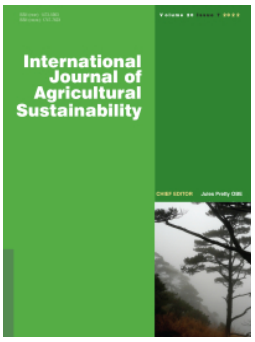

International Journal of Agricultural Sustainability

ISSN: 1473-5903 (Print) 1747-762X (Online) Journal homepage: www.tandfonline.com/journals/tags20

Approaches to participation and knowledge equity in agricultural climate impacts modelling: a systematic literature review

R. Sarku, S. Whitfield, S. Jennings & A. J. Challinor

To cite this article: R. Sarku, S. Whitfield, S. Jennings & A. J. Challinor (2025) Approaches to participation and knowledge equity in agricultural climate impacts modelling: a systematic literature review, International Journal of Agricultural Sustainability, 23:1, 2464509, DOI: 10.1080/14735903.2025.2464509

To link to this article: https://doi.org/10.1080/14735903.2025.2464509

INTERNATIONAL JOURNAL OF AGRICULTURAL SUSTAINABILITY
2025, VOL. 23, NO. 1, 2464509
https://doi.org/10.1080/14735903.2025.2464509

Approaches to participation and knowledge equity in agricultural climate impacts modelling: a systematic literature review

R. Sarku, S. Whitfield, S. Jennings and A. J. Challinor

School of Earth and Environment, University of Leeds, Leeds, UK

ABSTRACT

The importance of participation and co-development in the study of climate change impacts and adaptations, and in the production of climate services is widely acknowledged. There is a lot to be learnt from current attempts to achieve participatory modelling in climate impacts science. In this systematic review of climate impacts in agriculture research, we map out how participation is typically achieved, with whom and at what stages of the modelling process. We also look at the extent to which challenges and issues around inclusion and marginalisation are encountered and critically reflected on within this literature. We reflect on conventional and best practices and reveal areas in which there is currently insufficient attention given in order to encourage a more critical reflection on the design and implementation of participatory modelling. We argue that there is a current pre-occupation within participatory climate impacts modelling literature on instrumental reasons for including stakeholders and on technical barriers to this inclusion. Limited attention is currently paid to the potential transformative and emancipatory nature of participation in climate impacts modelling and there is a need for more critical reflection on the knowledge politics and power dynamics that act to limit equitable participation in such research.

ARTICLE HISTORY
Received 24 November 2023
Accepted 31 January 2025

KEYWORDS
Participatory modelling; stakeholders; climate risk; food security; food systems

1. Introduction

The importance of participation and co-development in the study of climate change impacts and adaptations, and in the production of climate services – that translate climate research into customized decision-making products – is widely acknowledged. The research and innovation roadmap set out by the European Commission's ad hoc Expert group on Climate Services', for example, highlights the need to prioritise co-design and co-delivery of climate services with users in order to: improve on the interpretation of climate information, better tailor this to decision-making, and build capacities of those that contribute (Street, 2016). Reed (2008) argues that participation and co-design can bring both pragmatic and normative benefits. Pragmatic claims focus on the quality and durability of decisions made through participatory process, pointing to the value of local and contextual knowledges in addressing knowledge gaps, the increased likelihood that local needs and priorities are met by research, and the potential for this to lead to more fully informed evidence-based decisions. Normative claims focus on benefits for democratic society, citizenship and equity and suggest, for example, that participation can contribute to increased public trust in science and empower stakeholders.

In the context of medium and long-term climatic change, in which impacts are associated with significant uncertainty, the participatory involvement of a variety of stakeholders can be vital for setting plausible parameters for alternative futures and interpreting the risks associated with them (Challinor et al., 2018). In recognition of this, we have seen over the past decade a proliferation of innovations in

CONTACT R. Sarku r.sarku@leeds.ac.uk

Supplemental data for this article can be accessed online https://doi.org/10.1080/14735903.2025.2464509.

participatory climate impacts modelling, which are collectively advancing the methods and approaches in this field. The Consultative Group on International Agricultural Research (CGIAR) has been one of the drivers of participatory research in agriculture (through pioneering methods in participatory breeding, for example). CGIAR is spearheading innovation in participatory modelling of climate impacts in agriculture and food systems through initiatives such as the ClimBeR programme, which is implementing a participatory integrated modelling approach to explore pathways of food system change (Jennings et al., 2022).

In this paper, we systematically review studies that have applied a participatory approach to modelling climate impacts in agriculture in order to address our overarching research question: what are the approaches for and barriers to improving participation in climate impacts modelling? In doing so, we seek to identify: (1) the methods and approaches that are currently employed for engaging stakeholders in climate impacts modelling research; (2) what challenges and issues around inclusion and marginalisation are encountered and critically reflected on within this literature; and (3) gaps in current practice for supporting inclusivity and the transformative potential of participation in climate impacts modelling.

There is a long history of critical literature on participatory research and governance (Brock & Mcgee, 2002; Cooke & Kothari, 2001), which highlights the potential for participation to be a purely instrumental exercise and one that inadvertently privileges certain knowledges over others, or in which the process and benefits are captured by powerful elites. Some of this critique has been centred on CGIAR research itself in recognition of the western donor-driven nature of agricultural research for development agendas and the instrumental way in which participation is used to legitimise these agendas (Sumberg & Thompson, 2012). The potential for power dynamics to influence whose voices and knowledge are heard, and whose are not, is an important consideration in participatory modelling exercises. Because of the complex, resource-intensive and technical nature of climate impacts science, modelling can be characterized a 'black-box' exercise in which the assumptions and uncertainties that underpin models become difficult to trace even for those that are directly contributing to this techno-scientific field (Whitfield, 2013). Coupled Model Intercomparison Project (CMIP) and efforts to synthesise across climate impacts literature (such as through the IPCC) have helped with creating conventions for highlighting and transparently communicating model uncertainty, but this remains difficult to navigate for those less directly involved in conventional climate science. Given this complexity, there is a danger that the scope to challenge or fundamentally shape the knowledge-generating process within this black box is limited, and participation becomes relegated to the margins of the process (i.e. it is about validating or passively receiving information). As Latulippe and Klenk (2020) and Vukomanovic et al. (2019) point out, in some examples of participatory climate modelling, stakeholders merely provide data to feed into and support technical modelling efforts.

As is often the case in participatory climate research, this dynamic in which local and lay knowledges are secondary to scientific-technical modelling outputs, might be particularly exacerbated and problematic in cases in which this technical modelling knowledge is rooted in institutions in the Global North, and the 'participants' in the modelling process are in the Global South. We therefore need to be cognisant of multiple and reinforcing levels of power dynamics (characterized by expert/lay; technical/tacit knowledge, and Global North/South binaries) within participatory modelling research.

There is a lot to be learnt from current attempts to achieve participatory modelling in climate impacts science. In this systematic review, we focus specifically on climate impacts in the context of agriculture and food systems, both from within and beyond the CGIAR. We map out, within existing efforts, how participation is achieved, with whom and at what stages of the modelling process. We also look at the extent to which challenges and issues around inclusion and marginalisation are encountered and critically reflected on within this literature. We do so with the intention of not only sharing best practice and learning from that, but also revealing areas in which there is currently insufficient attention given and encouraging a more critical reflection within the design and implementation of participatory modelling.

This systematic review is guided by a framework that brings together critical work on power and typologies of participation (White, 1996) and a participatory modelling process framework (outlined by Voinov et al., 2016). This combined framework is illustrated in Table 1, which briefly describes what different forms of participation (based on White (1996)) might look at different stages of participatory

Table 1. Analytical framework for participatory modelling based on White (1996) and Voinov et al. (2016).

		Forms of participation (based on White, 1996)			
		Nominal	Instrumental	Representative	Transformative
Stages of participatory modelling (based on Voinov et al., 2016)	1. Conception of research	e.g. Participants (possibly unrepresentative sample) informed about the research objectives.	e.g. Data about/from participants used to justify the research objectives.	e.g. Research objectives developed in workshop led by researchers but with participant representation.	e.g. Research objectives (associated with reducing inequality) proposed by participants.
	2. Construction, calibration, and verification of models	e.g. Pre-existing household survey data used to calibrate or verify models.	e.g. Participants asked for specific data to calibrate models.	e.g. Choice and verification of models is iterative and takes place through working groups.	e.g. Models are conceptualized by participants and modelling tools built around these conceptual models.
	3. Parameterisation of scenarios or pathways	e.g. Pre-determined scenarios are presented to stakeholders (possibly unrepresentative sample).	e.g. Participants are consulted on their opinions about the plausible parameters of a scenario (e.g. likely extent of land use change by 2050).	e.g. Scenarios are established through a participatory workshop that entails brainstorming and prioritising critical uncertainties in future systems.	e.g. Desirable futures are articulated by participants and modelling approaches structured around pathways to these futures.
	4. Determining appropriate complexity/ uncertainty in models	e.g. Participants (possibly unrepresentative sample) are informed about the uncertainty in model output and the scales and resolutions that existing models can achieve.	e.g. Participants are consulted on a range of options about potential temporal and spatial scales and resolutions for analysis.	e.g. A two-directional and iterative process with participants of matching modelling capabilities with articulated knowledge gaps and evidence needs.	e.g. Participants lead a process of explaining their decision-making processes and contexts and work back from that with modellers to determine evidence needs and appropriate scales and levels of certainty.
	5. Interpretation of data and implications of model outputs	e.g. Participants (possibly unrepresentative sample) review and verify model outputs,	e.g. Participants review, edit, refine and add qualifying detail to model outputs.	e.g. Model outputs are presented and implications statements from these are prepared in a forum with participants.	e.g. Participants own the model output data and are supported in continuing to use this in ways in which they choose.
	6. Communication and dissemination	e.g. Participants (possibly unrepresentative sample) review and verify communications outputs.	e.g. Participants help to identify audiences and channels for communication and are used as a means for disseminating.	e.g. Participants co-produce research outputs and knowledge products with researchers.	e.g. Participants have autonomy to share and use the data as they wish.
	7. Training and capacity building	e.g. Participants (possibly unrepresentative sample) attend training aimed at the understanding model outputs.	e.g. Participants are involved in capacity building that supports engagement in modelling.	e.g. Participants co-design a training programme associated with models.	e.g. Participants co-design a training programme orienting towards enabling them to generate further evidence.

modelling (based on Voinov et al., 2016) and this framework is further elaborated on below.

A number of typologies, underpinned by normative judgements about what 'good' or 'bad' participation looks like, are widely used and referenced in conceptual and methodological literature (e.g. Arnstein, 1969; Pretty, 1995; White, 1996). These share similar sentiments in distinguishing the extent to which influence and agenda setting lies with the participants themselves as opposed to processes in which participation may simply be a form of placating or informing stakeholders. However, the envisioned utopia for participation in these typologies differs. For example, we might compare Arnstein's vision for participation as one of citizen control and power, with Pretty's more individualistic focus on self-mobilization and autonomy. Such typologies can be a useful tool for identifying where different ideas about the purpose of participation might exist, even amongst and between those involved in the same initiative (Cornwall, 2008). White (1996) distinguishes between: 1. Nominal participation, which may be used to give legitimacy to pre-determined development plans or evidence bases; 2. Instrumental participation, which aims to access and use the specific skills and knowledge of participants to improve outcomes and further a particular agenda; 3. Representative participation, which aims to give participants a voice in the decision-making and research, and 4. Transformative participation, which results in the empowerment of those involved and ultimately alters the structures and institutions that lead to marginalisation and exclusion. Cornwall (2008) points out that these categories of participants may be less distinct in reality, not least because the expectations and objectives of those participating may be different from those who are initiating a participatory process.

Following Voinov et al. (2016), we explore seven stages in participatory modelling and use this as a framework particularly for thinking about where in the modelling process participation happens and how participation might look different at different stages. Firstly, the initial conception of research might involve scoping, selecting stakeholders, choosing modelling tools, and defining project goals. Stakeholders actively participate in choosing the research model, and formulating project goals. Secondly, the provision of data for calibrating/verifying models to ensure accuracy, reliability, and effectiveness of models might involve activities such as data collection, pre-processing, model calibration, verification, and iteration with stakeholders. Thirdly, the parameterisation of scenarios or pathways in modelling involves outlining potential drivers of change that will act as model inputs as well as making decisions about output variables, time horizons and temporal and spatial scales of analysis. Fourthly, discerning appropriate complexity/uncertainty in models, which may involve iterative experimentation, gradually adjusting the model's complexity, and evaluating its performance against various metrics and validation techniques such as Bayesian inference, Monte Carlo simulations, sensitivity analyses, and robust optimization. Fifthly, interpreting data and implications of model outputs as well as technical measures of model performance. Sixthly, communication and dissemination of results based on the previous interpretation step, this might involve the identification of audiences and the tailoring of messages to specific audiences or for specific purposes, through reports, presentations, visualizations, interactive tools and other media. Finally, training and capacity building is a phase, not necessarily sequential with the other six phases, but through which stakeholders are educated and empowered to effectively use model tools and outcomes. For the purpose of this review, we conceive of potential participants in climate impacts modelling broadly and inclusive of policy and decision-makers; local experts and advocacy groups; and individuals and communities. Although we recognise that different modelling initiatives will conceive and categorize participants according to different terminology, as we discuss further below.

2. Methodology

We take a systematic review approach to collating and analysing existing literature, following the PRISMA protocol for systematic reviews (Moher et al., 2009).

2.1. Data collection

To identify eligible studies, we conducted a search in Scopus and Web of Science, the two largest electronic scientific databases for the social sciences (Falagas et al., 2008). We selected keyword, title and abstract information as sources for electronic searching. The literature on participatory modelling of climate change impacts on agricultural systems includes studies at a wide range of spatial and temporal scales and of different scopes, inclusive of purely agricultural systems, but also of wider landscape or food system impacts. We chose search terms and screening criteria that would allow for this full breadth of work to be captured. The initial search string applied to select documents was: '*model* AND climate AND agriculture AND (participat* OR co-design OR collaborat* OR consultat*)*'. The Boolean search of literature from Scopus and Web of Science revealed a total of 4262 for full review. Only English papers were considered for language proficiency reasons.

2.2. Eligibility criteria and exclusion of studies

We assessed the abstracts of 4262 papers on the basis of the following criteria or **search filter:**

By abstract:

(1) Does the paper model a **climate impact** or adaptation to climate **in agriculture**?
(2) Does the paper describe an example or method of participatory modelling?

If yes, proceed to assess the following questions evaluating the methods used:

(1) Does the paper model a **climate impact** or adaptation to climate **in agriculture**?
(2) Does the paper describe an example or method of participatory modelling?
(3) Does the paper explain WHO participates in the modelling process and HOW they participate?

The exclusion criteria is not applied here as a judgement on the quality of the participatory process described within the papers, given that our intention is to capture the full breadth of ways in which participatory modelling is self-defined within literature. However, we do require that the claim to be conducting participatory modelling is qualified within the papers through a clear and explicit description of the method used and of who participates and how. As such, these final two evaluation questions serve as a quality assurance for mechanism, by testing the quality of the methodological detail in the papers that were screened.

To determine the level of screening precision a co-author conducted a verification search on every tenth result from an electronic data base (i.e. sampled 10% of the literature) and estimated the amount of falsely excluded studies by screening the abstracts. The exclusion criteria resulted in 1% of falsely excluded studies, which we found to be an acceptable percentage. We downloaded papers that scored yes to all 5 questions, thereby excluding 3875 studies that did not focus on a combination of the above 5 key questions and also deleted duplicate documents.

We screened the full text of the 387 selected studies again on the basis of the focus on participatory modelling and climate impacts on agricultural systems. In this round, we excluded 301 studies. We also selected on the basis of study design (only empirical papers) that used primary data were included. This resulted in a list of 94 studies suitable for full-text reading and analysis (Figure 1). We conducted a full-text exploration on the selection of 94 studies to select the required papers.

Because participatory climate impact modelling is a field of research that has developed within the past two decades, it was not necessary to use publication dates as exclusion criteria. The earliest paper that met the eligibility criteria was published in 2005.

2.3. Data Synthesis and Analysis

The analytical framework outlined above was used as a basis for categorizing the methodological approaches taken in each of the reviewed papers. We deployed an interpretive approach to organise the themes identified in the studies. We conducted a thematic analysis of the evidence to identify prominent or recurring (sub)themes following our analytical framework (Table 1). We inductively coded for the 'how' and 'who' aspects of engagement within the papers, eventually categorizing these on the basis of the most commonly used key words for participants and research methods. During the coding of documents, we deleted 8 documents due to the fact that the method applied focused mainly on secondary data derived from third-party organisations with limited empirical focus. Hence, we analysed 84 papers for the study. To safeguard the quality of our analysis, we discussed interpretations of categories and (sub)themes among co-authors, ascribing participation types (i.e. nominal, instrumental, representation and transformational) to the methods detailed in each paper was done on the basis of judgement, by comparing content with example descriptors, as illustrated in Table 1.

3. Results

3.1. Motivations for participatory modelling

Thirty-one of the reviewed studies explicitly articulated why a participatory approach was taken to modelling, and these revealed a relatively narrow range of motivations that were largely instrumental in nature. In particular, contextualized, local knowledge was viewed as valuable for improving the parameterisation and framing of modelled futures, and participation seen as bringing about improved uptake and use of model outputs, in some cases playing an explicit role in the development of down-the-line decision support tools or communication products.

In several studies (26% of those reviewed), stakeholder engagement focused on the articulation of

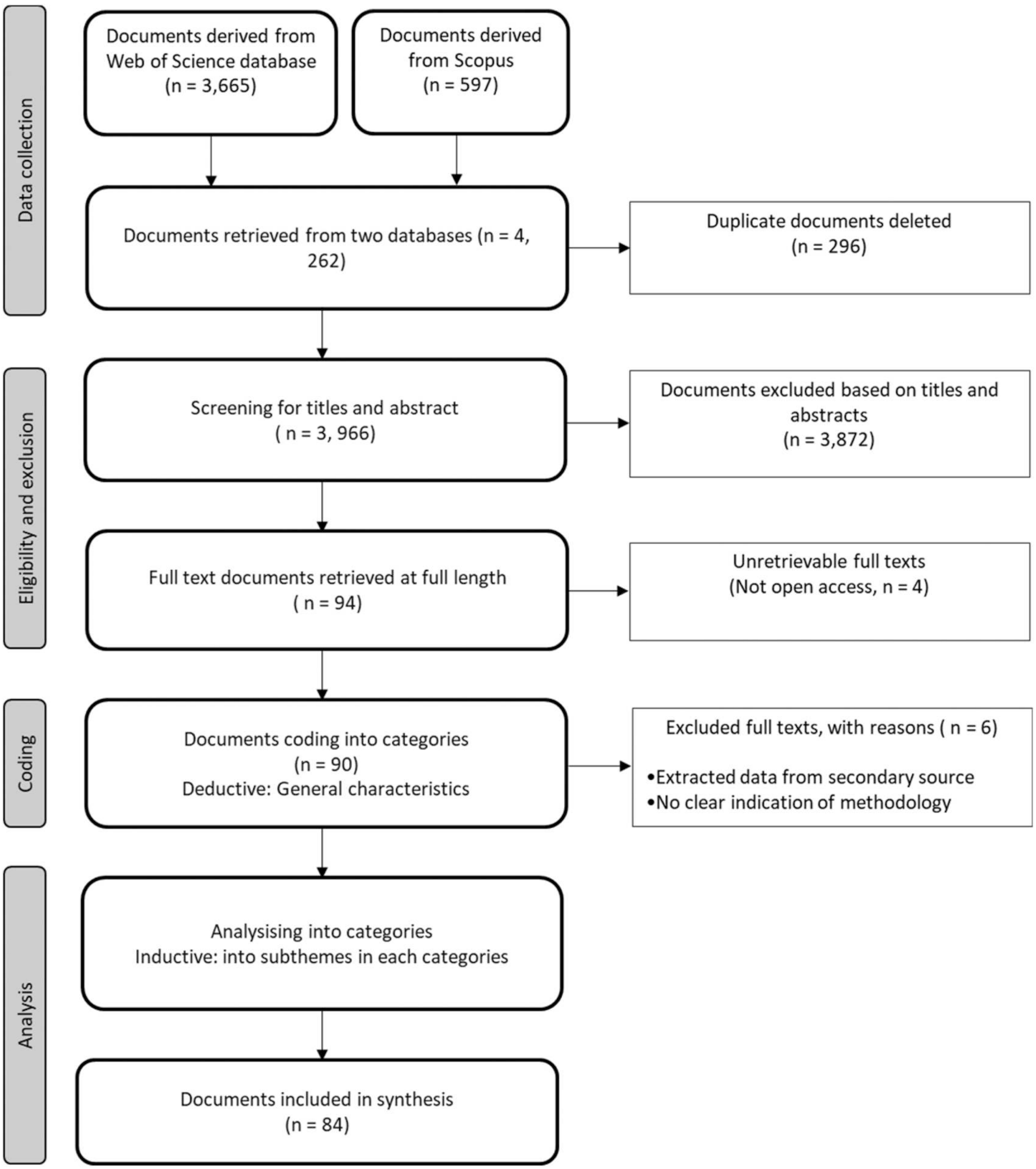

Figure 1. Flow diagram representing systematic approach used for data collection and analysis.

future pathways or scenarios of agricultural change, to be subsequently explored through modelling approaches. The iFEED approach, described by Jennings et al. (2022), begins with a participatory scenarios workshop in which critical uncertainties that are expected to shape agricultural and food system futures are collectively outlined. In other cases, participation focused on better understanding existing adaptation strategies or drivers of vulnerability that might in turn help with interpreting the implications of modelled pathways of change. Li and Ford (2019) involved stakeholders in identifying and categorizing the drivers of vulnerability to climate change of a community of swidden forest farmers in Panama and Bezner Kerr et al. (2019) used stakeholder experiences of practicing agroecology to contribute to an exploration of the cultural and social equity implications of agricultural change in Malawi.

