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Summary

Worldwide, with different frequencies and magnitudes, coastlines are increasingly being affected by climate change hazards. The high urbanization rate, due to economic opportunities and natural amenities, further exacerbates vulnerabilities in these areas, requiring prompt and effective adaptation to climate induced events – from gradual sea level rise to abrupt storms and floods. The ability of different actors (households, firms, financial entities and Government) to cope with such events can be addressed and studied through the use of agent-based models, which allow for an heterogeneous treatment of agents' behaviour, from individual risk perceptions' modelling to decision-making rules on the adaptation option to be put into practice (whether related to coastal management or to coastal defense). Since the natural system needs to be considered together with the socio-economic human system, if we are willing to enhance sustainable practices, integrated-assessment models can be used as a tool to account for these interrelated complexities. A comprehensive review on integrated-assessment agent based models on climate change adaptation in coastal zones, thus, is here provided to investigate the current state of the art.

Keywords: Agent-based models, Integrated-assessment models, Review, Climate change, Adaptation, Coastal zones

JELClassification: C63, Q01, Q26, Q54

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Jlenia Di Noia[*]

Abstract

Worldwide, with different frequencies and magnitudes, coastlines are increasingly being affected by climate change hazards. The high urbanization rate, due to economic opportunities and natural amenities, further exacerbates vulnerabilities in these areas, requiring prompt and effective adaptation to climate induced events –from gradual sea level rise to abrupt storms and floods. The ability of different actors (households, firms, financial entities and Government) to cope with such events can be addressed and studied through the use of agent-based models, which allow for an heterogeneous treatment of agents' behaviour, from individual risk perceptions' modelling to decision-making rules on the adaptation option to be put into practice (whether related to coastal management or to coastal defense). Since the natural system needs to be considered together with the socio-economic human system, if we are willing to enhance sustainable practices, integrated-assessment models can be used as a tool to account for these interrelated complexities. A comprehensive review on integrated-assessment agent-based models on climate change adaptation in coastal zones, thus, is here provided to investigate the current state of the art.

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1 Introduction

Among the list of *Representative Key Risks (RKRs)* associated with climate change identified by the IPCC[1], *coastal socio-ecological systems* grabs the attention for the current review. Coastal zones are fundamental areas of ecological preservation, given their biodiversity richness and their plentiness of natural resources and related ecosystem services, such as sediment retention or animals' and vegetation habitats[2]; attributes and characteristics now threatened by climate change, human urbanization and economic activity. According to the last available estimates, sea level rise (SLR hereafter) has dramatically accelerated, on average, from 1.35mm yr^{-1} during the period 1901-1990 to 3.25mm yr^{-1} from 1993 to 2018, further increasing concerns on coastal zones vulnerabilities: coastlines are more and more subject to erosion phenomena and permanent submergence and coastal areas are also exposed to sudden and violent events, apart from incremental SLR. High tides, storms, hurricanes and floods can cause temporary but dramatic damages and losses in terms of land and natural resources, agriculture (also due to increasing salinity), buildings and properties, infrastructures and eventually lives. The high vulnerability also depends on the density of population that such areas host: urbanization rates in flood-prone low-lying areas do not seem to want reversing the increasing path in the near future (Jongman, Ward, and Aerts (2012) found that the number of people living in the 1/100-year flood area has nearly doubled from 1970 to 2010). Coastal areas worldwide are, indeed, very densely populated, both for the economic services and economic opportunities they provide, both for the recreational value they offer. The incremental pace of SLR, together with the intensification of climate change related extreme events require a timely and quick response in terms of loss-reducing measures' implementation and adaptive behaviour enhancement, without incurring in what Malloy and Ashcraft (2020) define to be a *resilience trap*: short-term horizon adaptation options, indeed, do not favour vulnerability relief and adaptive capacity in the long run. Efforts to avoid the detrimental combined action of climate change and urban development (which further exacerbates, for example, flooding risks due to higher exposure and the destruction of ecosystems' resilience capacity) are necessary to avoid the *coastal squeeze*[3]. Protective measures that only rely on building infrastructures may exacerbate the situation if not associated with proper land use management, coastal realignment and preservation of natural habitats[4]. However, given the irreversibility of climate change induced effects nowadays, any measure but retreat is likely to only delay coastal hazards (see the work of Siders, Hino, and Mach (2019) on managed retreat). Further, especially concerning coastal protection measures, little effort has been made to assess some sinergies between adaptation solutions and mitigation strategies, as pointed out in IPCC 2022. Emission constraints need to be accounted for when dealing with adaptation as well as spillover effects stemming from renewable energy. Ecosystem-based solutions are, environmentally speaking, the most attractive options to

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[1] According to the IPCC 2022 (Pörtner et al. (2022)), the RKRs are classified as: coastal socio-ecological systems; terrestrial and ocean ecosystem services; water security; food security; critical infrastructure, networks and services; human health; living standards and equity; peace and human mobility and other cross-cutting risks.

[2] Costanza et al. (1999, 1997)

[3] Schleupner (2008).

[4] IPCC 2022 Cross-Chapter Box SLR:Sea Level Rise.

adapt to climate change, but they require time for their effective implementation and, possibly, the dismantlement of human settlements (coastal defenses included). There is an urgent need to implement effective adaptation along coastlines; this would call for a strategic interplay between planned adaptation and autonomous adaptation. The present review aims at collecting all studies treating adaptation to climate change in coastal zones that employ Agent-Based Models (ABMs), which are a useful tool to gain insights, not only on adaptation outcomes once implemented, but also on interaction dynamics between individuals and/or groups of them with the natural system they live in. By departing from the assumption of full rationality and allowing for learning and social influence, ABMs give the possibility to more realistically shape complex realities, especially if empirical data can be retrieved at local scale to study specific adaptation options. Integrated Assessment ABMs, can be, therefore, a useful instrument for policy-makers. Nevertheless, it must be borne in mind that although ABMs are a useful tool to understand the complex interconnections between the human system and the natural system, they are still based on specific assumptions and are usually parameter-sensitive.

The review is structured as follows: section 2 describes the procedure adopted to search for pertinent papers, their selection and the main descriptive outcomes. Section 3 gives an overview of of selected studies, providing some insights on the research questions addressed. Section 4 addresses the models' agentization and data sources, illustrates adaptation and environmental scenarios and the modelling of climate-related adverse events. Section 5 provides a comprehensive narrative of agents' behaviour and selected theories. Section 6 then concludes.

2 Methodology and Overall Information

In order to make a comprehensive review of ABMs dealing with climate change adaptation in coastal zones, three main keywords could not be omitted in the search for papers in available databases, i.e. "agent-based", "coastal" and "adaptation" (or similar). The search has been conducted into Scopus and ScienceDirect, managing the strings according to the database specific rules in order to make the search homogeneous[5]. The final strings were the following:

- For Scopus (Title, abstract or author-specified keywords):

  (TITLE-ABS-KEY (agent-based) OR TITLE-ABS-KEY (agent based) OR TITLE-ABS-KEY (ab) OR TITLE-ABS-KEY (abm)) AND ((TITLE-ABS-KEY (coast*)) OR ((TITLE-ABS-KEY (adapt*)) AND (TITLE-ABS-KEY (sea-level AND ris*) OR TITLE-ABS-KEY (slr) OR TITLE-ABS-KEY (flood*) OR TITLE-ABS-KEY (storm) OR TITLE-ABS-KEY (erosion) OR TITLE-ABS-KEY (ecosystem))))

- For ScienceDirect (Title, abstract or author-specified keywords):

  ("agent based" OR ab OR abm) AND (coast OR coastal)

  ("agent based" OR ab OR abm) AND ((adapt OR adaptation) AND ("rising sea level" OR "sea level rise" OR ("sea level" AND rise)))

  ("agent based" OR ab OR abm) AND ((adapt OR adaptation) AND (flood OR flooding OR storm OR erosion))

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[5] In Scopus the search could had been done including all keywords in a unique string; in ScienceDirect multiple strings had to be typed.

("agent based" OR ab OR abm) AND ((adapt OR adaptation) AND (ecosystem))

The search has been further limited to peer-reviewed papers, published in English. Using the PRISMA approach, the total of the findings has been reduced following a strict methodology, as shown in Figure1: Among the 748 total number of studies retrieved using the strings, 34 were duplicates. Only one paper has been sought for retrieval[6], but at the time of the search it was

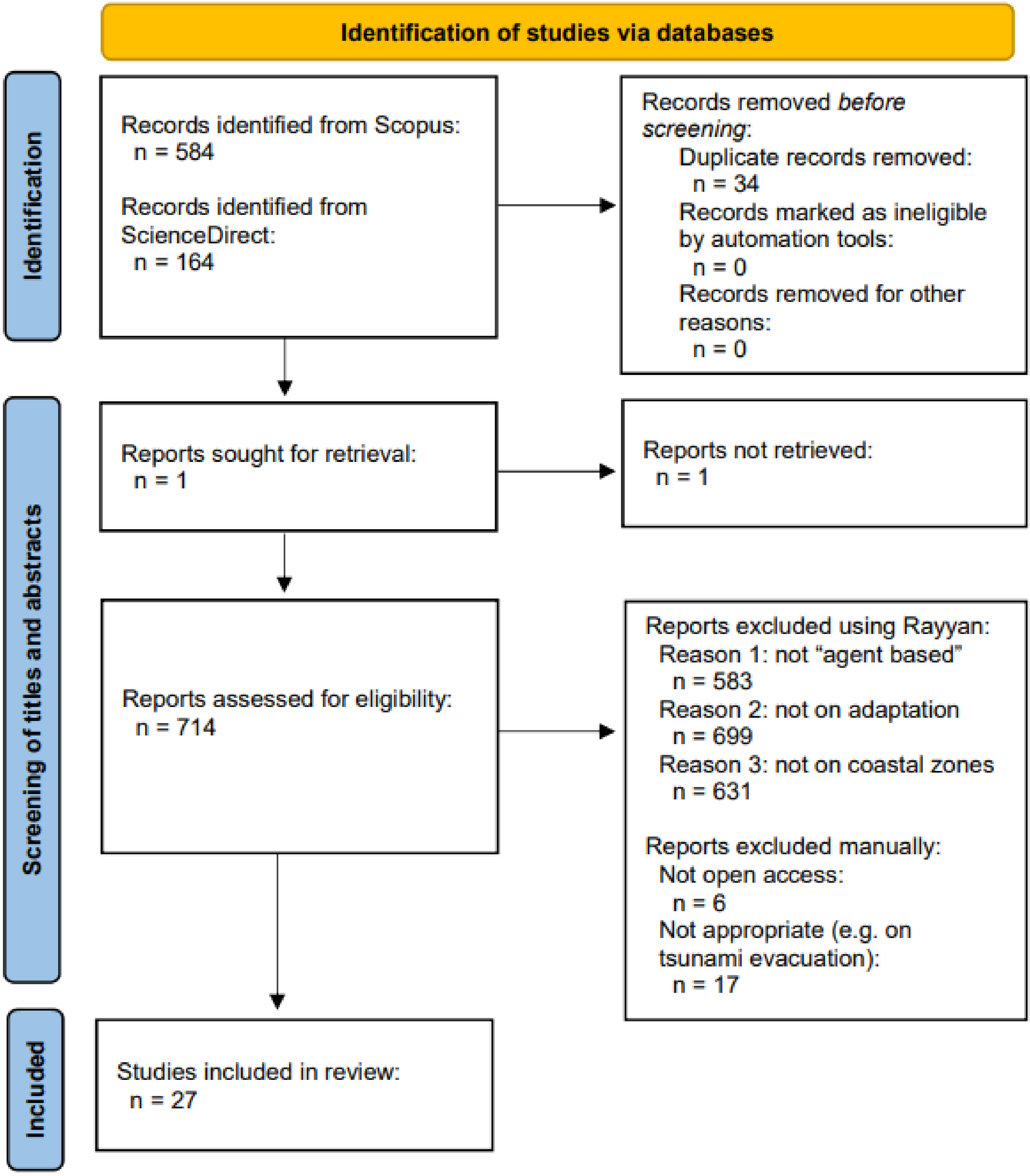

Figure 1: **PRISMA 2020 flow diagram**

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[6] The most interesting feature of that working paper is the fact that address climate change adaptation (where the only form of adaptation is migration) from a more abstract and macroeconomic perspective.

still a working paper and could not be included in this review. We have then taken advantage of the software Rayyan to speed up the selection process and, by inserting the main reasons for exclusion (that is to say if the paper is not about agent-based modelling, if it does not deal with climate change adaptation and if the study area is not located in coastal zones). After this process the remaining papers have been screened individually by carefully reading abstracts and only 28 studies were finally considered appropriate for the scope of the review (other than non-open access papers, we also excluded papers describing, for example, tsunami evacuation; real market prices trends in coastal zones –without any adaptation option considered– and adaptation to flood events along rivers[7]). Almost all studies included in this revision are spatially explicit agent-based models (24 out of 27), with 5 of them making use of GIS data. Since adaptation to climate change, differently to mitigation, is highly context specific, we only found 2 studies that address it in abstract terms. The remaining 25 cases refer to a geographical location, generally a regional area (only 4 papers use local areas), with the vast majority situated in the US as shown in Figure2: The detailed table with the list of papers and related study areas can be found in the Appendix A.

