

Affordances of agricultural systems analysis tools: A review and framework to enhance tool design and implementation

Lenora Ditzler^{a,*}, Laurens Klerkx^b, Jacqueline Chan-Dentoni^{a,b,c}, Helena Posthumus^c, Timothy J. Krupnik^d, Santiago López Ridaura^e, Jens A. Andersson^{b,e}, Frédéric Baudron^f, Jeroen C.J. Groot^a

^a Wageningen University & Research, Farming Systems Ecology Group, P.O. Box 430, Wageningen 6700 AK, The Netherlands

^b Wageningen University, Knowledge, Technology and Innovation Group, Hollandseweg 1, Wageningen 6706 KN, The Netherlands

^c Royal Tropical Institute (KIT), Mauritskade 64, Amsterdam 1092 AD, The Netherlands

^d International Maize & Wheat Improvement Center (CIMMYT), Sustainable Intensification Program and CGIAR Research Program MAIZE, House 10/B, Road 53, Gulshan-2, Dhaka 1213, Bangladesh

^e International Maize & Wheat Improvement Center (CIMMYT), Sustainable Intensification Program, Apdo. Postal 6-641, Mexico City, DF 06600, Mexico

^f International Maize and Wheat Improvement Center (CIMMYT), 12.5 km Peg Mazowe Road, Harare, Zimbabwe

ARTICLE INFO

Keywords:

Farming systems analysis
Stakeholder participation
Fuzzy cognitive mapping
Bio-economic farm models
Role play and serious games
Literature review

ABSTRACT

The increasingly complex challenges facing agricultural systems require problem-solving processes and systems analysis (SA) tools that engage multiple actors across disciplines. In this article, we employ the theory of affordances to unravel what tools may furnish users, and how those affordances contribute to a tool's usefulness in co-design and co-innovation processes. *Affordance* is defined as a function provided by an object through an interaction with a user. We first present a conceptual framework to assess the affordances of SA tools. This framework is then applied in a literature review of three SA tools used in agricultural systems research (fuzzy cognitive mapping, bio-economic whole-farm models, and role play and serious games). Through this exercise, we extend the SA tool design and implementation dialogue by illuminating (i) links between lower-level affordances, tool design, and heuristic functioning, and (ii) the central role of use setting and facilitation in mobilizing higher-level, productive affordances. Based on our findings, we make five propositions for how SA tool design and implementation in participatory problem-solving settings can be improved.

1. Introduction

The challenge of reconciling food security and agricultural production issues within changing ecological conditions, political climates, market structures, and development goals (Foley et al., 2011; Godfray et al., 2010) requires problem-solving approaches suited for handling dynamic and entangled system variables and drivers. Incorporation of the divergent viewpoints of multiple stakeholders is equally crucial (Le Gal et al., 2011; Meynard et al., 2017; Schut et al., 2015). To identify practical solutions that are credible, salient, actionable, and legitimate, direct involvement of stakeholders in research on social-ecological systems (including agriculture) has been widely advocated (e.g. Cvitanovic et al., 2016; Fazey et al., 2014; Raymond et al., 2010; Reed et al., 2013). Stakeholder involvement is also part of current approaches that strive for what have been called co-design and co-innovation processes in agricultural systems (Botha et al., 2017; Dogliotti et al., 2014; Meynard et al., 2017). Assembling stakeholders, however,

is often not enough to move agriculture towards sustainable redesign (Berthet et al., 2016). Effective multi-stakeholder involvement in collaborative processes requires “mechanisms that promote change in understanding of the individuals involved and the cogeneration of new knowledge” (Reed et al., 2013, p. 318). Such mechanisms should facilitate knowledge exchange, co-learning, reframing of problems and solutions, and co-innovation (Hermans et al., 2017; Jones et al., 2017; Schindler et al., 2015; Voinov and Bousquet, 2010). This has implications for how scientists support stakeholder involvement: if scientific knowledge is to be “put to use” in the real world, participatory approaches must be aimed at catalyzing action (Geertsema et al., 2016; Schut et al., 2014).

In the agricultural sciences, a range of systems analysis (SA) tools have been applied to support problem solving in the context of co-design and co-innovation processes. These include, but are not limited to, computer-based models (e.g. Le Gal et al., 2011), cognitive mapping (e.g. Christen et al., 2015), serious gaming (e.g. Speelman et al., 2014),

* Corresponding author.

E-mail address: lenora1.ditzler@wur.nl (L. Ditzler).

innovation dynamics diagnostics (e.g. Schut et al., 2015), and decision support systems (e.g. Rose et al., 2016). SA tools facilitate integrated analyses of agricultural systems by incorporating environmental, economic, social, and political perspectives (van Ittersum et al., 2008). This enables assessment of the behavior and processes of interacting entities within a system (e.g. biophysical components, stakeholder concerns, market dynamics, policies, etc.). SA tools may also provide artifacts, visualizations, or discourses through which different actors can navigate both congruence and disagreement around key issues and decision making (Jakku and Thorburn, 2010; Klerkx et al., 2012a). While SA tools have the capacity to act in such a manner, an enduring challenge is to understand to what extent SA tools can be designed to function in this way.

Both long-standing (e.g. McCown, 2001) and more recent (e.g. Cerf et al., 2012; Jakku and Thorburn, 2010; Sterk et al., 2009) critiques citing the limited uptake of agricultural SA tools have called for a rethinking of how to enhance tool appeal and ease of use. Of key interest is the often-missing link between a tool's design and its intended use setting or target audience (Cerf et al., 2012; Prost et al., 2012; Ravier et al., 2016; Sterk et al., 2011), which may leave research results unused by stakeholders due to a tool's complexity and/or institutional, cultural, and language barriers (Cvitanovic et al., 2016). To this end, the participatory design and implementation of SA tools in agricultural systems settings has been widely advocated (e.g. Cerf et al., 2012; Delmotte et al., 2017; Jakku and Thorburn, 2010; Prost et al., 2012; Voinov and Bousquet, 2010). Why a participatory approach is needed has been well elaborated; however, *how* the design of SA tools contributes to their usefulness in collaborative problem-solving processes remains largely unexplored (Matthews et al., 2011).

We address this gap in light of current debates on next-generation SA tools in agriculture, which draw attention to the need for more collaborative, flexible, accessible, transparent, and interdisciplinary approaches to solving complex system problems (Duru et al., 2015; Janssen et al., 2017; Jones et al., 2017; Kragt et al., 2016; Martin, 2015). We consequently employ the concept of affordances, defined broadly as what an object provides in an interaction with a user (Gibson, 1979). Affordance theory has been applied in science and technology, education, and design studies. To our knowledge, however, it is unused in agricultural systems sciences. We hypothesize that affordance theory can help unravel links between *what* a tool furnishes users and *how* those affordances contribute to a tool's usefulness in participatory agricultural problem-solving processes. We posit that a better understanding of the affordances of SA tools, and therefore their potential and limitations, can inform how SA tools may be designed for improved affordance. Affordance analysis can also help identify how SA tools may need to be adapted or used complementarily in portfolios to meet the objectives of diverse users.

In this article, we present a conceptual framework for identifying and classifying the affordances furnished by SA tools in participatory problem-solving settings. Based on literature review, we demonstrate how this framework can be employed to assess three SA tools widely applied in agricultural systems: fuzzy cognitive mapping (FCM), bio-economic whole-farm models (BEFM), and role play and serious games (RPSG). Next, we discuss key contributions and limitations of the affordance framework to facilitating a better understanding of what SA tools provide in collaborative design and innovation processes, thereby exploring how they may enhance such processes. We conclude with five propositions for how SA tool design and implementation can be improved, with an emphasis on the role of affordances in participatory use settings.

2. Conceptual framework for affordance analysis of SA tools

2.1. Affordance theory

Gibson (1979) first defined affordances in the context of ecological

psychology: “The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill” (p. 127, italics original). Since Gibson's introduction, the concept has been adopted in other disciplines, notably in product design, science and technology studies, and educational studies, where it has been used primarily to understand what objects and technologies afford users and therefore to drive their design towards more intuitive and effective operation (Antonenko et al., 2017; Bower and Sturman, 2015; Srivastava and Shu, 2013). As our focus is on SA tool design and implementation, we draw most from the affordance literature in the design field to build our conceptual framework.

Central in the literature is the notion that affordances emerge from an “entangled relationship” (Maier and Fadel, 2009), that is, the interaction between designers, artifacts,¹ and users (Bernhard et al., 2013; Norman, 2013). While a designer can to some extent direct the way an artifact is used by designing it with specific affordances in mind (Maier and Fadel, 2009), a user may not necessarily be interested in, aware of, or able to actualize those affordances (Norman, 2013). As a relational concept (Gibson, 1979), an affordance must be measured relative to a user's abilities and needs: particular users have particular goals and expertise which drive their interaction with the artifact. This may lead different users to derive different affordances from the same artifact (Bernhard et al., 2013). A simple example is a chair. For an adult of a certain height and weight, a chair affords sitting. For a crawling baby, a chair does not afford sitting, but might afford grasping or support while attempting to stand. In our analysis of SA tool affordances, we adopt the relational design approach, and consider the tool designer in addition to the tool and the tool user (Hartson, 2003; Maier and Fadel, 2009; Norman, 2013).

We conceptualize affordance emergence from SA tools as the result of interactions between a tool, its designer, the tool use setting, and the studied system (Fig. 1). We build on the framework for affordance-based design described by Maier and Fadel (2009). In our conceptualization, the tool designer is directed by information about the system's characteristics and the user's objective(s). The designed tool is then equipped with potential affordances which may emerge through interaction with users, who are driven by their unique abilities and needs and operate within a unique setting. These affordances may in turn be activated within the system.

2.2. A layered model of affordance emergence

Unpacking the interaction between tool and user is required to understand affordance emergence and activation. To untangle this dynamic, several authors have proposed methods to classify affordance perception and actualization as discrete concepts. Drawing from four theoretical threads in the affordance literature (Bernhard et al., 2013; Bower, 2008; Burton-Jones and Grange, 2013; Markus and Silver, 2008), we conceptualize affordance emergence as a layered model in which *structural* and *functional* affordances are distinguished.

We define *structural* affordances as the objective material features, properties, or capabilities of a tool. These dictate what the tool itself does (e.g. collate data or produce a system map). Structural affordances are determined by the tool designer, who delineates tool boundaries in the development process. Complementarily, we define *functional* affordances as what the tool enables when a user interacts with structural affordances, for example an overview of the current system state.

To further untangle the emergence of functional affordances, we combine Bower's (2008) classification of functional affordance types with Burton-Jones and Grange's (2013) first- and second-order affordances, distinguishing first-order *instructive* (clarifying or deepening

¹ In the affordance design literature, the objects of study are usually tangible (e.g. door handle, wine bottle opener, light switch), and are often referred to as artifacts to denote human fabrication.

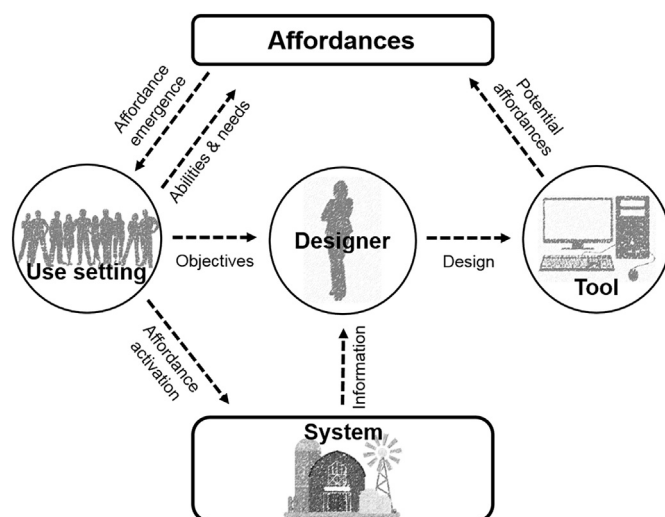


Fig. 1. The entangled relationship between a system, tool, designer, and use setting. We distinguish “use setting” from “user” to acknowledge that a tool may be used by an individual or group, with or without a facilitator.

system understanding), and second-order *productive* (leading to new action) functional affordances. First- and second-order functional affordances may be leveraged to a user's advantage. The result of such leveraging defines the usefulness of that tool for the given user. Leveraging functional affordances forms a link between tool outputs (e.g. a visual representation of a farm's structure) and action-oriented outcomes (e.g. enabling informed action to improve farm sustainability).

Finally, we propose a taxonomy which may be used to classify the affordances furnished by SA tools in participatory settings (Table 1). This taxonomy draws upon affordance literature (Antonenko et al., 2017; Bower, 2008; Hartson, 2003; Kirschner et al., 2004), as well as the authors' experiences with designing and employing SA tools for research purposes. Different from the affordance taxonomies proposed in other papers, the one used here has been developed specifically for agricultural SA tools and use settings.

3. Methods

To illustrate the affordance approach, we selected three SA tools widely used for analyzing agricultural systems (Table 2) and applied the analytical framework outlined in Section 2 via an abridged literature review. The three tools (FCM, BEFM, and RPSG) were chosen because they vary substantially in systems analysis approach and the support they may offer in co-design and co-innovation processes, while

having sufficient case study examples.

We first reviewed the literature on the three selected SA tools. For each tool, we conducted searches in *Scopus* and *Web of Science* using combinations of the search terms “[tool name]” and “agriculture”, “farm”, “participatory research”, and “multi-stakeholder” in the article title, abstract, and keywords. We then selected the ten most relevant papers applying the tool in agricultural settings. Papers in which tools were used in multi-stakeholder processes were deemed more relevant than those where a tool was used strictly by and for researchers. If applications with examples of direct tool use by stakeholders were scant, we also selected papers where a tool was used in a stakeholder-driven research approach, for example in participatory action research projects, or in iterative analysis and design cycles. We excluded papers in which a tool was applied but its use was not reflected upon. Where agricultural context criteria could not be met, we widened the search to include uncovered papers discussing natural resources and environmental management. To include a wider range of perspectives, we selected only one paper by the same first author. Rather than an exhaustive review, our aim was to demonstrate the application of a novel framework and illustrate the potential for affordance theory to enrich SA tool design and use in participatory settings.

In our literature review, we looked systematically for indications of what the authors perceived to be the affordances of the given tool. As the majority of the reviewed papers did not use the term “affordance”, we looked for (i) what the authors described as the capabilities of the tool (i.e. structural affordances), and (ii) what the authors said those capabilities helped them or other stakeholders to achieve (i.e. functional affordances). For each paper, we annotated the text to collect supporting evidence of each affordance level. We then classified the affordances of each tool by type. To do this, we cross-referenced the collected evidence with the affordance taxonomy from Table 1, seeking the closest alignment between authors' descriptions of a tool's capacities and the definitions in our taxonomy. We considered a tool to possess an affordance if at least two papers referenced what we interpreted as evidence of said affordance.

4. Results: affordances of three SA tools in agricultural systems settings

4.1. Fuzzy cognitive mapping

FCM is a semi-quantitative, participatory tool for modelling stakeholders' perceptions of the components within a system, the strength of their interrelations, and their influences at multiple scales. It utilizes cognitive mapping techniques whereby a system is represented as a diagram composed of boxes symbolizing concepts or variables which are causally connected by directional arrows (Fig. 2). Connections are

Table 1
Taxonomy for classifying the affordances furnished by agricultural systems analysis tools.

| Affordance level and definition | Affordance type | Description |
|--|--|---|
| Structural <i>The essential and objective features, properties or capabilities of a tool, which dictate what the tool does</i> | Harnessing Naming Aggregating Framing | Place-specific data are harnessed in a structured format System components are named using common vocabulary Different data types and sources are aggregated in a common platform A shared space of experience and system representation is created |
| First-order functional <i>What the tool enables when a user interacts with structural affordances; instructive</i> | Integration Quantification Visualization | Data are integrated to describe system functioning The values of particular performance indicator(s) are calculated System structure is represented visually |
| Second-order functional <i>What the tool enables when a user interacts with structural and first-order functional affordances; productive</i> | Analysis Exploration Manipulation Visioning | Tool output provides a basis for analyzing the performance of the system and current problems with system configuration or functioning Stakeholders can explore alternative management options and scenarios to solve system problems System representations can be adapted and manipulated to incorporate new data or perspectives and simulate management changes Stakeholders engage in a process of jointly developing a shared vision of a desired future system state or direction |

Table 2
Systems analysis tools analyzed with the affordance framework and the literature reviewed.

| SA tool | Tool description | Literature reviewed |
|-----------------------------|--|--|
| Fuzzy Cognitive Mapping | A semi-quantitative and participatory tool for modelling stakeholders' perceptions of causal relationships between system components and processes as directional graphs with feedbacks. | Christen et al. (2015) Dodouras and James (2007) Gray et al. (2012) Halbrendt et al. (2014) Kok (2009) Murungweni et al. (2011) Özesmi and Özesmi (2003) Pacilly et al. (2016) Soler et al. (2012) van Vliet et al. (2010) Alary et al. (2016) |
| Bio-Economic Farm Models | Models simulating interacting biophysical and economic components of farm inputs and outputs, thereby quantifying production-related, environmental, and socio-economic performance indicators as affected by farm management decisions. | Andrieu et al. (2012) Blazy et al. (2010) Cortez-Arriola et al. (2016) Delmotte et al. (2016) Giller et al. (2011) Groot et al. (2012) Louhichi et al. (2010) Sempore et al. (2015) van Wijk et al. (2009) |
| Role Play and Serious Games | Board- and/or computer-based games designed to simulate realistic resource use and decision making scenarios in which players act out different roles and management choices. | Castella et al. (2005) Dolinska (2017) Dung et al. (2009) Farrié et al. (2015) Garcia-Barrios et al. (2008) Martin et al. (2011) Salvini et al. (2016) Souchère et al. (2010) Speelman et al. (2014) Van der Wal et al. (2016) |

marked with numerical weights signifying the strength of their influence in driving the system and/or relationship (Kosko, 1986). The term “fuzzy” refers to the fact that the approach deals with the uncertainty of causal knowledge by using fuzzy causal functions (Kosko, 1986). In the reviewed literature, we found FCM to be commonly applied in two ways: (a) to generate a system representation that integrates the views of multiple stakeholders, or (b) to generate system representations for different stakeholders or stakeholder groups for comparative analysis. Several open-source computer-based programs exist (e.g.

FuzzyDANCES, Mental Modeler, FCM Expert, and FCMapper) that draw and evaluate FCMs with input from questionnaires, interviews, focus groups, or stakeholder workshops.

4.1.1. Structural affordances

Depending on the mode of application, our review indicates that FCM may afford different suites of structural affordances. In all ten papers, authors indicated that with FCM, stakeholders' perceptions of a system's components and causal relationships are identified (structural

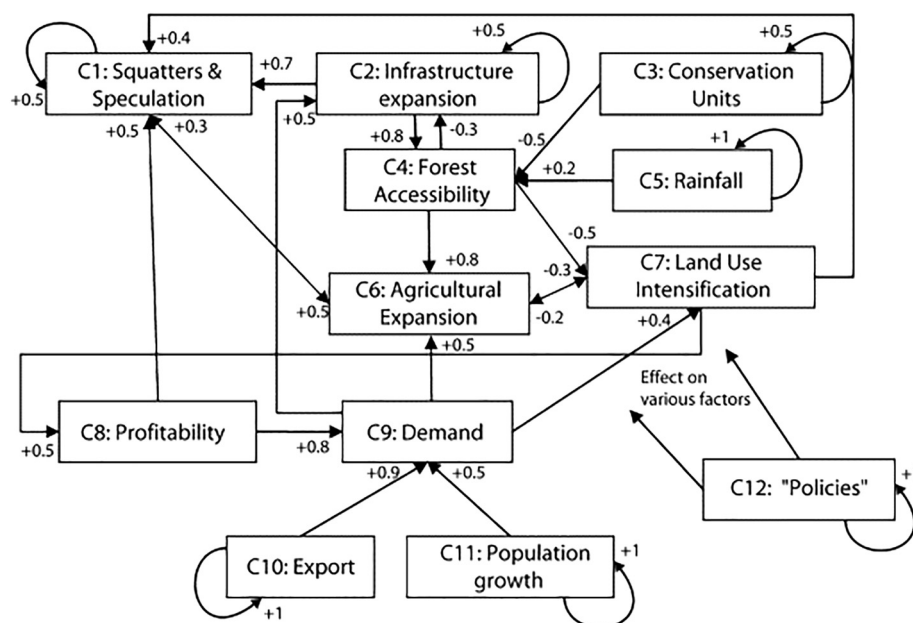


Fig. 2. A fuzzy cognitive map of deforestation in the Brazilian Amazon. Looped arrows indicate system drivers.
Source: Kok (2009)

affordance *naming*) and captured in a structured format (structural affordance *harnessing*). Additionally, all reviewed papers described FCM construction as a process through which knowledge of different system components (e.g. biophysical and social) are organized and combined in a complex network structure (structural affordance *aggregating*). In settings where multiple stakeholders collaboratively construct a FCM, for example in an interactive workshop (e.g. Murungweni et al., 2011; van Vliet et al., 2010), FCM may also afford *framing*. The literature indicated that workshop settings afford a shared space of experience, in which “the interactions involved in developing FCMs present an opportunity for knowledge synthesis among stakeholders” as they “negotiate what is relevant and should be included” in the FCM (Murungweni et al., 2011, p.12).

4.1.2. First-order functional affordances

After system components and relationships are identified and described, all reviewed FCM papers explained that actors' system knowledge and perceptions are integrated (either manually or with FCM software) into a network visualization. This finding points to three first-order functional affordances: *visualization*, *integration* and *quantification*. FCM visualizations can be classified as concept maps (Hyerle, 2009), which, as Christen et al. (2015) explain, provide “a detailed picture of perceived factors of importance as well as perceptions of how these factors interact” (p. 72). The reviewed literature showed *integration* and *quantification* to be closely linked. Authors described the method's qualitative capacities for “integrating vague data and generating cross-disciplinary links” (Dodouras and James, 2007, p. 825), which then allow for calculating state values and network metrics, such as the centrality of concepts and the density or complexity of the map (Özesmi and Özesmi, 2004).

4.1.3. Second-order functional affordances

Our analysis of the reviewed literature showed that leveraging FCM's first-order functional affordances may enable two types of second-order functional affordances relevant to problem-solving settings. First, by generating a visualization of causal relationships and feedbacks within a system and quantifying current state values, FCM can be used to understand how system components and processes effect one another, and how stakeholders' perceptions of the same system are similar or different (Halbrendt et al., 2014). These examples illustrate the affordance *analysis*. Second, FCM is flexible: maps can be manipulated to reflect evolution of participants' perceptions, to integrate new data, and explore how a system might change due to disturbances or interventions (Dodouras and James, 2007; Kok, 2009; van Vliet et al., 2010). This illustrates the affordance *manipulation*. In the context of FCM, *manipulation* permits “what if” scenarios to be run to see how the system might change under a range of conditions” (Gray et al., 2012, p. 92). Scenario analysis via model manipulation is a widely noted asset of FCM in collaborative redesign processes (Kok, 2009; Murungweni et al., 2011; Pacilly et al., 2016; Soler et al., 2012; van Vliet et al., 2010).

4.2. Bio-economic whole-farm models

As defined by Janssen and van Ittersum (2007), a BEFM is “a model that links formulations describing farmers' resource management decisions to formulations that describe current and alternative production possibilities in terms of required inputs to achieve certain outputs and associated externalities” (p. 623). BEFM may be further classified as mechanistic vs. empirical (Janssen and van Ittersum, 2007), or static vs. dynamic (Flichman and Allen, 2015). BEFM are increasingly paired with typology construction and may be parameterized to represent generalized farm types (e.g. Alary et al., 2016; Blazy et al., 2010; Cortez-Arriola et al., 2016; Delmotte et al., 2016; Louhichi et al., 2010). Components that may be included in a BEFM are shown in Fig. 3.

4.2.1. Structural affordances

In all the reviewed papers, authors explain that biophysical and socioeconomic data are combined with farm structural data in BEFM to make explicit the characteristics and resource flows of a farming system. Groot et al. (2012), for example, describe in detail how input and output data for each agricultural activity (e.g. crops, livestock, manure management) is formalized for different production environments to represent the structure and functioning of a farming system, based on real farm case data. The structural affordances of BEFM as described in the reviewed literature can therefore be classified as *harnessing* and *aggregating*.

4.2.2. First-order functional affordances

Discussions of how BEFM link land-use and management decisions with biophysical processes and individual farm sub-systems (e.g. crops and livestock) to represent farm functioning were common in the reviewed literature. This capacity may be seen as evidence of the first-order affordance *integration*. *Integration* allows a model to account for feedbacks between subsystems (Alary et al., 2016; van Wijk et al., 2009). *Integration* may further help users to frame key problems and production constraints in the current system (Cortez-Arriola et al., 2014). By establishing reference values to be used in successive exploration phases of model use (cf. Delmotte et al., 2016) BEFM also afford *quantification*. As with FCM, the literature showed *integration* and *quantification* are closely linked: model calculations formalize integrated reasoning (Andrieu et al., 2012) and thereby provide a “concrete translation” of interactions between different farm activities (Sempore et al., 2015). Finally, all reviewed BEFM papers also indicated that integrated system data and quantified reference values may be represented as system diagrams or other graphical outputs (e.g. trade-off curves or resource flow diagrams, as shown by Groot et al. (2012)), thus affording *visualization*.

4.2.3. Second-order functional affordances

The reviewed literature provides evidence that BEFM may furnish three second-order functional affordances when first-order functional affordances are leveraged. First, all reviewed papers illustrated how integrated data, quantified indicators, and system visualizations may together allow model users to investigate drivers of the functioning of the studied system, thereby affording *analysis*. Giller et al. (2011) and van Wijk et al. (2009) showed how BEFM allowed analysis of the farm-scale effects of resource allocation choices made at the sub-system scale. Second, several reviewed papers illustrated how first-order functional affordances may be leveraged for *ex-ante* assessment of innovations (Blazy et al., 2010) or alternative farm configurations (Andrieu et al., 2012; Groot et al., 2012), resource allocations (Giller et al., 2011), or policies (Louhichi et al., 2010) at different scales. These functions are made possible by the affordance *manipulation*. Working from the modeled representation of a studied system, a BEFM can be used to simulate change scenarios or conduct optimization routines. Manipulation thus goes hand-in-hand with the third second-order functional affordance, *exploration*. Model manipulation results may be assessed relative to established system thresholds and reference values, providing a framework to explore “solution spaces” to improve the current system (Cortez-Arriola et al., 2016; Groot et al., 2012).

4.3. Role play and serious games

Board- and computer-based RPSG are designed to simulate realistic resource use and decision-making scenarios. Participants play games by acting out different roles and action trajectories. These games may be analog in nature (with tangible objects such as game boards and pieces), or supported by dynamic model-based simulations and calculations. Opportunities for game development are vast. Interesting examples relevant to agricultural SA include Forage Rummy, a game in which farmers and advisors design alternative livestock systems and

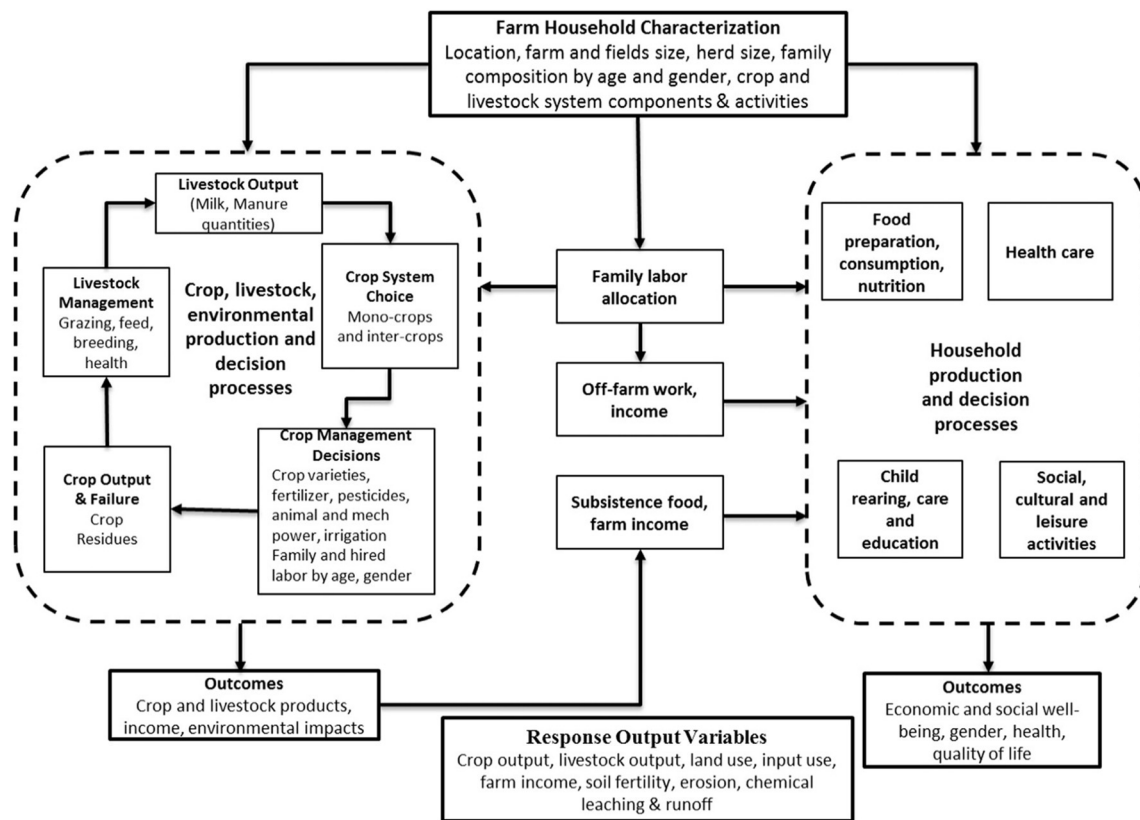


Fig. 3. Components of a farming system that may be included in bio-economic whole-farm models.

Source: Jones et al. (2017).



Fig. 4. The RESORTES game board, developed for players in Chiapas, Mexico (Speelman and García-Barrios, 2010).

evaluate their feasibility (Martin et al., 2011), role playing to explore climate smart agriculture to combat deforestation (Salvini et al., 2016), and RESORTES, a land-use board game in which players evaluate the financial and ecosystem services benefits of different agricultural landscape configurations (Speelman and García-Barrios, 2010, Fig. 4).

4.3.1. Structural affordances

Many of the reviewed articles highlight what can be seen as *framing* afforded by game play, whereby players meet in a structured environment with defined rules of conduct which frame the shared experience of the participants. García-Barrios et al. (2008) describe the gaming environment as a “joint reality” shared by the players. These authors imply that *framing* is afforded by the stylized and simplified version of reality portrayed in the game. Dung et al. (2009) echo this by highlighting the importance of game design principles which create the “playful atmosphere”. Similarly, Dolinska (2017) refer to the “collective character” built during the shared play experience. In addition, game objects (e.g. cards, boards, computer simulations, etc.) contribute to *framing* by acting as boundary objects (cf. Star and Griesemer, 1989) around which players both literally and conceptually congregate (Farrié et al., 2015; Martin et al., 2011). Multiple authors note that the same artifacts and rules which frame the game space also afford *naming* because they establish a common vocabulary among participants (e.g. Dolinska, 2017; Farrié et al., 2015).

4.3.2. First-order functional affordances

Several authors describe how the game objects, vocabulary, shared space of play, participant experiences, and records of play trajectories together comprise a shared representation of a system, which may be interpreted as evidence of the first-order functional affordance *visualization*. *Visualization* may be expressed as configurations of game objects that reflect the course and outcome of game play, or as social expressions of actors' conceptual models, actions, and action impacts (e.g. players' conversations) which can be recorded by game facilitators (cf. Speelman et al., 2014). Both Martin et al. (2011) and Farrié et al. (2015) discuss the importance of visualizations, which they contend act as a “material expression of the conceptual model underpinning the game” (Martin et al., 2011, p. 1444). Furthermore, RPSG may be said to afford *integration* in two ways. First, as described by Farrié et al. (2015),

Table 3

Overview of the affordances found to be furnished by three systems analysis tools.

| | | Tool | | |
|-------------------------------------|----------------|-------------------------|--------------------------|-----------------------------|
| | | Fuzzy cognitive mapping | Bio-economic farm models | Role play and serious games |
| Structural affordances | Harnessing | ✓ | ✓ | |
| | Naming | ✓ | | ✓ |
| | Aggregating | ✓ | ✓ | |
| | Framing | ✓ | | ✓ |
| First-order functional affordances | Integration | ✓ | ✓ | ✓ |
| | Quantification | ✓ | ✓ | |
| | Visualization | ✓ | ✓ | ✓ |
| Second-order functional affordances | Analysis | ✓ | ✓ | |
| | Exploration | | ✓ | ✓ |
| | Manipulation | ✓ | ✓ | ✓ |
| | Visioning | | | ✓ |

games integrate experimental knowledge (data-driven inputs and rules structuring the game and feeding into its design) with players' experiential knowledge. Second, Van der Wal et al. (2016) and Castella et al. (2005) show that the game setting affords *integration* between players' perspectives. This is further demonstrated by Dung et al. (2009) who describe a case in which players learned from each other by observing how others solved the same problems.

4.3.3. Second-order functional affordances

The reviewed literature showed evidence which may be interpreted to support three second-order functional affordances furnished by leveraging lower-order RPSG affordances. First, as game play allows participants to (virtually) modify the current situation by manipulating game objects within scenarios designed to represent real-world problems, RPSG afford *manipulation*. Farrié et al. (2015) illustrate manipulation when they describe games as “a material and social platform for virtual experimentation” (p. 243). Others (Martin et al., 2011; Van der Wal et al., 2016) use laboratory analogies, showing that games constitute “a kind of laboratory to conduct simulated experiments” (Martin et al., 2011, p. 1451) where players test choices.

Closely linked with *manipulation* is the affordance *exploration*. Several authors describe how through *manipulation*, players can explore real possibilities for system management changes without real-world consequences. For example, Salvini et al. (2016) observed that “[players] engaged in the game as an experimental environment in which round after round they could explore the consequences of their land-use decisions,” allowing players “to simulate and experience situations that would be too costly or risky to implement in the real world” (p. 118). Other authors also attribute *manipulation* and *exploration* affordances to the risk-free nature of the game environment. Garcia-Barrios et al. (2008) describe how play allowed participants to view a situation from a new perspective, and to test alternative actions. Similarly, players studied by Dung et al. (2009) said that “the [RPSG] provided conditions similar to reality...but playing a game was more fun and less difficult than making a decision in the real world” (p. 89).

Finally, the reviewed literature showed evidence of the affordance *visioning*. Salvini et al. (2016) illustrate *visioning* by explaining that the informality of the game setting lowers communication barriers. In a collaborative game, this can promote a shift away from individual thinking and towards the development of a collective vision. For instance, Speelman et al. (2014) observed players engaging in strategic collaboration to achieve collectively preferred outcomes, and Van der Wal et al. (2016) observed the visioning process as a “joint reconceptualization of a specific problem” (p. 120) by a group of players. According to Souchère et al. (2010), the opportunity to share visions of a system problem and possible solutions is a key asset of RPSG.

5. Discussion

Solving complex problems through co-design and co-innovation in agricultural systems requires that relevant stakeholders can integrate multiple disciplines, perspectives, and interests (Kragt et al., 2016). However, fostering productive interactions between diverse stakeholder groups with differing norms, jargon, and interests is a common challenge (Klerkx et al., 2012b). SA tools are widely used to support participatory problem solving, co-design, and co-innovation in agricultural systems settings. Here we have adopted the concept of affordances to propose a framework for assessing the contributions of such tools in these settings. We have illustrated a preliminary application of the affordance framework using three SA tools, and from this exercise can begin a discussion around the potential and limitations of the affordance model, providing insights into opportunities for improving SA tool design and implementation.

5.1. Affordances as evidence that SA tools support participatory processes?

By assessing three SA tools with the affordance framework, we demonstrated a new way to identify and classify the contributions of these tools to participatory problem-solving processes (Table 3). Complementarily, the exercise also provides insight into the limitations of these tools to support such processes by identifying the affordances they do not appear to furnish. While our limited review of literature on each tool does not allow formulaic linking of affordances to the specific needs of different participatory approaches, theories on what make these approaches successful can be generally linked to different affordance types. To this end, of particular interest is the work of Sterk et al. (2009), who identified three roles that land-use models may play in multi-stakeholder settings: (1) heuristic (using the tool improves systems understanding), (2) symbolic (tool outputs provide input for discussions), and (3) relational (tool outcomes mobilize stakeholders to collectively activate knowledge). Our application of the affordance framework provides preliminary evidence that affordances may act as indicators of a tool's performance of different role(s) and thereby its broader scope of usefulness.

The assessment of three SA tools presented here illustrates that certain affordances clearly contribute to improved system understanding. For instance, multiple authors (e.g. Farrié et al., 2015; Martin et al., 2011) linked *visualization* to learning, showing it allowed users to gain an overview of system structure by making underlying functional processes explicit. Others also linked *integration* and *quantification* to technical and social learning, for example through the process of parameterizing a model and discussing its outputs (e.g. Delmotte et al., 2016; Sempore et al., 2015). Furthermore, by facilitating iterative cycles of *integration*, *analysis*, *exploration*, and *visioning*, SA tools with these affordances could be said to support the stages of the experiential learning cycle (cf. Kolb, 1984). In an extensive review of agronomic

modelling tools, Prost et al. (2012) found improved system understanding to be the main objective of model use. Sterk et al. (2009) also associated heuristic functioning with all the models they examined. Affordance theory fine-tunes these authors' work by providing a framework within which to identify the specific capacities of a tool which may support a heuristic role.

Echoing Prost et al. (2012), evidence from our affordance analysis suggests that the designers of the SA tools reviewed focused primarily on heuristic functioning. However, research on participatory problem-solving approaches shows that simply understanding a situation better is not enough to support co-design and co-innovation. In multi-stakeholder settings, there is also a need for tools that inform exploratory processes and solution-oriented discussions, and for tools that mobilize collective action, occupying symbolic and relational roles, respectively (Berthet et al., 2016; Sterk et al., 2011). These needs have already been addressed by scholars working in agricultural systems sciences (e.g. Giller et al., 2008, 2011; Rossing et al., 2007) who propose participatory research and redesign cycles oriented around an “evolutionary” adaptation process, i.e. continual observation, learning, problem solving, and choosing new options to improve agroecosystem management (Groot and Rossing, 2011). The affordance framework can contribute by providing an *ex-ante* indication of how SA tools might support these cycles with symbolic or relational functioning, thereby assisting researchers in selecting and designing SA tools or tool portfolios. That said, our findings indicate that links between specific affordances and symbolic and relational roles cannot be easily drawn.

In the affordance model, the processes of leveraging and activating move tool users from instructive to productive affordances. With an improved understanding of the system and a formalized, shareable representation of its structure and functioning, actors can theoretically come together to collaboratively resolve complex challenges and make informed decisions about taking action to achieve system management and performance goals (Burton-Jones and Grange, 2013). Logically, certain affordances appear more likely than others to facilitate such outcomes. For example, *framing* and *visioning* contribute to “reframing”, a process in which stakeholders learn about the paradigms, problems, and interests of other actors and thus gain a broadened view of the context in which they are collectively involved (Aarts and van Woerkum, 2002). Reframing is relevant in situations where problems must be collectively owned and addressed for progress to occur (Sterk et al., 2006), as is often the case in agricultural systems co-design and co-innovation. It follows that the presence of affordances that catalyze reframing may be central to a tool's ability to perform a relational role. It also follows that the lack of such affordances may inhibit a tool from playing that role. Our analysis provides a clear example of how affordance gaps may align with the limitations of different tools: we found BEFM to lack *framing* and *visioning* affordances, reinforcing critiques that BEFM do not fully account for socio-cultural norms, rules, and priorities, nor real-world decision-making and power arrangements (Antle et al., 2017; Crane, 2010).

However, affordances aside, there are many additional factors at play in participatory problem-solving settings that may determine whether a tool performs a symbolic or relational role. As Jakku and Thorburn (2010) contend, “...understanding the social context of how multiple parties communicate, share their perspectives, and work together as a group to solve problems is central to ensuring that this process reaches its full potential” (Jakku and Thorburn, 2010, p. 676). In addition to how a tool is designed and therefore which structural affordances it furnishes, which productive affordances emerge, and whether they are activated in a given setting, are directly related to multiple factors. These may include the abilities and needs of the user(s), the composition, dynamics, and objectives of the use setting, whether or not tool users are guided by a facilitator, and if and how tool outputs are interpreted or explained, by whom, and to whom. These factors highlight the relational nature of affordance emergence referred to by Gibson (1979), while showing that from an affordance

perspective, a tool's ability to perform symbolic and relational roles is inextricably linked to interaction with a particular use setting.

5.2. Affordance-based tool design and implementation

Our conceptual framework proposes that affordance emergence is the result of interactions between a tool, its designer, the tool use setting, and the studied system (Fig. 1). The focus of our affordance analysis, however, as driven by the evidence found in the reviewed literature, is primarily on the one-way transfer of affordances from the tool to the user. Although moving scientific knowledge into action requires that tool outputs are interpretable and actionable by users, the reviewed literature generally focused on higher-order tool usefulness. With few exceptions (e.g. Andrieu et al., 2012), authors did not describe users' experiences with the operational aspects of tool use. The lack of attention given to this topic implies that SA tool output is largely still geared towards researchers' perceptions of users' needs, reinforcing critiques around the lack of regard for end users in tool design (Cerf et al., 2012; Prost et al., 2012). This gap can down-play the entanglement between tool design, use setting, and the actualization of affordances, and indicates a clear opportunity for elaborating the dialogue around SA tool design and implementation. The affordance model offers an entry point for elaboration, particularly in two ways.

First, affordance theory implies that structural and first-order functional affordances are embedded during the tool design process, mirroring what a tool developer has deemed relevant for the tool's intended application and directing how a user interacts with the primary features of the tool (Antonenko et al., 2017; Maier and Fadel, 2009). If these lower-order affordances do not align with the abilities and needs of a use setting, the tool may not perform the intended role (Prost et al., 2012). For example, the system representations produced by BEFM are prescribed since system components and relationships have been pre-defined based on measured trends, and information gathered from stakeholders is limited to those system components and relationships that are relevant to the research question(s) at hand. Thus, the scope of a tool's usefulness may be inherently limited by its design as manifested by its lower-order affordances. A starting point for improved SA tool design would therefore be to encourage designers to enhance the flexibility of their tools by building in a wider range of structural and first-order functional affordances. Feedback from tool users with different cognitive, functional, and operational viewpoints would be essential to this process (Cerf et al., 2012; Jakku and Thorburn, 2010). In our framework, we have proposed a short taxonomy of lower-order affordances for SA tools. Further empirical analysis, as well as drawing on other SA tool studies, could extend the taxonomy and widen its usefulness for affordance-based SA tool design.

Second, our application of the affordance framework highlights the centrality of the use setting in the activation of productive, second-order functional affordances. More so than structural and first-order affordances, the activation of second-order functional affordances depends on the capacity, agency, interest, and mandate of the users. In particular, many of the reviewed articles noted the essential role of the facilitator in leveraging tool outputs and engaging tool outcomes. Castella et al. (2005) elaborate: “Third-party facilitation plays a crucial role in a collective learning process to elicit and contrast the diverging perceptions and interest of stakeholders and to bring these into the open as part of facilitating the negotiation of options for improved [system management]” (p. 23). As discussed earlier, SA tools may enhance learning, but they cannot guarantee action (van Wijk et al., 2014). To this end, the affordance framework suggests that distinct from good design, the implementation of SA tools can be improved with the presence of a skilled facilitator who assists in mobilizing learning outcomes.

The depth with which we were able to address the reciprocal impact of different use settings on affordance emergence within this study was constrained by our theoretical approach (i.e. literature review as

opposed to empirical framework testing), as well as inherent limitations of the affordance model. To fully unravel the interplay between tool and use setting, one would need to know not only what a tool affords, but also precisely with what abilities, needs, and motivations the user (s) approach it. This information is not easily gleaned from the literature. Improving both the affordance model and SA tool design would require an iterative, two-fold approach in which (i) tools are designed in an affordance-based, dialogical, participatory process (Cerf et al., 2012) which takes a relational view on affordance emergence (Maier and Fadel, 2009), and (ii) tools are empirically assessed using the affordance framework across diverse settings. As suggested by Cerf et al. (2012), this approach could hone the design and implementation of SA tools by providing structure to the diagnosis of situations in which a tool may help in problem solving, in addition to enhancing understanding of the (mis)alignment between user needs and the affordances furnished.

6. Conclusions

SA tools employed to support participatory problem-solving, co-design, and co-innovation processes must be sophisticated enough to be relevant, yet simple enough to be applied in diverse settings, and also sufficiently flexible to respond to evolving system challenges. Affordance analysis can help achieve this balance by refining the design, selection, and implementation of SA tools. Our application of an affordance framework allowed the preliminary identification of functions provided by three different SA tools, and demonstrates a novel way of assessing what SA tools offer within participatory use settings. Our analysis showed that SA tools can furnish different and sometimes overlapping suites of affordances, which emerge through an interplay of factors related to a tool's design and the setting in which it is used. Recalling the role of perception in affordance actualization (Bernhard et al., 2013), and in light of the fact that we did not perform an exhaustive literature review for each tool, our findings should not be interpreted as prescriptive. Rather, this preliminary application of the framework sheds light on how affordance analyses might enrich SA tool designers' and users' understanding of the scope of usefulness of their tools. We summarize our findings with five propositions to improve the design and implementation of SA tools, emphasizing participatory research settings. These are presented 'backwards', from implementation to design:

- 1) Effective participatory SA tool use processes may require a facilitator trained in understanding socio-contextual factors who can act as an integrator and guide to help participants bridge disciplinary and practical divides, interpret tool outputs, and mobilize second-order functional affordances.
- 2) As the needs of complex social-ecological problem-solving settings may not be fully addressed by the affordances of a single tool, it may be necessary to apply multiple complementary tools in a portfolio. This may be built based on the alignment of tool affordances with the characteristics and objectives of different use settings.
- 3) To facilitate affordance-based selection of SA tools, authors who report on SA tool use in practice should reflect more explicitly on the interplay between tool design and use setting, thereby helping to define the scope of usefulness of their tools.
- 4) An iterative cycle of affordance-based design which takes a relational view on affordance emergence, incorporates feedback from tool users, and focuses not only on heuristic functioning but also on symbolic and relational roles, is likely to be necessary. Such a cycle can help ensure that SA tools are designed to meet the varied needs of participatory problem-solving, co-design, and co-innovation settings.
- 5) SA tool designers should build tools with a wider range of structural and first-order affordances in order to accommodate users with diverse viewpoints.

These propositions provide a foundation for moving the affordances research agenda forward. By empirically testing the framework we have presented, the affordance lens can be focused and remaining questions about how tools furnish affordances during the interplay with users can be further unraveled. Additional investigation into links between affordances and the role(s) a tool may play in participatory processes would provide highly relevant and complementary insights to the discussion initiated here.

Author contributions

L.D. developed the conceptual framework, conducted the literature review, interpreted the findings, and wrote the manuscript. L.K. and J.C.J.G. conceived of the original idea for the work, initiated the theoretical dialogue, and provided critical contributions to the development of the theoretical argument, framework, and analysis by supporting L.D. in the writing and contributing to the writing. J.C.D. and H.P. provided feedback on the framework and analysis, and contributed to the writing. T.J.K., S.L.R., J.A.A., and F.B. contributed through critical revision of the manuscript.

Acknowledgements

This research was conducted within the project "Enhancing the effectiveness of system analysis tools to support learning and innovation in multi-stakeholder platforms" (ESAP), funded by the CGIAR Research Program (CRP) MAIZE (www.maize.org), contract A4032.09.90. The authors thank the two anonymous reviewers whose valuable critical feedback helped improve the paper. The vector image of a farm used in Fig. 1 was designed by Momentbloom/Vecteezy.com.

References

- Aarts, N., van Woerkum, C., 2002. Dealing with uncertainty in solving complex problems. In: Leeuwis, C., Pyburn, R. (Eds.), *Wheelbarrows Full of Frogs: Social Learning in Rural Resource Management*. Koninklijke Van Gorcum BV, The Netherlands, pp. 421–435.
- Alary, V., Corbeels, M., Affholder, F., Alvarez, S., Soria, A., Xavier, J.H.V., da Silva, F.A.M., Scopel, E., 2016. Economic assessment of conservation agriculture options in mixed crop-livestock systems in Brazil using farm modelling. *Agric. Syst.* 144, 33–45.
- Andrieu, N., Dugué, P., Le Gal, P.-Y., Rueff, M., