D.; Das, T.; Hartmann, H.C.; Hidalgo, H.G.; Hoerling, M.; McCabe, G.J.; et al. Understanding uncertainties in future Colorado River streamflow. *Bull. Am. Meteorol. Soc.* **2014**, *95*, 59–78. [CrossRef]
143. Madani, K. Water management in Iran: What is causing the looming crisis? *J. Environ. Stud. Sci.* **2014**, *4*, 315–328. [CrossRef]
144. Ostrom, E. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* **2009**, *325*, 419–422. [CrossRef]
145. Ghorbani, A.; Bots, P.; Dignum, V.; Dijkema, G. MAIA: A Framework for Developing Agent-Based Social Simulations. *J. Artif. Soc. Soc. Simul.* **2013**, *16*, 9. [CrossRef]
146. Magnan, A.K.; Schipper, E.L.F.; Burkett, M.; Bharwani, S.; Burton, I.; Eriksen, S.; Gemenne, F.; Schaar, J.; Ziervogel, G. Addressing the risk of maladaptation to climate change. *WIREs Clim. Change* **2016**, *7*, 646–665. [CrossRef]
147. IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability. In IPCC WGII Sixth Assessment Report. 2022. Available online: https://www.ipcc.ch/report/ar6/wg2/ (accessed on 11 July 2023).
148. Kelly, R.A.; Jakeman, A.J.; Barreteau, O.; Borsuk, M.E.; ElSawah, S.; Hamilton, S.H.; Henriksen, H.J.; Kuikka, S.; Maier, H.R.; Rizzoli, A.E.; et al. Selecting among five common modelling approaches for integrated environmental assessment and management. *Environ. Model. Softw.* **2013**, *47*, 159–181. [CrossRef]
149. Drogoul, A. Agent-Based Modeling for Multidisciplinary and Participatory Approaches to Climate Change Adaptation Planning. Proceedings of the Reg. Forum Clim. Change, AIT, Bangkok. 2015. Available online: https://www.researchgate.net/publication/276267709 (accessed on 11 July 2023).
150. Johnson, P.A.; Sieber, R.E. An individual-based approach to modeling tourism dynamics. *Tour. Anal.* **2010**, *15*, 517–530. [CrossRef]
151. Gerst, M.D.; Wang, P.; Roventini, A.; Fagiolo, G.; Dosi, G.; Howarth, R.B.; Borsuk, M.E. Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework. *Environ. Model. Softw.* **2012**, *44*, 62–75. [CrossRef]
152. Jenkins, K.; Surminski, S.; Hall, J.; Crick, F. Assessing surface water flood risk and management strategies under future climate change: Insights from an agent-based model. *Sci. Total Environ.* **2017**, *595*, 159–168. [CrossRef]
153. Bradbury, R. Futures, predictions, and other foolishness. In *Complexity and Ecosystem Management: The Theory and Practice of Multi-Agent Systems*; International Society of Ecological Economics: Canberra, Australia, 2022.

154. An, L.; Grimm, V.; Sullivan, A.; Turner, B.L.I.; Malleson, N.; Heppenstall, A.; Vincenot, C.; Robinson, D.; Ye, X.; Liu, J.; et al. Challenges, tasks, and opportunities in modeling agent-based complex systems. *Ecol. Model.* **2021**, *457*, 109685. [CrossRef]
155. Reeder-Myers, L.A. Cultural Heritage at Risk in the Twenty-First Century: A Vulnerability Assessment of Coastal Archaeological Sites in the United States. *J. Isl. Coast. Archaeol.* **2015**, *10*, 436–445. [CrossRef]
156. Zhuo, L.; Han, D. Agent-based modelling and flood risk management: A compendious literature review. *J. Hydrol.* **2020**, *591*, 125600. [CrossRef]
157. Liu, J.; Hull, V.; Batistella, M.; DeFries, R.; Dietz, T.; Fu, F.; Hertel, T.W.; Izaurralde, R.C.; Lambin, E.F.; Li, S.; et al. Framing sustainability in a telecoupled world. *Ecol. Soc.* **2013**, *18*, 26. [CrossRef]
158. Grimm, V.; Berger, U.; DeAngelis, D.L.; Polhill, J.G.; Giske, J.; Railsback, S.F. The ODD protocol: A review and first update. *Eco. Model.* **2010**, *221*, 2760–2768. [CrossRef]
159. Grimm, V.; Railsback, S.F.; Vincenot, C.; Berger, U.; Gallagher, C.; DeAngelis, D.; Edmonds, B.; Ge, J.; Giske, J.; Groeneveld, J.; et al. The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *J. Artif. Soc. Soc. Simul.* **2020**, *23*, 7. [CrossRef]
160. Grimm, V.; Johnston, A.S.A.; Thulke, H.-H.; Forbes, V.E.; Thorbek, P. Three questions to ask before using model outputs for decision support. *Nat. Commun.* **2020**, *11*, 4959. [CrossRef] [PubMed]