A conceptual framework for the contextualization of crop model applications and outputs in participatory research

Timothée Cheriere, Katrien Descheemaeker, Gatien N. Falconnier, Aminata Ganeme, Juliette Lairez, Hamado Sawadogo, Myriam Adam

Agronomy for Sustainable Development (2025) 45:8
https://doi.org/10.1007/s13593-024-01001-2

RESEARCH ARTICLE

A conceptual framework for the contextualization of crop model applications and outputs in participatory research

Timothée Cheriere[1,2,3,4] · Katrien Descheemaeker[5] · Gatien N. Falconnier[6,7,8,9] · Aminata Ganeme[10] · Juliette Lairez[6,7,11] · Hamado Sawadogo[11] · Myriam Adam[1,2,12]

Accepted: 16 December 2024

Abstract

Contextualization of generic scientific knowledge to context-specific farmer knowledge is a necessary step in farmers' innovation process, and it can be achieved using crop and farm models. This work explores the possibility to simulate a large number of scenarios based on farmers' descriptions of their environment and practices in order to contextualize the discussion for each participating farmer. It presents a novel framework consisting of six actions divided in three phases, namely, phase I—reaching out to the farmers' world: (i) project initialization; (ii) determination of the agronomical question anchored in farmers' context; (iii) characterization of the environment, the management options, and the indicators to describe the system under consideration; phase II—within researchers' world: (iv) crop model parametrization; (v) translation of model outputs into farmer-proposed indicators; and phase III—back to farmers' world: (vi) exploration of contextualized management options with farmers. Two communication tools are created during the process, one containing the results of simulations to feed the discussions and a second one to create a record of it. The usefulness of the framework is exemplified with the exploration of soil fertility management with manure and compost applications for sorghum production in the smallholder context of Sudano-Sahelian Burkina Faso. The application of the framework with 15 farmers provided evidence of farmers' and agronomists' understanding of options to improve cropping system performance with better organic amendment management. This approach allowed farmers to identify and relate to the scenarios simulated, but highlighted interrogations on how to adapt the crop model outputs to particular situations. Though applied on issues related to tactical change at field level, the framework offers the opportunity to explore broader issues with farmers, such as farm reconfiguration.

Keywords Participatory research · Agroecology · Contextualization of knowledge · Sub-Saharan Africa · Smallholder farming

✉ Timothée Cheriere
timothee.cheriere@cirad.fr

1 AGAP Institut, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France

2 CIRAD, UMR AGAP Institut, F-34398 Montpellier, France

3 ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, 34060 Montpellier, France

4 CIRAD, UMR ABSys, F-34398 Montpellier, France

5 Plant Production Systems Group, Wageningen University & Research, P.O. Box 430, 6700AK Wageningen, The Netherlands

6 AIDA, Univ Montpellier, CIRAD, Montpellier, France

7 CIRAD, UPR AIDA, F-34398 Montpellier, France

8 International Maize and Wheat Improvement Centre (CIMMYT)-Zimbabwe, 12.5 km Peg Mazowe Road, Harare, Zimbabwe

9 Department of Plant Production Sciences and Technologies, University of Zimbabwe, Harare, Zimbabwe

10 Laboratoire de Biologie et Ecologie Végétales (LaBEV, UFR/SVT), Université Joseph Ki-Zerbo, Ouagadougou, Burkina Faso

11 Département Gestion des Ressources naturelles et Système de Production, Institut de l'Environnement et de Recherches Agricoles (INERA), BP 04, 8645 Ouagadougou, Burkina Faso

12 National University of Battambang, Battambang Province, 021402 Battambang, Kingdom of Cambodia

Published online: 03 February 2025

1 Introduction

Agricultural systems need to evolve to help achieve food security for a growing world population in a sustainable way (Fig. 1). By applying social and ecological concepts to agricultural systems in an integrative approach, agroecology is increasingly recognized and promoted as a pathway towards sustainability. The transition towards agroecological systems benefits from the involvement of stakeholders and attention to their specific context (Duru et al. 2015; Côte et al. 2022). Indeed, participation of stakeholders aims at increasing credibility, saliency, and legitimacy of the propositions emerging during the design process (Cash et al. 2003) and helps to tailor innovations to farmers' objectives and constraints (Falconnier et al. 2017; Périnelle et al. 2021). Turning generic scientific knowledge into context-specific farmer knowledge is a critical challenge for agricultural knowledge and innovation systems (Duru et al. 2015; Coquil et al. 2018). Farmers, researchers, and advisory services are constrained by their different understanding of the issues at stake when trying to define shared objectives.

Farmers make decisions with knowledge of their natural, technical, and socio-economic environment. These decisions are influenced by farmers' values, aspirations, and life experiences and therefore the type of knowledge that they consider relevant to their situation varies (Šūmane et al. 2018; Coquil et al. 2018). Farmers' learning originates from different sources and their use of new knowledge takes different forms, including directly experimenting with practices in their fields or formulating their own hypothesis before experimenting (Šūmane et al. 2018; Hansson 2019). As such, contextualization is part of farmers' processes to link generic scientific knowledge to their own system (Toffolini et al. 2017). Contextualizing generic scientific knowledge within farmers' context is expected to foster knowledge exchange and shorten the path to cropping system innovation. To facilitate contextualization of generic scientific knowledge into context-specific farmer knowledge, studies have used models in a participatory manner, to evaluate the performance of prototypes co-designed with farmers (Rossing et al. 1997; Dogliotti et al. 2014; Martin 2015; Queyrel et al. 2023; Blanc et al. 2024), and to foster social learning (Carberry et al. 2004; Jakku and Thorburn 2010; van Paassen et al. 2011; Thorburn et al. 2011), resulting, in some cases, in changes in practices.

Crop models are particularly valuable for understanding how cropping systems perform across diverse environments and under various management practices (e.g., Queyrel et al. 2023; Blanc et al. 2024). They are built around generic scientific knowledge. The user can define the environment and the management practices under which the crop grows—offering an opportunity to bridge the gap between generic and context-specific farmer knowledge. Also, crop models can help quantify processes (e.g., N losses) that are tedious to measure (e.g., Thorburn et al. 2011; Blanc et al. 2024). Finally, and despite the time required for parametrization, their flexibility and relatively low cost of operation enable the simulation of a great number of situations that would be difficult to obtain with field experiments. Crop models have been used in participatory research following various protocols, simulating cropping system prototypes that were co-designed beforehand to assess their performance (e.g., Queyrel et al. 2023; Blanc et al. 2024), or directly engaging farmers with the models, simulating real farmer contexts for experiential learning (e.g., Carberry et al. 2004; Thorburn et al. 2011). Regardless of the approach, researchers had to

Fig. 1 Sorghum field in Plateau-Central region of Burkina Faso (Timothée Cheriere, 2022).

put efforts into understanding the systems they were modeling to properly parametrize the models, while the ways of presenting the outputs to the famers were little discussed. Finally, in both approaches, the authors have pointed out that farmers could feel left out because the scenarios considered are not feasible in their farms or that their own context was not simulated (e.g., Carberry et al. 2004; Queyrel et al. 2023).

Regardless of the objectives of the participatory project in which models are employed, the contextualized practices and indicators that may spark the interest of farmers are highly diverse. Thus, we argue that methods offering farmers a large choice of options, as per the concept of "baskets of options"—sets of co-designed agricultural innovations fitting the context of farmers (Falconnier et al. 2017; Descheemaeker et al. 2019; Ronner et al. 2021)—could be combined with modeling. As such, a carefully co-designed basket of options gathering practices of interest to farmers, modeled within multiple specific farmers' contexts—contextualizing knowledge on the effect of practices in various specific contexts—should offer each participant farmer the opportunity to find contexts and options corresponding to their individual situation.

In an attempt to facilitate the use of models in participatory research, we propose and test a framework that can (i) be mobilized regardless of participants' scientific background; (ii) can cover a diversity of practices and environments to approximate farmers' contexts; and (iii) be used to present the effect of a change in practices through the simulation of "baskets of contextualized options." The ultimate goal is to contribute to easing the contextualization of generic scientific knowledge into context-specific farmer knowledge for the design of agricultural innovations. We hypothesize that (i) farmers' description of their environment and management practices can serve as input for crop models, (ii) model outputs relevant to farmers can be extracted to provide quantified examples; and (iii) simulations of contrasting management options for a diversity of environments constitute a "basket of contextualized options" that fit farmers' expressed interest and context.

2 Methodology

2.1 Theoretical considerations

This framework draws inspiration from the concept of a boundary object (Star and Griesemer 1989; Leigh Star 2010) to structure the exchange of information and knowledge between two different social worlds, the one of the researchers, and the one of the farmers, participating in the project. Both worlds differ by the knowledge associated with the problem to be addressed, the interest in, and expectations from the project. The "boundary object" concept has three main properties according to Leigh Star (2010): (i) "it resides between social worlds (or communities of practice) where it is ill-structured"; (ii) "it can be worked on by a group who maintains its vaguer identity as a common object, while making it more specific, more tailored to local use within a social world"; and (iii) "groups that are cooperating without consensus tack back-and-forth between both forms [the ill-structured form at the boundary of the different social worlds and the more precise form within each social worlds] of the object."

Although not using a boundary object per se, this approach operationalizes the three main properties of a boundary object for farmers and researchers to identify, share, and work on an agronomical question which is abstract and resides between farmers' and researchers' worlds. The agronomical question is embedded within a given context and can be general (e.g., improving food production for smallholder households in region X) or specific (e.g., comparison of soil tillage techniques in environment X, Y, and Z). It is ill-structured in the sense that its functioning is not represented in the same way nor through the same interests and objectives for farmers and researchers. This agronomical question and its operating context, the "system under consideration," do not need to be clearly and precisely characterized. The "ill structured" or unprecise nature of the agronomical question allows farmers and researchers to discuss the same subject without having to agree on every aspect of it.

2.2 A framework for the use of crop models with farmers

2.2.1 Reaching out to the farmers' world

A1—project initialization To create a bridge between the two social worlds, farmers and researchers must first understand each other, share information, and establish mutual trust (Fig. 2, A1; Carberry et al. 2004; Faure et al. 2010). When presenting the approach to farmers, researchers present in simple terms what a crop model is, how it works, and what it can be used for, without detailing the mathematical equations constituting a model. Solicitating farmers to describe their system and their experience of the effect of environment and practices on the systems outcomes—through "what if?" questions (e.g., What happens to crop X if it does not rain during more than 20 days?)—helps anchoring the explanations on crop model functioning into their reality (Carberry et al. 2004). Mentioning limits of the use of crop models is advised as crop models do not represent reality as experienced by farmers (Whitbread et al. 2010).

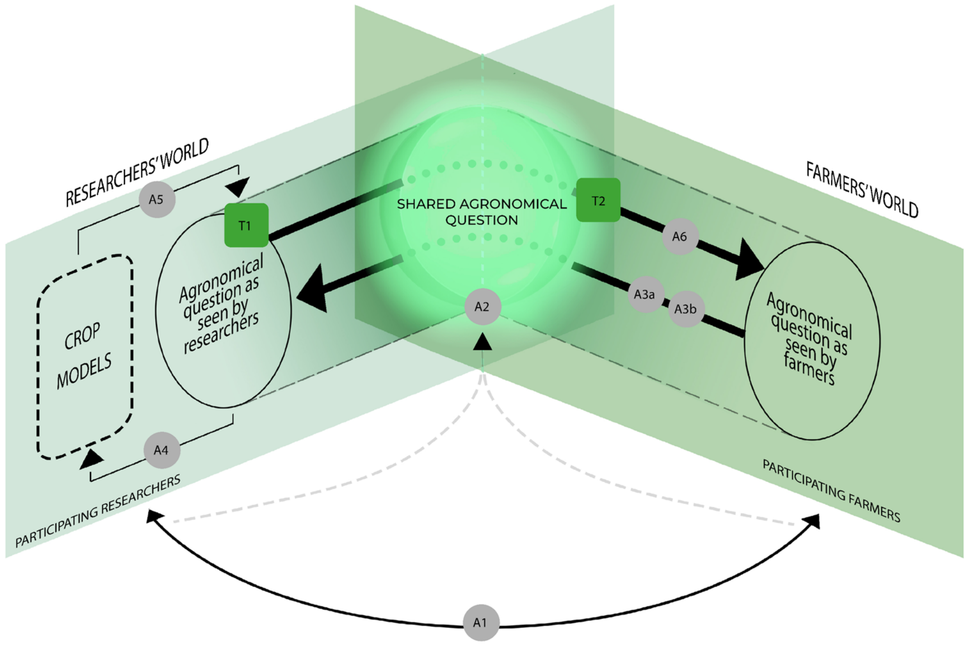

Fig. 2 Schematic representation of the framework to use crop models in participatory approaches with farmers. The framework is composed of 6 actions (A1 to A6, gray circles) divided in three phases. Phase I—reaching out to farmers' world: A1—project initialization, A2—identification of the agronomical question, A3—characterization of the environments, the management options (A3a), and the indicators to describe the system under consideration (A3b); phase II—within researchers' world: A4—crop model parametrization, A5—translation of model outputs into farmer-proposed indicators; phase III—back to the farmers' world: A6—exploration of contextualized management options with farmers. The problem to be explored is represented in its shared ill-structured form at the intersection of farmers' and researchers' worlds, while it is more specific within each world. T1, a first communication tool gathering contextualized management options whose effects are quantified through a crop model and described through farmer-proposed indicators. T2, the "summary handout" is a second communication tool that substantiates the management options considered by farmers and is offered to them.

A1 should result in farmers having notions of what a model is, its functioning, and usefulness, while researchers should have an understanding of how to refer—words, concepts, and units—to the system under consideration.

A2—definition of the agronomical question Further discussions with farmers aim at identifying the problems they encounter and want to explore (Fig. 2, A2). Farmers' problems are expected to be anchored in their context (e.g., Why crop X does not produce as well in field A as in field B?). Oppositely, researchers may consider more global issues, outside of farmers' context (e.g., How to sustainably increase crop production in Region Y?). At the intersection of farmers' and researchers' worlds, the agronomical question is not precisely defined ("Shared agronomical question," Fig. 2) but constitutes a basis to share information (e.g., What cropping practices contribute to crop X performances?). Within each world, the agronomical question takes a more precise form. For farmers (Fig. 2, "Agronomical question as seen by farmers"), the precise form is associated with their own experience, their knowledge of their constraints and opportunities, and their representation of the processes at stake. On the other hand, researchers represent the agronomical question based on their scientific knowledge and the analytical approaches they know (Fig. 2, "Agronomical question as seen by researchers").

A3—characterization of the environments, the management options (A3a) and the indicators to describe the system under consideration (A3b) Once the agronomical question has been identified and agreed upon, farmers and researchers can define the contours of that object and its main characteristics. The agronomical question being embedded in the space and time of the farmers, information on the pedoclimatic, technical, and socio-economic environment in which farmers operate is collected. Collecting this information aims at accounting for the specificities of the system under consideration and facilitating crop model parametrization. The management options that will be considered in the system under consideration are selected (Fig. 2, A3a).

Investigating the indicators used by farmers to evaluate the system under consideration is at the center of action 3b (Fig. 2, A3b). This action also aims at deepening the identification of the concepts and representations by farmers of their systems and how they refer to it (i.e., units, concepts, and vocabulary) to facilitate later discussions.

2.2.2 Within the researchers' world

A4—crop model parametrization The identification of the agronomical question (Fig. 2, A2) and the characterization of the system under consideration and the management options to consider (Fig. 2, A3a) provide the basis for adequate crop model selection by researchers. Crop model selection is further informed by data availability, required outputs to compute indicators (Fig. 2, A3b), and available skills for model manipulation and output interpretation. Based on the description of the management options and the environments, the researchers parametrize the crop model and simulate the Management × Environment combinations required to address the agronomical question (Fig. 2, A4).

A5—translation of model outputs into farmer-proposed indicators The model outputs that match or can be used to calculate the indicators proposed by farmers in A3b are identified (Fig. 2, A5). The values of the indicators of each simulated contextualized management option are used to construct the basket of contextualized options. The basket of contextualized options is transcribed to a communication tool (Fig. 2, T1) which may take various forms (tables, radar charts, and diagrams).

2.2.3 Back to the farmers' world

A6—exploration of contextualized management options with farmers In action 6 (Fig. 2, A6), researchers and farmers use the communication tool T1 to discuss the effect of the contextualized management options. Starting with an option that approximates the farmer's own context allows the farmer to confront the simulation results to his/her own experience (Carberry et al. 2004; Hansson 2019). The farmer-proposed indicators help to establish references for further discussion. Farmers can then explore the management options and environments of their choice. The corresponding indicator values are presented in relative terms compared to the reference option. All options explored during the discussion are reported in a communication tool, the summary handout (Fig. 2, T2) that summarizes the content of the exchange and the relative changes in indicators values.

Although this framework may seem linear, the actions can be mixed for practical reasons. Depending on the nature of the project, and the reactions of the participants, this process can be repeated several times starting on actions 1, 2, or 3 once a first cycle has been completed.

2.3 Communication tools

Two communication tools are part of the present framework: a communication tool (T1) containing the basket of contextualized options and a summary handout (T2). T1's main purpose is to ease the researchers' work when presenting and discussing specific situations with farmers in A6 and to avoid the distraction that can occur when having a computer in the room (Carberry et al. 2004). It also aims at gathering the model's outputs translated into farmers' indicators. The researchers can use T1 to discuss with farmers and navigate between the various options and contexts without necessarily needing to be the one that ran the models and created the communication tool. T1 can take various forms, such as radar charts, tables, drawings, depending on the indicators considered and the way they are going to be used in the communication process with farmers.

The summary handout helps to construct a coherent discussion. First, a baseline corresponding to the current farmers' situation is established. Then, one after the other, the differences between the options considered by the farmer are highlighted for each indicator with visual aids. It also aims at providing farmers with a record of the discussions that took place and that they can bring home.

2.4 Case study: implementation of the framework

2.4.1 Burkina Faso–Arbollé: site and farmer group description

We worked with a group of 15 farmers (six women and nine men of all ages) from Arbollé (12° 50′ 40″ N, 2° 02′ 18″ W), in the region Nord of Burkina Faso. This area is characterized by a Sudano-Sahelian climate with average annual precipitation around 650 mm between June and October. Average daily temperatures range from 20 to 35 °C. Rainfed cropping systems include sorghum, pearl millet, cowpea, and groundnut with the primary purpose of producing staple food. The main biophysical challenges for cropping systems in this area are nutrient management, dry spells, and parasitic weeds (*Striga* sp.) (e.g., Félix 2019 and references therein).

2.4.2 Reaching out to the farmers' world: A1 to A3

Three workshops were held on April 29th, May 5th, and August 18th of 2022, with the entire group of farmers, and a field visit took place on August 10th with five farmers from the group. All these meetings aimed at addressing A1 to A3; their content and chronology are presented in Table 1. From the beginning of the workshops, the aim of the project was clearly exposed to the farmers, and researchers dedicated some time during each workshop to share knowledge on soil and plant functioning with farmers as well as answering any question arising from the discussion. Sorghum was chosen as an example crop as it is the most cultivated cereal in the area by both women and men. To anchor the presentation

Table 1 Collective workshop aims, activities, and main outputs. A1, A2, and A3 indicate actions of the framework.

	Workshop 1 (29/04/2022)	Workshop 2 (5/05/2022)	Field meeting (10/08/2022)	Workshop 3 (18/08/22)
Aim	- Meeting with farmers - Project presentation - Introduction to crop modeling	- Gathering information about farmers' context - Presentation of possible uses of models	- Identification of indicators used by farmers to evaluate crop growth and soil fertility during cropping season	- Prepare for individual activities - Test crop model output presentation (sorghum yields with farmers' management on generic soils)
Activities	- Description of sorghum management by farmers (A1 and A3) - "What if…?" questions: using farmers' experience to explain crop modeling (A1)	- Identification of indicators used by farmers to assess sorghum performance (A3) - Description of their soils and how they evaluate their fertility (A3) - Presentation of possible use of crop models (A1)	- Field visit (A3) - In situ discussion on the indicators farmers use to assess crop performance and soil fertility (A3)	- Presentation of soil organic matter and nutrient supply functioning (A2) - Presentation of simulation outputs and confrontation to farmers' estimates (A1) - Survey on the management options to be explored (A3)
Main outputs	- Most common sorghum crop management - Measurement units and vocabulary used by farmers	- Description of four soil types (Table 2) - Indicators used to describe and assess crop performance and soil fertility (Tables 2 and 3) - Farmer interest for continuing the project	- Indicators used to describe and assess crop performance and soil fertility (Tables two and three)	- Common representation of soil organic matter and nutrients - Alignment between crop model outputs and farmers' estimates - Need to parametrize farmers' soil types - Agronomical question: "soil fertility management through manure and compost applications" - System under consideration: "sorghum crops in the fields of Arbollé"

of crop model concepts and uses in farmers' context during A1, farmers were solicitated to describe their cropping systems and to share their experience for comparison with the simulated sorghum yields on two generic soils (sand and silty-loam).

2.4.3 Within the researchers' world: A4 and A5

Before starting discussions with farmers, researchers identified three crop models—DSSAT (Jones et al. 2003), Samara (Kumar et al. 2016), and STICS (Brisson et al. 2003)—that were calibrated for soils and sorghum cultivar common in the region (Akinseye et al. 2017; Adam et al. 2018; Traoré et al. 2022). These three crop models, complementary, offered the possibility to explore topics from Genotype × Environment comparisons to cropping systems scale questions. It is only once the agronomical question of interest for farmers had been defined (Workshop 3—Table 1) that DSSAT was selected amongst the three above-cited as it suited the agronomical question. T1 was a set of tables containing simulation outputs, gathering management options and farmers-proposed indicators for one given field. For the researchers, having all indicators and management options in the same table aimed at navigating more easily among management practices as farmers were expected to focus on one field at the time.

2.4.4 Back to the farmers: A6

The researchers held individual discussions with farmers and considered their reactions to the assessment of contextualized management options. The latter were recorded in the summary handout, taking the form of a table with a simplified representation of the indicators' trends. The changes relative to the initial situation were represented with pictograms of different colors. The summary handout was completed and commented during the discussion and handed over to farmers.

3 Results and discussion

This section follows the three main phases of the framework from the point of view of the researchers that conducted the work. Researchers first reached out to farmers' world. Secondly, they used farmers' information as input in the selected crop model and prepared communication tools. Thirdly, they went back to farmers to present and discuss the outputs of the contextualized model. This section ends with a reflection on the value of the framework and the opportunities it offers.

3.1 Reaching out to the farmers' world (actions 1, 2, and 3)

Discussions with farmers during the collective workshops covered the first three actions of the framework (Table 1).

3.1.1 Project initialization (action 1)

During the project initialization activities (Table 1), farmers' description of sorghum management allowed researchers to explain how this information served as inputs to crop models. Similarly, farmers' explanations of sorghum growth throughout the season allowed to explain how crop models function.

Farmers' sorghum crop management described in workshop 1 (Table 1) was used to simulate sorghum yield on generic soils through DSSAT and yield outputs were presented to farmers in workshop 3 to exemplify what could be done through modeling. The confrontation of sorghum yield obtained from simulations (3 to 13 bags/ha accross soil types and practices) to farmers' estimates (3 to 15 bags/ha accross soil types and practices) revealed convergent yield estimates (Sup. Mat. 1). Though the model (dealing with potential growth, water, and N stress) did not capture all the processes leading to actual yields (weed competition, pests or P and K stresses), the alignment between farmers' estimates and the simulations confirmed the possibility to present a reference cropping system that matched farmers' experience. When dealing with the effects of increasing the amount of manure applied before tillage (increasing quantity by 5 carts) on sorghum yield on a silty loam soil, the yield increase expected by farmers (3 bags) was more optimistic than model's simulation (1 bag; Sup. Mat 1). The questions about expected and simulated yields generated animated discussions amongst farmers.

