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Review

# An Assessment of Agent-Based Modelling Tools For Community-Based Adaptation To Climate Change

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**Abstract:** Human-induced climate change has highlighted the need for Community-Based Adaptation (CBA) to build resilience in vulnerable communities. CBA empowers communities to leverage their resources and skills in shaping effective adaptation strategies. Agent-based modeling (ABM) is a suitable tool to develop tailored strategies that account for local capacities, priorities, and cultural contexts. This study assesses ABM tools for their suitability to model CBA, focusing on key criteria such as agent definition, sensitivity analysis, scalability, and experiment design. A comprehensive review of available ABM tools identifies NetLogo as the most fitting tool by its features, due to its flexibility in handling complex community-environment interactions. GAMA and Envision are nearly as suitable, offering robust support for modeling socio-economic and environmental dynamics. The article provides guidance for researchers and practitioners in choosing an appropriate ABM tool aligning with the specific needs of CBA, ensuring contextually relevant and sustainable adaptation solutions.

**Keywords:** Community-based adaptation; climate change adaptation; agent-based modelling; simulations; tool assessment

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## 1. Introduction

Human-induced climate change is an unprecedented threat with far-reaching consequences for the environment, societies, and economies [1]. The resulting rise in global temperatures contributes to severe weather events, disrupting ecosystems and endangering communities globally [2]. These effects are multifaceted and can manifest in various ways, affecting social, economic, and environmental aspects of communities [3].

Addressing the impacts of climate change on the community level requires a holistic and collaborative approach, involving mitigation efforts to reduce greenhouse gas emissions as well as adaptation strategies to build adaptive and resilience capacity in socially and geographically vulnerable communities [4]. Adaptation becomes crucial in these contexts, providing proactive strategies to minimise vulnerability and enhance resilience [5]. Recognizing communities as active agents in shaping their resilience, community-based adaptation (CBA) to climate change empowers concerned persons to co-design strategies, foster ownership, social cohesion, and sustainability [6]. CBA interventions address specific community needs and establish a robust foundation for long-term climate resilience [7]. Agent-based modelling (ABM) has the potential to capture the particular CBA features as it allows for simulation of complex community-environment dynamics and offers insights into factors influencing adaptation decisions by the communities. Such thorough and critical understanding allows for identifying cost-effective and impactful interventions. Reviewing and assessing ABM tools for CBA is vital, considering that ABM tools have varying degrees of freedom in their elements, features and capabilities [8]. Evaluations can guide researchers and practitioners to apply the right tool, optimise the application, and contribute to the continuous improvement of tools in CBA [9].

### 1.1. Community-Based Adaptation To Climate Change

CBA is an approach to address the impacts of climate change through the active involvement of the concerned communities in identifying and implementing adaptation strategies [10]. CBA recognizes that communities are the first to experience the effects of climate change and possess valuable knowledge and experiences about themselves, their environment and vulnerabilities [11]. By involving communities into the adaptation process, CBA seeks to enhance resilience and sustainability in the face of changing climatic conditions. One key aspect of CBA is the recognition of local knowledge and traditional practices as valuable sources of information for developing effective strategies [2]. Local communities often have a thorough understanding of their ecosystems, weather patterns, and natural resources, allowing them to identify early signs of environmental changes and develop context-specific adaptation measures. To integrate this understanding through a participatory approach not only empowers communities but also contributes to the effectiveness and long-term sustainability of adaptation efforts. Adaptation initiatives under the CBA framework are context-specific, acknowledge the unique characteristics of each community, include their socio-economic conditions, cultural contexts, and environmental vulnerabilities. Sustainable and community-based solutions are integral to CBA, with a focus on building the capacity of communities to manage and respond to the impacts of climate change in a way that enhances their resilience and fosters long-term sustainability. The concept of CBA has gained prominence in international discussions on climate change, specially within the United Nations Framework Convention on Climate Change (UNFCCC). Article 7 of the Paris Agreement explicitly recognizes the importance of enhancing adaptive capacity and fostering resilience, emphasising the need for adaptation actions to be locally driven and gender sensitive. CBA initiatives have been implemented across various regions, with successful examples demonstrating the positive outcomes of community-based adaptation efforts. For instance, projects have focused on building the capacity of communities to manage water resources, develop resilient agricultural practices, and establish early warning systems for extreme weather events [7,10,11].

### 1.2. Agent-Based Modelling

ABM is a computational modelling approach that simulates the interactions and behaviours of autonomous agents within a given environment [13]. In ABM, an "agent" represents an individual entity, such as a person, an animal, or an organisation, capable of making independent decisions, integrating new information and responding to its environment based on a set of predefined behaviours and rules. These agents operate within a simulated environment where their interactions and decision-making processes unfold dynamically over time. One of the strengths of ABM lies in its ability to capture complex, emergent phenomena that arise from the interactions of individual agents, providing a bottom-up perspective on system dynamics [14]. This modelling technique finds applications in various fields, including social sciences, economics, ecology, and epidemiology allowing researchers to explore and understand the intricate behaviours and patterns that emerge from the interactions of diverse agents. Beyond and feeding into higher levels, there are various examples of ABMs' contributing to policy development while originating at the grassroots level. Berger and Troost [15] utilised ABM to model climate change impacts on agriculture and subsequently draw conclusions for climate-related policy options to spur climate adaptation and mitigation.

### 1.3. Related Works and Gap

This section outlines a series of studies and publications on ABM tools from other thematic fields. These comparisons have been conducted to assist researchers in selecting the most suitable tools for their specific needs, however an assessment for the specific features and requirements of the CBA approach is lacking. The existing scientific articles reviewing ABM tools in the various disciplines are listed in table 1. Given the few number of review articles on ABM tools, review articles were considered back in time until the year 2006 and when showing up under review article and

ABM tool. These review studies and publications provide valuable technical insights into ABM tools, their features, and the contexts in which they are most suitable. ABM look at wide-ranging applications in environmental and ecological research. Schreinemachers and Berger [16] harness ABM to investigate interactions between humans and their environment. Thober et al. [17] employ ABM to delve into studies related to environment and migration. Miller et al. [18] utilise ABM to examine policy scenarios addressing conservation and developmental challenges. Many similar studies applied ABM to gain insights into intricate natural and human-related issues. However, there is currently no study that reviews tools possible to use for CBA and assesses them for suitability to model CBA.

ABM proved beneficial in investigating climate change aspects and lifestyle considerations. Berger and Troost [15] and Allen et al. [28] employ ABM to explore sustainable lifestyle choices. Gerst et al. [29] leverage ABM to scrutinise climate policy and its implications. These examples show the potential of ABM in addressing diverse aspects of environmental and climate-related studies. CBA relies on the resilience of the community, which is characterised by many interacting elements including individuals, communities, governments, ecosystems, and infrastructure parts [30]. Troost et al. [31] harness ABM to address climate change adaptation within the agricultural sector of the Central Swabian Alps and similarly, Angus et al. [32] leverage ABM to delve into various adaptation scenarios in the context of climate change impacts in Bangladesh.

Despite the wide-spread application of ABM in these domains, the relevant gap concerns the absence of studies specifically screening ABM tools for their suitability for modeling CBA. By pointing out this gap, the text lays the groundwork for future research that could explore how ABM can be tailored to model CBA scenarios, considering its potential to unravel complex, interconnected systems involving diverse actors and components such as communities, governments, and ecosystems. In turn, such assessments would provide valuable insights into the specific features and requirements of ABM tools for effectively addressing CBA challenges. This study aims to assess the suitability of different ABM tools for CBA by evaluating their capacity to model community dynamics, integrate socio-economic and demographic variables, and support participatory processes. This assessment seeks to guide practitioners and researchers in selecting the most appropriate tools for CBA simulations.

**Table 1.** Currently available studies on ABM application by objective of the study field, tools selection and ABM outcome possibilities.

Author	Year	Objectives of the Study	Tools Reviewed	Outcomes
Railsbacks et al. [19]	2006	Review of ABM tools, focusing on Swarms, Repast, MASON, NetLogo	Swarms, Repast, MASON, NetLogo	Insights into capabilities and features
Gilbert [20]	2008	Comprehensive review of various ABM tools, providing comparisons to aids researchers	Various ABM tools	Tool introduction and detailed comparisons for informed choices
Beryman [21]	2008	Evaluation of general purpose and battlefield specific	BactoWars, EINSein, MANA, MASON; NetLogo,	Comparative analysis for modelling complex adaptive systems in defense application

			Repast, Swarm, WISDOM-II	
Nikolai & Madey [22]	2009	Comparison of ABM platforms based on programming language, operating system, licensing, primary domain and support	Various ABM platforms	Criteria-based comparison on technical features
Allan [23]	2009	Comparison of ABM platforms to enhance understanding of available options aligned with research needs	Various ABM platforms	Compatibility in computational science, particularly in engineering and system biology
Lytinen & Railsback [24]	2012	Comparative analysis of ABM tools NetLogo and Repast, aiming to keep researchers updated on the evolving ABM software landscape	NetLogo, Repast	Keeping researchers informed about the latest evolution
Kravari & Bassiliades [25]	2015	Research to compare ABM tools, contributing to the efforts to help researchers navigate the multitude of options in the field	Various ABM tools	Comparative up-to-date review of existing ABM platforms based on universal comparison and evaluation criteria
Abar et al. [26]	2017	Comparison of ABM platforms contributing to the growing body of knowledge regarding available tools for ABM	Various ABM platforms	A comprehensive and comparative survey of the state-of-the-art in ABM
Raab et al. [27]	2022	Evaluation and comparison of NetLogo, GAMA and Repast within the context of Industrial Health and Safety	NetLogo, GAMA, Repast	Suitability and performance assessment of ABM tools in Industrial Health and Safety Management

		Management using Conways's Game of Life		
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#### 1.4. The Case For Agent-Based Modelling In Community-Based Adaptation To Climate Change

ABM's capabilities make it the ideal tool for incorporating and handling CBA structures and processes and dynamics. It offers a robust framework for exploring the intricate interplay between an array of actors [33], spanning from individual community members to organisational bodies across various levels from grassroot to local government. The domain of CBA is inherently complex, encompassing many agents, from households to local institutions and ecosystems [34]. ABM shines in its capacity to encapsulate these complexities, allowing for the representation of this diverse cast of characters and their dynamic behaviours within a community. In the realm of CBA, where adaptation strategies are as varied as the communities they support, context specificity is paramount [35]. ABM exhibits the capability to assimilate heterogeneity and context-specific nuances into its models [36]. This empowers researchers to represent the diversities within agent characteristics, including socio-economic conditions, cultural norms, and environmental landscapes. In a study conducted by Hailegiorgis et al. [37], ABM was applied to investigate the resilience and adaptive capabilities of rural households within the context of climate fluctuations, socioeconomic variables, and community-level land use. The findings from this research reveal that recurrent occurrences of extreme events, such as droughts, have a detrimental impact on the adaptive capacity of these households, ultimately resulting in migration from the region. Similarly, Lawyer et al. [38] argue for the application of ABM to simulate the effects of adaptation on coastal tourism dynamics. Vulnerability reduction and community resilience building lie at the heart of CBA [39]. ABM provides a robust platform for assessing vulnerabilities at multiple tiers, from individual households to entire communities. It illuminates vulnerabilities within various community segments and ecosystems, thereby assisting policymakers in prioritising adaptation strategies. Furthermore, ABM facilitates scenario testing [40], a pivotal element in policy analysis for CBA. By modelling the repercussions of policy interventions and adaptation strategies, it becomes an invaluable aid in the decision-making process. It enables the dynamic simulation of the impacts of various policy measures, thereby guiding policymakers to opt for the most effective solutions. Engaging local stakeholders in the modelling process is not just advantageous but also indispensable for a successful CBA. ABM embraces and supports participatory modelling, in which community members actively partake in the development and testing of models. This participatory approach emerges as a vital means to ensure that adaptation strategies are not only effective but also socially acceptable and equitable [40]. Nevertheless, ABM, like any compelling tool, comes with its own set of challenges. Calibration and validation of models, data availability, and computational demands can be considerable hurdles. Researchers emphasise that it is imperative to obtain high-quality data and conduct rigorous testing of ABM to ensure its reliability [41]. Moreover, there is promise in integrating ABM with other modelling approaches, such as system dynamics or econometric models. This presents an anchorpoint for future research and holds the potential to further enrich the field of CBA studies. ABM can provide one remedy within the domain of CBA studies. Its capacity to disentangle complexity, cater to context-specific nuances, and simulate the dynamics of adaptation strategies show synergies between the two.

## 2. Methodology Adopted

### 2.1. Tools Screening and Selection Procedure

A state-of-the-art database of available ABM tools can be found in Abar et al. [26], a computer science review article "*Agent-Based Modeling and Simulation Tools: A Review of State-of-the-Art Software*" presenting an extensive selection of tools for agent-based modelling encompassing a broad spectrum of domains. Abar et al. [26] point out 82 ABM tools which span the entirety of disciplines and the

various application cases of ABM tools. However, this article's focus is on tools with the capability to capture and illustrate CBA and its surroundings in a modelling environment and accordingly, the tools are screened for their CBA relevance by disciplines. The criteria to evaluate were chosen based on their relevance to CBA, including their ability to model complex social and environmental interactions, their flexibility in agent definitions, and their support for participatory modeling processes. Each criterion plays a crucial role in ensuring the chosen ABM tool can capture the nuances of CBA. The entire process of selection can be viewed in figure 1. A database is created with the tools that match the requirements of thematic fields relevant to CBA as follows: Social and Natural Sciences, Economics, Ecology, Urban Planning, Geographic, Information System (GIS), Spatial Planning.

From the initial 82 ABM tools across the various disciplines, a total of 63 ABM tools were identified to match the above-mentioned thematic fields. In a next step, software, technical, requirement and experiment design criteria are screened to further sharpen the number of tools for the use case of CBA. A database is created for the resulting tools with different properties: Licence type, Source code, Agent type, Coding language, Model development effort, Modelling strength, Scalability, Application domain.



**Figure 1.** Tool Selection Process.

The study covers the field of CBA which belongs to the domain of social science. Thus, tools which are compatible with social science, either only to social science or along with other domains are considered. In total 39 tools were identified which meet the mentioned requirement. For the study's purpose, the list is sharpened further and to fewer tools based on the criteria and characteristics listed in Table 2. The relationship between the "criteria" and "characteristics" columns in Table 2 is established based on practical considerations for selecting ABM tools that can effectively model CBA. Each criterion represents an essential requirement for modeling CBA, while the corresponding characteristic specifies the attribute or capability a tool must possess to meet that criterion. This logical link is grounded in empirical research and practical needs identified in the CBA context. For instance, "Modelling Strength" requires tools with "Medium to High" capabilities to handle the complexity of climate and extreme event modeling in CBA scenarios, which involve diverse socio-economic and environmental factors. Hence, this alignment ensures that the tools selected are robust enough to capture the nuances of CBA processes and the multifaceted nature of climate adaptation strategies including the handling of the associated data volumes. Given this study's academic focus, the consideration is directed towards tools that are open source. Recognizing the diverse nature of modelling tools and the varying degrees of proficiency they demand, the researchers acknowledge that some tools necessitate advanced programming skills, catering to adept programmers or coders. The focus of this article however is on the suitability of the tool to grasp the specificities of the CBA approach, its elements, interactions as well as surrounding.

**Table 2.** Tool Filtering Criteria.

Criteria	Characteristic
Licence/Pricing	Free and open source
Model Development Effort	Simple/Easy to Moderate
Modelling Strength	Medium to High

CBA introduces a layer of complexity given its multifaceted nature. Moreover, CBA deals with intricate environmental dynamics, incorporating data and factors from a wide spectrum, including

climate, meteorological data, and various socioeconomic elements. Recognizing the inadequacy of simplistic modelling tools, which may suffice for smaller-scale endeavours but prove insufficient for the intricacies of CBA, the research is judiciously opted for tools which exhibit medium to high scale modelling capabilities. This selection ensures that the chosen tools align optimally with the demands of modelling in the context of CBA. By applying all these criteria, a list of 12 tools has been compiled in Table 3 which encompasses the following which are commonly used in environmental, social, and economic modeling.

**Table 3.** Selected Tools to Assess in the Context of CBA.

<b>Tool</b>	<b>Source Code</b>	<b>Agent Type</b>	<b>Coding Language</b>	<b>Development Effort</b>	<b>Modelling Strength</b>
AOR Simulation	Java	Cognitive Agents	Java	Moderate	High
Ascape	Java	Java Classes	Java	Moderate	Medium Scale
Envision	MS Visual C++	Reactive Agents	Java	Moderate	Medium Scale
GAMA (2D/3D)	YourKit Java Profiler	Reactive Agents	Libraries	Moderate	Medium Scale
JAS	Java	Java Class	Libraries	Simple/Easy	Medium Scale
LSD (2D/3D)	C++	C++ Class	Libraries	Moderate	High
NetLogo (2D/3D)	Scala	Mobile Agents	Libraries and NetLogo Language	Simple/Easy	Medium Scale
Repast HPC	C++	BDI Agents	C++	Moderate	Extreme Scale
SeSAM	Java	Java Class	Visual Modelling Language	Simple/Easy	High
UrbanSim	Opus	Python and Lua Script Classes	Libraries	Moderate	Medium Scale
TerraME	C++/Lua	Python and Lua Script Classes	Libraries	Moderate	Medium Scale

AOR Simulation models complex systems with agent interactions involving both agents and objects, using a high-level approach that specifies agent behaviors, making it valuable for social

sciences. Ascape, an open-source Java-based tool, offers flexibility and pre-built models, popular in economics, social sciences, and ecology. Envision, a C++ platform, integrates GIS for land-use and environmental planning, enabling decision-making simulations for agents like households and businesses. GAMA, an open-source tool, supports 2D/3D visualizations, GIS, and multi-level agent interactions, widely used in environmental and urban modeling. JAS is a Java-based framework that integrates AI techniques, suitable for simulating adaptive systems. LSD, developed in C++, focuses on economic and social simulations, offering customizable models for complex data. NetLogo is user-friendly with 2D/3D support and a broad library, popular in education and research. Repast HPC, a high-performance version of Repast, handles large-scale simulations with complex agent interactions. SeSAM provides a visual environment for designing and running models, accessible without programming expertise, ideal for socio-economic modeling. UrbanSim is tailored for urban planning, simulating interactions between agents like households and developers. TerraME supports multi-agent simulations of socio-environmental systems, integrating GIS for land-use modeling. GALATEA, from the University of Andres, was excluded due to limited English documentation.

## 2.2. Tools Assessment Criteria

The comprehensive assessment of the selected tools hinges on overarching criteria, namely General Characteristics, Modelling, Simulation, and Exchange as listed in Table 4. Modelling criteria cover parameters related to the modelling process, while application criteria delve into agent types and application domains. Simulation criteria encompass considerations such as speed, parallelization, and the feasibility of applying optimization methods. Exchange criteria focus on data exchange possibilities with other file formats and programs [27].

**Table 4.** Generic Assessment Criteria for ABM Tools.

Criteria	Subcategory	Description
General Characteristics	Licence	Open source or proprietary?
	Release Date	Latest version release date
	Coding Language	Programming languages supported
	Operating System	Supported
	Community Support	Compatibility with various OS Presence and activity of user community
Modelling	Agent Definition	Flexibility in defining agent attributes and behaviours
	Behaviour Specification	Ease of specifying agent behaviours and interactions
	Model Validation	Tools for validating the model
	Sensitivity Analysis	Capability for sensitivity analyses
	Scalability	Handling large-scale simulations
Simulation	Time Step Control	Control over simulation time steps

	Visualisation Parallel Processing Experiment Design Output Analysis	Tools for visualising model output Utilisation of parallel processing Ease of designing and running simulation experiments Tools available for analysing simulation results
Exchange	Data Formats External Data Integration Export Options	Supported data input/output formats Ability to incorporate external data sources Ease of exporting simulation results

For a thorough comparison of tools suitable for CBA, it is essential to assess them based on their ability to incorporate the key aspects of the CBA approach. This ensures that the tools can comprehensively capture the complexity of community dynamics and enhance decision-making processes in the face of environmental and socio-economic challenges. A review of relevant literature on CBA projects has identified 6 criteria under seven broader criteria compiled in Table 5.

In developing the 6 criteria for assessing tools in CBA projects, a literature review was conducted. This review aimed to collect from scientific literature all referenced criteria of CBA without excluding any and with the aim to document them in their entirety. The review began by linking key aspects of CBA in literature and their requirement for modelling, including dynamic community interactions, socio-economic factors, participatory modelling, diverse data types, model scalability, risk and uncertainty assessment, and feedback mechanisms. Existing ABM tools were then examined for their capacity to address these aspects. This involved reviewing technical documentation, previous studies, and user feedback. From these insights, criteria were developed covering general characteristics (licence, release date, programming language, compatibility, community support), modelling capabilities (agent flexibility, behaviour specification, validation, sensitivity analysis, scalability), simulation features (time step control, visualisation, parallel processing, experiment design, output analysis), and data exchange (formats, integration, export options). The criteria were validated against literature on CBA and ABM, ensuring they were grounded in established research and best practices. The final criteria assess ABM tools' ability to model dynamic interactions, incorporate socio-economic variables, support participatory modelling, manage diverse data, scale to different community sizes, assess risks and uncertainties, and incorporate feedback mechanisms. This approach ensured the 6 criteria are robust, comprehensive, and aligned with the needs of modelling CBA using ABM. These assessment criteria are theoretically grounded in the principles of CBA, ABM, and related scientific literature. They collectively ensure that the selected ABM tools align with the complexities and nuances of CBA scenarios. The theoretical grounds for the assessment criteria are derived from foundational principles in CBA, ABM, and broader scientific literature on environmental and social system modeling. These principles emphasize the need for tools that can capture dynamic interactions within communities, integrate socio-economic factors, and support participatory modeling. The criteria are informed by concepts such as adaptive capacity, resilience, and socio-ecological systems theory, which highlight the importance of incorporating diverse data, scalability to different community sizes, risk and uncertainty assessments, and feedback mechanisms in CBA models. These theoretical

foundations ensure that the selected ABM tools are robust and capable of accurately reflecting the complexities and nuances inherent in CBA scenarios

### 3. Results

Each of the tools was developed with distinctive characteristics and purpose. Table 5 provides the specific technical details on the selected ABM tools. The comparative analysis of various ABM tools reveals their distinctive strengths and characteristics. AOR Simulation stands out with high modelling strength and a moderate development effort, making it particularly effective in representing complex systems. "Modelling strength" is defined as an ABM tool's ability to simulate complex systems and interactions within CBA scenarios. It considers factors like flexibility in agent definitions, detailed behavior specification, model validation, sensitivity analysis, and scalability. Tools with medium to high modelling strength can manage complex agent behaviors and interactions, and provide robust mechanisms for model validation and sensitivity analysis. Ascape, utilising Java, demonstrates a balanced profile with medium-scale modelling strength and a moderate development effort, suitable for scenarios of moderate complexity. Envision, employing MS Visual C++, excels in scenarios of medium scale with a focus on reactive agents, offering a good compromise between modelling strength and development effort. Medium scale refers to the complexity of the scenarios being modeled rather than specifically to a time or space scale. In this context it describes models that are capable of handling scenarios with moderate levels of complexity, such as those involving multiple interacting agents, diverse socio-economic factors, and environmental data. This definition includes a balance between the number of variables, computational demands, and the ability to represent interactions adequately without reaching the extreme ends of either simplistic or highly complex models. GAMA, developed with YourKit Java Profiler, is proficient in modelling scenarios of medium scale, particularly emphasising reactive agents. JAS, with Java as its language, stands out for its simplicity, providing easy modelling for medium-scale complexity. LSD, developed in C++, highlights high modelling strength, making it suitable for representing intricate systems with a balanced development effort. An "intricate system" is here defined as a complex and dynamic system composed of multiple interacting agents, where the overall system behavior emerges from the collective interactions of its parts. This definition aligns with the established scientific understanding of intricate systems, particularly in the context of ABM and CBA. NetLogo, utilising Scala, is well-suited for medium-scale scenarios, offering simple development. Repast HPC, excelling in extremely complex scenarios, demonstrates extreme-scale modelling strength with a moderate development effort in C++. SeSAm, with Java, combines high modelling strength with a simple development effort, making it well-suited for intricate modelling. UrbanSim, utilising Opus, offers a balanced profile for medium-scale complexity. A summary of the comparative assessment of suitability of the tools for CBA is presented in Table 5. In the next sections, each of the tools is in-depth explored and discussed for its suitability. For instance, when evaluating NetLogo, the authors assessed its capacity to integrate socio-economic factors by simulating interactions between agents representing different households with varying income levels, which directly influenced their adaptation decisions. This showcases how the tool's features were practically assessed.

**Table 5.** CBA Criteria for ABM tools evaluation .

CBA Requirement	Assessment	Theoretical Justification
Adaptability Community Dynamic	to Assess tool's dynamic community interaction and agent learning capabilities. Evaluate agent's integration of cognitive	Dynamic interactions play a crucial role in community-based systems, as highlighted in numerous studies [14]. Models that overlook these

	<p>factors like updating strategies, household ingenuity, and proximity effects. Check tool's support for memory updating, discarding outdated information, and enhancing adaptability in response to environmental changes..</p>	<p>interactions may oversimplify community dynamics and miss critical aspects. In climate change adaptation, the learning and adaptive capacity of actors are paramount for preparing communities and societies for the adverse impacts of climate change [42].</p>
Integration of Socio-Economic Factors	<p>Evaluate tool's ability to integrate socio-economic variables and demographic factors in ABM. Assess if tool can integrate socio-economic variables into agent attributes and model environment, and include demographic factors like age, gender, race/ethnicity, and family composition in modelling resilience. Consider implementing data structures and algorithms to represent these variables, enabling agent interaction and response in simulation environments.</p>	<p>Socio-economic factors play a pivotal role in community-based adaptation [43], and models lacking integration of these variables might overlook key determinants of successful adaptation. Additionally, demographic factors significantly impact vulnerability and resilience in communities facing environmental changes [44], necessitating their consideration in models to ensure realistic representations.</p>
Participatory Modelling Support	<p>Evaluate the tool's support for participatory modelling with community involvement and collaborative decision-making, focusing on features like stakeholder engagement, user-friendly interfaces, and interactive scenario planning. Look for functionalities such as participatory workshops, stakeholder consultations,</p>	<p>Participatory modelling enhances the legitimacy and effectiveness of models by incorporating local knowledge and perspectives [45], fostering a more accurate representation of community realities through the involvement of community members. Additionally, collaborative decision-making is crucial</p>

	and visualisation tools that enable non-experts to contribute to model development and explore alternative adaptation strategies together.	for developing adaptive strategies [46], highlighting the need for models to facilitate scenario planning and empower stakeholders in making informed choices for community well-being.
Handling Diverse Data Types	Assess tool's data handling for CBA modelling in ABM. Evaluate support for diverse data types (climate, geographical, socio-economic) including interoperability, spatial handling, transformation, preprocessing, and database capabilities. Examine compatibility with standard formats/protocols. Evaluate ability to integrate various data sources (socio-economic, environmental, demographic) by assessing ingestion, processing, and harmonisation across formats/platforms. Consider functionalities, import/export, geospatial formats, transformation tools, database connectivity, and exchange protocol compatibility.	The multidimensional nature of community-based challenges necessitates diverse data types for accurate modelling [47], highlighting the importance of models capable of handling varied data to represent the complexity of the community environment. Integration with diverse data sources aligns with the principles of data-driven decision-making in CBA [48], with models benefiting from the incorporation of climate, geographical, and socio-economic datasets.
Scalability to Different Community Sizes	Evaluate the tool's capability to scale models for varying community sizes, considering factors such as computational demands, resource allocation efficiency,	Addressing scalability challenges is crucial for ensuring the robustness of models in varying community contexts [19, 49]. Scalable models are essential to accommodate

	scalability of algorithms and data structures, parallel computing capabilities, optimization techniques, performance monitoring features, parameter tuning support, sensitivity analysis, and flexibility in adjusting model resolution and granularity to meet specific modelling objectives and computational constraints	diverse community sizes, ensuring applicability to both small and large communities and enabling adaptation to the size and complexity of the community being simulated.
Feedback Mechanisms and Monitoring	Evaluate the tool's ability to incorporate feedback loops for modelling the impact of adaptation measures over time and to support continuous monitoring and evaluation of strategies. This includes assessing its capability to model dynamic interactions and feedback processes, track and analyse outcomes, and provide features such as data logging, performance dashboards, visualisation tools, and support for scenario analysis to assess strategy robustness and resilience.	Feedback loops are central to understanding the long-term impacts of adaptation measures [52], as models without feedback mechanisms may overlook delayed or indirect effects. Additionally, continuous monitoring and evaluation are essential for adaptive management [53], emphasising the need for models to support the ongoing assessment of implemented strategies for community well-being.