Participation is also commonly seen as instrumental in improving the uptake and usability of climate impact evidence, and 55% of reviewed studies refer to the role of stakeholders in developing tailored decision support tools, advisories and communication products. Gonçalves et al. (2022) adopted an approach that integrated scientific and local stakeholder knowledge into designing a support tool for climate change adaptation decision-making in northern Portugal. Similarly, Cabrera et al. (2008) and Alexander and Block (2022) applied agent-based modelling to integrate forecast information into local-level decision-making for smallholder farming communities.

In many cases, affecting and informing decision-making and behaviours, either at a local and individual level or at a policy level were key to the underlying motive of taking a participatory approach. There is a clear recognition, across studies that participation in understanding local systems goes hand-in-hand with the development of appropriate and tailored outputs and communications. A number of studies (15%) sought to maintain stakeholder participation across the initial input and end-use aspects of research (Egerer et al., 2021; Ho, 2022; Jennings et al., 2022; Laureta et al., 2021; Natalini et al., 2019; Olabisi et al., 2018; Olabisi et al., 2021; Salvini et al., 2016; Stigter et al., 2017).

Less evident in the explicit motivations of the reviewed studies were having input into the initial problem framing or objectives of the research itself, although depending on the approach taken this may be an implicit or even explicit component of a scenarios exercise (e.g. Jennings et al., 2022). Similarly, there is limited evidence of participation in more technical aspects of knowledge creation, modelling and validation. It is also striking that in no cases were more normative or ontological priorities, such as education, empowerment or reflecting under-represented or marginalized worldviews, evident in the rationales of studies of participatory modelling of climate impacts on agriculture.

3.2. Stages of participatory modelling

Participation of stakeholders in the studies took place at various points, across the seven stages of modelling that we derive from Voinov et al. (2016). Although most studies mentioned iterative/cyclical processes in involving stakeholders, the implementation often reflects a more one-direction and linear process (Delmotte et al., 2017; Gonçalves et al., 2022; Henly-Shepard et al., 2015; Mason-D'Croz et al., 2016; Naulleau, Gary, Prévot, Berteloot, et al., 2022; Selbonne et al., 2022). For example, Egerer et al. (2021) mentioned that: 'Our framework consists of the following stages: problem formulation, system conceptualization, model formulation, analysis of model behaviour, policy analysis, and model use' Jagustović et al. (2021) also mentioned in their study that:

> The iterative modelling process implemented in this paper has four steps: (i) identification of system drivers and processes, (ii) qualitative modelling of the causal processes operating in the system, leading to a basic model structure, (iii) development of stock-and-flow diagrams (SFD) and a simulation model, and (iv) model validation and simulation to analyse the dynamics of the entire food system.

We also observed that when the term 'iterative' is used, it was often referring to the back-and-forth engagement of stakeholders at a particular stage of the participatory modelling process, rather than cyclical overall approach to modelling, in which the conceptualisation or construction and calibration of models are revisited on the basis of initial model outputs.

Participation can vary significantly across specific research projects, with some stages exhibiting active engagement (representative participation) while others show a more passive involvement (nominal participation) (Table 2). For example, we identified five studies where representative participation was actively applied during the research's conceptualization phase. In contrast, during the interpretation of data and drawing implications from model outputs, we found 14 studies demonstrating representative participation. Notably, at the research's conception stage, overall participation levels were relatively low, particularly concerning instrumental and representative purposes. In contrast, nominal participation, which often involved informing participants (potentially an unrepresentative sample) about the research objectives, was more prevalent.

3.2.1. Conception of research

In 35% of the studies, stakeholders were provided an opportunity to express their opinion and also ask questions which were incorporated into the research design or even resulted in changes in the initial research strategy and outline. In Gonçalves et al.'s (2022) study, a multidisciplinary team was constituted as an initial step, leading to the

Table 2. Number of studies displaying nominal, instrumental, representative and transformative participation at each stage of the participatory modelling process.

		Forms of participation (based on White, 1996)				
		Little evidence of participation	Nominal	Instrumental	Representative	Transformative
Stages of participatory modelling (based on Voinov et al., 2016)	1. Conception of research	$n = 48$	$n = 23$	$n = 8$	$n = 5$	$n = 0$
	2. Construction, calibration and verification of models	$n = 0$	$n = 16$	$n = 58$	$n = 10$	$n = 0$
	3. Parameterisation of scenarios or pathways	$n = 44$	$n = 16$	$n = 13$	$n = 11$	$n = 0$
	4. Determining appropriate complexity/uncertainty in models	$n = 49$	$n = 14$	$n = 9$	$n = 12$	$n = 0$
	5. Interpretation of data and implications of model outputs	$n = 48$	$n = 12$	$n = 10$	$n = 14$	$n = 0$
	6. Communication and dissemination	$n = 68$	$n = 13$	$n = 0$	$n = 3$	$n = 0$
	7. Training and capacity building	$n = 80$	$n = 1$	$n = 3$	$n = 0$	$n = 0$

Total $n = 84$. Darker shades of blue indicate a high proportion of studies including that form of participation.

organisation of initial meetings with the scientific team and stakeholders to map stakeholder interests and defined the methodologies, objectives, and intended outcomes of the work. Other studies mentioned the involvement of stakeholders early in the process (Conde et al., 2006; de Jalón et al., 2014; Naulleau, Gary, Prévot, Vinatier, et al., 2022; Palosuo et al., 2021; Ruiz-Agudelo et al., 2015).

After introducing research objectives to stakeholders during data collection, Rodriguez et al. (2014) described how stakeholders asked questions with a request for knowledge on the implications of the modelling outcomes for their livelihoods which were relevant for the data collection and modelling process.

> … .. farmers wanted to know the implications of adjusting his cropping intensity, in terms of trade-offs between profits, and business risk, in face of present climate variability and expected changes in climate … This farmer was interested in determining the optimum cropping intensity in terms of trade-offs between profits and risks, for climatology and expected changes in climate. (Rodriguez et al., 2014)

Across several studies (29% of those reviewed), meetings with stakeholders served as a means to construct and evaluate research problems (see, Bharwani et al., 2005; Bhave et al., 2013; Conde et al., 2006; Dockerty et al., 2006; Henly-Shepard et al., 2015; Ho, 2022; Naulleau, Gary, Prévot, Vinatier, et al., 2022; Zimmerer et al., 2020). Mitter et al. (2014) organized a peer group workshop aimed at specifying perceived challenges in their case study region and suggested that '*In th[is] first step, the problem was defined*' (Mitter et al., 2014).

More commonly, however, such initial engagements served more of a sensitization role, raising awareness and seeking validation of pre-determined problem framings and research objectives, rather than these being co-developed, and in the case of the study by Andersson et al. (2013) such consultations were, in part, about managing stakeholder expectations:

> Although project objectives had been defined when the application was written, activities within the project had to be shaped according to participants' interests and needs in order to ensure stakeholder engagement. An initial open dialogue of project objectives was perceived as important in order to ensure transparency of what to expect in order to build confidence and avoid future disappointment. (Andersson et al., 2013)

3.2.2. Constructing, calibrating and verifying models

Construction, calibration and verification of models in the reviewed studies involved varied participatory and iterative processes that differently integrated local knowledge, expert insights, and empirical data. Various types of data were collected, through interviews and workshops, with 38% of studies relying on secondary household survey data. Typically, studies aimed to construct conceptual or qualitative models based on stakeholder input to inform the building of numerical models around this (Gahi et al., 2015; Jagustović et al., 2021; Palosuo et al., 2021; Rodriguez et al., 2014; Selbonne et al., 2022).

> Using the information about directionality and causality of changes discussed by interviewees, the researchers constructed diagrams that illustrated the linkages between different items of change. … causal-loop diagrams were then compiled from these diagrams, indicating the influences of different items of change on one another. Important current and future stresses and vulnerabilities in the community were identified through causal-loop analysis through the integration of field data and projections on the impacts of climate change in the area. (Li & Ford, 2019)

> Local land use decisions were explored using participatory rural appraisal (PRA). We further conducted interviews in 56 households during a four-week fieldwork period in March 2013. The interviews provided sufficient information for an initial characterisation of the study site and farmers. Various categories of farmers (the "agents" in our ABM) were identified, based on assets, knowledge and risk aversion. This information was used to build a conceptual model reflecting the local context, and subsequently fed into the role-playing game and ABM. (Salvini et al., 2016)

In other cases, socio-economic data or participatory input was used to calibrate specific model variables, and researchers undertook exercises with the participants to confirm or co-develop indicators which were subsequently used for modelling (de Jalón et al., 2014; Gonçalves et al., 2022; Mitter et al., 2014; Olabisi et al., 2021).

> For this study fifteen participating farmers provided technical coefficients for the model such as input quantities and costs, market prices for different crops and labour requirements for different season types ('deficient', 'below normal', 'normal', 'above normal' and 'excess'). (Nidumolu et al., 2016)

> During this workshop we undertook an exercise with the participants to confirm which of the natural climate change and agricultural vulnerability hazards (exposure) affects each of the respective crops. We used this information to create exposure specific indexes for each of the crops. (Parker et al., 2019)

In some cases, the initial technical coefficients used in the models were fine-tuned based on the feedback and knowledge obtained during the validation process. For instance, yields in different seasons were adjusted to better match stakeholders' regional knowledge (Nidumolu et al., 2016). In other studies, workshops and discussions were conducted with experts to confirm that the model's behaviour aligns with observed patterns and their intuitive understandings of real-world systems (Andersson et al., 2013; Garcia de Jalon et al., 2014; Egerer et al., 2021; Henly-Shepard et al., 2015).

> A workshop with CCAFS scientists and experts in SD and food systems was conducted to review the output behaviour for the key variables of interest and evaluate whether the model produces the pattern of behaviour observed in the site and documented in the studies for the right reasons. (Jagustović et al., 2021)

In almost all cases, participation in these technical modelling aspects of research was inevitably done on an instrumental basis, to improve, refine or contextualise the modelling tools to the identified research questions.

3.2.3. Parameterizing scenarios or pathways

In 42% of the studies, scenarios are developed with participants to offer a structure within which to explore a range of possible future outcomes and their associated uncertainties (Andersson et al., 2013; Cabrera et al., 2008; Hossain et al., 2020; Jennings et al., 2022; Karlsson et al., 2018; Laureta et al., 2021; Mitter et al., 2014). We identified the use of specific participatory methods in the development of scenarios with stakeholders in some cases. For instance, Salvini et al. (2016) describe a Companion Modelling (ComMod) process, which involves a role-playing exercise with participants:

> The game provided a participatory means to develop policy and climate change scenarios … The scenarios developed in the game are then fed into an agent-based model, which allows inclusion of both spatial and temporal considerations in simulations of long-term and short-term effects of trade-offs and synergies associated with different strategy options. (Salvini et al., 2016)

In 26% of the studies reviewed, scenarios are used to describe plausible and desirable futures, and participatory input may be used in the making of normative judgements of the relative plausibility and desirability of scenarios (e.g. Stigter et al., 2017). In other cases, scenarios were chosen to reflect alternative 'extremes', and thus set the parameters of the total range of possible futures (e.g. Mason-D'Croz et al., 2016). In the latter approach, participatory input into the plausibility of these extremes may still be warranted, but grounding the scenarios in reality or in normative preferences is less important, and therefore participatory approaches play a less instrumental role.

Mitter et al. (2014) drew on expert participation in workshops to select climate change scenarios following on two jointly formulated decision criteria:

> First, they should provide sufficient information to understand a broad range of potential climatic impacts for the case study region. Secondly, they should represent those climate parameters that are perceived as driving forces of change. The peer group identified precipitation sums and annual distributions as most relevant parameters for the case study region.

Engagement of participants with less technical knowledge was restricted to a more nominal role of validating expert-derived scenarios that were known to fit with model capabilities. Stigter et al. (2017) mentioned in their study that

> SED scenarios were developed using a combination of methods and then presented in workshops to the farmers and to other stakeholders, including the Water Basin Authority and the Regional Agricultural Administration, among others, in order to obtain feedback regarding which scenarios they found the most probable and the most desirable.

3.2.4. Determining appropriate complexity/uncertainty in models

There are limited examples in the surveyed literature of how participants have been engaged in determining the appropriate complexity of modelling initiatives, identifying the scales and resolutions at which modelled information is desirable or in helping to weigh up the trade-offs between model complexity, uncertainty and the potential use and needs for modelling. Understanding appropriate complexity requires a bringing together of understandings about model skill and sensitivity, which requires niche and complex technical knowledge (that may be distributed across scientific disciplines and domains), worth understanding about how modelled outputs would be used and the determinants of usability.

Without significant input from the decision-making side, complexity is likely to be determined or constrained by the technical instruments of modelling, and there are examples from the reviewed studies of how models set the limits around what complexity can be captured and incorporated:

> First, the participatory established knowledge base would have suggested integrating more aspects into the scenario analysis. But, mainly due to modelling limitations, the complexity had to be reduced in order to produce consistent sets of inputs. (Walz et al., 2007)

> The decision to exclude information flow dynamics in the model within members of the village was explicitly taken to reduce the analytical complexity of the model and maintain tractability. (Sanga et al., 2021)

There were no explicit examples found where a discussion of appropriate complexity was formative in the co-design of research and in the selection of modelling tools and methodologies.

3.2.5. Interpreting data and implications of model outputs

Engagement of participants towards the end of the modelling process often focused on the presenting of model outcomes for purposes of validation or further interpretation. Walz et al. (2007) closely engaged a small advisory group in the interpretation of model outputs. In a series of workshops, including the presentation of qualitative scenarios and initial modelling results, the research team interacted with an advisory group. The group played a significant role in critiquing and analysing the simulation results. This process allowed stakeholders to express their agreement or disagreement with the findings and suggest improvements to the model. This iterative feedback loop resulted in adjustments to model inputs and parameters, ensuring that the model better represented the complex realities of the agricultural landscape.

In the study by Jennings et al. (2022), engagement had further instrumental value. In this case, a similar advisory group was engaged not only in the validation or refining outcomes but in developing 'implication statements'. In essence, these are interpretations of modelled outputs, grounded in contextual or sector-specific knowledge that seek to translate numerical outputs into decision-relevant narrative descriptions of the model findings. In other cases, these stakeholder interpretations of results were used to highlight outcomes that warranted further exploration and to iterate the modelling cycle to further interrogate these findings:

> The results of the climate projections and simulations of each scientific area were used as a basis for discussion with local stakeholders through workshops to reflect on which ecosystem services and dimensions of economic activity will be most affected. The results obtained in these workshops allowed some adjustments to the outputs of simulation models. Based on the results of scientific models and the know-how of local stakeholders, several adaptation measures were proposed. In the final phase of the study, the impact that these measures would have on the other sectors were discussed by the multidisciplinary team. (Gonçalves et al., 2022)

3.2.6. Communication and dissemination

Many studies (81% of those reviewed) discuss communication strategies aimed at disseminating and explaining the outcomes of models to key audiences, often with associated and targeted advisories that had been developed on the basis of modelled evidence. The studies adopted diverse media and formats for communication. For example, in Olabisi et al.'s study of climate change adaptation within the poultry sector, pamphlets were developed for poultry producers detailing recommended strategies for poultry sector adaptation. Similarly in the study by Andersson et al. (2013) derived adaptation plans disseminated widely, reaching farmers, school children, and other citizens.

In the study by Walz et al. (2007), an 'enhanced' storyline approach was used to combined narrative language with numerical outcomes, making the research results more accessible. It ensured that the communication process catered to the specific needs and understanding of the local community.

However, few studies discuss how participation and stakeholder engagement were used in the development of communication strategies or in the identification of the target audiences or most relevant communication tools. There was little evidence of the co-production of communications products within the studies reviewed.

3.2.7. Training and capacity building

There were very few examples found in the reviewed studies of stakeholders being engaged in training and capacity building as part of the modelling process. Typically training and capacity building may be integrated with the dissemination of model outputs, but this predominantly focused on training related to understanding and implementing the advisories or recommendations that are derived from model results (e.g. Gonçalves et al., 2022; Olabisi et al., 2021), rather than building knowledge and capacities around the research methodologies and modelling tools and techniques.

3.3. Who participates

The studies we reviewed applied various methods for data collection and stakeholder engagement at different stages of the participatory modelling process, inclusive of surveys, interviews, workshops and focus group discussions. We also identified studies where secondary data (census data or national surveys) were integrated into the models in addition to stakeholder engagement through workshops. Although studies mentioned the methods used for stakeholder engagement, they rarely provided justification for the selection of methods.

Although diverse descriptions and categorisations of stakeholders are used across these studies we identify three broad groups: Policy makers – consisting of government and civil service officials, local authorities, and local councils; Experts – inclusive of agronomists and climate scientists, extension service agents, supply chain actors, and representatives of civil society and non-governmental organisations; and Individuals – including farmers and members of rural households and communities.

Figure 2 indicates that the group most commonly engaged in participatory modelling were individuals, particularly in the construction and calibration of models and in the communication and dissemination of model outputs. The greatest diversity in approaches to engaging individuals comes in this early stage of model construction and calibration, in which we see a variety of individual and collective engagement approaches as well as uses of both primary and secondary survey data. Workshops and interviews are similarly commonly utilized for engaging experts and policy makers in the early stages of model development, and it is common across studies to disseminate findings though workshops with high-level audiences at their conclusion.

Few studies (27%) stated how stakeholders were identified and sampled. Some studies aimed for representation among selected stakeholders in terms of gender, age, diverse groups (e.g. residents, businesses and various local, County and State organizations and institutions), study communities and other socioeconomic characteristics (Andersson et al., 2013; Bedeke et al., 2018; Lasco et al., 2016; Mekonnen et al., 2021; Mitter et al., 2014; Naulleau, Gary, Prévot, Berteloot, et al., 2022; Naulleau, Gary, Prévot, Vinatier, et al., 2022; ZHAI et al., 2018).

> For the workshops with farmers two groups were created, distinguishing farmers between the eastern and western part of the area covering the Querença-Silves aquifer. This distinction also reflected differences in the type of farming systems (small-scale farms producing mostly rain-fed market garden and traditional dry farming crops in the east, versus medium-scale farms specialised in irrigated citrus production in the west). The composition of the groups assured representativeness, including farmers from different

> geographical areas, age groups, crop types and farm size. An additional workshop, carried out with institutional stakeholders, included very experienced researchers, public officers and members of associations in the fields of hydrology, agriculture and tourism. (Bhave et al., 2013)

Barbeau et al. (2016), Purwanti et al. (2022), Helminen et al. (2018) and Parker et al. (2019) also focused mainly on the number and the divisions among participants in their study to justify their sampling. In their study, Olabisi et al. (2021) and Naulleau, Gary, Prévot, Berteloot, et al. (2022), Naulleau, Gary, Prévot, Vinatier, et al. (2022) also mentioned how they divided participants into groups according to their position. Some studies (10%) also mentioned how stakeholders were engaged following sampling strategy such as systematic random procedure (Henly-Shepard et al., 2015; Turunen et al., 2016); Sok et al., 2021; Ahmed et al., 2022; Alexander & Block, 2022; Jennings et al., 2022; Liu et al., 2023; Nelson et al., 2022; Kabir et al., 2023).

In some cases, like the Doñana rice fields initiative, stakeholders were selected using snowball sampling. This technique involves identifying direct beneficiaries and using their input to identify and invite indirect beneficiaries. This method helped in expanding the network of stakeholders and ensured a comprehensive representation (Garcia de Jalon et al., 2014; Mitter et al., 2014).

> Direct beneficiaries of the Doñana rice fields were identified as rice farmers, environmentalists and policy makers among others, and subsequently through a snowball sampling technique, indirect beneficiaries were identified and invited to participate in the workshops. These beneficiaries included stakeholders representing other sectors such as other agricultural activities, aquaculture and tourism. (Garcia de Jalon et al., 2014).

Stakeholders were often mapped based on their interest, influence, and relevance to the project or initiative. Iglesias et al. (2017) purposefully map out a power/interest matrix to determine how varied forms and levels of influence can be reflected in targeted stakeholder engagements. Despite a recognition of differing levels of decision-making power, however, the intention here was not to address power dynamics within participatory processes, but had a much more instrumental purpose, focused on ensuring that model derived recommendations would translate into action. Reflecting this instrumental view of participation, they suggest that:

> People should be involved if they have information that cannot be gained otherwise, or if their participation is necessary to assure successful implementation of adaptation strategies Iglesias et al. (2017)

In 50% of cases, peer groups, consisting of extension officers, administration, scientists and other relevant individuals, were formed to enhance knowledge sharing and contributions from a wide range of sources (Ho, 2022). In some instances, stakeholders who had significant decision-making influence at the district or regional level were chosen. For example, agricultural extension officers in Ghana were selected because of their mediating role between farmers and district policymakers, making them key influencers in land-use decisions (Koo et al., 2020).

Results show studies (71%) could not explicitly state the measures taken to ensure representation/equity amongst the stakeholder groups. Similarly, we found that studies did not indicates how different opinions were expressed by stakeholders during the modelling process. At most, they mentioned stakeholders' opinions regarding the model outcomes, without stating contestation of power or views. Only one study stated how they dealt with situations where different opinions were expressed. They mentioned how they ensured that dominant individuals could not excessively influence the results. This was partly remedied by focusing on small-group exercises based on nominal group techniques.