A learning arising from the presentation of crop model outputs to farmers was the importance of considering farmers' own soils. The generic silty loam soil of the crop model was translated to "Zii kiemde" in the local language (Mooré). Before indicating their sorghum yield expectation on that soil type, farmers asked themselves who had "Zii kiemde" soils in their farm. One farmer had it, as well as some neighbors of participating farmers and these fields were used by participating farmers as references to provide a yield estimate. This process echoes the fact that farmers have their own controls when experimenting (Hansson 2019) and that refining soil input is important when working with crop models with farmers (Whitbread et al. 2010).

3.1.2 Definition of the agronomical question (action 2)

At the end of the workshops, farmers mentioned the management options they wanted to explore: "stone lines," "Sorghum varieties comparison," and "comparison between manure and compost application" were mentioned. Soil fertility management had been of interest for farmers from the beginning and appeared to appeal to all farmers present. Thus, the agronomical question was formulated by researchers as "soil fertility management through manure and compost applications" and the systems of interest were the "sorghum crops in the fields of Arbollé." In order to build a common understanding of soil fertility, the researchers presented the role of organic matter for nutrient supply following the "plate of food" comparison (Marinus et al. 2021). The agronomical question embedded within a specific context allowed both worlds to exchange on crop management and its impact on cropping system performances. On the one hand, it was understood by farmers based on their local knowledge and experience of sorghum response to contrasting organic amendments as well as soil fertility change over years, within their own and neighbors' fields. On the other hand, researchers did not have the local knowledge of sorghum response to local soil fertility levels and management. Within their world, they interpreted the agronomical question through their generic knowledge of soil texture, organic matter and nutrient cycles, and sorghum crop growth and development.

3.1.3 Characterization of the environments, the management options, and the indicators to describe the system under consideration (action 3)

Soil characteristics as described by farmers are reported in Table 2. Sorghum crop management had already been described in A1. Farmers asked to compare manure (raw animal faeces) and compost (decomposed mix of animal faeces and other organic matter) in applications of 0 to 30 carts (about 5 t) per hectare through 5 cart increments (except for 25).

Throughout A1 to A3 of the framework, researchers identified concepts, indicators, benchmarks, and units used by farmers to describe their cropping systems. For example, they determined the appropriate management application dates based on indicative tree species and/or rainfall. Farmers used carts and bags to measure yield, carts for organic amendment application, spacing between thumb

Table 2 Description of soil properties by farmers (A) complemented with literature sources (B) and their translation into DSSAT inputs (C).

	Local soil name	Baongo	Zegdega	Zii Miuwa	Zii Naaré
A—farmers' description of soil characteristics	Texture	Clayey with high water accumulation.	Gravelly, a lot of gravel on the surface, clayey.	Sandy with a bit of red clay.	Clayey, not a lot of sand nor gravel.
	Relative fertility ranking	+	-	- -	+ +
	Water holding capacity	High water holding capacity, poor drainage leading to excess water.	Low water holding capacity.	Low water holding capacity, easily drying out.	High water holding capacity.
	Sorghum growth	Sorghum may suffer from waterlogging.	Sorghum leaves are yellow at harvest.	Sorghum can be cultivated in those soils but is less adapted than pearl millet.	Sorghum leaves are green at harvest, better grain and forage quality. Better plant resistance during dry spells.
	Other comments	In low rainfall years, yields can be better in Baongo than in Zii naaré Lowland fields.	Zegdega are located few meters above Zii Naaré.		Zii Naaré are located few meters below Zegdega.
B—literature sources	Schutjes and van Driel (1994)	Loam and clay loam	Gravels > 20%		
	Félix (2019) p.84		Texture comparable to Zii Naaré (silty loam).		Texture comparable to Zegdega (silty loam).
C—soil inputs for DSSAT	Soil texture	Clay loam	Silty loam	Sandy loam	Silty loam
	DSSAT generic soil	HC - *HC_GEN0014	Soil - *IB00000005	Soil - *IB00000008	Soil - *IB00000005
	% clay	30	10	10	10
	% sand	45	30	60	30
	% silt	25	60	30	60
	% stones	0	40	0	0

and the little finger for soil depth and plant spacing. A bag of sorghum grain weighed 100 kg while a cart of manure was estimated at 167 kg (values provided by INERA). Farmers considered many in-field indicators to evaluate the performance of sorghum (Table 3, Column A).

Soil quality was important for farmers. Water holding capacity appeared to be an important factor for soil appraisal by farmers. Two concepts were highlighted: "soil softness" ("tenga bougsma" in mooré) and "plant food" ("kooda riibô"). Soil softness, with "soft soils" being more easily tilled and with better water holding capacity than "hard soils," seems to be related to some extent to soil texture and structure. It was clear from farmers' explanations that organic matter played an important role as one stated: "as long as we bring organic amendment [to a field], 'soil softness' only increases." It was hypothesized that organic matter content could be used as a proxy for "soil softness." "Plant food" referred to nutrients available to crops. Identifying and using, when possible, the concepts that farmers were familiar with, eased the dialogue with farmers. The discussion around soils also highlighted that farmers' knowledge of their soil depth and "softness" can match some of researchers' soil fertility indicators (Berazneva et al. 2018).

3.2 Within the researchers' world (actions 4 and 5)

3.2.1 Crop model parametrization (action 4)

Farmers wanted to deepen their knowledge on the effects of manure and compost amendments on sorghum. The researcher decided to use DSSAT 4.7 for its ability to simulate the impact of contrasting fertilization strategies on nutrient supply and crop growth (Soler et al. 2011). Using the four soils descriptions made by farmers (Table 2, A) to parametrize soils was challenging: farmers classified soils with their own method (Schutjes and van Driel 1994) and focused on sorghum growth, water holding capacity, and comparisons between contrasting fields to describe soils (Table 2, A). Using soil vernacular names and corresponding textures found in literature (Schutjes and van Driel 1994; p.84, Félix 2019; Table 2, B), researchers matched farmers' soils to three generic soil types from the DSSAT soils database (Table 2, C). Elements of Zii naaré and Zegdega descriptions were provided by farmers and literature

Table 3 Indicators mentioned by farmers, potentially corresponding DSSAT outputs and chosen indicators. [1]These indicators were not presented to farmers due to difficulties encountered to (re)present them.

Indicators observed at	A—indicators mentioned by farmers	B—potential DSSAT variable	C—chosen indicator
Early stages	Emergence homogeneity	Plant population at emergence (plants/m^2; input variable)	
	Plant density	Plant population at seeding (plants/m^2; input variable)	
	Row spacing	Row spacing (cm; input variable)	
During growth	Disease presence	None	
	Leaf color	None	
	Parasitic plant presence	None	
	Plant and seed rot	Excess water stress index	Number of years with excess water stress
	Plant height	Plant height (cm)	Discarded[1]
	Plant volume	Vegetative biomass (t DM/ha)	Discarded[1]
	Stem diameter	Stem diameter (cm)	Discarded[1]
	Time before wilting during dry periods	Water stress index	Number of years with drought stress
Last stages and harvest	Biomass production	Biomass yield (t DM/ha)	Discarded[1]
	Grain production (based on number of bags collected)	Grain yield (t/ha)	Grain yield (bags/ha)
	Grain size	Thousand grain weight (g/1000 seeds)	Discarded[1]
	Panicle shape	None	
	Panicle size	None	
Additional indicators to capture the value of fertilization practices			Soil organic carbon (kg/ha)
			N applied (kgN/ha)
			N uptake (kgN/ha) N balance (kgN/ha)

suggesting a very similar texture, with soils differing mainly by gravel content and depth; the same DSSAT generic soil texture was use to parametrize them (Table 2). Because farmers knew soil depth and "softness," researchers further parametrized two soil depths (60 and 120 cm; except for Zegdega which are shallow soils thus only parametrized with 60 cm depth) and two levels of organic matter content (0.7% and 1.2%), resulting in four "quality" levels for Baongo, Zii miuwa and Zii naaré and 2 for Zegdega.