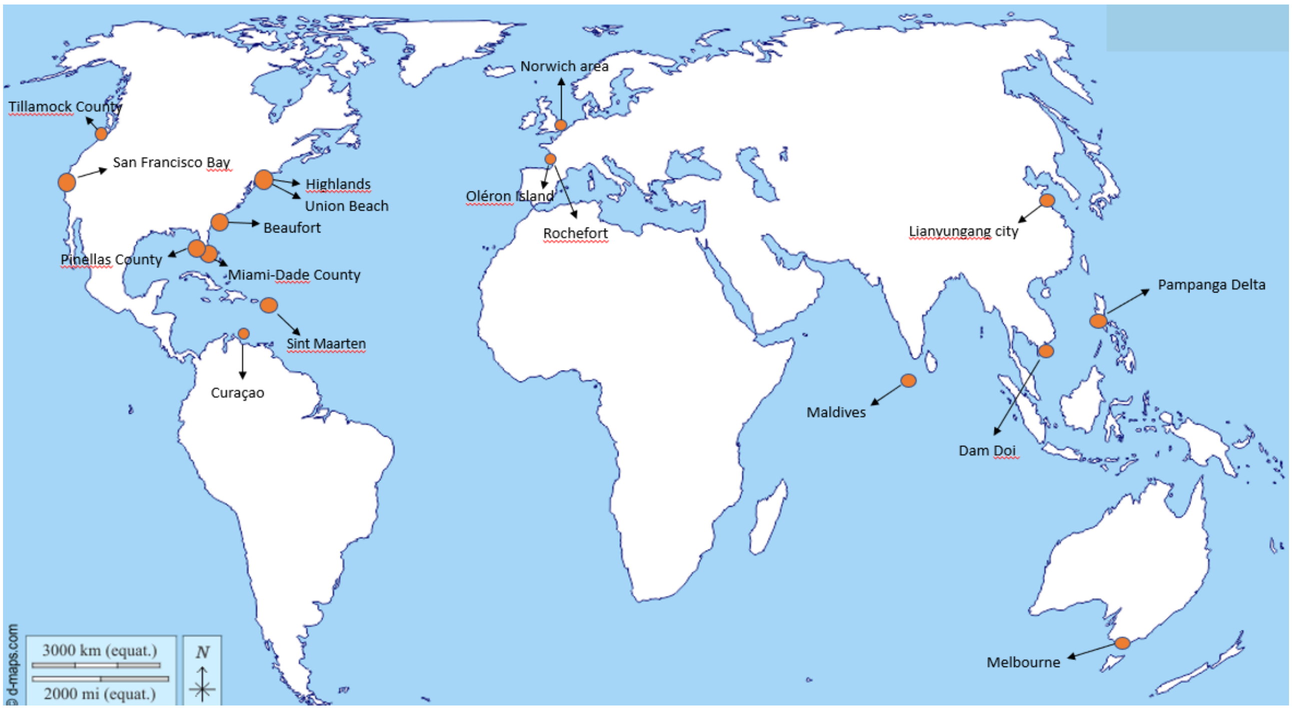

Figure 2: **Highlights of local and regional areas of studies included in the current review.**

Planned adaptation and autonomous adaptation are modeled together in 7 studies, whilst 11 contributions only treat the former and only 9 the latter. A complete list of adaptation solutions encountered during the revision can be found in Appendix B. Adaptation to slow-onset hazards is investigated in 16 cases, the majority of which (15) included SLR and 3 of them erosive phenomena. Disaster risk reduction, instead, is formalized 20 times, with flooding events counting for 14 cases. SLR alone is taken into account only in 4 cases. In only three cases, there is no explicit mention to coastal hazards, but the analysis are meant to preserve coastal ecosystems in relation to human activity. Land use is studied in 11 cases (only 2 of them, however, are related to agricul-

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[7] For a review on ABMs and flooding events, see Taberna, Filatova, Roy, and Noll (2020)

ture and crop production), and the same amount of studies –although partially different– applies also to urbanization and housing. Real estate and insurance related topics are present in 7 papers. Infrastructures, instead, are studied in 6 cases, whilst engineered-based solutions (both stemming from planned adaptation and from autonomous adaptation) can be found in 15 studies. Nature-based solutions (NbS) only in 4 (2 of them also cover engineered options), indicating that there is an urgency to switch towards them in ABMs literature. Despite the low effort put on NbS, ecosystems and biodiversity are specifically modelled in 10 cases. Migration, the last adaptation option one has, is considered in 8 ABMs. A co-occurrence network of abstract's words is shown in Figure 3:

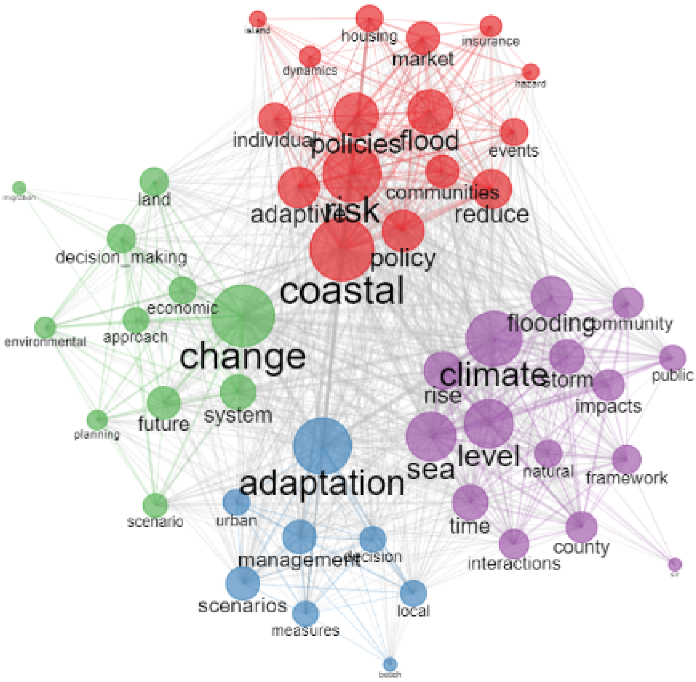

Figure 3: **Co-occurrence network.**

3 Overview of Included Papers

To begin with, Abebe, Ghorbani, Nikolic, Vojinovic, and Sanchez (2019) and Speelman, Nicholls, and Safra de Campos (2021) decide to focus on climate change related issues and risk drivers on small islands (Nurse et al. (2014)), whose level of exposure can be particularly high because of a number of trends and characteristics, such as the urbanization rate and coastal concentration. Whilst the former builds a flood risk management framework to cope with flood risk in Sint Maarten (CLAIM model), the latter analyses demographic trends and abandonment rates in the Maldives employing the *theory of planned behaviour*[8]. The model presented is the CMM (Conceptual Model of Migration), which combines Kniveton, Smith, and Black (2012) work with the

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[8] Ajzen (1991)'s theory of planned behaviour is based on three individual pillars, which, if positive make a person perform a behaviour: (i) attitude (positive or negative evaluation of a certain behaviour); (ii) subjective norms (i.e. social pressure); (iii) perceived behavioural control (perceived ability of behaving in a certain way.). Other factors (such as habits or knowledge) can then positively or negatively impact on the final decision.

above mentioned theory of Ajzen (1991) and the drivers of migration listed in Black et al. (2011) –demographic, economic, social, political and environmental. Migration is the last adaptation option one has when alternative adaptation solutions become increasingly expensive and/or the the level of risk rises and, as a complex process, requires the co-creation of the above mentioned conditions also inland to push people to abandon coasts. Nevertheless, risky coastal zones continue to attract individuals (because of labor market opportunities, cultural heritage or environmental amenities for example) or might transform in a trap for low income people, unable to leave[9]. Bell et al. (2021) address these multiple migration pressures under SRL in Bangladesh by using MIDAS (Migration, Intensification and Diversification as Adaptive Strategies) ABM platform, which allows to take into account people's resources and credit/location constraints, risk perceptions and social interactions on the basis of the push-pull-mooring theory of migration[10]. The model is then used to investigate migration under different *representative concentration pathways* (RCP)[11], which will return different sea level changes according to increasing GHG emissions. The main conclusions are partially at odds with De Koning and Filatova (2020), who claim that outmigration occurs and further locks low-income people in vulnerable coastal areas. According to their model (REHA) applied to Beaufort and Greenville in South Carolina, the issue of climate gentrification cannot be ignored[12]. De Koning and Filatova (2020) recognize the importance of shaping risk perceptions and social interactions in analyzing people's behaviour towards flood risk and associated actions they are willing to take. Indeed, as Ge, Peacock, and Lindell (2011) point out, indeed, risk mitigation measures adopted by households depend on their own perception of risks. Other interesting ABM works explore more in depth the role of risk perceptions, in particular concerning the purchase of insurance and various loss-reducing and adaptation solutions (both planned and autonomous). Of particular relevance is the use and declination of the well-known *Prospect Theory*[13] in the stream of literature initiated by Haer, Botzen, de Moel, and Aerts (2017) and followed by Han and Peng (2019), Han, Ash, Mao, and Peng (2020). In particular, Haer et al. (2017) introduce households' learning process through the bayesian prospect theory model, which allows to manage opinion dynamics, social influence and feedbacks to study how heterogeneous individual assumptions and external influences impact on flood-risk predictions (the case study is located in Heijplaat, Rotterdam)[14]. Taking inspiration from Haer et al. (2017) and the US National Flood Insurance Program (NFIP) by FEMA (the Federal Emergency Management Agency), Han and Peng (2019) try to model a first interaction between federal and private insurance in the Miami-Dade County (Florida), showing that the implementation of public adaptation options would reduce flood risk in the area under consideration. Nevertheless, there are cases in which public risk mitigation measures can lead to higher risk exposure and eventually to maladaptation, by decreasing

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[9] See Seto (2011), Black et al. (2011), Adams (2016)

[10] See Moon (1995)

[11] See Moss et al. (2010)

[12] On climate gentrification and environmental social justice see also Walker and Burningham (2011) and Keenan, Hill, and Gumber (2018).

[13] Kahneman and Tversky (1979)

[14] Haer et al. (2017) is not included in the current review because the location considered, Heijplaat, has a distance from the sea of more than 10-12 km.

people's risk perceptions (i.e. the so called *safe development paradox*)[15]. Based on this consideration, Han et al. (2020) stresses also the importance of private effective adaptation measures other than buying flood insurance. A synthesis among results stemming from Han and Peng (2019) and Han et al. (2020) is reached by Han et al. (2021), that conclude that there is a need of community adaptation and that too much emphasis has been put on insurance as a way to adapt to climate change[16]. Slightly departing from previous cited works, Han et al. (2021) –in trying to integrate coastal hazards' randomness, agents cognition and adaptation policies– employ the *Protection motivation theory* to shape households' behaviour which involves agents' risk and coping appraisal in their perceptions and efforts to mitigate risk: the model, thus, accounts for learning in order to form agents' cognition. Another ABM on insurance and risk perceptions can be found in Magliocca and Walls (2018), that adapt an existing model (the Coupled Housing and Land Markets model, CHALM)[17] to investigate housing market dynamics (prices and insurance) in coastal zones and in presence of uncertainty about climate change impacts[18]. Agents with heterogeneous risk perceptions can be found also in McNamara and Keeler (2013), that base the agentization on the different weights US people of the East coast give to past climate trends and damages and to the value of environmental characteristics. Coastal amenities and ecosystem services are thus considered explicitly in this last study, where, among buying insurance, agents can also decide to engage in soft engineering protection measures such as beach nourishment or dune restoration to preserve the services provided by barrier-islands. The ABM is implemented starting from McNamara and Werner (2008) and by introducing defensive engineering. Barrier islands, with their own vegetation and ecosystems are particularly important for lagoon's protection and are, at the same time, exposed to SLR and storms. The above mentioned model is able to reproduce the negative impacts of climate change, such as beach erosion or barrier-island inundation, and the positive re-generation of vegetation and physical processes in periods of tranquility.

Attention to ecosystems and biodiversity in coastal zones has been paid by a number of adaptation ABMs. Filatova et al. (2011), for example, rely on the *ALMA-C* model to simulate land market mechanisms and price formation when agents interact in a fiscal policy framework that aims at preserving coastal amenities through the maintenance of an eco-buffer (i.e. unexploited coastal zone). While in Filatova et al. (2011) taxation is intended as an adaptation solution in order to discourage urbanization too close to the coastline, Mullin, Smith, and McNamara (2019) use it as a policy instrument to fund collective beach reinforcement investment, addressing the challenge

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[15] Overall, among the studies included in this review, maladaptation arises and is addressed in five works (by Filatova, Voinov, and van der Veen (2011), De Koning and Filatova (2020), Han et al. (2020), Sun, Chow, and Madanat (2020) and Bell et al. (2021)).

[16] The argument usually if favour of insurance as adaptation option is the one of Botzen, Aerts, and van den Bergh (2009), that is that premium discounts in insurance programs increase households' willingness to engage in adaptation measures that decrease their losses.

[17] Magliocca, Safirova, McConnell, and Walls (2011), Magliocca, McConnell, Walls, and Safirova (2012), Magliocca, McConnell, and Walls (2015)

[18] On these issues, the search on the two databases (Scopus and ScienceDirect) returned some interesting ABMs that did not meet the whole criteria, but are worth mentioning. For example, Nie, Zhou, Cheng, and Wang (2021), do not directly treat adaptation but explore the field of decision making under subjective and objective risk preferences in coastal farms. Another interesting excluded paper, unrelated with the previous works, is the one of McDonald et al. (2008), that interestingly address ecosystem management in coastal areas but is not properly related to climate change.

of financially sustainable public good investment to tackle climate change, taking into account public opinion by means of an ABM of political decision-making. Zhang, Jin, Wang, Zhou, and Shu (2015) introduce environmentalist agents to account for environmental reasons in simulating the urban process and land use management in Lianyungang city. More recently, Student, Kramer, and Steinmann (2020b) (building on Student, Kramer, and Steinmann (2020a), *Coasting* model in Curaçao that accounts for many coastal features –including tourism operators and environmental operators among agents– and explicitly considers the linkage between pollution, environmental degradation –due to gradual sea level rise or sudden events– and tourism) simulate an agent-based model where environmental attractiveness is used as a proxy for vulnerability and collaboration among tourism operators determines the success or failure of adaptation. Among the already cited ABMs, different attempts to introduce cooperation or social learning are present also in Bell et al. (2021), Han et al. (2020); Han and Peng (2019) and Zhang et al. (2015). On the importance of knowledge sharing and cooperation, another stream of ABM literature (Joffre, Bosma, Ligtenberg, Ha, and Bregt (2015), Becu et al. (2016) and Laatabi et al. (2022)) employ a participatory modelling approach[19], by setting up a game framework with real stakeholders. The last two games are one the extension of the other one: Becu et al. (2016) develop the LittoSIM model for Oléron Island (France) to address the lack of social learning in coastal adaptation planning[20]. By allowing for social interactions, a collective scenario emerges. The model has been generalized by Laatabi et al. (2022) into the LittoSIM-GEN, in order to make it reusable using different regional data (Rochefort has been used as a first application). Joffre et al. (2015) perform a Role Playing game (RPG) on the CASS model to study how shrimp farmers' decisions can shape shrimp production in Ca Mau Province. RPGs' workshops and learning indeed can be used to implement scenarios and agents' behaviour in ABMs, respectively, and to test policies. The study aims at the preservation of ecosystem services (and the mitigation of disease outbreaks) instead of simulating implemented autonomous/planned adaptation to face climate change impacts or risk mitigation. Real farmers (players), confirmed the relevance of the RPG in fostering learning about disease outbreak risk evaluation (given the simulation horizon). The authors here try to address an issue of fundamental relevance, but usually little considered, i.e. the change in production systems to tackle climate change and promote sustainable production. Along this line, Toft, Punt, and Little (2011) focus on fishery management in the US West coast taking in consideration two particular approaches: trip limits and individual transferable quotas (ITQs). Mialhe, Becu, and Gunnell (2012) as well propose an ABM on farmers' decision-making in the Pampanga Delta (Philippines), a territory characterized by tectonic subsidence, increasing storm events, dike erosion and increasing salinity.

