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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 led to the recognition of Community-Based Adaptation (CBA) as one of the remedies in building adaptive capacity and resilience of communities. It recognizes the resources and the skills as well as the agency of communities in shaping the optimal strategy. CBA interventions are vital in addressing community needs and contextual specificities, enable participatory and inclusive engagement and thereby facilitate more profound adaptation impacts. Agent-based modelling (ABM) harbors the potential to be the ideal tool to support developing of tailored adaptation strategies while considering capacities, resources, skills, priorities, needs and the cultural context of local communities. ABM allows to capture the complex relationships among various components within community decision making on CBA actions, the CBA actions themselves and the environment. There exist plenty of tools, however they provide for varying degrees of freedom in agent definition, sensitivity analysis, scalability, experiment design and output analysis to name a few. A set of required key criteria for CBA modelling is developed and all available ABM modelling and simulation tools are assessed for their suitability for CBA. NetLogo emerges as the most fitting tool for incorporating and handling the special features of CBA. It is closely followed by GAMA and Envision. The article provides insights and guidance to researchers and practitioners in selecting ABM tools aligned with the specific requirements of their CBA simulations and projects.

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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 this context, providing proactive strategies to minimise vulnerability and enhance resilience [5]. Recognizing communities as active agents in shaping their resilience, community-based adaptation to climate change (CBA) 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 specific CBA features as it allows for simulation of complex community-

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environment dynamics and offers insights into factors influencing adaptation decisions by the communities. This thorough and critical understanding supports identifying cost-effective and impactful interventions. Assessing ABM tools for CBA is vital, considering that ABM tools have varying degrees of freedom in their elements, features and capabilities [8]. Such evaluations guide researchers and practitioners to apply most suitable tools, 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 deep 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 grassroot 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 overview of these studies is compiled in table 1. These studies and publications provide valuable technical insights into ABM tools, their features, and the contexts in which they are most suitable. ABM looks 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 offers an assessment of ABM tools 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. In summary, the authors conclude that ABM could be suited to unravelling the intricate web of CBA. 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 assessing 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.

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.

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, Repast, Swarm, WISDOM-II	Comparative analysis for modelling complex adaptive systems in defense application
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

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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 Management using Conways`s Game of Life	NetLogo, GAMA, Repast	Suitability and performance assessment of ABM tools in Industrial Health and Safety Management

2. Assessment Methodology

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 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, 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:

AOR (Agent-Object-Relationship) Simulation is an ABM tool designed to model complex systems where agents interact not only with each other but also with objects in their environment. It employs a high-level, declarative modeling approach that allows for detailed specifications of agent behaviors, relationships, and interactions, making it particularly useful for social science applications.

Ascape is an open-source, Java-based ABM framework that provides a flexible and user-friendly environment for developing and running simulations. It comes with a variety of pre-built models and supports the creation of custom agent behaviors and interactions, making it popular in fields such as economics, social sciences, and ecology.

Envision: Envision is a C++-based ABM platform that focuses on modeling land-use and environmental planning scenarios. It integrates Geographic Information System (GIS) data to support complex decision-making processes, allowing users to simulate the impact of policy and environmental changes on agents like households, businesses, and governments.

GAMA (2D/3D) is a comprehensive, open-source ABM tool designed for creating and simulating complex spatial models. It supports both 2D and 3D visualizations and offers advanced capabilities for handling GIS data, parallel computing, and multi-level agent interactions. GAMA is widely utilized in environmental, urban, and socio-economic modeling.

JAS (Java Agent-Based Simulation) is a Java-based ABM framework that offers a flexible environment for modeling agent behaviors using various libraries and tools. It integrates evolutionary algorithms and other artificial intelligence techniques, making it suitable for simulating complex adaptive systems in both research and educational settings.

LSD (2D/3D) (Laboratory for Simulation Development) is an ABM framework focused on economic and social simulations. Developed in C++, it allows users to create highly customizable models by defining mathematical equations that govern agent behaviors. LSD excels in handling complex data sets and modeling adaptive behaviors, making it particularly valuable for economic and social science research.

NetLogo is a widely-used, user-friendly ABM platform known for its accessibility and versatility. It provides a simple environment for creating simulations of natural and social phenomena, with built-in support for both 2D and 3D visualizations. Due to its extensive library of models and strong community support, NetLogo is popular in education, research, and policy-making.

Repast HPC is the high-performance computing version of the Repast ABM toolkit, designed for running large-scale simulations on distributed computing systems. Written in C++, it supports complex agent interactions, parallel computing, and integration with other modeling frameworks, making it ideal for research in fields like economics, ecology, and social sciences.

SeSAM (Generic Simulation Environment for Agent-based Models) is an ABM tool that provides a visual modeling environment for designing, implementing, and running agent-based models. It emphasizes ease of use, enabling users to define agent behaviors and interactions through graphical interfaces without extensive programming knowledge. SeSAM is well-suited for modeling socio-economic and ecological systems.

UrbanSim is an ABM platform specifically tailored for urban planning and simulation of land use, transportation, and environmental impacts. It models the interactions between urban agents, such as households, businesses, and developers, to analyze policy interventions and their effects on urban development over time.

TerraME (Terrestrial Modeling Environment) is an ABM tool designed for modeling complex spatial and temporal dynamics of socio-environmental systems. It integrates GIS capabilities and supports multi-agent simulations, making it ideal for modeling land-use change, environmental management, and sustainability planning.

The tool GALATEA from the University of Andres in Venezuela with most of the documents and publications related to GALATEA in Spanish was hence removed from the list.

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

Tool	Source Code	Agent Type	Coding Language	Development Effort	Modelling Strength
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

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 Release DateCoding LanguageOperating SystemCommunity Support	Open source or proprietary?Latest version release date Programming languages supported Compatibility with various OSPresence and activity of user community
Modelling	Agent Definition Behaviour Specification Model Validation Sensitivity Analysis Scalability	Flexibility in defining agent attributes and behaviours Ease of specifying agent behaviours and interactions Tools for validating the model Capability for sensitivity analyses Handling large-scale simulations

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Simulation	Time Step Control	Control over simulation time steps
	VisualisationParallel ProcessingExperiment 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	Supported data input/output formats
	External Data Integration	Ability to incorporate external data sources
	Export Options	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

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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.

Table 5. CBA Criteria for ABM tools evaluation .

CBA Requirement	Assessment	Theoretical Justification
Adaptability to Community Dynamic	Assess tool's dynamic community interaction modelling and agent learning capabilities. Evaluate agent's integration of cognitive factors like updating strategies, household ingenuity, and proximity	Dynamic interactions play a crucial role in community-based systems, as highlighted in numerous studies [14]. Models that overlook these interactions may oversimplify community dynamics and miss critical

	effects. Check tool's support for memory updating, discarding outdated information, and enhancing adaptability in response to environmental changes..	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].
Integration of Socio-Economic Factors	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.	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.
Participatory Modelling Support	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, and visualisation tools that enable non-experts to contribute to model	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 for developing adaptive strategies [46], highlighting the need for models to

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	development and explore alternative adaptation strategies together.	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, scalability of algorithms and data structures, parallel computing	Addressing scalability challenges is crucial for ensuring the robustness of models in varying community contexts [19,49]. Scalable models are essential to accommodate diverse community sizes, ensuring applicability to both small and large

	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	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

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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

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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]. 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

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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. The adeptness of NetLogo in supporting participatory modelling, advocating for the active involvement of community members in the modelling process to enhance model credibility and relevance. 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

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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[1]	TRUE	False[1]	False[1]
Handling Diverse Data Types	False[1]	False[1]	TRUE	TRUE	TRUE	TRUE
Scalability to Different Community Size	False[1]	TRUE	TRUE	TRUE	TRUE	TRUE
Risk and Uncertainty Assessment	False[1]	False[1]	TRUE	False[1]	False[1]	False[1]

1 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

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Participatory Modelling Support	TRUE	False[1]	False[1]	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[1]	False[1]	False[1]
Feedback Mechanisms and Monitoring	TRUE	TRUE	False[1]	TRUE	False[1]

1 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].

5. Conclusions

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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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