3.4. Limitations to participation

Some studies (57%) reflected on the barriers to participatory research. These are summarized in Table 3 and mostly focus on technical and logistical challenges. Integrating different models and methods within a participatory approach was a challenge mentioned in 5% of studies. Salvini et al. (2016) highlighted that challenges exist in linking different methods in an integrated approach, and the ways in the modelling tools being used dictated the extent to which certain impacts and concerns, particularly those of socio-economic nature, could be interrogated within the study:

> The framework as presented here does not yet consider aspects that should be taken into account when evaluating the impact of mitigation/adaptation policies on social issues such as income distribution and poverty. Hence, we suggest that further research should be

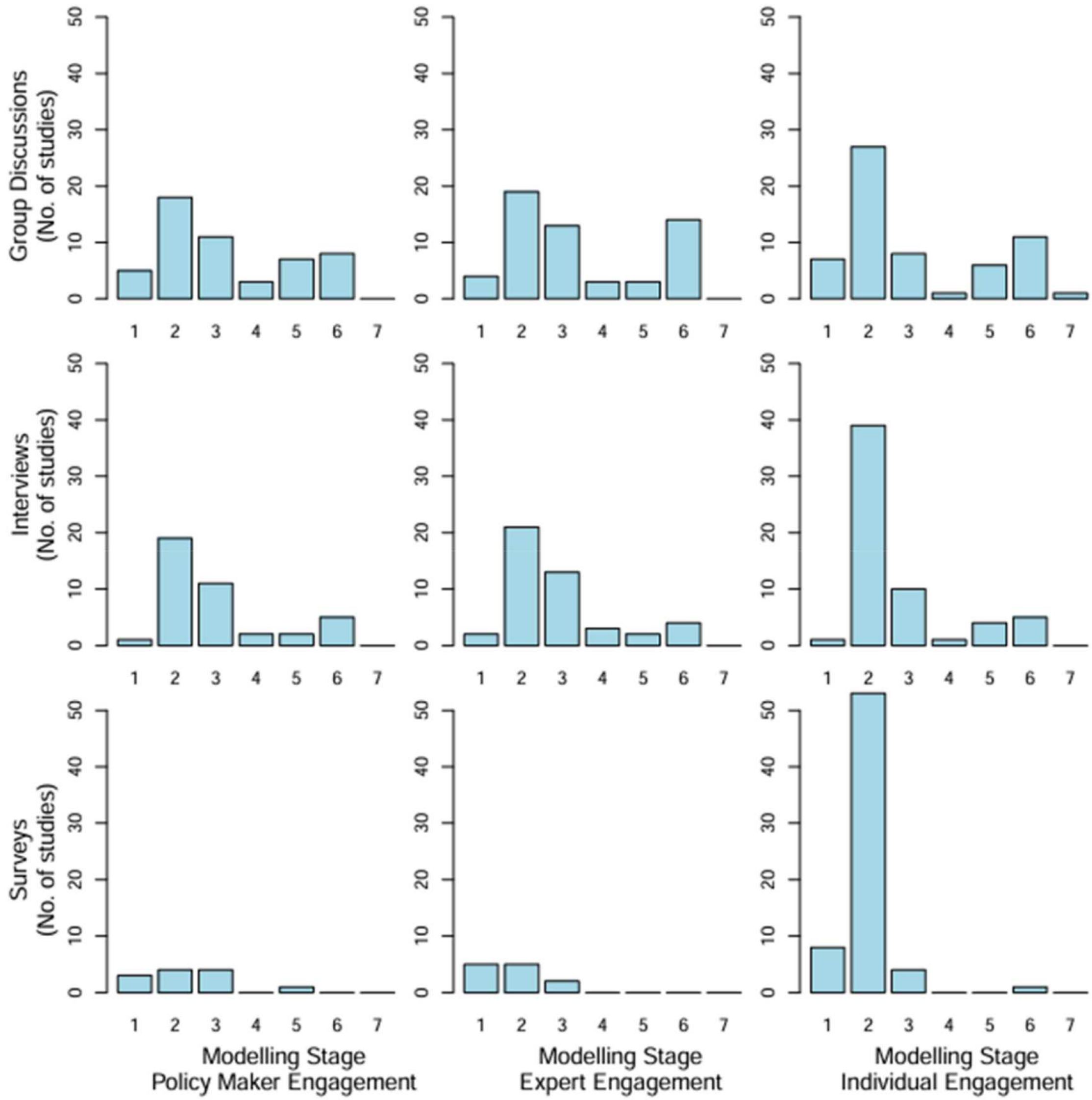

Figure 2. Stakeholder engagement at various stages with specific methods. Bars indicate the number of studies in which a specified stakeholder group (policy maker, expert, individual) was engaged through a given method (survey interview, group discussion) at each of seven participatory modelling stages: 1. Conception of research; 2. Construction, calibration and verification of models; 3. Parameterisation of scenarios or pathways; 4. Determining appropriate complexity/uncertainty in models; 5. Interpretation of data and implications of model outputs; 6. Communication and dissemination; 7. Training and capacity building.

> done on how to include such aspects, in order to have a more complete overview of the expected outcome of the policies under analysis. (Salvini et al., 2016)

Similarly, the process of transforming qualitative scenarios into specific input parameter values for models, in most cases was seen as a largely technical that remained in the domain of the climate modellers, because of the need for these input variables to be compatible with modelling tools:

> The participatory process could not contribute to the critical process of scenario parameterisation and quantification. The transformation of qualitative scenarios into sets of coherent input parameter values remained with the researchers, mainly because it would have required very specific and detailed knowledge of the numerical modelling framework (Walz et al., 2007)

Walz et al. (2007) also identified the 'bottleneck' between the qualitative and quantitative information,

Table 3. Barriers or challenges associated with participation in modelling documented in the papers.

Type of barriers	Specific barriers	References
Participant engagement	Difficulty in reaching or involving certain stakeholder groups or achieving representative sample sizes	Ali and Gölgeci (2020), Egerer et al. (2021), He et al. (2022), Iglesias et al. (2017), Jagustović et al. (2021), Koo et al. (2020), Natalini et al. (2019), Olabisi et al. (2021), Truelove et al. (2015).
	Difficulty in sustaining active participation over time	Andersson et al. (2013), Gonçalves et al. (2022), Sanga et al. (2021).
	Lack of clear consensus or agreement among stakeholder participants	Stigter et al. (2017)
Technical limitations	Important variables mentioned by stakeholders that cannot be modelled or outside of scope of available modelling tools	Bhave et al. (2013), Karlsson et al. (2018), Sapkota et al. (2021)
	Uncertainties in models (associated with assumptions and complexity of processes)	Jennings et al. (2022), Laureta et al. (2021), Natalini et al. (2019), Naulleau, Gary, Prévot, Berteloot, et al. (2022), Naulleau, Gary, Prévot, Vinatier, et al. (2022), Palosuo et al. (2021), Sanga et al. (2021), Sapkota et al. (2021), Ugbaje et al. (2019)
	Data inaccuracies/ data availability/lack of high-quality compatible datasets for model calibration and testing	Delmotte et al. (2017), Gonçalves et al. (2022), Jagustović et al. (2021), Liu et al. (2023), Mahmood et al. (2020), Natalini et al. (2019), Nidumolu et al. (2016), Palosuo et al. (2021), Parker et al. (2019), Rondhi et al. (2019), Salvini et al. (2016), Sanga et al. (2021), Selbonne et al. (2022), Truelove et al. (2015)
Knowledge translation	Incompatibility of, or difficulty in, integrating quantitative and qualitative data or approaches	Bedeke et al. (2018), Jagustović et al. (2021), Palosuo et al. (2021), Truelove et al. (2015).
	Models may be too complex, or processes/assumptions may be too hidden with models for stakeholders to be able to sufficiently understand and interpret	Andersson et al. (2013), Eitzel et al. (2020), Gonçalves et al. (2022), Sanga et al. (2021).
	Model assumptions and limitations frame too narrowly stakeholder discussions and inputs	Stigter et al. (2017)
	Different or competing conceptual understandings of risk and vulnerability	Laureta et al. (2021).
	Scenarios (particular those significantly different from status quo) or model outputs may be an insufficient basis for informing decision-making	Koo et al. (2020), Stigter et al. (2017).
Appropriate complexity and scale	Necessity of over-simplifying complex scenarios for the purpose of modelling	Sanga et al. (2021), Selbonne et al., 2022.
	Incompatibility between scale of model and scale/location of study	Gonçalves et al. (2022), Rodriguez et al. (2014)
Logistical	Lack of time and/or financial resources for revisiting and iterating modelling	Gonçalves et al. (2022), Nidumolu et al. (2016), Olabisi et al. (2021).

indicating a challenge in identifying a technique to 'translate' qualitative data into quantitative modelling input. Sanga et al. (2021) also mentioned their inability to explicitly model diffusion of beliefs, norms and information within networks in the social norms experiment.

These challenges of knowledge translation within modelling were largely framed as technical issues embedded in the design and infrastructure of modelling tools used, but it was rare to see this point extended to a questioning of the relative privileging or exclusion of certain knowledges by nature of the design of the research itself, and particularly the centring of (usually pre-selected) modelling tools within a linear process of knowledge production.

4. Discussion

Through this study we have systematically reviewed approaches for and barriers to improving participation in climate impacts modelling Our review reveals a tendency towards nominal and instrumental forms of participation within participatory modelling studies of climate impacts on agriculture. The finding that less than half of reviewed papers explicitly articulate a motivation for adopting a participatory approach to modelling is telling. As participatory approaches become increasingly mainstream within modelling studies, there is perhaps an inevitable tendency towards less reflection on the rationale, purpose or even underlying philosophy and ethics or participation. However, there is perhaps also an associated tendency for this participation to become somewhat narrow in its scope. The involvement of stakeholders in the cases identified often centres around articulating and refining future scenarios to be explored in modelling, in some cases making normative judgements about the plausibility or desirability of these scenarios, as well as in improving the accuracy and relevance of the models, validating and helping to interpret model results or being recipients of disseminated model outputs.

In other fields, authors have made distinctions between participatory modelling (seeing this as typically more instrumental in nature) and collaborative modelling (Basco-Carrera et al., 2017) and companion modelling (Mathevet et al., 2014). In each case, with the latter terms are used to reflect a more intensive and ongoing negotiation, and even confrontation, between diverse knowledge holders over the co-production of modelling for joint decision-making or collaborative learning. This has a parallel with what White (1996) describes as transformative participation, sustained across multiple modelling stages, as defined by Voinov et al. (2016).

It is clear that often what limits more representative or transformational forms of participation are the extent to which the scope and boundaries of modelling studies are determined by the pre-selection of modelling tools, and their associated limitations, or in the scientific norms that underpin the methodological design of modelling research. This is evident in multiple ways.

Firstly, the complex, technical and black-box nature of pre-selected modelling tools means that there is limited scope for non-technical experts to input into discussions about appropriate complexity and evaluations of model outputs and judgements about uncertainty or the robustness of findings. Without having an in-depth understanding of the assumptions inherent within models, which itself can only be accessed via technical experts, there is a limited extent to which participants can challenge the legitimacy of model results or propose alternatives. This in turn acts to inevitably privilege certain knowledges (typically those that are quantitative and modellable) over others.

Secondly, pre-selected models and associated research design dictate what pathways and inputs are 'modellable' and therefore within the scope of the research, and which are not. In several studies, questions or priorities raised within stakeholder engagement activities were deemed to be out of scope of the study because of the nature of the tools, available data, and expertise that were already fixed within the research. The complexity, scale and resolutions of models, for example, were much more frequently discussed as a technical barrier to participation, as opposed to being criteria for selecting and designing the most appropriate tools for addressing stakeholders' priorities.