On land use (and housing), another ABM contribution is from Fontaine and Rounsevell (2009), that stress the importance of households' location decisions over their life cycle on the natural environment by means of simulations using the HI-LIFE model in East Anglia (Uk). Along with

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[19] Participatory simulation games are computerized experiments where people can collect information, interact according to certain rules, make decisions and see the consequences of their decision-making and of specific events (e.g. floods).

[20] Namely the fact that in Oléron, (i) municipalities do not implement long-term strategies; (ii) different municipalities do not coordinate; (iii) there is substantial ignorance of the spatiotemporal processes of floods.

urban development environment Löwe et al. (2017), build upon the DAnCE4Water model[21] to assess systematic testing and screening of adaptation options (both structural and non-structural) under a combination of population growth and climate scenarios[22] and future pathways to mitigate flood risk. On urbanization and housing, Chandra-Putra, Zhang, and Andrews (2015) and Chandra-Putra and Andrews (2020) focus on the trade-off between policy effectiveness and equity issues, through reduced damage costs and flood risk capitalization into housing prices. The main adaptation options concern public policies about home insurance and vouchers and households compliance with subsequent rules. Mills, Ruggiero, Bolte, Serafin, and Lipiec (2021) instead focus on many other adaptation policies –such as backshore protection structures, beach nourishment, relocation etc.– and in a context of uncertainty using the Envision platform. Among the studies considered, it is the only project that collaborated with local entities (the Tillamock County Coastal Knowledge-to-Action Network) in setting up and defining the model.

Recently, Shuvo, Yilmaz, Bush, and Hafen (2021) tried to address stakeholders' reactions to SLR in Pinellas County (USA) using deep reinforcement learning. A particular focus is on costs: (i) a cost-benefit analysis related to human investment and natural disasters is firstly carried and (ii) an assessment on total damage costs with optimized adaptation is implemented. Finally, on transportation infrastructure, Suh, Siwe, and Madanat (2019) and Sun et al. (2020) use the Multi-Agent Transport Simulation (MATSim) model[23] to study how to reduce negative effects of sea level rise such as highways' disruptions and traffic congestion on local communities, through the protection of the shoreline (the studied area is the San Francisco Bay).

4 Agents' Heterogeneity, Adaptation and Scenarios

4.1 Agentization and Data

Agentization is the core of ABMs and, the identification of the main actors promoting or putting in place adaptation solutions is a fundamental step to start mapping the state of the art concerning the use of agent-based models in studying adaptation to climate change in coastal zones. A preliminary fundamental distinction applies to the nature of adaptation, i.e. planned adaptation vs. autonomous adaptation. Whenever the authors (i) explicitly mention the existence of a Government –or more coherently in this context– of a local authority among agents or (ii) any time they are not expressly modeled, but policies or community-based investment are accounted for, the public agent has been considered in the classification. Overall, we came across 18 papers dealing with planned adaptation, as one can see from Table 2. As easily conceivable, within heterogeneity does not particularly interest this category of agents, although in few cases, for example, different municipalities have been taken into account (this is particularly true for participatory games). Studies on planned adaptation, then, required the presence –concrete or fictitious– of a "public

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[21] See Urich and Rauch (2014)

[22] They consider three population growth rates per year scenarios –0.4%, 0.8% and 1.2%– and three rain intensity rates per year –0%, 0.5% and 1%.

[23] Waraich, Charypar, Balmer, and Axhausen (2009) for the model's details.

Paper	Households	Firms	Banks/Insurance	Gov/Local authority	Adaptation
Abebe et al. (2019)	✓			✓	Both
Becu et al. (2016)				✓	Planned
Bell et al. (2021)	✓				Autonomous
Chandra-Putra et al. (2015)	✓		✓	✓	Both
Chandra-Putra and Andrews (2020)	✓		✓	✓	Both
De Koning and Filatova (2020)	✓				Autonomous
Filatova et al. (2011)	✓			✓	Planned
Fontaine and Rounsevell (2009)	✓				Autonomous
Han and Peng (2019)	✓		✓	✓	Both
Han et al. (2020)	✓		✓	✓	Both
Han et al. (2021)	✓		✓	✓	Both
Joffre et al. (2015)		✓		✓	Planned
Laatabi et al. (2022)				✓	Planned
Löwe et al. (2017)	✓	✓		✓	Planned
Magliocca and Walls (2018)	✓	✓			Autonomous
McNamara and Keeler (2013)	✓				Autonomous
Mialhe et al. (2012)		✓			Autonomous
Mills et al. (2021)				✓	Both
Mullin et al. (2019)	✓			✓	Planned
Shuvo et al. (2021)	✓	✓		✓	Planned
Speelman et al. (2021)	✓				Autonomous
Student et al. (2020a, 2020b)[24]		✓			Autonomous
Suh et al. (2019)	✓			✓	Planned
Sun et al. (2020)	✓			✓	Planned
Toft et al. (2011)		✓		✓	Planned
Zhang et al. (2015)	✓	✓		✓	Both

Table 2: **Categories of agents modelled in the studies included in the current review and type of adaptation option they implement (planned vs. autonomous).**

agent". The direct relationship (Governmental agent → planned adaptation) does not hold for private agents: any time different households/businesses/financial entities enter the ABM, an autonomous adaptation measure is not necessarily implemented. As shown in Table 2, although households for example are agentized 19 times, in only 13 related papers they are called to play the role of adaptation actors. Households are, however, the most agentized "private agents" in studying adaptation to climate change in coastal zones and constitute the main source of heterogeneity, as they are assumed to be diverse in individual characteristics, economic attributes, location preferences and risk perceptions. The productive sector follows, with 9 out of 27 studies that comprehend businesses and *developers* included among agents. The low share of studies treating firms' behaviour, however, is a signal of poor attention to a sector that contributes consistently to climate change, both through land degradation and emissions and whose aggregation properties (job opportunities and salaries attract workers) do influence adaptation paths[25]. The role of fi-

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[25] The productive sector should be furhter monitored in ABMs not only for its effects on climate change, but for its impact on sustainability as a whole, which also include inequality issues. Since inequality has been identified as one

nance and credit has also been little considered in these first streams of ABMs on climate change in coastal zones and, when a financial entity is present it usually coincides with a representative insurer.

To collect demographic attributes and socio-economic characteristics (gender, age, education, income, race, property etc.), three main data sources have been used: surveys, census data and national statistics. To cite some examples, Bell et al. (2021) take advantage of the Bangladesh Income and Expenditure Survey and demographc data. De Koning and Filatova (2020) use survey data among 1040 households from eight flood-prone states in the USA as well as US national statistics. To generate a new household, Han et al. (2020) refers to the American Community Survey data. Han et al. (2021) construct a specific survey –that 520 respondents living in the Miami-Dade County had to compile online– on SLR, flood risk perceptions and experience as well as on households' predisposition towards public adaptation or the purchase of flood insurance. Mialhe et al. (2012) submitted questionnaires directly to farmers during field visits. Speelman et al. (2021) make use of different waves of census data, whilst Han and Peng (2019) use only one census of population and the Florida Parcel Data to generate the model's population. Fontaine and Rounsevell (2009) gather data from a population census by the British Office for National Statistics and a properties' database (Uk National Property Database). Overall, despite the usual criticism affecting calibration and validation of ABMs, much effort has been put in finding reliable data in order to fit behavioural rules.

4.2 Agents' Adaptation Implementation, Environmental Scenarios and Main Results

Simulations and experiments are based on agents' adaptation implementation and/or environmental changes impacting on the artificial economy and system. In order to assess the nature of the adaptation solutions analyzed in all studies included in the current review, we have divided options into two main broad categories to be aligned with IPCC 2022: (i) coastal defense and (ii) coastal management. Coastal defense includes the building of infrastructures to protect human settlements from adverse events, but also individual measures such as house elevation or wet proofing. Generally speaking it involves hard and/or soft and engineering-based solutions, both at community level and at individual level. Coastal management, instead, is more related to land use policies, relocation or eco-buffer and ecosystem preservation measures (like taxation). Insurance enters this second category. A more detailed description of adaptation solutions encountered in the included papers can be found in the Appendix B, whilst an overall aggregate glance is provided by Figure 4, which shows the share of studies dealing with planned adaptation, autonomous adaptation or both as well as those implementing coastal defense, coastal management or both:

Concerning environmental scenarios and climate boxes, the included studies adopt different modelling strategies. Many authors do not fully integrate agent-based models with model repli-

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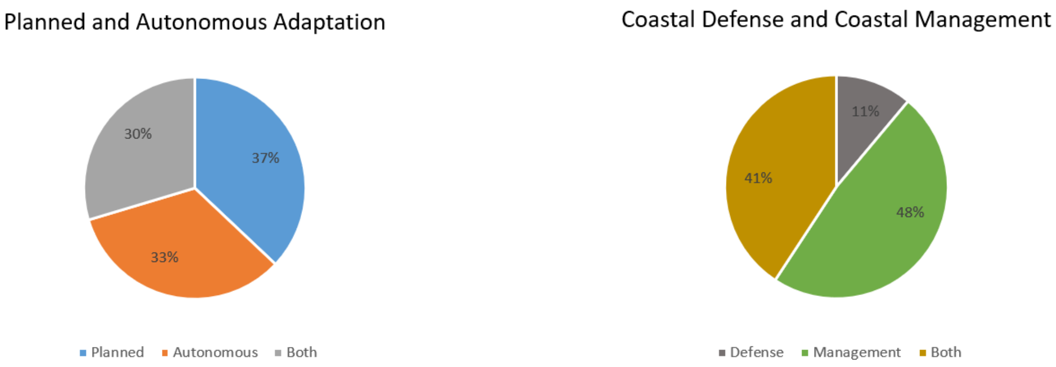
of the outcomes of maladaptation, the role of businesses cannot be left apart. Major attention to firms also implies an effort for the academic community in rethinking production processes and plant locations in such a way that adaptation could create sinergies with mitigation.



(a) Percentage of studies treating planned adaptation, autonomous adaptation or both.

(b) Percentage of studies modelling coastal defense, coastal management or both.

Figure 4: **Share of papers dealing with planned/autonomous adaptation, adopting coastal defense/management measures.**

cating climate change hazards and simply change parameters according to the scenario they want to reproduce. Bell et al. (2021), for example use parameters from the Representative Concentration Pathways; Speelman et al. (2021) use environmental narratives from Uk Foresight. On flood frequency and related damages, De Koning and Filatova (2020) simply run different models under different flood frequency scenarios (i.e. none, once, repetitive). Chandra-Putra and Andrews (2020); Chandra-Putra et al. (2015) estimate flooding according to the probability of flood occurrence (Flood-Depth Curve), $f(x) = 2.781e^{-0.6039x}$, where x is the flood depth; (residential) flood damages are then calculated through two further submodules (Depth-Damage Curve and Damage Loss Curve). The depth-Damage Curve is taken from FEMA: $f(x) = 170(1-e^{-a(x+b)})$. Magliocca and Walls (2018) explore alternative storm climates, where storms occur according to historical probabilities, while the Damage Loss Curve is given by the % damage multiplied by the building value. Mialhe et al. (2012) take typhoones data from the Philippines Atmospheric, Geophisical and Astronomical Services Administration, allocate salinity depending on the distance to seawater basins and attach three different parameters to land subsidence. Regarding SLR, McNamara and Keeler (2013) just run the model under diverse SLR scenarios. Shuvo et al. (2021) simply cumulate SLR levels over time to account for climate change impacts and uses the generalized Pareto distribution to calculate nature's cost, which is spread to Government, households and firms and is assumed to be directly proportional to SLR and inversely proportional to the infrastructure state. Some other authors assign dynamic equations to particular natural phenomena, which also depend on human actions. Mullin et al. (2019), treating beach erosion, directly insert an erosion state equation in the ABM (w_t), depending on the annual erosion amount γ and beach nourishment (represented by two parameters μ_t and θ): $w_{t+1} = w_t - \gamma + \mu_t\theta$ Also Mills et al. (2021) calculates coastal erosion, but make it dependent of the long-term change rate in the shoreline (CCR_{SB}), the coastal change rate due to SLR ($CCR_{Climate}$) and the beach retreat due to sudden climate events, e.g. storms (CC_Event, which depends on total water levels[26]): $Coastal\ Erosion = (CCR_{SB} + CCR_{Climate})xT + CC_{Event}$. Half of the studies, however, couple ABMs with hydrodynamic models. Abebe et al. (2019) couple an agent-based model with a flood-

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[26] Both variables, CC_{Event} and TWL are calculated and extensively explained in the dedicated paragraph.

ing model to study the interaction between human behaviour and/or policies and flood risk. Four hydrologic and hydrodynamic processes are considered (both pluvial and coastal), but for coastal zones 2D floodings depend on storm surges induced by hurricanes and are modeled using MIKE21 FLOOD software[27], which returns a map with flooded zones. Human system and environmental system communicate through the urban environment, where agents are hit by floods and can implement adaptation solutions. Input/output data resulting from the different systems are connected through the Repast Simphony ABM environment. MIKE FLOOD (1D-2D) has been employed by Löwe et al. (2017) also. Han and Peng (2019) follow Haer et al. (2017) that fully integrate a damage model into the ABM and define the local flood risk as the estimate of *Expected Annual Damage, EAD* for direct damages to properties under a given SLR scenario, where the occurrence of floods is stochastic. Han and Peng (2019) takes the same definition of flood risk, but using data on Miami sea level to determine the distribution of flood frequency. The level (or height) of floods, $N(z)$, instead is modeled through the generalized extreme value distribution: $N(z) = \lambda\left(1 + \frac{\xi(z-u)}{\omega}\right)^{-\frac{1}{\xi}}$ where λ=1, ω is a scale parameter, u is a location parameter and ξ the shape parameter[28]. Han et al. (2020), similarly treat the the flood damage model, enriching it by calculating the annual sea level rise and considering four scenarios based on the National Oceanic and Atmospheric Administration (NOAA). Flood risk is once again identified with the EAD measure, but following Olsen, Zhou, Linde, and Arnbjerg-Nielsen (2015). A similar approach has been adopted also by Han et al. (2021), which eventually compute the damage function following Han and Mozumder (2021) and Han and Mozumder (2022). Becu et al. (2016) and Laatabi et al. (2022) employ a 2D hydrodynamic model –the LISFLOOD-FP model[29], chosen for its computational efficiency– to simulate submersion events. An hydrological model has been used by Joffre et al. (2015) to assess the suitability of land for shrimp production. Student et al. (2020a, 2020b) construct a submodel for environmental attractiveness, that takes into account pollution, sudden events, SLR and biodiversity. Finally, Suh et al. (2019) and Sun et al. (2020) couple the ABM with the CoSMoS[30] hydrodynamic model, parametrizing SLR at 0.5.

Table 4.2 briefly resumes agents' heterogeneity, actions and simulation scenarios:

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[27] https://www.mikepoweredbydhi.com/products/mike-flood

[28] Extensive explanation as well as all main references are provided in a specific paragraph.

[29] Neal et al. (2011)

[30] The software has been developed by USGS, but the link provided by the authors, at the current date, is no longer returning results.

Paper	***Adaptation/Environmental Scenarios***	***Results***
Abebe et al. (2019)	Households are identified with residents. They have different compliance rates with respect to four different institutions (i.e. three policies –**BP**, beach policy, **FZ**, flood zoning and **BO**, building and housing ordinance– and one hazard mitigation structural measure), enforced by the Government. Experiments are run by changing policy-related variables (floor height elevations in BO and FZ and compliance thresholds for BP, FZ and BO).	Strict policy enforcement forces people to higher compliance rates and reduces the damage risk, but with a low contribution (especially concerning localized policies, FZ and BP). Structural measures have the greater risk reduction impact.
Becu et al. (2016)	There are different levels of public authority, from County Council to Municipalities. The latter can interact to decide on adaptation planning (short-term, such as dikes) or long-term (strategic withdrawal). It is a participatory game (no scenarios). Through interactions and learning, municipalities can rely on **engineering practices** (build, restore or destroy dikes) or decide to benefit from **alternative land use management adaptation strategies** (such as from agriculture or authorized urbanized to nature to avoid damages to the human system when floods occur; from authorized urbanized to agriculture; from nature to), including expropriation (from urbanized to nature) and even consider non-adaptive measures (from agriculture to authorized urbanized; from nature to authorized urbanized).	The learning process has not been effective enough in promoting the adoption of alternative adaptation strategies and few players actually tried to build up coordination strategies. Players mainly focused on the implementation of usual dikes' strategies[31].
Bell et al. (2021)	Households Are heterogeneous in income, properties, age, social networks and risk perceptions. They can relocate. Simulations are based on the following scenarios: **RCP 2.6**: migration after flood events under an increase in sea level under a temperature increase of 2.3°C by 2100. **RCP 4.5**: migration after flood events under an increase in sea level under a temperature increase of 3.2°C by 2100. **RCP 8.5**: migration after flood events under an increase in sea level under a temperature increase of 5.4°C by 2100.	Damages on income only are not enough to push people out from the coasts. Out-migration does not occur in any of the scenarios, rather two effects prevail: on the one hand agents are attracted by coastal zones because of working opportunities (increasing floods switch production from agricultural to non agricultural); on the other hand income damages caused by floods make migration difficult to afford (liquidity constraints and difficult access to credit do not allow people to move). Nevertheless, increase access to credit does not lead to out-migration either, perhaps because all investment made make it difficult to find other comparable livelihood alternatives.

Chandra-Putra et al. (2015)	Households' heterogeneity depends on their home status: they can be homebuyers, homesellers or homeowners. Location preferences are the same but levels of income are different. They can sell or elevate houses. A representative bank makes loans. Government is not explicitly modeled, but there is a top-down policy on insurance purchase requirement. Simulations depend on the following scenarios: **Foresight**: no insurance requirement. **100-year flood zone**: all households are required to buy insurance if they live within the 100-year flood zone. Reimbursement is 100% **80% reimbursement**: same requirement but damages are repaid at 80% and only if the house suffers a damage of more than 50% of its value. **Cap reimbursement**: same requirement but insurance pays back only up to a certain amount. **Cap reimbursement assuming contagion**: from the fourth scenario, but households have a positive probability of influencing each other on selling or elevating houses. **Cap reimbursement assuming higher incomes**: from the fourth scenario, but a higher fraction of households is wealthier.	Damage costs diminish with insurance requirements, but become more volatile if the insurance does not fully cover them. Contagion then lowers housing prices with respect to the same scenario not allowing from neighbours, whilst a gentrification phenomenon arise due to increasing prices in different scenarios.
Chandra-Putra and Andrews (2020)	Households' heterogeneity depends on their home status: they can be homebuyers, homesellers or homeowners. They can buy insurance, sell or elevate houses. A representative bank makes loans. Insurance updates loss ratio and calculate different premiums. Government implements different adaptation policies. Experiments are as follows: **Baseline**: CRS[32] and insurance optional. **Elevation required**: for buildings in the floodplain. **Eliminate disclosure requirement**: no obligation of disclosing about flood risks. **CRS requirement**: voluntary incentive program to foster flood risk mitigation strategies[33]. **Voucher requirement**: homeowners with houses located in certain zones can receive insurance discounts. **Insurance requirement**: houses located in the floodplain must be covered by insurance.	House elevation requirement simulations produce few insurance claims but at the expenses of very high housing prices, which significantly decrease when flood risk disclosure is not mandatory (but increasing insurance claims). In between housing prices stem from CRS required and voucher required scenarios, with insurance payouts levels similar to those of the baseline scenario. The worst case scenario seems to be the one associated with insurance requirement, that returns high prices and high claims.
De Koning and Filatova (2020)	Households have different properties, incomes and location preferences and can be either buyers or sellers, where the latter also differ in expectations about selling prices. Heterogeneity also stems from risk perceptions and risk aversion. They can move it they can afford it. Three scenarios: **Benchmark**: no floods. **Single flood**: there is a unique flood occurring in 2020 and households can migrate. **Repetitive floods**: two floods occur, one in 2020 and the other in 2024 and households can migrate.	After a flood, houses located in the hazard zone decrease in value, but recovers thanks to newly entered households in the coastal zone (have less fear due to lack of flooding experience and generally less income), meanwhile safe inland houses increase in value due to higher demand. Significant outmigration occurs especially when damages are recorded by few households because it is easier for sellers to find enough buyers. As low income people can better afford buying a house when it drops in value, they eventually find themselves locked-in in hazard zones and climate gentrification issues arise.

Filatova et al. (2011)	Buyers, sellers, traders[34] have heterogeneous incomes (the former), and form different expectation about land prices (the latter). A local government imposes taxes to preserve the eco-buffer. The different scenarios are here enlisted: **Base case**: all households have the same income. No taxes. **Income increase**: households are endowed with higher levels of income. **Tax introduction**: agent have to pay an environmental tax if they want to buy a house close to the sea. **Tax and income increase**: households' income is higher, but the tax rate remains the same. **Income distribution and tax**: households income follow a normal distribution. Same tax rate.	In the base case prices are high around the center and along the coast, if not too far from the center. When income increases, the higher purchasing power translates into even higher prices and lower coastal zone preservation, which instead is enhanced when the environmental tax is introduced. However, both when income of the representative household increase and when income distribution heterogeneity is considered, the eco-buffer diminishes.
Fontaine and Rounsevell (2009)	Households differ in family composition, their stage of life and status (children, adults, workers, retired etc.), wealth. Depending on these evolving characteristics they have different location preferences and eventually migrate. No scenarios and no proper adaptation measure considered. Households make housing decisions based on coastal amenities and disamenities, among other things.	On aggregate, individual risk perceptions about storms and erosion phenomena, fade out because of the preference for amenities' effect (especially of retirees), leading to coastal pressure.
Han and Peng (2019)	Households have different socio-economic and demographical attributes and therefore different risk perceptions. They can buy insurance or elevate their house. Private insurance applies different premiums. Local government has some budget to implement adaptation, among which public insurance plans. **Default**: pre-FIRM (Flood Insurance Rate Map[35]) properties are subsidized for the 60% with public insurance[36]. Households then choose the option (among no adaptation, buying private insurance, elevating house) returning the minimum prospect utility. Simulations are run according to the following scenarios: **Voucher-based**: the voucher coupled house elevation program (public voucher and low interest rates for houses satisfying an elevation requirement) is considered as an additional adaptation solution and substitutes the public pre-FIRM subsidy. Low-income people are subsidized. **Scenario 1**: voucher-based plus public adaptation solution reducing flood risk by 25% in 100 census tracks. **Scenario 2**: voucher-based plus public adaptation solution reducing flood risk by 25% in 500 census tracks. **Scenario 3**: default plus plus public adaptation solution reducing flood risk by 50% in 100 census tracks. **Scenario 4**: default plus plus public adaptation solution reducing flood risk by 50% in 500 census tracks.	The voucher-based scenario performs better in terms of households' adaptation actions and risk mitigation, but decreases the number of policies compared to the default scenario. Overall, public risk mitigation policies that cover a greater area have a positive impact on flood risk reduction, but at the expense of higher private adaptation costs.

Han et al. (2020)	Households have different incomes and heterogeneous risk perceptions and can implement adaptation strategies. Insurance can apply different risk-based insurance rates. Government can subsidize low income homeowners and/or build seawalls. Scenarios: **Base**: households can buy insurance. **Risk-based**: households can buy risk-based flood insurance and elevate houses. Government can subsidize. **Twice and out policy**: to avoid their property to get out of the market, households implement adaptation when their property is damaged once. **4-ft SW**: construction of seawalls (no insurance). **2-ft SW + twice-out**: construction of a lower seawall combined with twice and out policy. Risk mitigation actions (among which the community one, decreases flood insurance) **2-ft SW + risk-based + twice-out**: the previous combination including also risk-based insurance policy. Government can subsidize.	Under high SLR projections, only buying insurance does not effectively mitigate risks. With no market foresight[37], even with low SLR, the base scenario displays high flood damage; whilst the 2-ft + risk based + twice-out policy shows the greatest resilience (due to combination of private adaptation and property risk-based insurance rates, non-excessive costs of building seawalls[38] and subsidization of low-income people.)
Han et al. (2021)	Households have different risk perceptions. Insurance applies insurance rates. Local government applies discount rates based on NFIP and can implement community adaptation (building floodwalls). Scenarios are as follows: **Scenario 1**: NFIP with pre-FIRM (discount of 60% applied to interest rates on pr-FIRM buildings). No community adaptation. **Scenario 2**: risk-based insurance policy and retrofitting (FEMA) and insurance requirement for destroyed houses that have to be rebuilt. Government can buy more that once lost properties. **Scenario 3**: NFIP with pre-FIRM plus community adaptation (local government constructs a 2-foot floodwall). **Scenario 4**: risk-based insurance policy plus community adaptation (floodwall).	Property value seems to be one of the most influential factors for households' insurance purchase and when risk-based insurance replaces grandfathered insurance (NFIP), the higher associated costs decrease households' willingness to buy it (and rather to engage in house elevation). Community adaptation reduces the average damage consistently but at the same time lowers households' risk perception.
Joffre et al. (2015)	Shrimp farmers with different socio-economic characteristics (drawn from statistical distributions), decide upon the production system to use. Decisions also depend on the heterogeneity of biophysical characteristics of their plots. Local government provides incentives to preserve ecosystem services. Diverse experiments: **Baseline**: current situation in Dam Doi District about shrimp farming. **Organic coast**: local authority provides payments for ecosystem services to farmers in order to promote the most sustainable shrimp production system. **Intensification**: policies and investment favour intensive farming and diversification of aquaculture. **Climate change**: sea level rise decreases the eligibility for intensive production. No policies.	Although at initialization intensive production accounts only for the 27% of the total, in all scenarios (except for climate change) they eventually become dominant,whilst the integrated mangrove-shrimp increase but only up to 13-15%. The intensification scenario, however, is the one with associated higher social costs and abandonment due to higher disease outbreaks and tend to spread where the plot is suitable (i.e. along the buffer zone). In the organic scenario, hybrid forms of production systems arise and develop on plots suitable for intensification.

Laatabi et al. (2022)	District decision makers take on adaptation solutions on land use and coastal defense. Heterogeneity stems from location, population growth and budget constraints, as well as for individual characteristics such as experience and risk perceptions. A risk agency provides advice to foster coordination plans. Participatory game (no scenarios). Players can engage in three different actions simultaneously (building dikes, soft defense –dunes, inland dikes– and withdraw strategically) and the corresponding weights assigned to these three strategies define the agent's action. Also, a system of bonus and penalties encourages ecological strategies.	The new release of the model should make collaboration and learning more effective with respect to the original model in Becu et al. (2016)
Löwe et al. (2017)[39]	Households have Heterogeneous location preferences and can contribute to adaptation through rainwater harvesting. Residential developers adapt to urban regulations. City councils can enforce different adaptation strategies, from more resilient urban development plans to expropriation as well as relying on engineering adaptation solutions (tanks, pipes). Scenarios: **Business as usual**: no adaptation. **Water sensitive city**: master plans to control for urban development (e.g. multi-storey blocks). **Flood zoning**: purchase of buildings located in flooding zones. **Implementation rainwater tanks**. **Widening of pipe capacity**.	WSC urban plan can effectively reduce flood exposure and, therefore, risk. So do expropriation and increasing capacity of pipes, but at a much higher cost. At the same time, the latter returns immediate reductions in expected damage, whilst the first two require more time. The least performing solution seems the implementation of rainwater tanks.
Magliocca and Walls (2018)	Households are divided into consumers and landowners. The former have heterogeneous incomes and housing/location preferences[40] and move/buy insurance according to their risk perceptions; the latter own land to be sold to a developer. A representative developer build new constructions for consumers, once he buys new undeveloped land from landowners. Four storm climates[41] are performed in two decision models (expected utility (EU) and salient (ST) models). Agents can relocate and/or buy insurance. **MA storm climate**: historical storm probability in the Mid-Atlantic region is p=0.025 (low). **NC storm climate**: historical storm probability in North Carolina is p=0.299 (moderate). **TX storm climate**: historical storm probability in Texas is p=0.383 (moderate). **FL storm climate**: historical storm probability in Florida is p=0.714 (high).	In all scenarios population growth push housing prices to rise, softened by storm events. Reactive relocation does not show up in waterfront/water view areas because of the high value and attractiveness of coastal amenities (rebalancing risk perceptions), unless coastal amenities are randomly distributed.In the infrequent storms (MA) scenario insurance is not purchased. Insurance exhibits higher uptake rates when consumers use ST decision rule (which seems to be able to reproduce empirical evidence).

McNamara and Keeler (2013)	Households differ in the value they attach to historical trends and future projections on environmental characteristics and therefore in their beliefs about property risks associated with sea level rise. They can decide upon defensive coastal measures and (collectively) invest in beach nourishment or dune restoration. They can also decide to buy a property or abandon it. Experiments: **3mm yr**$^{-1}$: low sea level rise rate. **10mm yr**$^{-1}$: high sea level rise rate.	Defensive engineering is a first reaction to an increase in climate risks, but is more costly to put forward in the long run especially when SLR rate is greater. In the case of low SLR rate, defensive measure still become less and less effective (e.g. shorter nourishment cycles) and agents perceiving high levels of risk, abandon the property irrespective of defensive costs.
Mialhe et al. (2012)	Farmers and investors can be of different types depending on their behaviour: rational, collective-minded or with bounded rationality. They determine land use changes. The model comprehends 12 scenarios, based on the combination of agent types A (rational), B (collective-minded) or C (boundedly rational) and the following environmental dynamics: **Dynamic 1**: no deltaic subsidence. **Dynamic 2**: constant subsidence rate. **Dynamic 3**: after 1990, the subsidence rate increases. **Dynamic 4**: higher subsidence rate and external factors.	Dynamic 1 implies homogenization of land use change among agents, whilst subsidence make land use patterns to differentiate. Typhoones, by impacting on profits, have major effects on Type A agents. Rational agents can adapt their strategy to economic and environmental changes increasing acquaculture development, but would worsen ecosystem services because of their inability of considering other agents' strategies and landscape reconfiguration. Collective-minded agents, characterized by a lack of rationality, cannot make decisions according to environmental changes, but only according to collective strategies. External factors impact on boundedly rational agents' decisions on land use change, however they still lack of informed environmental conditions and base their cognitive strategy most on social conformity criteria (as Type B).
Mills et al. (2021)	Individuals are grouped into "county-defined tax lots"[42], which constitute an actor. Actors then apply different land-use management policies. 33 baseline climate scenarios derive from three different SLR values. Six policies are then implemented, arriving at 99 scenarios. Further individual narratives scenarios are then simulated for each scenario. Policies: **BPS**: maintain existing backshore protection stuctures and allow for new ones in eligible lots. **Nourishment**: add beach nourishment. **Easements**: withdraw from repeatedly flooded zones. **Relocate**: move buildings according to FEMA Base Flood Elevation plus 3ft. **Safest-Site**: build new constructions above FEMA Base Flood Elevation plus 3ft. Individual policies: **Status Quo**: present-day policy over the time horizon. **Hold the Line**: aims at preserving existing buildings and human activities. **Realign**: aims at realigning to climate change. **Laissez-Faire**: all policies are relaxed. **Hazard Zone**: determine boundaries.	By analyzing variability and uncertainty across simulations, Tillamock County Knowledge-to-Action Network is able to discriminate across possible adaptation policies in planning community adaptation. The wide variety of future scenarios assessed the relative importance of climate drivers, policies and individual policies (e.g. for landscape metrics, uncertainty with respect to climate depends on policies).

Mullin et al. (2019)	Homeowners differ in location (oceanfront or inland), and property value[43]. The local authority applies different tax rates according to property values. Experiments are run according to the following assumptions: **Thick communities**: only 5% of properties are oceanfront. **Thin communities**: 25% of properties are oceanfront. **Flat tax**: in both community scenarios, oceanfront and inland owners have to pay the same tax rate. **Increasing tax ratio**: in both community scenarios, the local government imposes different tax rates and oceanfront owners have a higher tax ratio with respect to inland households.	In both community scenarios, under a flat tax, homeowners will not contrast beach erosion, whilst if the nourishment project burden is born by oceanfront households (different tax ratio) the beach width increases (inland voters will be favourable).
Shuvo et al. (2021)	Households are grouped into a representative agent, called residents' community. The residents' community make decisions about their contribution to infrastructures. Businesses are represented by a single business association and make decision similarly to the residents' community. The government decides upon a list of adaptation investments. Agents can be reactive or can be modelled using a deep reinforcement learning algorithm (two algorithms are considered: the **deep Q-network** and the **advantage actor-critic**). **Intermediate-to-low**, **intermediate** and **high** scenarios depending on different projections of SLR are used to simulate the model over years. Finally, **reactive threshold-based** policies are simulated for comparisons.	Deep-reinforcement learning using the advantage actor-critic algorithm is able to simulate a wide range of stakeholders' prototypes. High costs from nature stem from non-cooperation, whilst cooperation lowers them consistently. Assuming full cooperation for the deep Q-network algorithm, the costs are higher with respect to advantage actor-critic one. Costs also perform better for the advantage actor-critic algorithm with respect to the threshold scenarios.
Speelman et al. (2021):	Agents have different personal characteristics and different attitudes towards migration. Narratives of future population development. **A**: high demographic growth; high environmental impact; globalized world with strong public intervention. **B**: high demographic growth; high environmental impact; globalized world with no public intervention. **C**: high demographic growth; low environmental impact; local development with no public intervention. **D**: low demographic growth; high environmental impact; local development with no public intervention. **E**: low demographic growth; high environmental impact; globalized world with strong public intervention. **F**: low demographic growth; low environmental impact; local development with no public intervention.	The magnitude of environmental impacts does influence migration flows in the islands because of its effects on economic variables such as employment opportunities and on the overall quality of life. Whilst the capital is increasing in migration inflows, less urbanized islands see declining populations. Adaptation policies can only be successful if combined with population policies covering all national islands (e.g. improved tourism, education and facilities in rural islands, agricultural and industrial policies outside the capital).

Student et al. (2020a, 2020b)	Businesses are represented by tourism operators, heterogeneous in their activities and sustainable needs and actions, mobility (they can be water-based or land-based) and preferences for environmental attributes. Scenario discovery[44]: extreme losses values for tourism operators and for the environment are set as thresholds to identifying unacceptable (and acceptable) future and socio-ecological parameters (tourism-returns; revenue-limited; pollution threshold; cost-pollution; pollution-change; SLR-increase;linear-SLR; minimum-acceptable-elevation-above-sea-level; increased-elevation; geospatial-weight; biodiversity-weight; pollution-weight; environmental-degradation-weight) are combined.	With no new businesses allowed to enter the model, on average, the number of tourism operators decreases for all types but for dive operators and boat operators (less sensitive to parameters' changes). Environmental attractiveness strongly depends on parameters' combinations. Overall, tourism returns have the highest impact on the number of operators, for land-based operators the interplay with SLR plays a significant role too. Tourism returns is determinant also for collaborative actions, whilst the pollution threshold takes its place when it comes to individual actions. Economic failure (mainly driven by low tourism-returns and followed by minimum-acceptable-elevation-above-sea-level and revenue-limit) does not imply ecological failure (due to pollution-weight mostly, followed by tourism-returns) and the other way round, but correlations can arise. In a case of combined failures, pollution-change, pollution-weight and tourism returns are the two most influential parameters.
Suh et al. (2019)	Households are travelers that use their car to reach different locations and perform a set of activities. Government can engage in shoreline protection activities. Protection scenarios of two different counties have been analyzed taking into account hydrodynamic interactions (resulting in a total of 72 protection scenarios). For each county: **Scenario a**: the shorelines of two counties are always protected, whilst the others not. **Scenario b**: a different county (with respect to the one under consideration) is protected by embankment or not. **Scenario c**: each segment of the considered county is protected or not.	A county protection is effective when considered with neighborhood counties' protections as well. Not considering hydrodynamic interactions between counties when planning shoreline protection against sea level rise, may lead to highways disruptions and traffic congestion, worsening households' life.
Sun et al. (2020)	Travel by car and use public transport to reach different locations and perform activities. Government can install levees, raise causeway decks. Given the four counties considered and the possibility to build levees or not, together with raising causeways or not, there are a total of 32 possible combination scenarios.	Results are not clear-cut and are spatially heterogeneous: coastal protection may reduce congestion in one area and increase it in another area (Braess paradox[45]). Authors highlight the need of collaboration among local transit authorities.
Toft et al. (2011)	Fishers are aggregated into port groups but no ex-ante heterogeneity is modeled. Government not explicit, but implicit through trip limits and quotas mechanisms' policies. **Trip limits, coastwide**: in each period fishers can schedule trips according to 2-month time steps limits and the stocks are not confined. **Trip limits, regional**: in each period fishers can schedule trips according to 2-month time steps limits and the stocks distributed into 4 different regions per species. **ITQs, coastwide**: in a full year fishers can schedule trips according to quotas and the stocks are not confined. **ITQs, regional**: in a full year fishers can schedule trips according to 2-month time steps limits and the stocks distributed into 4 different regions per species.	The overfished species remains far from the landing limit in all scenarios and the target species goes closer. ITQs lead to higher profits and less fishing. Shifting to ITQs may also have positive implications concerning the reduction of habitat degradation and the safeguard of species. Nevertheless there is a need to monitor ITQs mechanisms.

Zhang et al. (2015)	Residents and environmentalists have diverse location desires and objectives,on the basis of urban growth observation. Each farmer and each industrial enterprise form its own preference on newly developed urban land. Government decides upon macroscopic land-use urban plans, taking into account households' and firms' preferences. Scenarios: **Current trends**: no adaptation (the urban plan is shaped upon the coastal industrial city). **Ecological protection priority**: Government and microagents focus more on the safeguard of the ecosystem in planning urban development. **Economic development priority**: high demand for major construction to foster industrial agglomeration.	When the priority is of ecological type, the urban growth rate is slower and some natural resources are preserved, whilst the opposite holds when the priority is economic development. Nonetheless, even in the environmental protection scenarios, waters and tidal flats are not fully protected.

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[31] However, it is recognized that choosing to implement dikes was influenced by budget availability.

[32] Community Rating Systems

[33] For more details: https://www.fema.gov/floodplain-management/community-rating-system

[34] The model is constructed upon the original ALMA-C model (Filatova, Van Der Veen, and Parker (2009)), where sellers are identified with farmers. However, since there is no production in the model, farmers' only have to decide to sell or not their land and therefore they cannot be considered as entrepreneurs.

[35] See https://www.fema.gov/glossary/pre-firm-building

[36] They rely on the National Flood Insurance Program, NFIP. Details can be found at https://www.fema.gov/flood-insurance

[37] For completeness: the authors also run simulation for the perfect market foresight.

[38] The construction of high seawalls without other private adaptation measures, instead, may result in maladaptation due to the associated huge costs and the reduced households' risk perception.

[39] 288 pathways identified stemming from 9 population growth-climate scenarios and 32 combination of public flood risk-management adaptation options

[40] Both characteristics are randomly taken from a uniform distribution.

[41] Storms and hurricanes are generated randomly using historical probabilities.

[42] The information can be retrieved in Mills et al. (2018).

[43] Home properties' and hedonic price for beach. Oceanfront and inland properties' specific characteristics, as well as hedonic prices' ranges are taken from a uniform distribution.

[44] Instead of designing scenarios ex-ante, they are allowed to be designed ex-post depending on complex interactions. See Lempert, Groves, Popper, and Bankes (2006) and Bryant and Lempert (2010)

[45] See Arnott and Small (1994).

5 Agents' Behaviour and Theories

5.1 Government and Local Authorities

With due exceptions and coherently with the context, the governmental agent is hardly modelled in heterogeneous or behavioural terms: it usually represents a single entity/institution that provides top-down policies –private agents have to implement– or makes community-based investments. In few studies, however, more than one governmental entity is considered: in participatory games, for example, different municipalities participate to the experiment and, consequently, "public agents" are allowed to behave differently from one another. For instance, Becu et al. (2016) consider different levels of public authorities to account for vertical coordination: the County Council (exogenously controlled by a computer avatar), the Community of municipalities and four different municipalities (embodied by stakeholders participating in the game) and, finally, residents' association (again controlled by the avatar) to account for horizontal coordination. The focus is on the ability of municipalities to implement effective adaptation planning to prevent coastal flood losses: with collected taxes and/or additional budget gained coming from the County Council as a reward for having adopted righteous strategies, the local public authority can (i) build, repair, raise or destroy dikes (considered a short-horizon adaptation option) after collecting information on their state on the *dike management interface* or (ii) change land use (natural, agricultural, urbanized, authorized urbanized) after having retrieved data on population and real estate prices of its units on the *land use management interface*. Players are real life stakeholders, have their own strategies and are assumed to be able to learn and coordinate themselves after a number of submersion events[46]. However, the process as it is has shown no ability to foster coordination on land use management adaptation options. In the expanded version by Laatabi et al. (2022), districts' decision makers are identified as *players* –that can be traced back to Becu et al. (2016)'s municipalities– together with a risk agency (called *leader*)[47] which should foster collaboration among districts, by allowing single districts to communicate with each other or by promoting debates for collective planning. The local authorities can manage land use (similarly to the LittoSIM, but with the addition of cells "Adapted-Urban", "Authorized-for-Adapted-Urbanization" –which entail subsidized adapted infrastructures and buildings– and "Urban-in-Densification") or engage in coastal defense. Once again, therefore, decision makers can behave differently from one another.

As previously seen, a consistent share of studies consider together coastal defense and coastal management. In the case of public intervention, it translates into a combination of policies and adaptation measures involving infrastructures and engineering, as in the case of Mills et al. (2021). In Abebe et al. (2019), for example, the Government is conceived as a combination of three departments, which can shape both climate hazards and residents' vulnerability by designing and implementing policies related to private buildings and the planning of spaces and to public building and

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[46] Taking inspiration from Kolb (1984) *experiential learning cycle*.

[47] For completeness, there is a third model, *manager*, that communicate with the previous two and controls submersion flood events.

drainage work[48]. Three adaptation policies are taken into account: one preserving beaches' recreational value to avoid further constructions and two setting house elevation minimums, differentiating among flood zones. Enforcements of such policies depend on households' compliance rates. On the other side, the Government can also implement the construction/maintenance of drainage channels or dikes. Löwe et al. (2017) conceive the public authority as a driver of adaptation, both through regulation –which can avoid over soil-exploitation through urban development plans favouring the construction, for example of building blocks instead of single-unit houses– and through the implementation of public facilities devoted to flood-risk mitigation. The model directly links expected flood damage to adaptation investment. In order to implement adaptation options or a combination of them, s, Löwe et al. (2017) first recur to the estimation of annual expected flood damages (EAD_t), following Stedinger (1997) and then perform a cost-benefit analysis, $I_{s,t}$ being the cost and $B_{s,t}$ the benefit, calculating the *expected discounted damage*, $ED*$, over the period of interest, τ (i.e. the time horizon the adaptation investment should cover), with r being the discount rate, and its *net present value*, NPV_s under population growth and climate scenarios:

$$ED^* = \sum_{t=\tau_{min}}^{\tau_{max}} EAD_t \frac{1}{(i+r)^{(t-\tau_{min})}} \tag{1}$$

Naming ED^*_{ref} the flood damage when no adaptation option is put in place and ED^*_s the same damage when adaptation s is improved:

$$NPV_s = ED^*_{ref} - ED^*_s + \sum_{t=\tau_{min}}^{\tau_{max}} (B_{s,t} - I_{s,t}) \frac{1}{(i+r)^{(t-\tau_{min})}} \tag{2}$$

Remaining in the field of public actions related to urbanization and housing issues, Chandra-Putra and Andrews (2020) and Han et al. (2020) consider both the role of government subsidies in shaping private adaptation (vouchers to low-income households favours private adaptation, also lowering insurance rates) through insurance, and the role of a *community* hard adaptation measure such as the construction of seawalls, which constitute shared knowledge, having effects on households' decisions. In Chandra-Putra et al. (2015), Government is not explicitly modeled (as, for example, also in Toft et al. (2011)), but households are required to buy a flood insurance in order to reduce their incurred damage costs in case of flooding: even though the policy requirement is effective in reducing such costs, when the reimbursement is not full, (cost) volatility increases, suggesting that the rate of reimbursement should be carefully addressed. In a following extension, Chandra-Putra and Andrews (2020) broaden the set of policies by introducing elevation, voucher, community rating system (CRS) requirements and show how forcing households to implement house elevation, effectively mitigates flood risk and associated damage costs, whilst policies requiring the disclosure of information or based on incentives does not. A controversial issue arising from the former result, however, indicates that the most effective measure against flood risk is at the same time the one that amplifies gentrification mechanisms. Han and Peng (2019) model local government as a subsidizer on the one hand and as an adaptation actor on the other hand:

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[48] The Government agent represents the VROMI, which is composed by three different departments: Permits, Inspection and New Projects

households indeed can benefit both from voucher-coupled systems and from public adaptation solutions that mitigate flood risk. However, public adaptation has a costs that has to be born by households, estimated by the authors through a fixed benefit-cost ratio (ARCCA (2018)[49]). Han et al. (2021) allows the local government to build a 2-foot floodwall to protect the interested area when the percentage of damaged houses reaches a certain threshold (p_c), other than regulating insurance discounts and insurance/retrofitting requirements for flood damaged houses. Planned adaptation then enters households' coping appraisal approach through their perceptions about seawall's effectiveness in reducing risk. The focus is on the importance of integrating private and community adaptation policies, arguing that the latter are more effective in improving risk mitigation.

Suh et al. (2019) focus on shoreline protections such as the building of levees in order to avoid the disruption of highways and the subsequent traffic congestion (which decreases households' utility). Most importantly, the study shows how coastal protections should be integrated taking into account hydrodynamic interactions between different counties (i.e. the decision not to protect an area may have implications also on another location, in a sea level rise scenario of 0.5m, expected by 2054). Sun et al. (2020) further extend and complete the model[50] by introducing public transit infrastructure and considering the effectiveness of implementing levees' construction. Despite previous works' results, coastal protection in the form of levees does not lead to clear benefits in terms of traffic congestion.

Among studies particularly attentive to long-term natural system preservation and not merely on short-term risk reduction responses to coastal hazards, Zhang et al. (2015), for example, consider Government as the urban planner deciding upon land use, but its decision depends on (i) interactions with microagents and (ii) a set of spatial natural, socioeconomic and ecological factors, whose weights depend on the different scenarios looked upon. These two features of the macroagent decision making reflect the Government consideration of other stakeholders' preferences on the one side, and the necessity to evaluate land use *suitability* to control for urban growth on the other side. When environmental protection matters, the interplay between microagents' preferences and Government's planning actually impedes a rapid expansion of urban areas detrimental to natural coastal areas. Filatova et al. (2011), instead, show how environmental taxation on land use properties close to the coast can disincentive households to buy in eco-buffer zones, thus helping preserving ecosystem services. According to the simulations, however, this is true only if agents are endowed with the same low level of income. As we move from this simplifying assumption and we introduce higher income endowments or income heterogeneity (i.e. inequality), not adjusting taxation accordingly, a portion of eco-buffer shades away because of the high purchasing power of the representative agent in the former case and of rich people in the latter, raising some gentrification issues. Simulations thus suggest that taxation should be carefully addressed in order to avoid a trade-off between environmental protection and social justice and

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[49] http://arccacalifornia.org/resources/learning-sessions/

[50] In a preliminary experiment, the authors show that cutting access to public transit (e.g. the BART Transbay Tube in San Francisco, can cause a spike of 35% in travel time, whilst closing the Bay Bridge implies an increase of only 5%, given the absorbing capacity of the tube.)

a crucial issue that the paper does not take into account is the effect of progressive tax rates. The question is investigated in Mullin et al. (2019), who apply a differential property taxation approach to finance short-term adaptation plans: by applying higher tax rates to households owning oceanfront houses (which proxy for wealth[51]), the government can finance shoreline defense projects (whose burden would be unaffordable by individuals[52]) without incurring into regressive effects on poorer people and without eventually loosing support (the realization of a nourishment project is constrained by public opinion). Simulations show the effectiveness of a redistributive fiscal adaptation policy, where the burden transfer to the wealthiest has positive effect for the collectivity and the environment. Shifting to public incentives, Joffre et al. (2015) make use of local policies in order to influence shrimp farmers' decisions to shift to more sustainable production systems, to reduce the risk of disease outbreaks: local authorities indeed can encourage farmers to take care of natural capital (mangroves in this case) by paying them premiums (i.e. *payments for ecosystem services*). The state of the ecosystem environment, in turn, affects farmers' decision making. Finally, Shuvo et al. (2021) address public adaptation from an optimality perspective: Government (G) is the major adaptation actor and based on costs from nature (used as a feedback) and on other actors' actions (Government has perfect knowledge, $O_{G,t}$ on that) it decides how much to invest in adaptation measures; the total cost ($C_{G,t}$) will then depend on the cost from nature and on the cost of the investment. Government's optimal investment policy requires a cost minimization (i.e. a minimum expected cost in each state s_t, l_t), by means of the optimal value function, where the Bellman equation is characterized as follows:

$$V_G(s_t, l_t, O_{G,t}) = \min_{G_t} E[C_{G,t} + \lambda_G V_G(s_{t+1}, l_{t+1})|G_t] \tag{3}$$

where λ_G is a parameter indicating cooperation. Deep reinforcement-learning algorithms are then applied to overcome the infinite number of possible states issue arising from continuous SLR.

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5.2 Households' Behavioural Rules

Due to data availability, different behavioural rules –from randomness to economic theory– have been applied to households in order to study their adaptation to climate change. Households behaviour also depends on whether the model comprehends a "public agent" or not. In the former case, indeed, compliance with policies and/or feedbacks from planned adaptation need to be formalized. In Abebe et al. (2019) households build new houses and are heterogeneous in their compliance rate to existing policies (i.e. houses have certain locations and elevations). The compliance process is random[53] and the single household plans to build according to a simple rule of thumb, by comparing its compliance rate to policies (beach policy, building and housing ordinance, flood

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[51] It is assumed that a fraction of oceanfront houses are second properties used for recreational value and/or rents. From this assumption it follows that households owning such properties, vote elsewhere and thus imposing higher taxes on them would not lead to voting losses for the local administration.

[52] Beach nourishment has high fixed costs that include permits, project design and final implementation.

[53] There is a draw from a uniform distribution at any run of the simulation

zoning) with the threshold compliance rate. Policy compliance also appears in Löwe et al. (2017), where households have to conform with location policies but can buy new properties according to their own preferences and can place new rainwater tanks. Households in Chandra-Putra et al. (2015) can decide to elevate their house after a flood event and are required to buy insurance in the different scenarios. They can also sell their house and their decision-making is influenced by neighbors' actions. House prices and damage costs evolve according to their incomes, the rate of damage reimbursement and the possibility to influence each other. Chandra-Putra and Andrews (2020) further introduce a double auction market for real estate and hedonic pricing in the model. Households have preferences for residential location. Zhang et al. (2015), instead, consider two types of households: residents and environmentalists. The formers' land use desires concern proximity to the city and public facilities; the latters' ones, instead, aim at preserving natural reserves, beaches and wetlands, thus avoiding urbanization close to those areas. Households' desires and preferences will be taken into account by the Government when deciding upon new urban land use development. Filatova et al. (2011) addresse households' location preferences relying on consumer theory, thus maximizing utility[54]. Households have different preferences for location, and both preferences are represented by individual utility functions for location: land buyers then decide upon location depending on (i) the proximity to the city center (Px_{CBD}), (ii) personal preferences for green coastal amenities (Px_A) and their perceived flood risk probability. In logarithmic terms it translates into:

$$U = \alpha ln(Px_A) + \beta ln(Px_{CBD}) \tag{4}$$

which is taken from Alonso (1964) in order to account for the distance to the city center (Px_{CBD}) and green amenities Px_A, with preferences captured by α and β. To rule out perfect rationality, buyers are assumed to search for a local maximum. Further, to allow for some substitutability effect between consumption goods and houses, utility is internalized into the *willingness to pay* (WTP) function, along with the budget net of travel costs (Y) and non-housing goods' prices, leading to the demand function, which corresponds to buyers' bid price:

$$P_{wtp} = \frac{YU^2}{b^2 + U^2} = P_{bid} \tag{5}$$

The interesting feature stemming from this formulation regards its ability to replicate demand patterns so that demand increases with income and utility and decreases with the distance to the center[55] and with other goods' price increase[56]. Whilst buyers have a budget constraint and form

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[54] The original ALMA-C model in Filatova et al. (2009), also considers climate change impacts' uncertainties (e.g. flood risks), thus building up an expected utility maximization problem: $E(U) = PF_i U(1 - C_{dam}) + (1 - PF_i)U$ C_{dam} is the damage coefficient and *PF* is the subjective probability of flood events, which depends on its risk perception on future floods, RP_{dev}, compared to the objective probability, PF_{obj}: $PF_i = PF_{obj} \pm RP_{dev}$. The original formulation, thus, takes into account subjective expectations, which are worth of interest.

[55] As in the monocentric urban model of Alonso (1964)

[56] In Filatova et al. (2009) the additional interesting feature lies on the ability to include climate change issues alongside with economic and zoning characteristics in a context that accounts for agents' heterogeneity: diverse beliefs are internalized through the probability of flooding.

bid prices. The seller adjusts his selling price according to his preferences and risk perceptions and sells the undeveloped land if the bid price is above his reservation price. Buyers willing to buy undeveloped land near the coastline bear the cost coming from taxation to preserve the eco-buffer. In Mullin et al. (2019) an individual myopic household will support government decision to nourish beaches, if and only if the individual tax he has to pay does not exceed the gains in his home value from the adaptation project realization, which eventually occurs if the majority of them vote for it[57]. About Government adaptation investment, in Shuvo et al. (2021) residents' optimal value function resembles the Bellman equation for the Government, but considering residents' actions, R_t:

$$V_R(s_t, l_t, O_{R,t}) = \min_{R_t} E[C_{R,t} + \lambda_R V_R(s_{t+1}, l_{t+1})|R_t] \tag{6}$$

Contrarily to the Government case, households have bounded rationality, hence the set of observations $O_{R,t}$ does not reflect perfect knowledge.

In the field of transportation, in Suh et al. (2019) and Sun et al. (2020) households have a set of everyday activities that enhance their utility and suffer from disutility stemming from the amount of time[58] they spend along the highway (and on the tube, in Sun et al. (2020)) to reach different locations (as pointed out in Sun et al. (2020) agents want to minimize their lost time irrespective of the effects on other people).

A frequent approach for treating households' decision-making involves the modelling of their individual risk perceptions. In Han and Peng (2019), Han et al. (2020) and Han et al. (2021) for example, this is done by recurring to the *prospect theory* (Kahneman and Tversky (1979)) and the *protection motivation theory*, that will be addressed later in the paragraph. To start with, although not included in the review, we briefly present the risk perception formulation exposed in the work of Haer et al. (2017), since it has been borrowed by Han and Peng (2019) and Han et al. (2020). Households in Haer et al. (2017) decide among insurance purchase/cancellation and water barriers' construction. Two particular characteristics are accounted for: the life cycle of an agent (households indeed are assumed to move in at the age of 20, get older and exit once at 80 years old) and different decision models. On the latter, three are the specific theories under consideration: (i) the expected utility theory model; (ii) the prospect theory model; (iii) Bayesian prospect theory model. In all frameworks, by considering a portfolio of events $i = 1, 2, .., I$ and their probability of occurring (either objective, p_i, or subjective,π_i), each risk averse household has to decide among taking action or not:

(i) if his behaviour follows Von Neumann and Morgenstern *expected utility theory*, the formal-

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[57] In order to allow households to calculate the difference in property value with and without beach nourishment, the authors introduce an *erosion state equation*, $w_{t+1} = w_t - \gamma + \mu_t \theta$, where w_t represents the beach width in time, γ is erosion and μ_t and θ are two parameters associated with beach nourishment.

[58] The chosen variable is the vehicle hours of travel (VHT).

ization is as follows:

$$\begin{aligned} EU(action) &= \sum_{i=1}^{I} p_i U(W - C - R_i + D) \\ EU(no\ action) &= \sum_{i=1}^{I} p_i U(W - L_i) \end{aligned} \tag{7}$$

where W corresponds to the value of his house (which proxies wealth), C the cost of the adaptation solution and D the applied discount, R_i is the residual loss after a flood event when it occurs, being then L_i the loss an agent would face if none of the adaptation options has been implemented.

(ii) if the agent tends to overweight catastrophic events that however have a low probability of occurring (or at the contrary underweight low-magnitude events that occur more frequently) he behaves according to the *prospect theory* (Kahneman and Tversky (1979)) and therefore will have an individual-specific risk-aversion[59] which would make him attaching more value to a loss, and will decide among:

$$\begin{aligned} PT(action) &= \sum_{i=1}^{I} \pi_i U(-C - R_i + D) \\ PT(no\ action) &= \sum_{i=1}^{I} \pi_i U(-L_i) \end{aligned} \tag{8}$$

and the initial wealth in this case is taken as a point of reference to determine gains and losses. Of fundamental importance is the subjective probability (of an event to occur) measure, since individual heterogeneity (δ) shows up:

$$\pi_i = \frac{p_i^{\delta}}{(p_i^{\delta} + (1 - p_i)^{\delta})^{1/\delta}} \tag{9}$$

(iii) lastly, if the agent is assumed able to learn from past events and decisions can be influenced by social interactions (i.e. by flood experience, opinions and media), the *bayesian prospect theory* is applied. In this last case, the agent would have different risk perception, which are updated period after period, similarly to Viscusi and Zeckhauser (2015):

$$RP_t = \frac{aRP_{t-1} + bI_{experience} + cI_{social} + dI_{media}}{a + b + c + d} \tag{10}$$

with a, b, c, d being weighting parameters[60] and the subjective probability of an event to occur becomes:

$$\pi_i = \frac{(10^{2RP_i - 1} p_i)^{\delta}}{((10^{2RP_i - 1} p_i)^{\delta} + (1 - (10^{2RP_i - 1} p_i)^{\delta}))^{1/\delta}} \tag{11}$$

The introduction of updating risk perceptions, together with opinion dynamics, allows for a more

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[59] Drawn from a normal distribution

[60] Detailed explanations of parameters' values can be found in the paper.

realistic decision making among heterogeneous agents, interacting with each other and with their context. This decision-making rule has been adopted also by Han and Peng (2019), who introduces the benefits stemming from planned adaptation into the prospect expected utility and revise the set of influential factors shaping households' risk perceptions, using income, race, education, home ownership and community adaptation (made by local government):
$RP = \frac{aI_{income}+bI_{race}+cI_{education}+dI_{ownership}+eI_{government}}{a+b+c+d+e}$[61]. Time (experience and previous risk perceptions) exit the estimation equation, so as social influence and opinion dynamics, whilst static personal characteristics are accounted for. The reason behind it is the willingness to provide a stable environment in order to better focus on the effects of community adaptation in shaping agents perceptions. Han et al. (2020) reintroduces these aspects by enlarging both Haer et al. (2017) and Han and Peng (2019) definition, so that risk perception finally depends on income, race, property ownership, flood experience, community adaptation actions and social interactions, where time enters only in terms of past experience[62]: $RP = \frac{aI_{income}+bI_{race}+cI_{ownership}+dI_{experience}+eI_{community}+fI_{social}}{a+b+c+d+e+f}$
In all three papers, there are only two adaptation measures possible: buying insurance, elevating house and/or implementing a hard-adaptive measure (such as implementing water barriers, wet proofing or dry proofing (as in FEMA's (2017) homeowners' guide for retrofitting), depending on the perceived risk of floods and how they weight flood losses and gains from adaptation measures. Also Han et al. (2021) recur to a measure of risk perception –that single agents update period to period– that accounts for direct and indirect experienced floods, $RP_i = \frac{\alpha_i+m_{i,1}+\omega m_{i,2}}{c_i+n_{i,1}+\omega n_{i,2}}$, representing individual household's posterior risk perception where α_i and β_i are prior distributions, $c_i = \alpha_i + \beta_i$, ω is a weighting parameter for flood indirect experience and $m_{i,1}, n_{i,1}$ represent the number of individual successes and trials, respectively, and $m_{i,2}, n_{i,2}$ other agents' ones, observed by the single agent[63]. By employing the *protection motivation theory*, the authors make households protect themselves through risk-reducing attitudes shaped by their risk and coping appraisal. An agent risk appraisal starts when his risk perception goes beyond a threshold, p_t, or when his property has been totally destroyed; it ends when he decides whether to do nothing or to engage into a cost-effective adaptation strategy, based on his willingness to pay and on the insurance cost for minimum coverage. The coping appraisal process, which determines agents' risk-reducing behaviour, is a collection of perceptions about the costs and effectiveness of adaptation measures and the individual ability to cope with adverse effects.

Risk perceptions *expected utility* and/or *prospect theory* have been also employed to address migration decision making, for example in Magliocca and Walls (2018), in De Koning and Filatova (2020) and in Bell et al. (2021). The *prospect theory* applies to Bell et al. (2021)'s boundedly rational agents, whose livelihood portfolio is also influenced by social networks. Social interactions,

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[61] For the sake of correctness, in Han and Peng (2019) risk perception is identified with RT, instead of RP.

[62] A note on social interaction: neighborhood can positively influence the adoption of adaptation measures (Poussin, Botzen, and Aerts (2014)) but at the same time opinion convergence does not necessarily translates into higher correctness (Lorenz, Rauhut, Schweitzer, and Helbing (2011)) and, together with social interactions, could lead to risk underestimation because of the tendency of people to forget. Simulations from Haer et al. (2017), where households' heterogeneous decisions are affected by learning and social interactions are in line with such results, making the model suitable for representing real decision making about adaptation strategies.

[63] See Viscusi and Zeckhauser (2015). Network creation relies on the drawn of neighbors from a Poisson distribution (Yang, Mao, and Metcalf (2019)).

indeed, dynamically shape agents' decisions according to the strength of connections, which also determine information and resource sharing, whose expectations are incorporated into a livelihood portfolio, which can be reconsidered in each period. In every time step, agents are allowed to give birth, meet, ask for credit, interact and die. Households have to decide whether to migrate or not on the basis of such livelihood portfolios under different emission scenarios (and therefore under different sea level rise scenarios, that translate into income damages). In De Koning and Filatova (2020) both theories have been tested for households willing to buy a new house, and expected utility was chosen upon[64]. Floods risk aversion may prevent buyers to effectively buy a house in a flood zone and meanwhile, flooding experience may induce households to sell their house[65]. Risk perceptions are updated according to agents' past experience, house damages and level of fear of floods, by modifying posterior probabilities of buyers and sellers. Sellers form hedonic prices and (i) sell to the highest proposed bid price, (ii) reduce the ask price if no buyer shows up. The dynamics of real estate market shapes location distribution of households and endogenously let gentrification mechanisms to emerge. Consumers in Magliocca and Walls (2018) decide whether to buy an insurance or not or to eventually buy a new house in another location after a storm event. Decision making about location and insurance occur according to two alternative theories: *expected utility theory* and *salience theory*[66], an extension of the *prospect theory* that overcomes the estimation problem of the reference point and its inability to explain risk-seeking attitudes in a context of high possible gains. According to the former valuation, the agent maximizes his expected utility. Utility is assumed to be a Cobb-Douglas, with consumer good, x^{α_c}, and amenity level (depending on the distance to the coast), $A(d_i)^{\beta_c}$, are the two factors: $U(c,i) = x^{\alpha_c} A(d_i)^{\beta_c}$. Subjective risk perceptions are modeled through Bayesian learning (Viscusi (1991)) and following Gallagher (2014), so that after each storm event, households update their expectations on future storms' probability, conditional on observed storms and occurrence (S' and t'):

$$E(p|S'_t, t') = \frac{S'_t + \epsilon}{t' + \epsilon + \in} \tag{12}$$

with ϵ and $\in$ coming from a Beta distribution. Subjective risk perception enters the consumer's budget constraint and his willingness to pay when he searches for a house. The second valuation requires the calculation of the salience function, $v(x_s^j, x_s^{-j}) = \frac{|x_s^j - x_s^{-j}|}{|x_s^j| + |x_s^{-j}| + \theta}$ where s are possible states (i.e. the storm event occurs; the storm event does not occur), j agents' behavioural option (i.e. location with insurance; location with no insurance) and x_s^j the payoff of the lottery (x_s^{-j} is the payoff from the alternative lottery). Consumer's perceived value of the lottery, $V(L_j)$ then is the sum of possible payoffs multiplied by their probability, π_s and associated weights, ω_s^j, which capture risk-averse or risk-seeking behaviours:

$$V(L_j) = \sum_{s \in S} \pi_s \omega_s^j v(x_s^j) \tag{13}$$

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[64] See de Koning, Filatova, and Bin (2017).

[65] See de Koning, Filatova, Need, and Bin (2019).

[66] Bordalo, Gennaioli, and Shleifer (2012)

The weighting parameter, then, allows for distortions in an event valuation.

Remaining on households' perceptions, McNamara and Keeler (2013) assume that each agent i forms projections of prospective environmental characteristics (E^j, where the index j represents environmental characteristic), based on his own *calculation of past behaviour* S^j of the characteristic j as follows:

$$\begin{aligned} E_i^j(t) &= \alpha_i M^j(t) + (1-\alpha_i) S_i^j(t) \\ S_i^j(t) &= \beta_i E^j(t) + (1-\beta_i) S_i^j(t-1) \end{aligned} \tag{14}$$

with α and β_i being two weighting parameters and M the model prediction. Households then have to choose the amount of money to invest in defensive engineering –such as beach nourishment and dune restoration– or how much to pay for properties, whose valuation depend on rents, expenses and expected costs and discounts coming from climate change impacts and implemented adaptation measures (including insurance). Owners decide upon the defensive engineering plan to be enforced through a voting mechanism that leads to a collective choice. In practice when people assign a high value to model predictions, defensive measures are perceived as not being worth it and exit the market, causing a high volatility in housing prices.

Finally, on relocation decisions, Fontaine and Rounsevell (2009) identify five households' key characteristics that shape their decisions: location; the amount of adults; their age; the number of children and their age. Households are not static in this model: adults meet and create a family at a certain rate (coupling rate, c%), have children at a birth rate b%, retire and die at a rate d%. Life cycle is determinant in this model since it allows agents to change location. Before moving, households rank their preferred locations according to their *Potential Attractiveness, PA*, which in turn depends on agents' life stage and constitutes the trade-off between local amenities/disamenities (summed up as *local externalities,* LX[67]) and its accessibility, A. The former puts together environmental and social externalities, which depend on their turn on the degree of *local urban density,* ρ (higher urbanization implies lower environmental amenities). Hazards such as floods or erosion cause PA=0 if agents are risk averse and are captured by the variable A, which also accounts for other distance features such as jobs and transports. Speelman et al. (2021), instead, develops a Conceptual Model for Migration (CMM), merging together the *theory of planned behaviour* by Ajzen (1991) and the drivers of migration of Black et al. (2011). An agent intention (i.e. probability) to migrate, μ is identified with the sum of the probabilities to migrate to different locations, O (μ_{O1}, μ_{O2}, μ_{O3}), and the willingness to migrate to a specific location is shaped according to Ajzen (1991) *theory of planned behaviour*: it depends on the individual attitude to migrate towards the interested location (A_O), on subjective norms (N_O) and finally on the (random) perceived behavioural control (PBC):

$$\begin{aligned} \mu &= \mu_{O1} + \mu_{O2} + \mu_{O3} \\ \mu_O &= A_O * N_O * PBC \end{aligned} \tag{15}$$

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[67] Following Caruso, Peeters, Cavailhès, and Rounsevell (2007).

The attitude towards migration behaviour depends on a series of personal characteristics and push factors; subjective norms describe the pressure to migrate an agent feels when other agents in his social network do.