### 3.1. AOR Simulation

AOR Simulation excels in modelling dynamic interactions within a community by representing interactive entities as agents with beliefs and perceptions. The tool supports learning and adaptation processes through an interactive simulation environment, enabling the replacement of agent simulators with real counterparts [54]. While AOR Simulation can integrate demographic factors and uses rules for high-level declarative behavior modelling [55], it lacks detailed documentation on participatory modelling, collaborative decision-making, and scenario planning. Information on integrating diverse data types and interacting with relevant data sources for CBA is not clearly provided. The documentation falls short in addressing scalability challenges for different community sizes, explicit mechanisms for assessing uncertainties and risks, and details on sensitivity analysis, scenario testing features, feedback loops, and monitoring and evaluating strategy effectiveness.

### 3.2. *Ascape*

Ascape demonstrates notable capabilities in modelling community dynamics and exhibits adaptability for different community sizes, rendering it a suitable choice for various scenarios. Its strength lies in its ability to adjust models to accommodate different community sizes, providing a versatile platform for simulating diverse contexts. However, a significant limitation of Ascape becomes apparent when considering its application in CBA modelling, particularly in the incorporation of socio-economic factors. While Ascape excels in easily integrating demographic factors into models, its functionality falls short when attempting to represent the intricate interplay of socioeconomic variables within the community dynamics. This limitation hinders the tool's capacity to comprehensively capture the socio-economic dimensions crucial for understanding and adapting to climate-induced challenges. Another noteworthy drawback of Ascape in the context of CBA modelling is its inability to facilitate participatory modelling. Participatory modelling involves active engagement with community members in the modelling process, ensuring that local knowledge and perspectives are incorporated. Ascape's lack of support for participatory modelling restricts its ability to benefit from the insights and experiences of the community, potentially leading to less accurate and relevant model outcomes. Handling diverse data types is a fundamental requirement for comprehensive CBA modelling, considering the multidimensional nature of environmental and socioeconomic challenges. Unfortunately, Ascape faces limitations in this aspect, lacking robust features for efficiently managing and integrating diverse data types relevant to CBA initiatives. This constraint can impede the tool's effectiveness in capturing the complexity of community environments and may compromise the accuracy of simulation outcomes. Moreover, Ascape's inadequacy extends to the absence of support for risk and uncertainty assessment, as well as feedback and monitoring mechanisms—essential components for robust CBA modelling. The ability to assess risks, account for uncertainties, and incorporate feedback loops is critical for understanding the dynamic nature of community responses to environmental changes. The absence of these features in Ascape diminishes its suitability for projects where a comprehensive evaluation of potential risks and the long-term impact of adaptation measures is imperative.

### 3.3. *Envision*

Envision excels in modelling dynamic community interactions, defining agents and their behaviours [56], crucial for understanding community dynamics in adaptation planning. The tool supports agent learning and adaptation, allowing modelling of adaptive strategies based on experiences or changing conditions. Envision integrates socio-economic variables, enabling economic impact modelling of adaptation strategies. It considers demographic factors through policies, guiding agent decision-making [57]. The tool handles diverse data types, including climate, geographical, and socio-economic data, enhancing model comprehensiveness and accuracy [57]. Envision is scalable for different community sizes, addressing challenges in both larger and smaller contexts. It assesses and models uncertainties and risks associated with adaptation strategies, supporting scenario testing and sensitivity analysis for stakeholder decision-making. The tool incorporates feedback loops to represent the long-term impact of adaptation measures, enabling monitoring and evaluation of strategy effectiveness over time [56]. In conclusion, Envision is a potent tool for community-based adaptation modelling, offering dynamic interaction modelling, learning processes, socio-economic integration, demographic considerations, data handling, scalability, risk assessment, sensitivity analysis, scenario testing, and feedback mechanisms. It serves as a versatile platform for integrated planning and environmental assessments in community-based adaptation.

### 3.4. *GAMA (2D/3D)*

GAMA excels in modelling dynamic interactions within communities, allowing users to define agents, behaviours, and interactions efficiently [58]. This capability is crucial for effective adaptation planning, as the tool supports learning and adaptation processes for community agents, enabling dynamic adjustments based on experiences or environmental changes [59]. The tool integrates socio-

economic variables into adaptation strategies by modelling agents with relevant attributes [60]. GAMA also considers demographic factors impacting vulnerability and resilience by allowing the modelling of agents with demographic characteristics. GAMA facilitates participatory modelling, involving community members in development and testing. The platform supports collaborative decision-making and scenario planning, fostering a cooperative approach. Additionally, GAMA handles diverse data types, including climate, geographical, and socio-economic data, and connects to databases and external tools like R [61]. 'R' refers to the R programming language used for statistical analysis and data handling. The tool offers flexibility in scaling models for different community sizes, addressing scalability challenges in both larger and smaller contexts [62]. While explicit mechanisms for assessing uncertainties and risks are limited, GAMA supports feedback loops, representing the impact of adaptation measures over time. GAMA allows monitoring and evaluating the effectiveness of implemented strategies, enabling users to assess outcomes and contribute to an iterative and adaptive modelling process [63]. In conclusion, GAMA is a powerful and comprehensive tool for community-based adaptation modelling, with strengths in dynamic interaction modelling, learning processes, socio-economic integration, demographic considerations, participatory modelling, collaborative decision-making, data handling, scalability, and feedback mechanisms.

### 3.5. JAS (*Java Agent-Based Simulation*)

JAS excels in modelling dynamic interactions, learning processes, and adaptability to socio-economic and demographic dimensions. It incorporates evolutive algorithms through its AI package, *jas.ai* [64], allowing community agents to adjust behaviours dynamically based on experiences [65]. The Java toolkit and diverse packages provide flexibility in incorporating socio-economic variables [64]. JAS supports various data types but lacks details on participatory modelling tools. It enables XML data I/O and SVG file formats, with integration for CSV, XML, and Excel, enriching simulations with real-world data. Scalability is a strength, but GIS features are absent, impacting spatial modelling. While JAS acknowledges scalability challenges, explicit mechanisms for assessing uncertainties and risks, sensitivity analysis, and monitoring effectiveness are limited in documentation. A comprehensive evaluation of JAS for CBA requires further exploration of collaborative features, data handling, scalability challenges, and mechanisms for assessing uncertainties and risks.

### 3.6. LSD (*2D/3D*) (*Laboratory for Simulation Development*)

LSD (*2D/3D*) (*Laboratory for Simulation Development*) LSD excels in modelling dynamic community interactions through its pure C++ API, granting modellers the freedom to implement various computational models. The tool focuses on equations, representing code snippets for updating model variables during simulations, enabling the modelling of adaptive agents [66]. It integrates socio-economic variables seamlessly, enhancing adaptability to diverse community scenarios. LSD accommodates demographic factors and a range of data types, offering versatility in model development. While supporting scalability for different community sizes and addressing scalability challenges, details on participatory modelling, collaborative decision-making, and scenario planning support are unclear. LSD enables sensitivity analysis and scenario testing but lacks explicit documentation on uncertainty assessment mechanisms. Although it allows for model error correction, information on feedback loops for long-term impact representation and monitoring and evaluating adaptation strategy effectiveness is scant. In summary, LSD is a robust platform for dynamic community-based modelling, particularly in economic and social science simulations. Its strengths include flexibility in handling diverse data, modelling dynamic interactions, and incorporating learning and adaptation processes. However, further documentation is needed for a comprehensive evaluation of its capabilities in participatory modelling, scalability challenges, risk assessment, and feedback loop integration for effective community-based adaptation modelling.

### 3.7. NetLogo

NetLogo excels in modelling dynamic interactions within a community, representing agent-based systems with adaptability and responsiveness [67]. It incorporates learning mechanisms for agents to adapt based on experiences, contributing to dynamic simulations [68]. NetLogo integrates socio-economic variables and demographic factors, allowing for a realistic portrayal of community dynamics [69, 70]. Participatory modelling is facilitated through NetLogo's HubNet, enabling community members to actively participate in model development and testing [71]. Collaborative decision-making and scenario planning are supported, fostering exploration of different scenarios [72]. NetLogo handles diverse data types and supports scalability for different community sizes [67, 73]. It addresses uncertainties and risks associated with adaptation strategies, offering flexibility for various community contexts [74]. Sensitivity analysis and scenario testing are facilitated through the NLRX package [75]. NetLogo incorporates feedback loops for modelling the impact of adaptation measures over time, allowing users to observe and influence future states. It supports monitoring and evaluating the effectiveness of strategies, enabling a comprehensive assessment of their performance [76]. In conclusion, NetLogo is a versatile and accessible tool for community-based adaptation modelling, offering dynamic interaction modelling, learning processes, socioeconomic integration, participatory modelling, scalability, uncertainty assessment, and comprehensive strategy evaluation across various domains, including social and natural sciences, teaching, and research.

### 3.8. Repast HPC

Repast HPC proficiently models dynamic community interactions, simulating urban dynamics by representing individuals as agents engaged in movement, social interactions, and resource utilisation [77]. It supports learning and adaptation processes, allowing agents to dynamically adjust behaviours for realistic simulations [78]. The tool integrates socio-economic variables influencing adaptation strategies, with specifics depending on the model's design and implementation within the Repast HPC framework [79]. Repast HPC considers demographic factors, allowing inclusion of agents with different characteristics for a more realistic representation of community dynamics. While not emphasising participatory modelling, Repast HPC excels in scalability and performance, especially for large-scale simulations. It lacks explicit support for collaborative decision-making but is well-suited for larger-scale and complex simulations due to its focus on high-performance computing [78]. Repast HPC efficiently handles diverse data types, including climate, geographical, and socio-economic data, incorporating spatial, temporal, network, and external data sources like CSV and Excel, depending on the model framework. It efficiently scales models for different community sizes, optimised for parallel computing to address scalability challenges in both larger and smaller community contexts. The tool includes mechanisms to assess and model uncertainties and risks associated with adaptation strategies. Although details on sensitivity analysis and scenario testing are limited, Repast HPC supports feedback loops to represent the impact of adaptation measures over time. Monitoring and evaluating implemented strategies are feasible, with the flexibility to integrate mechanisms as part of the simulation design.

### 3.9. SeSAM

SeSAM excels in dynamic community interactions, enabling intricate agent decision making and supporting learning and adaptation processes for agents [80]. It integrates socio-economic variables and demographic factors, enhancing realism in community-based adaptation scenarios. SeSAM's strength lies in its flexibility, allowing the incorporation of various socio-economic variables through plugins. It considers demographic factors, contributing to a more realistic representation of community dynamics. Despite limited documentation on participatory modelling, SeSAM stands out in handling diverse data types, enhancing scenario complexity and accuracy. Its compatibility with GIS-based data makes it adaptable to different community sizes, from small-scale to larger urban or regional contexts. SeSAM addresses scalability challenges in both larger and smaller community contexts, ensuring efficiency across simulation scales. However, explicit mechanisms for assessing

uncertainties, modelling risks, sensitivity analysis, scenario testing, feedback loops, and monitoring strategies are not clearly outlined. In summary, SeSAM is a powerful and user-friendly platform for agent-based modelling in social science domains. While documentation provides insights into modelling strengths, additional details on participatory modelling and uncertainty assessment would enhance its utility in community-based adaptation research.

### 3.10. *UrbanSim*

UrbanSim effectively models dynamic community interactions, simulating relationships among households, businesses, and developers in real estate markets [81]. It integrates socio-economic variables, including demographic factors, contributing to a comprehensive understanding of community dynamics. The platform supports collaborative decision-making and scenario planning, allowing users to compare scenarios and assess the impacts of policy or investment changes. UrbanSim handles diverse data types, including household, GIS, demographic, zoning, and traffic data, with the capability to integrate external sources for enhanced accuracy [82]. It is scalable, offering templates at different geographic levels and addressing challenges in modelling urban systems of varying scales. While details on uncertainty modelling and sensitivity analysis are limited, UrbanSim supports feedback loops for adjusting and representing the impact of adaptation measures over time, making it a promising tool for urban simulations and community-based adaptation modelling.

### 3.11. *TerraME*

TerraME proficiently models dynamic community interactions, enabling agents to move and adapt freely in complex spatially distributed systems [83, 84]. The platform integrates socio-economic variables and considers demographic factors as agent attributes, capturing nuanced community dynamics [83]. While excelling in social and natural process modelling, TerraME lacks explicit tools for participatory modelling. However, it supports scenario planning through parameter adjustments for exploring diverse scenarios. The tool accommodates various data types, provides installation flexibility, integrates with other platforms, and is tailored for GIS data use, allowing adjustments for different spatial scales. Acknowledging scalability challenges, TerraME offers options for adapting models to different community sizes. Despite limited detailed information on uncertainty assessment, risk modelling, sensitivity analysis, scenario testing, feedback loops, and monitoring effectiveness, further exploration and documentation in these areas could enhance TerraME's capabilities in handling complex and uncertain scenarios.

## 4. Discussion

In a thorough examination detailed in Table 6 and 7, NetLogo unequivocally emerges as the premier selection for illustrating CBA modelling and simulation, surpassing comprehensively across all seven predefined criteria. Envision, GAMA, Repast HPC and UrbanSim closely follow suit, fulfilling six out of the seven evaluation criteria. This proclamation finds resonance in the broader literature, where NetLogo consistently proves its mettle in facilitating nuanced simulations reflective of community dynamics amidst environmental and socio-economic shifts. The superiority of NetLogo in the realm of ABM is substantiated by academic discourse. A study by Railsback & Grimm [85] underscores the tool's robust capabilities in capturing dynamic community interactions and facilitating learning and adaptation processes, emphasising its appropriateness for modelling intricate community responses to multifaceted challenges. The simplicity of NetLogo's interface, coupled with its advanced features, aligns with principles advocated by Bonabeau [14], who emphasises the importance of simplicity in ABM tools for broader accessibility and usability. The pivotal role of NetLogo in seamlessly integrating socio-economic variables aligns with the work of Filatova et al. [8], emphasising the significance of incorporating socioeconomic factors into ABM for a more accurate representation of community responses. Most of the tools selected for evaluation fall short when incorporating participatory modelling. Only NetLogo and GAMA among all the selected

tools have this capacity. NetLogo's capacity to handle diverse data types aligns with the findings of Crooks et al. [86], who highlight the importance of tools that can integrate various data types, including climate, geographical, and socio-economic data. Using the NL4Py package, simulations in NetLogo can be executed via Python, addressing speed, scalability, and simplicity issues for NetLogo [87], emphasising the adaptability of ABM tools to different scales. In contrast to some tools lacking explicit features for risk assessment, sensitivity analysis, and feedback mechanisms, NetLogo's comprehensive support for these components resonates with arguments by Thuele et al. [88] and Yin et al. [89], advocating for the incorporation of these elements for robust and credible modelling outcomes.

**Table 6.** Assessment Results of Selected Tools (Part 1).

Criteria	AOR Simulation	Ascape	Envision	GAMA (2D/3D)	JAS	LSD (2D/3D)
Adaptability to Community Dynamics	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Integration of Socio-Economic Factors	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Participatory Modelling Support	FALSE	FALSE	False <sup>1</sup>	TRUE	False <sup>1</sup>	False <sup>1</sup>
Handling Diverse Data Types	False <sup>1</sup>	False <sup>1</sup>	TRUE	TRUE	TRUE	TRUE
Scalability to Different Community Size	False <sup>1</sup>	TRUE	TRUE	TRUE	TRUE	TRUE
Risk and Uncertainty Assessment	False <sup>1</sup>	False <sup>1</sup>	TRUE	False <sup>1</sup>	False <sup>1</sup>	False <sup>1</sup>

<sup>1</sup> Limited information available to support or reject the statement in model documents and existing literature

**Table 7.** Assessment Results of Selected Tools (Part 2).

Criteria	NetLogo (2D/3D)	Repast HPC	SeSAm	UrbanSim	TerraME
Adaptability to Community Dynamics	TRUE	TRUE	TRUE	TRUE	TRUE

Integration of Socio-Economic Factors	TRUE	TRUE	TRUE	TRUE	TRUE
Participatory Modelling Support	TRUE	False <sup>1</sup>	False <sup>1</sup>	TRUE	FALSE
Handling Diverse Data Types	TRUE	TRUE	TRUE	TRUE	TRUE
Scalability to Different Community Size	TRUE	TRUE	TRUE	TRUE	TRUE
Risk and Uncertainty Assessment	TRUE	TRUE	False <sup>1</sup>	False <sup>1</sup>	False <sup>1</sup>
Feedback Mechanisms and Monitoring	TRUE	TRUE	False <sup>1</sup>	TRUE	False <sup>1</sup>

<sup>1</sup> Limited information available to support or reject the statement in model documents and existing literature

The selected criteria for the tool assessment, though comprehensive, may be open to interpretation. A crucial consideration is how adjustments of different weightings, additional criteria or sub-criteria, or modified scoring systems could impact the ranking of tools. This study focuses on the evaluation of ABMs for CBA projects in a general context. The “uniform weighting” approach was applied to all criteria related to CBA; however, it is acknowledged that specific project requirements may warrant a different approach, with certain criteria gaining greater relevance over others. While the strengths of NetLogo and its ideal suitability to CBA are clear and substantial, it cannot be ruled out that alternative ABM tools might prove fitting in particular cases too. To date there is no universally defined and standardised set of criteria for the CBA approach across settings. Various guidelines, frameworks, and principles have been put forth by international organisations, non-governmental organisations (NGOs), and research institutions to guide CBA efforts. This study focused solely on common themes and criteria that play key roles in CBA initiatives. Criteria for CBA vary based on the specific context, the nature of climate-related challenges faced by a community, and the goals of the adaptation efforts. Organisations involved in climate change adaptation often tailor their criteria to the unique characteristics of the communities they are assisting. This tailoring may lead to a particular ABM tool being suitable for this specific case. Additionally, instances exist where new ABM tools are developed, or existing ones are modified to create models fully customised for specific agendas and set-ups. For instance, Sugarscape, developed in the late 1990s by Epstein and Axtell [90], is tailored to simulate economic and social phenomena. TRANSIMS (Transportation Analysis and Simulation System) is specifically designed for simulating urban transportation systems. Recently, Shahpari and Eversole [91] combined Repast HPC and GIS to create Crop GIS-ABM which used to examine the impact of milk market price on changes in land use in Tasmania, Australia. In conclusion, NetLogo’s standing as the quintessential ABM tool for CBA is not only supported by the detailed assessment but is well-grounded in the broader literature of related disciplines. Its unique combination of accessibility and participation options and robust ideally suited features positions it as the optimal choice for effective and inclusive community-based adaptation

modelling. The transparency of its code, active user community, real-time visualisation, educational value, and open source nature further reinforce NetLogo's status as the choice for CBA modelling, aligning with the principles of open access and collaboration emphasised by Chiacchio et al. [92] and Janssen [93]. While this study highlights the potential of agent-based modeling (ABM) tools for community-based adaptation (CBA) to climate change, several critical areas require further exploration to enhance their applicability. First, although participatory modeling is essential for ensuring community relevance and ownership of adaptation strategies, only NetLogo and GAMA explicitly support this feature. Incorporating more tools with participatory capabilities, such as interfaces for stakeholder engagement and collaborative decision-making, would strengthen the integration of community input into the modeling process. Second, uncertainty and risk assessment remain underdeveloped in many of the evaluated tools. Given the inherent uncertainties in climate adaptation, enhancing tools with mechanisms for sensitivity analysis, scenario testing, and probabilistic risk assessment would improve their robustness and decision-making utility. Integrating more comprehensive methods, such as Monte Carlo simulations or Bayesian approaches, could address this gap. Third, while the integration of socio-economic factors is crucial for capturing the complexity of community vulnerability and resilience, this feature varies significantly across platforms. Tools such as GAMA and NetLogo offer flexibility, but future advancements should focus on deepening the incorporation of demographic, social, and economic variables, particularly to better represent marginalized groups and localized adaptation challenges. Fourth, scalability poses a limitation, particularly in models designed for small communities that may struggle with larger datasets or more complex systems. Improving computational efficiency, through techniques like parallel processing and optimization algorithms, will be essential to ensure that these tools can support both small and large-scale adaptation projects. Finally, data integration is a critical issue. Many tools lack robust mechanisms for handling diverse data types, which are vital for accurate CBA modeling. Enhancing interoperability with real-time data sources, geographic information systems, and socio-economic databases will improve model precision and relevance, enabling more comprehensive simulations that reflect the multi-dimensional nature of community adaptation.

## 5. Conclusions

The assessment of agent-based modelling (ABM) tools for community-based adaptation to climate change (CBA) finds NetLogo as the ideal fitting and comprehensively capturing software environment. NetLogo excels in all 14 CBA criteria, showcasing its versatility in capturing community dynamics amidst environmental challenges. Supported by literature emphasising its accessibility, adaptability and extensive features, NetLogo proves ideal for inclusive CBA modelling. Its ability to facilitate participatory modelling, handle diverse data and incorporate risk assessment aligns with evolving CBA needs. Limitations in other tools, like missing CBA-specific features or limited information, are transparent in the assessment. GAMA and Envision closely follow NetLogo in meeting the required criteria. Recognizing the dynamic nature of CBA, organisations may customise or develop tools for unique project requirements. The study emphasises NetLogo's optimal status while highlighting the importance of aligning modelling choices with evolving community needs. As CBA gains prominence, adaptable and inclusive modelling tools will be key to fostering sustainable community-driven adaptation.

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## References

1. UN: Key Findings. Publisher: United Nations (2023). <https://www.un.org/en/climatechange/science/key-findings> Accessed 2023-12-16
2. IPCC: Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C Above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, 1st edn. Cambridge University Press, ??? (2022). <https://doi.org/10.1017/9781009157940> . <https://www.cambridge.org/core/product/identifier/9781009157940/type/book> Accessed 2023-12-03
3. Gasper, R., Blohm, A., Ruth, M.: Social and economic impacts of climate change on the urban environment. *Current Opinion in Environmental Sustainability* 3(3), 150–157 (2011) <https://doi.org/10.1016/j.cosust.2010.12.009> . Accessed 2023-12-21
4. Byrnes, R., Surminski, S.: Addressing the impacts of climate change through an effective Warsaw International Mechanism on Loss and Damage: Submission to the second review of the Warsaw International Mechanism on Loss and Damage under the UNFCCC. London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science (2019)
5. Adger, W.N., Arnell, N.W., Tompkins, E.L.: Successful adaptation to climate change across scales. *Global Environmental Change* 15(2), 77–86 (2005) <https://doi.org/10.1016/j.gloenvcha.2004.12.005> . Accessed 2023-12-03
6. Tanner, T., Lewis, D., Wrathall, D., Bronen, R., Cradock-Henry, N., Huq, S., Lawless, C., Nawrotzki, R., Prasad, V., Rahman, M.A., Alaniz, R., King, K., McNamara, K., Nadiruzzaman, M., Henly-Shepard, S., Thomalla, F.: Livelihood resilience in the face of climate change. *Nature Climate Change* 5(1), 23–26 (2015) <https://doi.org/10.1038/nclimate2431> . Accessed 2023-12-03
7. Mfitumukiza, D., Roy, A.S., Simane, B., Hammill, A., Rahman, M.F., Huq, S.: Scaling Local and Community-Based Adaptation. Technical report, Global Commission on Adaptation Background Paper, Rotterdam and Washington, DC (2020). <https://gca.org/reports/scaling-local-community-based-adaptation/> Accessed 2023-12-03
8. Filatova, T., Verburg, P.H., Parker, D.C., Stannard, C.A.: Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environmental Modelling & Software* 45, 1–7 (2013) <https://doi.org/10.1016/j.envsoft.2013.03.017> . Accessed 2023-11-28
9. Anderies, J.M., Janssen, M.A., Ostrom, E.: A Framework to Analyze the Robustness of Social-ecological Systems from an Institutional Perspective. *Ecology and Society* 9(1), 18 (2004) <https://doi.org/10.5751/ES-00610-090118> . Accessed 2023-12-03
10. Kirkby, P., Williams, C., Huq, S.: Community-based adaptation (CBA): adding conceptual clarity to the approach, and establishing its principles and challenges. *Climate and Development* 10(7), 577–589 (2018) <https://doi.org/10.1080/17565529.2017.1372265> . Publisher: Taylor & Francis eprint: <https://doi.org/10.1080/17565529.2017.1372265> Accessed 2023-11-11
11. Reid, H., Alam, M., Berger, R., Cannon, T., Huq, S., Milligan, A.: Communitybased adaptation to climate change: An overview. *Participatory Learning and Action* 60, 11–60 (2009)
12. UNFCCC: Best practices and available tools for the use of indigenous and traditional knowledge and practices for adaptation, and the application of gendersensitive approaches and tools for understanding and assessing impacts, vulnerability and adaptation to climate change. Technical paper. | UNFCCC. Technical report (2013). <https://unfccc.int/documents/7927#beg> Accessed 2023-12-18
13. Turgut, Y., Bozdog, C.E.: A framework proposal for machine learning-driven agent-based models through a case study analysis. *Simulation Modelling Practice and Theory* 123, 102707 (2023) <https://doi.org/10.1016/j.simpat.2022.102707> . Accessed 2023-12-03
14. Bonabeau, E.: Agent-based modelling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences* 99(suppl 3), 7280–7287 (2002) <https://doi.org/10.1073/pnas.082080899> . Accessed 2023-11-27
15. Berger, T., Troost, C.: Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. *Journal of Agricultural Economics* 65(2), 323–348 (2014) <https://doi.org/10.1111/1477-9552.12045> . eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/1477-9552.12045> Accessed 2023-11-11
16. Schreinemachers, P., Berger, T.: An agent-based simulation model of human–environment interactions in agricultural systems. *Environmental Modelling & Software* 26(7), 845–859 (2011) <https://doi.org/10.1016/j.envsoft.2011.02.004> . Accessed 2023-11-11
17. Thober, J., Schwarz, N., Hermans, K.: Agent-based modelling of environmentmigration linkages: a review. *Ecology and Society* 23(2) (2018). Publisher: Resilience Alliance Inc. Accessed 2023-11-11
18. Miller, B.W., Breckheimer, I., McCleary, A.L., Guzmán-Ramirez, L., Caplow, S.C., Jones-Smith, J.C., Walsh, S.J.: Using stylized agent-based models for population-environment research: A case study from the Galápagos Islands. *Population and environment* 75(4), 279–287 (2010) <https://doi.org/10.1007/s11111-010-0110-4> . Accessed 2023-11-11

19. Railsback, S.F., Lytinen, S.L., Jackson, S.K.: Agent-based Simulation Platforms: Review and Development Recommendations. *SIMULATION* **82**(9), 609–623 (2006) <https://doi.org/10.1177/0037549706073695> . Publisher: SAGE Publications Ltd STM. Accessed 2023-11-11
20. Gilbert, N.: Agent-Based Models. SAGE Publications, Inc., ??? (2008). <https://doi.org/10.4135/9781412983259> . <https://methods.sagepub.com/book/agent-based-models> Accessed 2023-11-11
21. Berryman, M.: Review of Software Platforms for Agent Based Models. Technical report (April 2008). Section: Technical Reports. <https://apps.dtic.mil/sti/citations/ADA485784> Accessed 2023-11-11
22. Nikolai, C., Madey, G.: Tools of the Trade: A Survey of Various Agent Based Modeling Platforms. Publisher: JASSS (2009). <https://jasss.soc.surrey.ac.uk/12/2/2.html> Accessed 2023-11-11
23. Allan, R.J.: Survey of Agent Based Modelling and Simulation Tools (2009)
24. Lytinen, S., Railsback, S.: The Evolution of Agent-based Simulation Platforms : A Review of NetLogo 5 . 0 and ReLogo. (2012). <https://www.semanticscholar.org/paper/The-Evolution-of-Agent-based-Simulation-Platforms-%3A-Lytinen-Railsback/db55d2926325c4b04f2b1071d1b4f40b95272b43> Accessed 2023-11-11
25. Kravari, K., Bassiliades, N.: A Survey of Agent Platforms. *Journal of Artificial Societies and Social Simulation* **18** (2015) <https://doi.org/10.18564/jasss.2661>
26. Abar, S., Theodoropoulos, G.K., Lemariner, P., O'Hare, G.M.P.: Agent Based Modelling and Simulation tools: A review of the state-of-art software. *Computer Science Review* **24**, 13–33 (2017) <https://doi.org/10.1016/j.cosrev.2017.03.001> . Accessed 2023-11-09
27. Raab, R., Lenger, K., Stickler, D., Granigg, W., Lichtenegger, K.: An Initial Comparison of Selected Agent-Based Simulation Tools in the Context of Industrial Health and Safety Management. In: Proceedings of the 2022 8th International Conference on Computer Technology Applications. ICCTA '22, pp. 106–112. Association for Computing Machinery, New York, NY, USA (2022). <https://doi.org/10.1145/3543712.3543745> . <https://dl.acm.org/doi/10.1145/3543712.3543745> Accessed 2023-11-08
28. Allen, P., Robinson, M., Butans, E., Varga, L.: Innovations for sustainable lifestyles: an agent-based model approach. *Sustainability Science* **14**(2), 341–354 (2019) <https://doi.org/10.1007/s11625-018-0593-y> . Accessed 2023-11-11
29. Gerst, M.D., Wang, P., Roventini, A., Fagiolo, G., Dosi, G., Howarth, R.B., Borsuk, M.E.: Agent-based modelling of climate policy: An introduction to the ENGAGE multi-level model framework. *Environmental Modelling & Software* **44**, 62–75 (2013) <https://doi.org/10.1016/j.envsoft.2012.09.002> . Accessed 2023-11-11
30. Carmen, E., Fazey, I., Ross, H., Bedinger, M., Smith, F.M., Prager, K., McClymont, K., Morrison, D.: Building community resilience in a context of climate change: The role of social capital. *Ambio* **51**(6), 1371–1387 (2022) <https://doi.org/10.1007/s13280-021-01678-9> . Accessed 2023-12-05
31. Troost, C., Calberto, G., Berger, T., Ingwersen, J., Priesack, E., Warrach-Sagi, K., Walter, T.: Agent-based modelling of agricultural adaptation to climate change in a mountainous area of Southwest Germany. *International Congress on Environmental Modelling and Software* (2012)
32. Angus, S., Parris, B.W., Mahmooei, B.H.: Climate change impacts and adaptation in Bangladesh: an agent-based approach. In: Proceedings of the 18th IMACS World Congress and MODSIM09 International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences, Proceedings, pp. 2720– 2726. Modelling and Simulation Society of Australia and New Zealand (MSSANZ), ??? (2009). <https://research.monash.edu/en/publications/climate-change-impacts-and-adaptation-in-bangladesh-an-agent-base> Accessed 2023-11-11
33. Bruch, E., Atwell, J.: Agent-Based Models in Empirical Social Research. *Sociological Methods & Research* **44**(2), 186–221 (2015) <https://doi.org/10.1177/0049124113506405> . Accessed 2023-12-05
34. Galvin, M.: Making community based adaptation a reality : different conceptualisations, different politics - CORE (2019). [https://core.ac.uk/display/286852745?utm\\_source=pdf&utm\\_medium=banner&utm\\_campaign=pdf-decoration-v1](https://core.ac.uk/display/286852745?utm_source=pdf&utm_medium=banner&utm_campaign=pdf-decoration-v1) Accessed 2023-12-05
35. Hunter, K.: Community-based adaptation to climate change: An exploration (2018). Publisher: University of Guelph. Accessed 2023-12-07
36. An, L., Grimm, V., Sullivan, A., Turner II, B.L., Malleson, N., Heppenstall, A., Vincenot, C., Robinson, D., Ye, X., Liu, J., Lindkvist, E., Tang, W.: Challenges, tasks, and opportunities in modelling agent-based complex systems. *Ecological Modelling* **457**, 109685 (2021) <https://doi.org/10.1016/j.ecolmodel.2021.109685> . Accessed 2023-12-07
37. Hailegiorgis, A., Crooks, A., Cioffi-Revilla, C.: An Agent-Based Model of Rural Households' Adaptation to Climate Change. *Journal of Artificial Societies and Social Simulation* **21**(4), 4 (2018)
38. Lawyer, C., An, L., Goharian, E.: A Review of Climate Adaptation Impacts and Strategies in Coastal Communities: From Agent-Based Modeling towards a System of Systems Approach. *Water* **15**(14), 2635 (2023) <https://doi.org/10.3390/w15142635> . Number: 14 Publisher: Multidisciplinary Digital Publishing Institute. Accessed 2023-11-11

39. Schipper, E.L.F. (ed.): Community-based Adaptation to Climate Change: Scaling It up ; [based on Discussions and Materials Presented at the Fifth International Conference on Community-based Adaptation (CBA) Held at Dhaka in 2011]. Routledge, London [u.,a.] (2014)
40. Joffre, O.M., Bosma, R.H., Ligtenberg, A., Tri, V.P.D., Ha, T.T.P., Bregt, A.K.: Combining participatory approaches and an agent-based model for better planning shrimp aquaculture. *Agricultural Systems* 141, 149–159 (2015) <https://doi.org/10.1016/j.agsy.2015.10.006> . Accessed 2023-12-07
41. Vermeer, W.H., Smith, J.D., Wilensky, U., Brown, C.H.: High-Fidelity AgentBased Modeling to Support Prevention Decision-Making: an Open Science Approach. *Prevention Science* 23(5), 832–843 (2022) <https://doi.org/10.1007/s11121-021-01319-3> . Accessed 2023-12-07
42. Thi Hong Phuong, L., Biesbroek, G.R., Wals, A.E.J.: The interplay between social learning and adaptive capacity in climate change adaptation: A systematic review. *NJAS: Wageningen Journal of Life Sciences* 82(1), 1–9 (2017) <https://doi.org/10.1016/j.njas.2017.05.001> . Accessed 2023-12-06
43. Pelling, M., High, C.: Understanding adaptation: What can social capital offer assessments of adaptive capacity? *Global Environmental Change* 15(4), 308–319 (2005) <https://doi.org/10.1016/j.gloenvcha.2005.02.001> . Accessed 2023-11-27
44. Adger, W.N., Brooks, N., Bentham, G., Agnew, M.D., Eriksen, S.H.: *New Indicators of Vulnerability and Adaptive Capacity*, (2004)
45. Gray, S., Voinov, A., Paolisso, M., Jordan, R., BenDor, T., Bommel, P., Glynn, P., Hedelin, B., Hubacek, K., Introne, J., Kolagani, N., Laursen, B., Prell, C., Schmitt Olabisi, L., Singer, A., Sterling, E., Zellner, M.: Purpose, processes, partnerships, and products: four Ps to advance participatory socio-environmental modelling. *Ecological Applications* 28(1), 46–61 (2018) <https://doi.org/10.1002/eap.1627> . Accessed 2023-11-27
47. Reed, M.S., Evely, A.C., Cundill, G., Fazey, I., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C., Raymond, C., Stringer, L.C.: What is Social Learning? *Ecology and Society* 15(4) (2010). Accessed 2023-11-27
48. An, L.: Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling* 229, 25–36 (2012) <https://doi.org/10.1016/j.ecolmodel.2011.07.010> . Accessed 2023-11-27
49. Biggs, R.O., Rhode, C., Archibald, S., Kunene, L.M., Mutanga, S.S., Nkuna, N., Ocholla, P.O., Phadima, L.J.: Strategies for managing complex social-ecological systems in the face of uncertainty: examples from South Africa and beyond. *Ecology and Society* 20(1) (2015). Publisher: Resilience Alliance Inc. Accessed 2023-11-28
50. Edmonds, B.: The Use of Models - Making MABS More Informative. In: Goos, G., Hartmanis, J., Van Leeuwen, J., Moss, S., Davidsson, P. (eds.) *Multi-Agent-Based Simulation* vol. 1979, pp. 15–32. Springer, Berlin, Heidelberg (2001). [https://doi.org/10.1007/3-540-44561-7\\_2](https://doi.org/10.1007/3-540-44561-7_2) . [http://link.springer.com/10.1007/3-540-44561-7\\_2](http://link.springer.com/10.1007/3-540-44561-7_2) Accessed 2023-11-27
51. Walker, B., Holling, C.S., Carpenter, S., Kinzig, A.: Resilience, Adaptability and Transformability in Social-ecological Systems. *Ecology and Society* 9(2) (2004) <https://doi.org/10.5751/ES-00650-090205> . Accessed 2023-11-27
52. Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P.: Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. *Annals of the Association of American Geographers* 93(2), 314–337 (2003) <https://doi.org/10.1111/1467-8306.9302004> . Accessed 2023-11-27
53. Voinov, A., Bousquet, F.: Modelling with stakeholders. *Environmental Modelling & Software* 25(11), 1268–1281 (2010) <https://doi.org/10.1016/j.envsoft.2010.03.007> . Accessed 2023-11-27
54. Holling, C.S.: *Adaptive Environmental Assessment and Management*. John Wiley & Sons, ??? (1978). <https://pure.iiasa.ac.at/id/eprint/823/> Accessed 2023-11-27
55. Wagner, G., Tulba, F.: Agent-Oriented Modeling and Agent-Based Simulation. In: Jeusfeld, M.A., Pastor, (eds.) *Conceptual Modeling for Novel Application Domains*. Lecture Notes in Computer Science, pp. 205–216. Springer, Berlin, Heidelberg (2003). [https://doi.org/10.1007/978-3-540-39597-3\\_20](https://doi.org/10.1007/978-3-540-39597-3_20)
56. Wagner, G., Diaconescu, M.: *AOR-Simulation.org: cognitive agent simulation*, Budapest, Hungary, pp. 1405–1406 (2009)
57. McKane, R.B., Brookes, A.F., Djang, K.S., Halama, J.J., Pettus, P.B., Barnhart, B.L., Russell, M., Vache, K.B., Bolte, J.P.: An Integrated Multi-Model Decision Support Framework for Evaluating Ecosystem-Based Management Options for Coupled Human-Natural Systems. In: O’Higgins, T.G., Lago, M., DeWitt, T.H. (eds.) *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity : Theory, Tools and Applications*, pp. 255–274. Springer, Cham (2020). [https://doi.org/10.1007/978-3-030-45843-0\\_13](https://doi.org/10.1007/978-3-030-45843-0_13) . [https://doi.org/10.1007/978-3-030-45843-0\\_13](https://doi.org/10.1007/978-3-030-45843-0_13) Accessed 2023-11-24
58. ENVISION. <http://envision.bioe.orst.edu/> Accessed 2023-11-13
59. GAMA: *GAMA Platform* (2023). <https://gama-platform.org/wiki/DefiningActionsAndBehaviors> Accessed 2023-11-24
60. Wallentin, G.: *Spatial Simulation*, (2018). <https://gwallentin.github.io/UNIGIS/spatsim/agent-based-models.html> Accessed 2023-11-24

61. Taillandier, P., Grignard, A., Marilleau, N., Philippon, D., Huynh, Q.-N., Gaudou, B., Drogoul, A.: Participatory Modeling and Simulation with the GAMA Platform. *Journal of Artificial Societies and Social Simulation* 22(2), 3 (2019)
62. GAMA: GAMA | GAMA Platform (2023). <https://gama-platform.org/wiki/Home> Accessed 2023-11-24
63. Grignard, A., Taillandier, P., Gaudou, B., Vo, D.A., Huynh Quang, N., Drogoul, A.: GAMA 1.6: Advancing the art of complex agent-based modelling and simulation. In: Springer (ed.) *Pacific Rim International Conference on Multi-Agents (PRIMA)*. Lecture Notes in Computer Science, vol. 8291, pp. 117–131. Boella, Guido and Elkind, Edith and Savarimuthu, Bastin Tony Roy and Dignum, Franck and Purvis, Martin K., Dunedin, New Zealand (2013). [https://doi.org/10.1007/978-3-642-44927-7\\_9](https://doi.org/10.1007/978-3-642-44927-7_9). <https://hal.science/hal-00932406> Accessed 2023-11-24
64. Huynh, Q.-N.: CoModels, engineering dynamic compositions of coupled models to support the simulation of complex systems. phdthesis, Université Pierre et Marie Curie - Paris VI (December 2016). <https://theses.hal.science/tel-01544874> Accessed 2023-11-24
65. JAS library. <https://jaslibrary.sourceforge.net/index.html> Accessed 2023-11-13
66. Sonnessa, M.: JAS: JAVA AGENT-BASED SIMULATION LIBRARY, AN OPEN FRAMEWORK FOR ALGORITHM-INTENSIVE SIMULATIONS. *Industry and Labor Dynamics* (2004). Accessed 2023-11-13
67. Manual, L.: LSD Quick Help. <https://www.labsimdev.org/download/Manual1/Manual/LSDquickhelp.html#init> Accessed 2023-11-24
68. Wilensky, U.: NetLogo 6.4.0 User Manual (2018). <https://ccl.northwestern.edu/netlogo/docs/> Accessed 2023-11-25
69. Sulis, E., Taveter, K.: Agent-Based Simulation with NetLogo. In: *AgentBased Business Process Simulation*, pp. 53–75. Springer, Cham (2022). [https://doi.org/10.1007/978-3-030-98816-6\\_4](https://doi.org/10.1007/978-3-030-98816-6_4). [https://link.springer.com/10.1007/978-3-030-98816-6\\_4](https://link.springer.com/10.1007/978-3-030-98816-6_4) Accessed 2023-11-25
70. Merino, M.V.: MULTI-AGENT SIMULATION OF CLIMATE CHANGE ADAPTATION: ARCHETYPES OF CLIMATE VULNERABILITY IN THE PERUVIAN ANDES. Desertation, Technische Universität Dresden, Dresden (September 2020)
71. Nabinejad, S.: Flood Risk Management in coastal areas: The application of Agent Based Modeling to include farmer-flood interaction. Desertation, der RheinischWestfälischen Technischen Hochschule Aachen, Aachen, Germany (December 2019)
72. Berryman, M.J., Angus, S.D.: Tutorials on Agent-based modelling with NetLogo and Network Analysis with Pajek. In: *World Scientific Review Volume*, (2009)
73. Veloso, M.: An agent-based simulation model for informed shared decision making in multiple sclerosis. *Multiple Sclerosis and Related Disorders* 2(4), 377–384 (2013) <https://doi.org/10.1016/j.msard.2013.04.001>. Accessed 2023-11-25
74. Crooks, A.T., Castle, C.J.E.: The Integration of Agent-Based Modelling and Geographical Information for Geospatial Simulation. In: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (eds.) *Agent-Based Models of Geographical Systems*, pp. 219–251. Springer, Dordrecht (2012). [https://doi.org/10.1007/978-90-481-8927-4\\_12](https://doi.org/10.1007/978-90-481-8927-4_12). [https://link.springer.com/10.1007/978-90-481-8927-4\\_12](https://link.springer.com/10.1007/978-90-481-8927-4_12) Accessed 2023-11-25
75. Tisue, S., Wilensky, U.: NetLogo: A simple environment for modelling complexity. In: *Proceedings of the International Conference on Complex Systems*, Boston (2004)
76. Salecker, J., Sciaini, M., Meyer, K.M., Wiegand, K.: The `nlr` package: A next-generation framework for reproducible NetLogo model analyses. *Methods in Ecology and Evolution* 10(11), 1854–1863 (2019) <https://doi.org/10.1111/2041-210X.13286>. Accessed 2023-11-25
77. Carbo, J., Sanchez-Pi, N., Molina, J.M.: Agent-based simulation with NetLogo to evaluate ambient intelligence scenarios. *Journal of Simulation* 12(1), 42–52 (2018) <https://doi.org/10.1057/jos.2016.10>. Publisher: Taylor & Francis eprint: <https://doi.org/10.1057/jos.2016.10>. Accessed 2023-11-25
78. Zia, K., Riener, A., Farrahi, K., Ferscha, A.: A New Opportunity to Urban Evacuation Analysis: Very Large Scale Simulations of Social Agent Systems in Repast HPC. In: *2012 ACM/IEEE/SCS 26th Workshop on Principles of Advanced and Distributed Simulation*, pp. 233–242. IEEE, Zhangjiajie, China (2012). <https://doi.org/10.1109/PADS.2012.4>. <http://ieeexplore.ieee.org/document/6305916/> Accessed 2023-11-25
79. Laboratory, A.N.: Repast HPC Tutorial (2022). [https://repast.github.io/hpc\\_tutorial/TOC.html](https://repast.github.io/hpc_tutorial/TOC.html) Accessed 2023-11-25
80. Laboratory, A.N.: Repast Suite Documentation (2022). <https://repast.github.io/docs.html> Accessed 2023-11-25
81. Klügl, F.: SeSAM – SeSAM Home (2022). <https://multiagentsimulation.com/sample-page> Accessed 2023-11-25
82. UrbanSim: UrbanSim – UrbanSim Cloud Platform 3.13.1 documentation (2023). <https://cloud.urbansim.com/docs/general/documentation/urbansim.html> Accessed 2023-11-25
83. UrbanSim: UrbanSim – urbansim 3.2 documentation (2020). <https://udst.github.io/urbansim/index.html> Accessed 2023-11-25

84. Andrade, P.R.D., Tiago, G.S.C., Camara, G.: Introduction (2017). <https://github.com/TerraME/terrame/wiki/Introduction> Accessed 2023-11-25
85. Carneiro, T.G.D.S., Andrade, P.R.D., Camara, G., Monteiro, A.M.V., Pereira, R.R.: An extensible toolbox for modelling nature–society interactions. *Environmental Modelling & Software* 46, 104–117 (2013) <https://doi.org/10.1016/j.envsoft.2013.03.002> . Accessed 2023-11-25
86. Railsback, S., Grimm, V.: *Agent-Based and Individual-Based Modeling: A Practical Introduction*, (2012). Journal Abbreviation: *Agent-Based and Individual-Based Modeling: A Practical Introduction* Publication Title: *Agent-Based and Individual-Based Modeling: A Practical Introduction*
87. Crooks, A., Castle, C., Batty, M.: Key challenges in agent-based modelling for geospatial simulation. *Computers, Environment and Urban Systems* 32(6), 417–430 (2008) <https://doi.org/10.1016/j.compenvurbsys.2008.09.004> . Accessed 2023-11-28
88. Gunaratne, C., Garibay, I.: NL4Py: Agent-based modelling in Python with parallelizable NetLogo workspaces. *SoftwareX* 16, 100801 (2021) <https://doi.org/10.1016/j.softx.2021.100801> . Accessed 2023-11-28
89. Thiele, J.C., Kurth, W., Grimm, V.: Facilitating Parameter Estimation and Sensitivity Analysis of Agent-Based Models: A Cookbook Using NetLogo and R. *Journal of Artificial Societies and Social Simulation* 17(3), 11 (2014)
90. Yin, X., Xu, X., Chen, X.: Risk mechanisms of large group emergency decisionmaking based on multi-agent simulation. *Natural Hazards* 103(1), 1009–1034 (2020) <https://doi.org/10.1007/s11069-020-04023-7> . Accessed 2023-11-28
91. Epstein, J.M., Axtell, R.: *Growing Artificial Societies: Social Science from the Bottom Up*. Complex adaptive systems. Brookings Institution Press, Washington, D.C (1996)
92. Shahpari, S., Eversole, R.: Planning to ‘Hear the Farmer’s Voice’: an Agent-Based Modelling Approach to Agricultural Land Use Planning. *Applied Spatial Analysis and Policy* (2023) <https://doi.org/10.1007/s12061-023-09538-7> . Accessed 2024-01-03
93. Chiacchio, F., Pennisi, M., Russo, G., Motta, S., Pappalardo, F.: AgentBased Modeling of the Immune System: NetLogo, a Promising Framework. *BioMed Research International* 2014, 907171 (2014) <https://doi.org/10.1155/2014/907171> . Publisher: Hindawi. Accessed 2023-11-28
94. Janssen, M. (ed.): *Complexity and Ecosystem Management: The Theory and Practice of Multi-Agent Systems*. Edward Elgar Publishing, ??? (2002). <https://doi.org/10.4337/9781781957240> . <https://www.elgaronline.com/view/book/9781781957240/9781781957240.xml> Accessed 2023-11-28

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