Almost all the barriers identified and discussed in the cases reviewed pertained to technical challenges associated with participatory modelling. These challenges include: the quality and stability of data, integration of different models and methods (Gonçalves et al., 2022; Mason-D'Croz et al., 2016; Mitter et al., 2014), limitations of methodology (Iglesias et al., 2017), uncertainties in climate models, and the integration qualitative and quantitative data (Laureta et al., 2021; Walz et al., 2007). We observed limited reflections on social or epistemological barriers (beliefs, norms and information within networks in the social experiments) (Sanga et al., 2021). There are some good examples of, and emergent and novel methodologies for, participation happening at early stages and being formative in the refining of research questions and priorities. In most cases, this takes place within the constraints of what models can model, but there are also promising cases in which technical tools were selected and developed following a more participatory and conceptual modelling of system dynamics (Andersson et al., 2013; Cabrera et al., 2008; Delmotte et al., 2017; Egerer et al., 2021; Gonçalves et al., 2022; Hossain et al., 2020; Iglesias et al., 2017; Walz et al., 2007), and there were also cases in which there was an iterative cycle of revisiting research questions and design on the basis of participatory evaluations of model outputs (Gonçalves et al., 2022; Henly-Shepard et al., 2015; Mason-D'Croz et al., 2016; Mitter et al., 2014; Naulleau, Gary, Prévot, Vinatier, et al., 2022; Selbonne et al., 2022). Such cases point to the potential for more representative and transformational forms of participation. The difference with these approaches, to the more typical and conventional participatory modelling efforts, is that there is a less explicit privileging of the techno-scientific knowledge and tools at the outset.

Space and scope for iteration of research objectives and methods – ideally a cyclically process that allows for the revisiting of these following participatory evaluation of initial results or data – might be an important determinant of how representative and transformative participation could potentially be. Time and funding restrictions often squeeze this space and become, in themselves, a significant barrier to achieving more fundamental levels of participation.

Although the pragmatic benefits of participation – namely the improved and contextualized evidence that results from the inclusion of local knowledge – were broadly targeted in the design of participatory modelling studies, albeit largely limited to the less technical aspects of the modelling process, more normative benefits of participation were under-acknowledged. There was little focus on the emancipatory or educational benefits of participation in the knowledge construction process, the extent to which different voices and perspectives were represented within participatory processes, or the socio-cultural or political barriers that might prevent participation from marginalized voices. There is much more that could be done to design sampling and engagement in such a way as to reflect the diverse priorities and perspectives that could potentially be held within the stakeholders of a study and to systematically evaluate the extent to which those perspectives have a voice and agency in shaping knowledge production. Mathevet et al.'s (2014) vision of companion modelling is one in which this knowledge politics is more explicitly brought to the fore, and is acknowledged and negotiated within the collaborative process itself.

There was limited evidence on the selection (compositions and characteristics) and justification for the selection of stakeholders. The representation of minority groups such as women, landless or resource-poor groups were missing. There was little mention of representation and diversity within participatory processes, or critical reflection on the power dynamics within participatory spaces, such as workshops, created within research for participatory input (see for instance, Alexander & Block, 2022; Andersson et al., 2013; Iglesias et al., 2017; Karlsson et al., 2018; Koo et al., 2020; Li & Ford, 2019).

The privileging of techno-scientific knowledge within a modelling process may be one way in which certain perspectives and knowledges become marginalized. A co-design process that has embedded mechanism for learning, training and capacity building in all directions can help to redress such barriers and support more emancipatory outcomes from participation. This might include training participants in understanding and using some of the more technical modelling tools and data analysis techniques but should equally involve training of modellers or climate scientists in local environmental knowledge and indicators as well as contextual and social priorities and experiences. Under a more transformational participatory process, those involved would have more agency to contribute to the fundamental design, interpretation and iteration of the research, more agency to share their expectations and what they would seek to gain from participating, and more agency to call out and challenge existing power asymmetries within the research process (Moallemi et al., 2021).

Based on the above review, and drawing reference to some examples of good practice, we make the following recommendations for achieving more transformative participation within climate impacts modelling studies:

- Early inclusion of stakeholders in the modelling process, including at the conception of research questions and objectives, to ensure that the design of modelling studies is guided by the priority questions of stakeholders, as demonstrated by Gonçalves et al. (2022) and Conde et al. (2006). However, such stakeholder expectations within such engagements should be managed carefully and trust built through transparent communication (Andersson et al., 2013)
- Ensuring that stakeholder participation is guided by a clear rationale for who participates, with explicit consideration of the sampling strategies (including considerations of gender and socio-cultural characteristics), how participants are invited into collaborative spaces, and critical reflection who may be excluded from these processes and why.
- Creating opportunities or mechanisms for the validation of modelling assumptions, scales, resolutions, and appropriate complexity by stakeholders in a way that is based on a built understanding of the mechanics of models and in timely enough way that iteration of the modelling design and choices is still possible. As shown by Nidumolu et al. (2016) such iteration can enhance model credibility and accuracy.
- Parameterizing scenarios or pathways to include a range of plausible futures or extremes as done in studies such as Mason-D'Croz et al. (2016) can help to shift the dynamics of participation, by de-emphasizing the notion that the role of the model is in authoritative prediction and replacing

it with the idea of using models to explore and support decision-making for uncertain futures. Stakeholders themselves should have an important role in codeveloping these alternative scenarios, as in the study by Stigter et al. (2017).
- To enhance the effectiveness of communication strategies in disseminating model outcomes to key audiences, researchers should emphasise the importance of involving stakeholders in the development process of communication strategies. Engaging stakeholders at the early stages of the research could ensure that the communication materials are tailored to the specific knowledge levels, cultural contexts, and interests of the audiences, increasing their relevance and impact.

Fundamentally, achieving transformative and emancipatory participation within climate impacts modelling requires a rethinking of what and whom modelling is for, and a more critical reflection on the purposes and value of participation. There is precedent for such a rethinking in fields such as participatory crop breeding and participatory soil science, which have in turn transformed some of the approaches and institutional norms of international agricultural research and the CGIAR. There is a need for more studies, adequately supported by flexible and long-term funding, in which meaningful engagement and iterative co-design of research priorities and approaches are prioritized over techno-scientific norms of pre-selected modelling tools and approaches.

5. Conclusion

In this systematic review of participatory approaches to modelling climate change impacts on agriculture, we have outlined and evaluated current practices and revealed areas in which there is currently insufficient attention given. The black-box nature and mechanics of climate impact models create barriers to participation and knowledge equity that can only be overcome by rethinking what and whom climate impact modelling is for, and the linear, stepwise nature of its knowledge production. We argue that there is a current pre-occupation within participatory climate impacts modelling literature on instrumental reasons for including stakeholders and on technical barriers to this inclusion. Limited attention is currently paid to the potential transformative, collaborative and emancipatory nature of participation in climate impact modelling and there is a need for more critical reflection on the knowledge politics and power dynamics that act to limit equitable participation in such researchs'.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by CGIAR ClimBeR Initiative: [grant number rg.evea.126894.002]; CGIAR ClimBeR Intitiative: [grant number rg.evea.126894.002].

Notes on contributors

Dr R. Sarku is an interdisciplinary research scientist interested tackling poverty, food insecurity and environmental challenges through innovative and multidisciplinary result-oriented solutions. Rebecca has more than 10 years working experience in academia and international organizations, and is skilled in strategic and creative thinking, program design and management, research, and policy engagement. She is an expert in climate adaptation, climate information services, designing of innovative governance arrangement, adaptive decision-making, and digital technologies for agriculture and sustainable food systems. Her current research focuses on the CGIAR's Climate Science (ClimBeR initiative) and innovation in sustainability, policy, adaptation and resilience in Kenya (iSPARK) projects in Kenya and Zambia and analysing the politics in the UNFCCC's Sharm El Sheikh Climate Action on Agriculture and Food Security.

Prof S. Whitfield is the Director of the Global Food and Environment Institute at the University of Leeds. Stephen's research interests are in the social and political dimensions of international development in the context of agriculture and food systems. He currently co-leads the Food Systems Transformation in Southern Africa for One Health (FoSTA Health), a three and half year programme evaluating the human, animal and environmental health implications of changes in agriculture, land use, supply chains and diets in southern Africa. He is also co-investigator on the CGIAR ClimBeR programme which is aiming to transform the climate adaptation capacity of food and agricultural systems in low- and middle-income countries.

Dr S. Jennings studied Biological Sciences at the University of Oxford from 2008-2011 and completed his MSc in Quantitative Biology from Imperial College London in 2013. He started his PhD at the University of Leeds in 2013, working on the impacts of climate change on potato yields globally. His current research uses integrated assessment to analyse future food and nutrition security in sub-Saharan Africa.

Prof A. Chanillor is a Professor of Climate Impacts at the University of Leeds. He began his research career with a PhD at the University of Leeds on boundary layer flow through forests. He then spent some years at Reading, conducting postdoctoral research on the impacts of climate variability and change on food crops.

Andrew returned to Leeds in 2007 to take up a Lectureship position and initiated The Climate Impacts group. He led the NERC consortium End-to-end quantification of uncertainty for impacts prediction (EQUIP). He was Lead Author on the 'Food Production Systems and Food Security' chapter of the Fifth Assessment report of the IPCC and Lead Author for the UK Climate Change Risk Assessment 2017. He is also co-investigator on the CGIAR ClimBeR programme which is aiming to transform the climate adaptation capacity of food and agricultural systems in low- and middle-income countries.

References

Ahmed, Z., Shew, A. M., Mondal, M. K., Yadav, S., Jagadish, S. V. K., Prasad, P. V. V., Buisson, M. C., Das, M., & Bakuluzzaman, M. (2022). Climate risk perceptions and perceived yield loss increases agricultural technology adoption in the polder areas of Bangladesh. *Journal of Rural Studies*, *94*, 274–286. https://doi.org/10.1016/j.jrurstud.2022.06.008

Alexander, S., & Block, P. (2022). Integration of seasonal precipitation forecast information into local-level agricultural decision-making using an agent-based model to support community adaptation. *Climate Risk Management*, *36*, 100417. https://doi.org/10.1016/j.crm.2022.100417

Ali, I., & Gölgeci, I. (2020). Managing climate risks through social capital in agrifood supply chains. *Supply Chain Management: An International Journal*, *26*(1), 1–16. https://doi.org/10.1108/SCM-03-2020-0124

Andersson, L., Wilk, J., Graham, L. P., & Warburton, M. (2013). Design and test of a model-assisted participatory process for the formulation of a local climate adaptation plan. *Climate and Development*, *5*(3), 217–228. https://doi.org/10.1080/17565529.2013.812955

Arnstein, S. R. (1969). A ladder of citizen participation. *Journal of the American Planning Association*, *35*(4), 216–224. https://doi.org/10.1080/01944366908977225

Barbeau, C., Barbeau, G., & Joannon, A. (2016). Analyzing the sensitivity of viticultural practices to weather variability in a climate change perspective: An application to workable-day modelling. *Journal international des sciences de la vigne et du vin*, *48*(2), 141. https://doi.org/10.20870/oeno-one.2014.48.2.1563

Basco-Carrera, L., Warren, A., van Beek, E., Jonoski, A., & Giardino, A. (2017). Collaborative modelling or participatory modelling? A framework for water resources management. *Environmental Modelling & Software*, *91*, 95–110. https://doi.org/10.1016/j.envsoft.2017.01.014

Bedeke, S. B., Vanhove, W., Wordofa, M. G., Natarajan, K., & Van Damme, P. (2018). Perception of and response to climate change by maize-dependent smallholders. *Climate Research*, *75*(3), 261–275. https://doi.org/10.3354/cr01524

Bezner Kerr, R., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L., Msachi, R., Boateng, G. O., Snapp, S. S., Chitaya, A., Maona, E., Gondwe, T., Nkhonjera, P., & Luginaah, I. (2019). Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agriculture, Ecosystems & Environment*, *279*, 109–121. https://doi.org/10.1016/j.agee.2019.04.004

Bharwani, S., Bithell, M., Downing, T. E., New, M., Washington, R., & Ziervogel, G. (2005). Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1463), 2183–2194. https://doi.org/10.1098/rstb.2005.1742

Bhave, A. G., Mishra, A., & Raghuwanshi, N. S. (2013). A combined bottom-up and top-down approach for assessment of climate change adaptation options. *Journal of Hydrology*, *518*(PA), 150–161. https://doi.org/10.1016/j.jhydrol.2013.08.039

Brock, K., & Mcgee, R. (2002). *Knowing poverty: Critical reflections on participatory research and policy*. Earthscan.

Cabrera, V. E., Breuer, N. E., & Hildebrand, P. E. (2008). Participatory modeling in dairy farm systems: A method for building consensual environmental sustainability using seasonal climate forecasts. *Climatic Change*, *89*(3–4), 395–409. https://doi.org/10.1007/s10584-007-9371-z

Challinor, A. J., Adger, W. N., Benton, T. G., Conway, D., Joshi, M., & Frame, D. (2018). Transmission of climate risks across sectors and borders. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2121), 20170301. https://doi.org/10.1098/rsta.2017.0301

Conde, C., Ferrer, R., & Orozco, S. (2006). Climate change and climate variability impacts on rainfed agricultural activities and possible adaptation measures. A Mexican case study. *Atmósfera*, *19*(3), 181–194.

Cooke, B., & Kothari, U. (2001). *Participation: The new tyranny?* Zed Books.

Cornwall, A. (2008). Unpacking 'participation': Models, meanings and practices. *Community Development Journal*, *43*(3), 269–283. https://doi.org/10.1093/cdj/bsn010

Delmotte, S., Couderc, V., Mouret, J. C., Lopez-Ridaura, S., Barbier, J. M., & Hossard, L. (2017). From stakeholders narratives to modelling plausible future agricultural systems. Integrated assessment of scenarios for Camargue, Southern France. *European Journal of Agronomy*, *82*, 292–307. https://doi.org/10.1016/j.eja.2016.09.009

Dockerty, T., Lovett, A., Appleton, K., Bone, A., & Sünnenberg, G. (2006). Developing scenarios and visualisations to illustrate potential policy and climatic influences on future agricultural landscapes. *Agriculture, Ecosystems & Environment*, *114*(1), 103–120. https://doi.org/10.1016/j.agee.2005.11.008

Egerer, S., Cotera, R. V., Celliers, L., & Costa, M. M. (2021). A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture. *Agricultural Systems*, *189*, 103052. https://doi.org/10.1016/j.agsy.2021.103052

Eitzel, M. V., Solera, J., Wilson, K. B., Neves, K., Fisher, A. C., Veski, A., Omoju, O. E., Mawere Ndlovu, A., & Mhike Hove, E. (2020). Using mixed methods to construct and analyze a participatory agent-based model of a complex Zimbabwean agro-pastoral system. *PLoS ONE*, *15*(8), e0237638. https://doi.org/10.1371/journal.pone.0237638

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. *The FASEB Journal*, *22*(2), 338–342. https://doi.org/10.1096/fj.07-9492LSF

Gahi, Z. N., Dongo, K., & Badolo, M. (2015). Using a new approach to design innovative tools for monitoring and evaluating water policy of Burkina Faso in response to climate risks. *Climate*, *3*(4), 1057–1078. https://doi.org/10.3390/cli3041057

Gonçalves, C., Honrado, J. P., Cerejeira, J., Sousa, R., Fernandes, P. M., Vaz, A. S., Alves, M., Araújo, M., Carvalho-Santos, C., Fonseca, A., Fraga, H., Gonçalves, J. F., Lomba, A., Pinto, E., Vicente, J. R., & Santos, J. A. (2022). On the development of a regional climate change adaptation plan: Integrating model-assisted projections and stakeholders' perceptions. *Science of the Total Environment*, *805*, 150320. https://doi.org/10.1016/j.scitotenv.2021.150320

He, X., Yan, J., Yang, E. L., Wu, Y., & Zhou, H. (2022). Climate change adaptation of smallholders on the Tibetan plateau under government interventions. *Journal of Cleaner Production*, *381*, 135171. https://doi.org/10.1016/j.jclepro.2022.135171

Helminen, J., Myllynpää, V., Apiola, M., Dayoub, M., Westerlund, T., & Sutinen, E. (2018). Community climate services for small-scale farmers in Tanzania. In P. Cunningham & M. Cunningham (Eds.), *IST-Africa 2018 Conference Proceedings* (pp. 1–9). IIMC International Information Management Corporation.

Henly-Shepard, S., Gray, S. A., & Cox, L. J. (2015). The use of participatory modeling to promote social learning and facilitate community disaster planning. *Environmental Science & Policy*, *45*, 109–122. https://doi.org/10.1016/j.envsci.2014.10.004

Ho, C. H. (2022). Climate risks and opportunities of the marine fishery industry: A case study in Taiwan. *Fishes*, *7*(3), 116. https://doi.org/10.3390/fishes7030116

Hossain, M. S., Ramirez, J., Szabo, S., Eigenbrod, F., Johnson, F. A., Speranza, C. I., & Dearing, J. A. (2020). Participatory modelling for conceptualizing social-ecological system dynamics in the Bangladesh delta. *Regional Environmental Change*, *20*(1), 1–14. https://doi.org/10.1007/s10113-020-01599-5

Iglesias, A., Sánchez, B., Garrote, L., & López, I. (2017). Towards adaptation to climate change: Water for rice in the Coastal Wetlands of Doñana, Southern Spain. *Water Resources Management*, *31*(2), 629–653. https://doi.org/10.1007/s11269-015-0995-x

Jagustović, R., Papachristos, G., Zougmoré, R. B., Kotir, J. H., Kessler, A., Ouédraogo, M., Ritsema, C. J., & Dittmer, K. M. (2021). Better before worse trajectories in food systems? An investigation of synergies and trade-offs through climate-smart agriculture and system dynamics. *Agricultural Systems*, *190*, 103131. https://doi.org/10.1016/j.agsy.2021.103131-

de Jalón, G., Iglesias, S., Cunningham, R. A., & Dıaz, P. I. J. (2014). Building resilience to water scarcity in southern Spain: a case study of rice farming in Doñana protected wetlands. *Regional Environmental Change*, *14*, 1229–1242. https://doi.org/10.1007/s10113-013-0569-5

Jennings, S. A., Challinor, A. J., Smith, P., Macdiarmid, J. I., Pope, E., Chapman, S., Bradshaw, C., Clark, H., Vetter, S., Fitton, N., King, R., Mwamakamba, S., Madzivhandila, T., Mashingaidze, I., Chomba, C., Nawiko, M., Nyhodo, B., Mazibuko, N., Yeki, P., … Benton, T. (2022). A new integrated assessment framework for climate-smart nutrition security in sub-Saharan Africa: The Integrated Future Estimator for Emissions and Diets (iFEED). *Frontiers in Sustainable Food Systems*, *6*, 1–20. https://doi.org/10.3389/fsufs.2022.868189

Kabir, K., Baldos, U. L. C., & Hertel, T. W. (2023). The new Malthusian challenge in the Sahel: Prospects for improving food security in Niger. *Food Security*, *15*(2), 455–476. https://doi.org/10.1007/s12571-022-01319-3

Karlsson, J. O., Carlsson, G., Lindberg, M., Sjunnestrand, T., & Röös, E. (2018). Designing a future food vision for the Nordics through a participatory modeling approach. *Agronomy for Sustainable Development*, *38*(6), 1–10. https://doi.org/10.1007/s13593-018-0528-0

Koo, H., Kleemann, J., & Fürst, C. (2020). Integrating ecosystem services into land-use modeling to assess the effects of future land-use strategies in northern Ghana. *Land*, *9*(10), 379. https://doi.org/10.3390/land9100379

Lasco, R. D., Espaldon, M. L. O., & Habito, C. M. D. (2016). Smallholder farmers' perceptions of climate change and the roles of trees and agroforestry in climate risk adaptation: Evidence from Bohol, Philippines. *Agroforestry Systems*, *90*(3), 521–540. https://doi.org/10.1007/s10457-015-9874-y

Latulippe, N., & Klenk, N. (2020). Making room and moving over: Knowledge co-production, indigenous knowledge sovereignty and the politics of global environmental change decision-making. *Current Opinion in Environmental Sustainability*, *42*, 7–14. https://doi.org/10.1016/j.cosust.2019.10.010

Laureta, R. P., Regalado, R. R. H., & De La Cruz, E. B. (2021). Climate vulnerability scenario of the agricultural sector in the Bicol River Basin, Philippines. *Climatic Change*, *168*(1-2), 1–2. https://doi.org/10.1007/s10584-021-03208-8

Li, A., & Ford, J. (2019). Understanding socio-ecological vulnerability to climatic change through a trajectories of change approach: A case study from an indigenous community in Panama. *Weather, Climate, and Society*, *11*(3), 577–593. https://doi.org/10.1175/WCAS-D-18-0093.1

Liu, Y., Ruiz-Menjivar, J., & Zhang, J. (2023). Do soil nutrient management practices improve climate resilience? Empirical evidence from rice farmers in central China. *Environment, Development and Sustainability*, *25*(9), 10029–10054. https://doi.org/10.1007/s10668-022-02475-4

Mahmood, N., Arshad, M., Kächele, H., Ullah, A., & Müller, K. (2020). Economic efficiency of rainfed wheat farmers under changing climate: Evidence from Pakistan. *Environmental Science and Pollution Research*, *27*(27), 34453–34467. https://doi.org/10.1007/s11356-020-09673-5

Mason-D'Croz, D., Vervoort, J., Palazzo, A., Islam, S., Lord, S., Helfgott, A., Havlík, P., Peou, R., Sassen, M., Veeger, M., van Soesbergen, A., Arnell, A. P., Stuch, B., Arslan, A., & Lipper, L. (2016). Multi-factor, multi-state, multi-model scenarios: Exploring food and climate futures for Southeast Asia. *Environmental Modelling & Software*, *83*, 255–270. https://doi.org/10.1016/j.envsoft.2016.05.008

Mathevet, R., Antona, M., Barnaud, C., Fourage, C., Trébuil, G., & Aubert, S. (2014). Contexts and dependencies in the ComMod processes. In M. Etienne (Ed.), *Companion modelling: A participatory approach to support sustainable development* (pp. 103–125). Springer. https://doi.org/10.1007/978-94-017-8557-0_5

Mekonnen, A., Tessema, A., Ganewo, Z., & Haile, A. (2021). Climate change impacts on household food security and farmers adaptation strategies. *Journal of Agriculture and Food Research*, *6*, 100197. https://doi.org/10.1016/j.jafr.2021.100197

Mitter, H., Kirchner, M., Schmid, E., & Schönhart, M. (2014). The participation of agricultural stakeholders in assessing regional vulnerability of cropland to soil water erosion in Austria. *Regional Environmental Change*, *14*(1), 385–400. https://doi.org/10.1007/s10113-013-0506-7

Moallemi, E. A., de Haan, F. J., Hadjikakou, M., Khatami, S., Malekpour, S., Smajgl, A., Smith, M. S., Voinov, A., Bandari, R., Lamichhane, P., Miller, K. K., Nicholson, E., Novalia, W., Ritchie, E. G., Rojas, A. M., Shaikh, M. A., Szetey, K., & Bryan, B. A. (2021). Evaluating participatory modeling methods for Co-creating pathways to sustainability. *Earth's Future*, *9*(3), 1–19. https://doi.org/10.1029/2020EF001843

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., Gøtzsche, P. C., … Tugwell, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine*, *6*(7), e1000097. https://doi.org/10.1371/journal.pmed.1000097

Natalini, D., Bravo, G., & Jones, A. W. (2019). Global food security and food riots – an agent-based modelling approach. *Food Security*, *11*(5), 1153–1173. https://doi.org/10.1007/s12571-017-0693-z

Naulleau, A., Gary, C., Prévot, L., Berteloot, V., Fabre, J. C., Crevoisier, D., Gaudin, R., & Hossard, L. (2022). Participatory modeling to assess the impacts of climate change in a Mediterranean vineyard watershed. *Environmental Modelling & Software*, *150*, 105342. https://doi.org/10.1016/j.envsoft.2022.105342

Naulleau, A., Gary, C., Prévot, L., Vinatier, F., & Hossard, L. (2022). How can winegrowers adapt to climate change? A participatory modeling approach in southern France. *Agricultural Systems*, *203*, 103514. https://doi.org/10.1016/j.agsy.2022.103514

Nelson, W. C. D., Hoffmann, M. P., May, C., Mashao, F., Ayisi, K., Odhiambo, J., Bringhenti, T., Feil, J. H., Yazdan Bakhsh, S., Abdulai, I., & Rötter, R. P. (2022). Tackling climate risk to sustainably intensify smallholder maize farming systems in Southern Africa. *Environmental Research Letters*, *17*(7), 075005. https://doi.org/10.1088/1748-9326/ac77a3

Nidumolu, U. B., Lubbers, M., Kanellopoulos, A., van Ittersum, M. K., Kadiyala, D. M., & Sreenivas, G. (2016). Engaging farmers on climate risk through targeted integration of bio-economic modelling and seasonal climate forecasts. *Agricultural Systems*, *149*, 175–184. https://doi.org/10.1016/j.agsy.2016.09.011

Olabisi, L. S., Liverpool-Tasie, S., Rivers, L., Ligmann-Zielinska, A., Du, J., Denny, R., Marquart-Pyatt, S., & Sidibé, A. (2018). Using participatory modeling processes to identify sources of climate risk in West Africa. *Environment Systems and Decisions*, *38*(1), 23–32. https://doi.org/10.1007/s10669-017-9653-6

Olabisi, L. S., Osuntade, O., Liverpool-Tasie, L. S. O., & Adebiyi, J. (2021). Participatory modelling for climate change adaptation: The poultry sector in Nigeria. *Climate Policy*, *21*(5), 666–677. https://doi.org/10.1080/14693062.2021.1891019

Palosuo, T., Hoffmann, M. P., Rötter, R. P., & Lehtonen, H. S. (2021). Sustainable intensification of crop production under alternative future changes in climate and technology: The case of the North Savo region. *Agricultural Systems*, *190*, 103135. https://doi.org/10.1016/j.agsy.2021.103135

Parker, L., Bourgoin, C., Martinez-Valle, A., & Läderach, P. (2019). Vulnerability of the agricultural sector to climate change: The development of a pan-tropical climate risk vulnerability assessment to inform sub-national decision making. *PLoS ONE*, *14*(3), e0213641. https://doi.org/10.1371/journal.pone.0213641

Pretty, J. N. (1995). Participatory learning for sustainable agriculture. *World Development*, *23*(8), 1247–1263. https://doi.org/10.1016/0305-750X(95)00046-F

Purwanti, T. S., Syafrial, S., Huang, W. C., & Saeri, M. (2022). What drives climate change adaptation practices in smallholder farmers? Evidence from potato farmers in Indonesia. *Atmosphere*, *13*(1), 113. https://doi.org/10.3390/atmos13010113

Reed, M. S. (2008). Stakeholder participation for environmental management: A literature review. *Biological Conservation*, *141*(10), 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014

Rodriguez, D., Cox, H., deVoil, P., & Power, B. (2014). A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. *Agricultural Systems*, *126*, 50–61. https://doi.org/10.1016/j.agsy.2013.04.003

Rondhi, M., Fatikhul Khasan, A., Mori, Y., & Kondo, T. (2019). Assessing the role of the perceived impact of climate change on national adaptation policy: The case of rice farming in Indonesia. *Land*, *8*(81), 1–21. https://doi.org/10.3390/land8050081

Ruiz-Agudelo, C. A., Bonilla-Uribe, O. D., & Páez, C. A. (2015). The vulnerability of agricultural and livestock systems to climate variability: Using dynamic system models in the Rancheria upper basin (Sierra Nevada de santa marta). *Eco.Mont*, *7*(2), 50–60. https://doi.org/10.1553/eco.mont-7-2s50

Salvini, G., Ligtenberg, A., van Paassen, A., Bregt, A. K., Avitabile, V., & Herold, M. (2016). REDD+ and climate smart agriculture in landscapes: A case study in Vietnam using companion modelling. *Journal of Environmental Management*, *172*, 58–70. https://doi.org/10.1016/j.jenvman.2015.11.060

Sanga, U., Park, H., Wagner, C. H., Shah, S. H., & Ligmann-Zielinska, A. (2021). How do farmers adapt to agricultural risks in northern India? An agent-based exploration of alternate theories of decision-making. *Journal of Environmental Management*, *298*, 113353. https://doi.org/10.1016/j.jenvman.2021.113353

Sapkota, B. T., Khanam, F., Mathivanan, P. G., Vetter, S., Hussain, S. G., Pilat, A., Shahrin, S., Hossain, M. K., Sarker, N. R., & Krupnik, T. J. (2021). Quantifying opportunities for greenhouse gas emissions mitigation using big data from smallholder crop and livestock farmers across Bangladesh. *Science of the Total Environment*, *786*, 147344. https://doi.org/10.1016/j.scitotenv.2021.147344

Selbonne, S., Guindé, L., Belmadani, A., Bonine, C., L. Causeret, F., Duval, M., Sierra, J., & Blazy, J. M. (2022). Designing scenarios for upscaling climate-smart agriculture on a small tropical island. *Agricultural Systems*, *199*, 103408. https://doi.org/10.1016/j.agsy.2022.103408

Sok, S., Chhinh, N., Hor, S., & Nguonphan, P. (2021). Climate change impacts on rice cultivation: A comparative study of the Tonle Sap and Mekong River. *Sustainability (Switzerland)*, *13*(16), 8979. https://doi.org/10.3390/su13168979

Stigter, T. Y., Varanda, M., Bento, S., Nunes, J. P., & Hugman, R. (2017). Combined assessment of climate change and socio-economic development as drivers of freshwater availability in the South of Portugal. *Water Resources Management*, *31*(2), 609–628. https://doi.org/10.1007/s11269-015-0994-y

Street, R. B. (2016). Towards a leading role on climate services in Europe: A research and innovation roadmap. *Climate Services*, *1*, 2–5. https://doi.org/10.1016/j.cliser.2015.12.001

Sumberg, J., & Thompson, J. (2012). *Contested agronomy: Agricultural research in a changing world*. Routledge.

Truelove, H. B., Carrico, A. R., & Thabrew, L. (2015). A socio-psychological model for analyzing climate change adaptation: A case study of Sri Lankan paddy farmers. *Global Environmental Change*, *31*, 85–97. https://doi.org/10.1016/j.gloenvcha.2014.12.010

Turunen, M. T., Rasmus, S., Bavay, M., Ruosteenoja, K., & Heiskanen, J. (2016). Coping with difficult weather and snow conditions: Reindeer herders' views on climate change impacts and coping strategies. *Climate Risk Management*, *11*, 15–36. https://doi.org/10.1016/j.crm.2016.01.002

Ugbaje, S. U., Odeh, I. O. A., & Bishop, T. F. A. (2019). Fuzzy measure-based multicriteria land assessment for rainfed maize in West Africa for the current and a range of plausible future climates. *Computers and Electronics in Agriculture*, *158*, 51–67. https://doi.org/10.1016/j.compag.2019.01.011

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., & Ramu, P. (2016). Modelling with stakeholders – next generation. *Environmental Modelling & Software*, *77*, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016

Vukomanovic, J., Skrip, M. M., & Meentemeyer, R. K. (2019). Making it spatial makes it personal: Engaging stakeholders with geospatial participatory modeling. Land, *8*(2), 38. https://doi.org/10.3390/land8020038

Walz, A., Lardelli, C., Behrendt, H., Grêt-Regamey, A., Lundström, C., Kytzia, S., & Bebi, P. (2007). Participatory scenario analysis for integrated regional modelling. *Landscape and Urban Planning*, *81*(1–2), 114–131. https://doi.org/10.1016/j.landurbplan.2006.11.001

White, C. S. (1996). Depoliticising development: The uses and abuses of participation. *Development in Practice*, *6*(1), 6–15. https://doi.org/10.1080/0961452961000157564

Whitfield, S. (2013). Uncertainty, ignorance and ambiguity in crop modelling for African agricultural adaptation. *Climatic Change*, *120*(1–2), 325–340. https://doi.org/10.1007/s10584-013-0795-3

ZHAI, S. y., SONG, G. x., QIN, Y. c., YE, X. y., & Leipnik, M. (2018). Climate change and Chinese farmers: Perceptions and determinants of adaptive strategies. *Journal of Integrative Agriculture*, *17*(4), 949–963. https://doi.org/10.1016/S2095-3119(17)61753-2

Zimmerer, K. S., de Haan, S., Jones, A. D., Creed-Kanashiro, H., Tello, M., Amaya, F. P., Carrasco, M., Meza, K., Tubbeh, R. M., Nguyen, K. T., & Hultquist, C. (2020). Indigenous smallholder struggles in Peru: Nutrition security, agrobiodiversity, and food sovereignty amid transforming global systems and climate change. *Journal of Latin American Geography*, *19*(3), 74–111. https://doi.org/10.1353/lag.2020.0072