Firms' Behavioural Rules

As seen in Table 2, few papers include firms and businesses among agents in their ABMs, although adaptation behaviour of the productive sector should be taken into consideration more carefully, given its impacts on climate change: productive processes should probably be reassessed if we are willing to switch towards a more sustainable production. Concerning ABMs in coastal zones, Joffre et al. (2015) assume that shrimp farmers can change the production system by shifting from extensive (EXTS) or improved extensive (IES) systems to intensive (INTS) or integrated mangrove-shrimp (IMS) systems. IMS are low cost on one hand but also low productivity (similar to EXTS and opposite to INTS, which are very costly and highly remunerative; IES are in-beteween), however, they are the most effective systems in reducing the risk of disease outbreak. Nevertheless, farmers are profit maximizing agents, whose willingness to shift production system is modeled through a probabilistic approach, where plots' biophysical characteristics, social influence and governmental payments for ecosystem services, among other parameters, exert some influence. Zhang et al. (2015) design the productive sector as being composed of farmers (caring about closeness to city on the one side and about distance to existing agricultural land on the other side) and industrial enterprises (which favour proximity to industrial areas and form preferences by looking at the convenience of transportation and land prices). These desires enter Government's decision making on urban plans, since politics is not immune to entrepreneurial pressures. Toft et al. (2011) shape fishers' behaviours in two different submodels: trip limit and ITQs. In the former submodel, in each period, landing limits influence agents' behaviour[68], which operates (i.e. schedule trips for fishing) based on their expected profits, that depend upon the cost of trips themselves. Landings are basically limited by species-specific 2-month trips[69]. Each port group then stops fishing when (i) trip limits are over or (ii) the numer of trips is above the observed ones. In the latter submodel, instead, there is no landing limit but port groups are endowed with annual quotas so that each port group can schedule trips in terms of location and periods and decide when to fish (always by looking at expected profits). Quotas can be traded and the trading price differs among species: for the target species it depends on marginal profits from landing, whilst for the overfished species on the externality that its landing creates. By subtracting the cost per trip and the quotas' costs to expected revenues per trip, each port group decide whether to acquire quotas or to sell them and market mechanisms determine the amount of quotas finally traded. Mialhe et al. (2012) assign three different behaviours to business agents: they can be rational (Type A), pursuing profits and stable income; collective-minded (Type B), pursuing profits but trying to adopt Government guidelines and neighbors or network members' cropping system decision; or boundedly rational

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[68] Agents in Toft et al. (2011) are aggregated to some extent: single vessels are aggregated into port groups, p (which correspond to our definition of agent) and further into blocks j.

[69] See PFMC and NMFS (2009)

(Type C), which include all the previous objectives plus stable food supply and job decisions. Finally, each type of agent can have four cognitive strategies, following the *consumat approach*[70], which are implemented according to their level of satisfaction with their own objectives: repetition (they will maintain their cropping system), social comparison and imitation (they observe neighbors/network cropping systems and eventually adopt the the most used one), and deliberation (past salinity records are used to choose the best cropping system). Individual satisfaction indirectly depends on salinity, since it enters the value of production and all agents, independently of their type, care about profits.

On tourism, Student et al. (2020b) considers different types of tourism operators in their model, namely hoteliers, beach vendors, nearshore operators, dive operators, catamaran/boat operators. They are characterized by imperfect knowledge and can decide to act individually or collectively, depending on their own preferences, and move or stay after an environmental event. Their fundamental trade-off is between tourism output and the environment: the higher the emphasis on the former, the greater the negative impact on the latter when no sustainable investment is made. Tourism operators can enjoy higher earnings through environmental actions because of the enhancement of local attractiveness[71]. On the contrary, agents can go bankrupt because of the negative impact of pollution/degradation on revenues. Cooperation among agents depends on location direct/indirect degradation affection. In deciding their allocations, they have different options: maintain infrastructures, focus on tourism output, save or take environmental actions[72]. To conclude, Shuvo et al. (2021) adopt once again an optimality rule by employing the same value function and Bellman equation as for households, where residents' actions (R_t) are substituted by firms' actions (B_t).

Banks and Insurances' Behavioural Rules

The insurance market is modelled in all papers including a financial entity, whilst the banking sector is quite absent, emphasizing the important discard of themes regarding sustainable finance. Starting with insurance, Han and Peng (2019) take the governmental National Flood Insurance Program (NFIP) of FEMA as point of departure for their analysis and combine it with a private insurance market. Insurance agents have to estimate households' insurance costs. Insurance rates from private insurer is higher than the NFIP ones. In Han et al. (2020) the insurer always calculate insurance costs, but data on insurance rates are taken from 2012 and 2019 FEMA tables. The insurer differentiate insurance rates into default insurance rates (or *grandfathered*) and risk-based insurance rates (higher). Han et al. (2021) uses FEMA's risk-based insurance rates and calculates insurance rates according to the flooding zone: higher rates are applied if the difference between the house elevation and the BFE (base flood elevation) requirement is lower than 1-foot. Chandra-

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[70] Jager, Janssen, De Vries, De Greef, and Vlek (2000)

[71] More specifically, the local attractiveness depends on: beach, coast, nearshore, level of pollution and number of environmental agents.

[72] Student et al. (2020b) include the so called environmental operators among agents in the ABM and divide them into fish, sea turtles (mobiles), coral reefs and mangroves (static). Their main attributes concern their life: depending on environmental conditions they can move or either reproduce (if their health exceeds a given threshold) or die. If environmental agents multiply, there are gains in biodiversity.

Putra et al. (2015) calculate insurance premiums based on a number of building specific attributes and value, depending on the flood zone. Premium-to-loss ratios and the expected annual floos loss contribute in the calculus of flood insurance. In Chandra-Putra and Andrews (2020) the representative insurer behaviour is better designed since it calculates different insurance premiums by updating the loss ratios.

Finally, the representative bank in Chandra-Putra et al. (2015) and Chandra-Putra and Andrews (2020) gives loans to households and takes back houses when households' are not able to repay mortgages. The bank can resell houses at non-negotiable prices.

6 Concluding Remarks

The current literature review aims at providing a general picture on existing agent-based models on climate change adaptation in coastal zones. As easily noticeable by glancing to publication years, the majority of works are relatively recent and the field will be probably further explored in the near future, given the flourishing moment for ABMs. Four main considerations can be made. First, planned adaptation has not been left behind autonomous adaptation neither in ABMs –a tool that provides the greatest potential for modelling private agents– signaling that the scientific community is aware of the importance of Government intervention to successfully adapt to climate change. No general conclusion can be assessed on the effectiveness of public measures, even if, overall, there is a general agreement on their importance in risk mitigation. Results are hardly comparable since they include a wide variety of options (from fiscal policies to coastal protection infrastructures) and given they rely on different assumptions and several ways of considering vulnerabilities. Moreover, it is worth noting that in some cases vulnerabilities have been addressed not only from a strict environmental perspective, but also from a socio-economic viewpoint: we have seen how Government or local authorities, indeed, need to carefully design adaptation policies or coastal defense infrastructures in order to avoid harmful gentrification mechanisms besides further degradation of the natural environment. In line with the literature, also studies involving the use of ABMs stress the evidence of a delicate balance among successful adaptation and planned solutions to tackle climate change in coastal zones.

Second, the households' sector is the most agentized one. The huge focus on households, although necessary and useful, is counterbalanced by a poor attention to businesses and, therefore, to the productive sector. To seriously address climate change, productive systems are to be rethought, possibly integrating both adaptation and mitigation strategies. Very few ABM papers have approached adaptation in terms of changing productive systems and much more effort is needed. More studies on firms and on production are essential, not only because the productive sector has direct environmental impacts and externalities, but also because of the side economic and social effects associated with working establishments. Firms are indeed a source of agglomeration: they attract workers and if the rate of urbanization in coastal areas is to be challenged, working places cannot be ignored. Firms could also be a driving force for adaptation, that could be fostered by innovation and hence by investing more in research and development. Ports need to be made more efficient, the digitalization process is irreversibly in place: synergies among the public sector and the productive sector could be searched and developed along the coastlines. The productive sector should also be requested to guarantee wage adjustments to avoid low income people to remain trapped in hazard zones, perhaps. The role of finance –and more in detail– of sustainable finance as well represents a gap by now in these models and ulterior analysis should be welcomed.

Third, as already mentioned, there is few homogeneity among the different studies and results' comparisons are difficult to make. Since adaptation to climate change is highly context-specific, one could take advantage of that and unfold different research questions in the same location using the same data. Indeed, micro-scaled ABMs, compared to macroeconomic ABMs, show a greater calibration ability thanks to the use of local/regional and spatial data. Concerning assumptions and theories: an interesting number of works explicitly include learning and experience from flood events in risk perceptions or decision-making rules. Social influence and neighbors' network have been widely considered too, whilst cooperation has been less regarded. A couple of theories, most of all, has been retrieved for use in several studies to shape households' behaviour: the expected value theory and the prospect theory. This appears in line with the nature of the analysis, which comprehends decisions under uncertainty and behavioural rules should be able to reproduce specific patterns of risk aversion.

Lastly, operatively, a significant portion of ABMs are coupled with hydrodynamic models. Such technique represents an interesting tool for integrating economic (human) systems with natural systems, allowing for a multidisciplinary approach that avoids over-simplifications, enhancing ABMs' ability to be employed in specific locations.

A Study Areas

We present here the list of papers included in the review with the regional or local area used as case study.

Paper	Location	Country	GIS
Abebe et al. (2019)	Sint Maarten, Caribbean Islands	Sint Maarten	
Becu et al. (2016)	Oléron Island	France	
Bell et al. (2021)		Bangladesh	
Chandra-Putra et al. (2015)	Highlands, New Jersey	USA	
Chandra-Putra and Andrews (2020)	Highlands and Union Beach, New Jersey	USA	✓
De Koning and Filatova (2020)	Beaufort, South Carolina	USA	
Filatova et al. (2011)			
Fontaine and Rounsevell (2009)	Norwich area	Uk	
Han and Peng (2019)	Miami-Dade County, Florida	USA	
Han et al. (2020)	Bay County, Florida	USA	
Han et al. (2021)	Miami-Dade County, Florida	USA	
Joffre et al. (2015)	Dam Doi District, Ca Mau Province	Vietnam	✓
Laatabi et al. (2022)	Rochefort	France	
Löwe et al. (2017)	Melbourne	Australia	
Magliocca and Walls (2018)			
McNamara and Keeler (2013)	US East Coast	USA	
Mialhe et al. (2012)	Pampanga Delta	Philippines	✓
Mills et al. (2021)	Tillamock County	USA	
Mullin et al. (2019)			
Shuvo et al. (2021)	Pinellas County	USA	
Speelman et al. (2021)		Maldives	
Student et al. (2020a, 2020b)	Curaçao, Caribbean Islands	Curaçao	
Suh et al. (2019)	San Mateo County and Santa Clara County	USA	✓
Sun et al. (2020)	San Francisco, Marin, San Mateo Counties, Alameda County	USA	
Toft et al. (2011)	US West Coast	USA	
Zhang et al. (2015)	Lianyungang city, Jiangsu Province	China	✓

B Adaptation options

Policies and adaptation strategies to tackle climate change in coastal zones modelled in the different studies included in the current review.

Adaptation option	Planned	Autonomous	Coastal Defense	Coastal Management	Papers
Backshore protection stuctures (e.g. dune crest).	✓		✓		Mills et al. (2021)
Beach nourishment projects, widening of beaches, dunes.	✓		✓		McNamara and Keeler (2013)[73]; Mullin et al. (2019); Mills et al. (2021); Shuvo et al. (2021)
Beach policies impeding construction of new buildings close to the beach.	✓			✓	Abebe et al. (2019); Mills et al. (2021)
Building levees.	✓		✓		Suh et al. (2019) Sun et al. (2020) Shuvo et al. (2021)
Cleaning-up of beaches.		✓		✓	Student et al. (2020a, 2020b)
Construction/maintenance of dikes along the coast.	✓		✓		Becu et al. (2016); Abebe et al. (2019); Laatabi et al. (2022)
Construction/maintenance of drainage channels in flooded areas.	✓		✓		Abebe et al. (2019)
Construction of sand fences, loading pebbles.	✓		✓		Laatabi et al. (2022)
Construction of seawalls.	✓		✓		Han et al. (2020); Han et al. (2021); Shuvo et al. (2021)
Educating on reef-safety.		✓		✓	Student et al. (2020a, 2020b)

House elevation (and requirements).	✓	✓	✓		Abebe et al. (2019); Han and Peng (2019); Chandra-Putra and Andrews (2020); Han et al. (2020); Han et al. (2021)
House location preferences more inclined to protect wetlands, beaches and coastal natural resources.		✓		✓	Zhang et al. (2015)
Installing embankments along the shoreline.	✓		✓		Suh et al. (2019)
Installing stormwater pumps.	✓		✓		Shuvo et al. (2021)
Imposition of limits and individual transferable quotas as a fishery management strategy.	✓			✓	Toft et al. (2011)
Land use management.	✓			✓	Zhang et al. (2015); Becu et al. (2016); Löwe et al. (2017); Mills et al. (2021); Laatabi et al. (2022)
Payments for ecosystem services.	✓			✓	Joffre et al. (2015)
Property expropriation/properties' buyback.	✓			✓	Becu et al. (2016); Löwe et al. (2017)
Purchase of insurance.		✓		✓	McNamara and Keeler (2013); Chandra-Putra et al. (2015); Magliocca and Walls (2018); Han and Peng (2019); Chandra-Putra and Andrews (2020); Han et al. (2020); Han et al. (2021)
Raising causeways	✓		✓		Sun et al. (2020)
Raising roads.	✓		✓		Shuvo et al. (2021)

Reassessment of city streets.	✓		✓		Löwe et al. (2017)
Stormwater pipes capacity implementation.	✓		✓		Löwe et al. (2017)
Strategic retreat/withdrawal (dismantlement); relocation; migration	✓	✓		✓	Fontaine and Rounsevell (2009); McNamara and Keeler (2013); Magliocca and Walls (2018); De Koning and Filatova (2020); Bell et al. (2021); Mills et al. (2021); Shuvo et al. (2021); Speelman et al. (2021); Laatabi et al. (2022)
Switching towards more sustainable productive systems		✓		✓	Mialhe et al. (2012); Joffre et al. (2015)
Taxation depending on proximity to the coast.	✓			✓	Filatova et al. (2011); Mullin et al. (2019)
Voucher systems.	✓			✓	Han and Peng (2019); Chandra-Putra and Andrews (2020)
Wet proofing and dry proofing		✓	✓		Han et al. (2020)

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[73] Through collective choice of households

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