Sorghum management as described by farmers was relatively easy to translate into model inputs. Nonetheless, as farmers used rainfall and indicative plant species to decide when to perform the crop operations, finding the right input date for the model was challenging. These dates were chosen based on expert knowledge (values from INERA). Sorghum management was parametrized as follows: organic amendment was applied on the 15th of June, and 1 day afterwards, the soil was plowed to 10 cm depth. Manure (DSSAT's "Barnyard manure" set at 1.1%N and 0.5%P; Blanchard et al. 2014) and two compost qualities (DSSAT's "Compost"; low-quality set at 0.6%N and 0.2%P, Blanchard et al. 2014; good-quality set at 2.5%N and 0.53%P, Ganry and Badiane 1998) were parametrized. Due to the high nutrient content in good-quality compost, researchers took great care in later discussions to mention it was not easy to obtain such compost. Sowing of sorghum, variety CSM63E, occurred in the first days of July (once soil moisture at 20 cm depth reached 20%), and plant density was set to 62500 plants per hectare. Sorghum was harvested at maturity. The simulations were run for 5 years with weather data obtained from a weather station located in Yilou, Guibaré, Burkina Faso. Simulations were run for each contextualized management option by re-initializing the model every year, in order to capture climate variability. Model outputs were averaged over the five simulated years.

Zii Naaré was judged the most fertile soil type by farmers, followed by Baongo, Zegdega and Zii Miuwa, Zii Miuwa being the least fertile and where growing pearl millet should be preferred to sorghum according to farmers (Table 2, A). Simulated sorghum yields were in line with researchers' knowledge and farmers' relative soil fertility ranking. For example, simulated yield of sorghum grown without organic matter amendment were 922, 824, 802 and 419kg/ha for Zii Naaré, Baongo, Zii Miuwa (120cm depth), and Zegdega (60 cm depth) soils, respectively. This qualitative assessment confirmed that DSSAT was able to simulate farmers' context and management practices.

3.2.2 Translation of model outputs into farmer-proposed indicators (action 5)

The selection of model's outputs to be transformed into farmer-proposed indicators followed three principles: they should easily relate to farmers' experience and be relevant to the agronomical question; their number should be as small as possible to favor exploration of various management options; they should be expressed at the same scale (in space and time) to reduce possible confusion during discussion with farmers. Thus, the selection focused on field-level indicators expressed over several seasons to capture climate variability (Table 3, Column C).

Matching simulation outputs with farmer-proposed indicators was not straightforward. Farmers' indicators to evaluate crop performance were diverse and applied to different growth stages (Table 3, Column A). Grain and biomass yields were easily matched to corresponding simulation outputs. However, other indicators, such as plant volume and height, stem diameter, leaf color, panicle size and shape, and grain size, either could not be matched to existing DSSAT outputs or were associated to outputs that were too complex to describe to farmers (Table 3). Presenting these plant-level indicators could be overcome through the use of visuals, such as pictures for plant volume, height and diameter, and sorghum grain samples of different grain sizes (p.138, Faure et al. 2010). However, these are plant level indicators for which DSSAT provides a unique value, considering a homogeneous plant development in the field. This is not what happens in heterogeneous farmers' fields, which challenges the presentation of these plant-level indicators to farmers. Some indicators—emergence homogeneity, plant density, and row spacing—were considered in parametrizing crop management in DSSAT or discarded because DSSAT did not consider them (e.g., pests and weeds damage). Excess water stress and drought stress indicators were calculated as the number of years when such event happened over the 5 years of simulation. Because the agronomical question focused on soil fertility, researchers added soil organic carbon content (at the beginning and the end of one cropping year) as a proxy for soil organic matter and farmers' concept of "soil softness." Nitrogen uptake, nitrogen application, and nitrogen balance (N application - N uptake) were considered as additional indicators to discuss plant nutrition with farmers through the "plant food" concept.

The selected indicators were calculated for each soil type and gathered in a set of tables (T1) that was used for discussions with farmers (Table 4). The set of tables was composed of 14 pages, each one corresponding to one soil type and "quality" level. In each page, the indicators were presented for all the management options considered. As such, it constituted the basket of contextualized management options available to researchers to inform the discussions with farmers.

3.3 Back to the farmers' world (action 6)

Individual discussions allowed a personalized exploration of the basket of options following farmers' interests. It resulted

Table 4 Management options and the calculated indicators proposed by farmers for the Zii Naaré soil, 120 cm depth, and low organic matter content. One page example from the 14 pages the set of tables (communication tool; T1).

	Organic fertilizer applied (carts/ha; 1 cart ≈167 kg)	Grain yield (bags/ha; 1 bag = 100 kg)	Average soil organic carbon after one cropping season (t/ha) (initial content 35 t/ha)	N application (kg N/ha)	Average N uptake (kg N/ha)	N Balance (N application – N uptake) (kg N/ha)	Number of years (over 5) with water stress	Number of years (over 5) with excess water stress
Baseline	0	9	34.7	0	28	− 28	1	0
Manure	5	10	34.8	9	31	− 22	1	0
	10	11	35	18	33	− 15	1	0
	15	12	35.1	28	36	− 8	2	0
	20	13	35.3	37	39	− 2	2	0
	30	14	35.5	55	44	11	2	0
Low quality compost	5	9	34.8	5	28	− 23	1	0
	10	9	35	10	27	− 17	1	0
	15	9	35.1	15	27	− 12	1	0
	20	8	35.3	20	26	− 6	0	0
	30	8	35.6	30	24	6	0	0
Good quality compost	5	13	34.9	21	40	− 19	2	0
	10	16	35	42	52	− 10	2	0
	15	19	35.2	63	63	0	3	0
	20	21	35.3	84	72	12	3	0
	30	24	35.6	125	88	37	3	0

in the creation of a customized summary handout (Fig. 3) for each farmer that summarizes the discussions and translated model outputs on the impacts of management options within farmers' context.

Farmers were asked to select a soil type and to describe it with approximate soil depth, and "soil softness," as well as a reference management that fitted their own context, namely, the amount and nature of organic fertilizer they would usually apply before the cropping season. Once the researcher identified the most probable baseline management, farmer's estimated yield was compared to the simulated yield of this baseline situation (e.g., Fig. 3, 1). This necessary stage of the discussion was not straightforward as farmers did not always know the value of the required indicators (i.e.: soil depth, field size to compute the amount of manure applied, yield). When a farmer's description could not be related to an existing contextualized management option, the researchers chose the closest and explained the differences. An additional difficulty lied in the fact that contrary to model assumptions, farmer crop management is not homogeneous within one field, while their yield estimate usually referred to the whole field (Tittonell et al. 2015; Félix et al. 2018). After the description and discussion of the reference situation, farmers changed one management option or soil type at a time, and the impact of the changes was discussed with the aid of the summary handout visual (Fig. 3, row 1 for the baseline and row 2 for the new management option considered).

During the process, farmers asked for information about their particular situation. When offered to choose the soil, they mentioned their own, stating that "it is better to look at what you have. If you look at another soil that you do not have, you will listen but you will not know what to do with it." Furthermore, farmers explored the contextualized management options based on their own implementation capacity, saying "I want to see the good quality compost, 15 carts, it is better to choose a quantity that we can produce." Some asked researchers "to show [them] what will be sufficient" to "avoid soil resource withdrawal" (i.e., negative nitrogen balance). During the discussion farmers cultivating several fields with different soil types did not hesitate to change soil type and management options. Including the reference, between three and seven contextualized management options were explored and discussed with each farmer (Sup. Mat. 2).

When discussing the simulated changes and underlying processes, farmers received the information critically. They often commented by comparing with their knowledge. For example, reacting to diminishing soil organic carbon and negative nutrient balance a farmer stated "It is true, what we noticed is that often the soil is not able to retain organic amendment." Another farmer was not afraid to challenge the

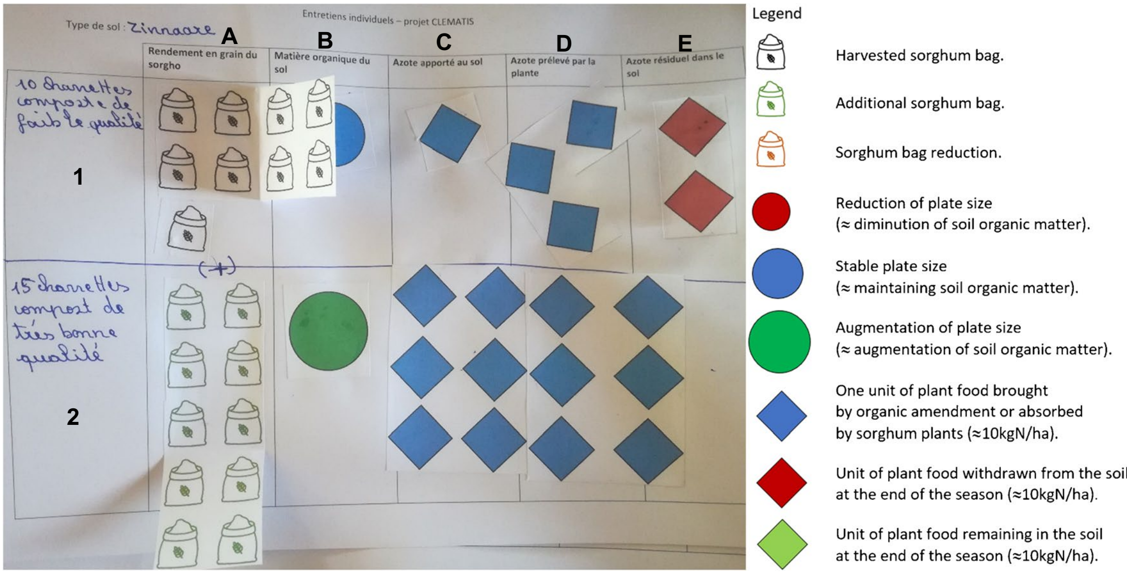

Fig. 3 A summary handout filled during the discussion with a farmer (left) and the accompanying legend (here translated in English) that was provided (right). The soil chosen by the farmer was "Zii Naaré" with low organic matter content and 120 cm depth. Column A: Sorghum grain yield in bags per hectares; column B: change in soil organic matter content at the end of the season; column C: nitrogen input to soil by organic amendment; column D: nitrogen uptake by sorghum; column E: nitrogen balance. Row 1: "10 carts of low-quality compost" which constituted the baseline situation described and confronted to farmers' experience; row 2: "15 carts of good quality compost" which was the management option selected by the farmer

information given. When discussing the effects of 15 carts of good quality compost on Zegdega soil, he stated: "do you speak of my Zegdega? Zegdegas are not all the same. There are Zegdegas where 15 carts of compost will be very good for the soil, but in mine, it would be merely enough." These reactions support the idea that researchers were able to anchor the discussion into farmers' reality. Furthermore, it suggests that the information will be used by some farmers to formulate their own hypothesis regarding their particular situation (Hansson 2019) and that the "actual relevance to a farmer depends in part on demonstration of the model's credibility against his known 'real world facts'" (McCown 2002).

During the exchanges, farmers often nuanced the outputs saying that "it depends on the rain." Researchers presented outputs averaged over 5 years of simulations, while farmers use specific climatic years as references to confront new results (Hansson 2019). Because climatic and soil data are key in successful farmers' engagement (Whitbread et al. 2010), averaged values could be complemented with the detailed description of some representative climatic years to further discuss the results when necessary.

The discussions of contextualized management options and associated processes sparked many broader questions from farmers. Recurring ones focused on how to produce good-quality compost and on what happened to "plant food" when the balance was either positive or negative.

3.4 General discussion on the framework

3.4.1 The crop model is not central in the framework…

Using a shared agronomical question embedded in farmers' context to structure the exchanges with farmers favored the understanding of the system under consideration, in line with previous studies (e.g., Cash et al. 2003; Thorburn et al. 2011). Because the researchers did not know which questions would be of interest to farmers, they had to first understand the farmers' environment and constraints. Furthermore, the perspective of presenting model outputs to farmers with the use of farmers' indicators forced the researchers to deepen their understanding of the observation and interpretation farmers made of their cropping systems.

On the farmers' side, we argue that organizing the exchanges around an agronomical question instead of a crop model facilitated their involvement. Indeed, during the workshops, most of the time was dedicated to let farmers express themselves regarding their own environment, cropping system, and problems they wished to explore as well as asking their opinion on the outputs presented. Thus, the exchanges with farmers revolved around their knowledge and their experience, improving the credibility of the approach, the model outputs, and associated knowledge shared.

In addition, organizing the discussions between farmers and researchers around an agronomic problem (i.e., question-driven approach) rather than around a specific crop model (i.e., tool-driven approach) increased the flexibility of the use of the framework. It allowed researchers to clearly understand farmers' contexts and preoccupations and later select the most appropriate model to address it. In the case study, in addition to the exploration of "soil fertility management through manure and compost applications for sorghum production in the fields of Arbollé," open discussions led to the alternative proposition of "sorghum cultivar comparisons in Arbollé" as an agronomical problem to tackle. If we would have decided to work on this, the crop models Samara, APSIM, or DSSAT could have been chosen, depending on the farmers' interest for indicators and development stages (Akinseye et al. 2017). Had the suggestion of discussing "stone lines" been more appealing to farmers, it could have led to mobilizing water erosion modeling (Visser et al. 2005) to quantify some of the impact of this improved management. Finally, the choice for a particular crop model can also be motivated by its ability to produce outputs matching indicators proposed by farmers.

As presented, the framework is organized around an agronomical question with two worlds sharing it and interacting around it. Nonetheless, it could be extended by integrating other worlds such as those of advisors, extension agents, or policy makers. Participants of the additional worlds can share their views, knowledge, and expectations with regard to the agronomical question. Then, researchers can mobilize modeling to substantiate the discussions with quantified outputs. In a setting involving the perspectives from several worlds, different models can be combined to explore the problem at multiple scales, e.g., a mechanistic model to assess biophysical outputs at field level and a multicriteria assessment tool to analyze socio-economic variables at the farm level and environmental variables at the landscape level (Queyrel et al. 2023). Lastly, the involvement of extension agents can contribute to capacitate them to co-design and learn about relevant innovations, before engaging in scaling-out activities.

3.4.2 … but communication tools are central

The communication tools that are generated during the process are a central piece of the framework. Indeed, they aim at (i) gathering the basket of options and the indicators that are calculated and translated into farmers' indicators and (ii) keeping track of the discussions and create a personalized hand-out of the discussions. One of the challenges identified by researchers was the way to share indicators and exemplify the effects associated with a change in practice. Even though symbols were used to represent the value of indicators, using more concrete representations such as samples of various grain sizes to exemplify the impact of a practice on grain size could facilitate even more the discussions. Also, the summary hand-out should be designed in such way that it helps keeping track of the discussions but most importantly so that farmers can understand it later on when revising it or using it in discussion with other farmers. With that purpose, the symbols, vocabulary, and concept mobilized must be adapted to farmers' knowledge and representations.

3.4.3 Opportunities for scaling-out

This framework is time consuming: we dedicated 3 workshops sessions to Phase I and pursued Phase III (exploration of contextualized options) individually with farmers. This resulted from a methodological choice to facilitate farmer's expression in the last part by avoiding peer pressure (self-censoring) or discussion revolving around only few members of the group. It also eased the creation and personalization of the summary handout (T2). Nonetheless, in an effort to scale-out the innovations arising from the application of the framework, several options exist. First, explorations of management practices should be done with small groups of farmers sharing similar specific contexts as working with groups of farmers should foster knowledge exchange between farmers (Šūmane et al. 2018). Second, if the group of farmers is representative of a village, the communication tools could be easily reused with other farmers from the same village to discuss the management practices within their context. These suggestions however raise questions on how to adapt the summary handout creation to group works as it aims at being specific to each farmer's questioning and context.

Furthermore, Hellin et al. (2008) argued that benefits for farmers were more likely to arise from long-term interaction with extension services and as a consequence participatory research should consider the strengthening of skills and knowledge of extension agents. Millar and Connell (2010) also reported that one key element in scaling out was the training of extension agents. Thus, with an objective of large-scale impact, the present framework could be used in an initial phase with both farmers and advisors to identify and characterize the environments and relevant management practices to address the considered agronomical question, consequently developing the communication tools. The advisors could then be trained in using these communication tools before applying them in other areas, with similar environments. After explaining the process used to obtain the values to the farmers, the advisors could proceed with action 6 with farmers and accompany them in their exploration of the problem considered.

3.4.4 From changing cropping practices to system redesign and examining broader issues

In this study, we explored options to improve crop management that leveraged local resources. Improving manure management and application to the field is critical to improve crop productivity. Yet, these incremental changes alone are unlikely to bring the drastic increase in productivity required to improve smallholder livelihoods (Rusinamhodzi 2015) and to guarantee long-term soil fertility (Falconnier et al. 2023). Broader changes at the farming system level and in the socio-economic environment of farms are required to sustainably lift smallholder farmers out of poverty (Falconnier et al. 2018; Giller et al. 2021). These changes include for example the growing of more legumes and improving forage and manure management in mixed farming systems (Assogba et al. 2023), or payments for ecosystem services (Jourdain et al. 2014). The impact of these broader changes can be explored with the use of farm models, for example, bio-economic models that help design farm configurations that improve income and food security given a set of farmers' constraints (Ricome et al. 2017; Lairez et al. 2023). We believe that the framework developed in this study around crop models could be adapted for the use with a farm model. The matrix of options would then consist of different farm configurations. These farm models include equations and formalisms that correspond to researchers' conceptualization. The framework here offers the opportunity to build bridges between researchers' and farmers' knowledge on optimal farm configurations for better food security, income, and environmental performance.

4 Conclusion

We presented a novel framework for the use of crop models in participatory research. The framework aims at facilitating the discussion between farmers and researchers through the simulation of multiple scenarios embedded in farmers' context so they can identify with and relate to these scenarios. It involves the design and use of two communication tools, one to foster discussions and the other to create a record of it. During the testing of the framework on soil fertility management for sorghum production in Burkina Faso, both farmers and researchers shared knowledge on the drivers of cropping system performance. They were able to discuss locally relevant management practices. As hypothesized, and despite some necessary approximations, farmers' description of their environment and management practices, complemented by literature, were sufficient to parametrize the model used. Secondly, the main farmer-proposed indicators could be matched to relevant model outputs to share quantified examples of practice changes. Nonetheless, it raised questions of model outputs adaptation to smallholder farming context as for example, within-field plant heterogeneity was not simulated in our case, complicating the use of many farmer-proposed indicators. Lastly and concordant with our hypothesis, the basket of contextualized options was credible enough to anchor the discussions into each farmer's reality and discuss alternative practices and their impact. By putting an emphasis on understanding farmers' understanding and observation of their context, crop and environment with the aim of properly parametrizing models and sharing the results of simulation, the framework formalized in this work revealed itself as a powerful process for researchers to identify key concepts to better communicate with farmers. It raised questions on how to appropriately capture the content of discussions in a take-away format and the ability of models to produce proxies to farmer-proposed indicators. Although tested with soil fertility management questions, this method could help in addressing a wider variety of problems through several cycles of use or in combination with other activities.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-024-01001-2.

Acknowledgements The authors are grateful to the farmers who participated in the study. The authors are thankful to the project FAIR-Sahel and its funders, the European Union, the Agence Française de Développement (AFD), the Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), and the Institut de Recherche pour le Développement (IRD). They thank Thomas Cheriere for the graphic design of Fig. 2 and the three anonymous reviewers for their valuable contribution to improve the manuscript.

Author contributions Conceptualization: T.C., K.D., G.F., J.L., and M.A.; investigations: T.C., K.D., A.G., J.L., H.S., and M.A.; writing—original draft preparation: T.C., K.D., and M.A.; writing—review and editing: T.C., K.D., G.F., A.G., J.L., H.S., and M.A.; funding acquisition: K.D., G.F., and M.A.

Funding This project (ID 2002-233) was funded through LabEx AGRO 2011-LABX-002 (under I-Site Muse framework) coordinated by Agropolis Fondation.

Data availability DSSAT input files created for the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The manuscript does not contain clinical studies or patient data.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication All participants to the study gave informed consent to the anonymous publication of the information collected during the project.

Conflict of interest The authors declare no competing interests.

References

Adam M, Dzotsi KA, Hoogenboom G et al (2018) Modelling varietal differences in response to phosphorus in West African sorghum. Eur J Agron 100:35–43. https://doi.org/10.1016/j.eja.2018.04.001

Akinseye FM, Adam M, Agele SO et al (2017) Assessing crop model improvements through comparison of sorghum (sorghum bicolor L. moench) simulation models: a case study of West African varieties. Field Crops Res 201:19–31. https://doi.org/10.1016/j.fcr.2016.10.015

Assogba GGC, Berre D, Adam M, Descheemaeker K (2023) Can low-input agriculture in semi-arid Burkina Faso feed its soil, livestock and people? Eur J Agron 151:126983. https://doi.org/10.1016/j.eja.2023.126983

Berazneva J, McBride L, Sheahan M, Güereña D (2018) Empirical assessment of subjective and objective soil fertility metrics in east Africa: implications for researchers and policy makers. World Dev 105:367–382. https://doi.org/10.1016/j.worlddev.2017.12.009

Blanc L, Rezgui F, Hossard L et al (2024) Performance of co-designed diversified Mediterranean cropping systems: hybridizing stakeholders' knowledge and modelling data. Eur J Agron 159:127282. https://doi.org/10.1016/j.eja.2024.127282

Blanchard M, Coulibaly K, Bognini S et al (2014) Diversité de la qualité des engrais organiques produits par les paysans d'Afrique de l'Ouest : quelles conséquences sur les recommandations de fumure ? Biotechnol Agron Soc Env 18:512–523

Brisson N, Gary C, Justes E et al (2003) An overview of the crop model stics. Eur J Agron 18:309–332. https://doi.org/10.1016/S1161-0301(02)00110-7

Carberry P, Gladwin C, Twomlow S (2004) Linking simulation modelling to participatory research in smallholder farming systems. ACIAR Proc

Cash DW, Clark WC, Alcock F et al (2003) Knowledge systems for sustainable development. Proc Natl Acad Sci 100:8086–8091. https://doi.org/10.1073/pnas.1231332100

Coquil X, Cerf M, Auricoste C et al (2018) Questioning the work of farmers, advisors, teachers and researchers in agro-ecological transition A Review. Agron Sustain Dev 38:47. https://doi.org/10.1007/s13593-018-0524-4

Côte FX, Rapidel B, Sourisseau JM et al (2022) Levers for the agroecological transition of tropical agriculture. Agron Sustain Dev 42:67. https://doi.org/10.1007/s13593-022-00799-z

Descheemaeker K, Ronner E, Ollenburger M et al (2019) Which options fit best? Operationalizing the socio-ecological niche concept. Exp Agric 55:169–190. https://doi.org/10.1017/S001447971600048X

Dogliotti S, García MC, Peluffo S et al (2014) Co-innovation of family farm systems: a systems approach to sustainable agriculture. Agric Syst 126:76–86. https://doi.org/10.1016/j.agsy.2013.02.009

Duru M, Therond O, Fares M (2015) Designing agroecological transitions; a review. Agron Sustain Dev 35:1237–1257. https://doi.org/10.1007/s13593-015-0318-x

Falconnier GN, Cardinael R, Corbeels M, et al (2023) The input reduction principle of agroecology is wrong when it comes to mineral fertilizer use in sub-Saharan Africa. Outlook Agric 00307270231199795. https://doi.org/10.1177/00307270231199795

Falconnier GN, Descheemaeker K, Traore B et al (2018) Agricultural intensification and policy interventions: exploring plausible futures for smallholder farmers in Southern Mali. Land Use Policy 70:623–634. https://doi.org/10.1016/j.landusepol.2017.10.044

Falconnier GN, Descheemaeker K, Van Mourik TA et al (2017) Co-learning cycles to support the design of innovative farm systems in southern Mali. Eur J Agron 89:61–74. https://doi.org/10.1016/j.eja.2017.06.008

Faure G, Gasselin P, Triomphe B, et al (2010) Innover avec les acteurs du monde rural. éditions Quae

Félix GF (2019) Slash-and-mulch exploring the role of shrub-based agroforestry systems for smallholder farmers in the Sahel. Wageningen University

Félix GF, Diedhiou I, Le Garff M et al (2018) Use and management of biodiversity by smallholder farmers in semi-arid West Africa. Glob Food Secur 18:76–85. https://doi.org/10.1016/j.gfs.2018.08.005

Ganry F, Badiane A (1998) La valorisation agricole des fumiers et des composts en Afrique soudano-sahélienne. Diagnostic et perspectives. Agric Dév

Giller KE, Delaune T, Silva JV, et al (2021) Small farms and development in sub-Saharan Africa: farming for food, for income or for lack of better options? Food Securhttps://doi.org/10.1007/s12571-021-01209-0

Hansson SO (2019) Farmers' experiments and scientific methodology. Eur J Philos Sci 9:32. https://doi.org/10.1007/s13194-019-0255-7

Hellin J, Bellon MR, Badstue L et al (2008) Increasing the impacts of participatory research. Exp Agric 44:81–95. https://doi.org/10.1017/S0014479707005935

Jakku E, Thorburn PJ (2010) A conceptual framework for guiding the participatory development of agricultural decision support systems. Agric Syst 103:675–682. https://doi.org/10.1016/j.agsy.2010.08.007

Jones JW, Hoogenboom G, Porter CH et al (2003) The DSSAT cropping system model. Eur J Agron 18:235–265. https://doi.org/10.1016/S1161-0301(02)00107-7

Jourdain D, Boere E, van den Berg M et al (2014) Water for forests to restore environmental services and alleviate poverty in Vietnam: a farm modeling approach to analyze alternative PES programs. Land Use Policy 41:423–437. https://doi.org/10.1016/j.landusepol.2014.06.024

Kumar U, MaR L, Soulié J-C et al (2016) Compensatory phenotypic plasticity in irrigated rice: sequential formation of yield components and simulation with SAMARA model. Field Crops Res 193:164–177. https://doi.org/10.1016/j.fcr.2016.04.036

Lairez J, Jourdain D, Lopez-Ridaura S et al (2023) Multicriteria assessment of alternative cropping systems at farm level. A case with maize on family farms of South East Asia. Agric Syst 212:103777. https://doi.org/10.1016/j.agsy.2023.103777

Leigh Star S (2010) This is not a boundary object: reflections on the origin of a concept. Sci Technol Hum Values 35:601–617. https://doi.org/10.1177/0162243910377624

Marinus W, Descheemaeker KKE, van de Ven GWJ et al (2021) "That is my farm" – an integrated co-learning approach for whole-farm sustainable intensification in smallholder farming. Agric Syst 188:103041. https://doi.org/10.1016/j.agsy.2020.103041

Martin G (2015) A conceptual framework to support adaptation of farming systems – development and application with Forage Rummy. Agric Syst 132:52–61. https://doi.org/10.1016/j.agsy.2014.08.013

McCown RL (2002) Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. Agric Syst 74:179–220. https://doi.org/10.1016/S0308-521X(02)00026-4

Millar J, Connell J (2010) Strategies for scaling out impacts from agricultural systems change: the case of forages and livestock production in Laos. Agric Hum Values 27:213–225. https://doi.org/10.1007/s10460-009-9194-9

Périnelle A, Meynard J-M, Scopel E (2021) Combining on-farm innovation tracking and participatory prototyping trials to develop legume-based cropping systems in West Africa. Agric Syst 187:102978. https://doi.org/10.1016/j.agsy.2020.102978

Queyrel W, Van Inghelandt B, Colas F et al (2023) Combining expert knowledge and models in participatory workshops with farmers to design sustainable weed management strategies. Agric Syst 208:103645. https://doi.org/10.1016/j.agsy.2023.103645

Ricome A, Affholder F, Gérard F et al (2017) Are subsidies to weather-index insurance the best use of public funds? A bio-economic farm model applied to the Senegalese groundnut basin. Agric Syst 156:149–176. https://doi.org/10.1016/j.agsy.2017.05.015

Ronner E, Sumberg J, Glover D et al (2021) Basket of options: unpacking the concept. Outlook Agric 50:116–124. https://doi.org/10.1177/00307270211019427

Rossing WAH, Meynard JM, van Ittersum MK (1997) Model-based explorations to support development of sustainable farming systems: case studies from France and the Netherlands. Eur J Agron

Rusinamhodzi L (2015) Tinkering on the periphery: labour burden not crop productivity increased under no-till planting basins on smallholder farms in Murehwa district, Zimbabwe. Field Crops Res 170:66–75. https://doi.org/10.1016/j.fcr.2014.10.006

Schutjes AHM, van Driel WF (1994) La Classification Locale des Terres par les Mossi: Paysans et Pedologues parlent-ils le meme Langage? Contribution au 1er Colloque International de l'AOCASS: Gestion Durable des Sols et de l'Environnement en Afrique Tropicale, Ouagadougou, 6-10 Décembre 1994. Aménagement et Gestion de l'Espace Sylvo-Pastoral au Sahel, Wageningen Agricultural University, The Netherlands, Wageningen, pp 1–12

Soler CMT, Bado VB, Traore K et al (2011) Soil organic carbon dynamics and crop yield for different crop rotations in a degraded ferruginous tropical soil in a semi-arid region: a simulation approach. J Agric Sci 149:579–593. https://doi.org/10.1017/S0021859611000050

Star SL, Griesemer JR (1989) Institutional ecology, "translations" and boundary objects: amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39. Soc Stud Sci 19:387–420

Šūmane S, Kunda I, Knickel K et al (2018) Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. J Rural Stud 59:232–241. https://doi.org/10.1016/j.jrurstud.2017.01.020

Thorburn PJ, Jakku E, Webster AJ, Everingham YL (2011) Agricultural decision support systems facilitating co-learning: a case study on environmental impacts of sugarcane production. Int J Agric Sustain 9:322–333. https://doi.org/10.1080/14735903.2011.582359

Tittonell P, van Dis R, Vanlauwe B, Shepherd K (2015) Managing soil heterogeneity in smallholder african landscapes requires a new form of precision agriculture. In: Soil-Specific Farming Precision Agriculture., CRC Press,. Boston, London, New York, pp 199–224

Toffolini Q, Jeuffroy MH, Mischler P et al (2017) Farmers' use of fundamental knowledge to re-design their cropping systems: situated contextualisation processes. NJAS - Wagening J Life Sci 80:37–47. https://doi.org/10.1016/j.njas.2016.11.004

Traoré A, Falconnier GN, Ba A et al (2022) Modeling sorghum-cowpea intercropping for a site in the savannah zone of Mali: strengths and weaknesses of the Stics model. Field Crops Res 285:108581. https://doi.org/10.1016/j.fcr.2022.108581

van Paassen A, de Ridder N, Stroosnijder L (2011) Role of an explorative model for learning about sustainable agricultural development in Burkina Faso. Int J Agric Sustain 9:310–321. https://doi.org/10.1080/14735903.2011.582360

Visser SM, Sterk G, Karssenberg D (2005) Modelling water erosion in the Sahel: application of a physically based soil erosion model in a gentle sloping environment. Earth Surf Process Landf 30:1547–1566. https://doi.org/10.1002/esp.1212

Whitbread AM, Robertson MJ, Carberry PS, Dimes JP (2010) How farming systems simulation can aid the development of more sustainable smallholder farming systems in southern Africa. Eur J Agron 32:51–58. https://doi.org/10.1016/j.eja.2009.05.004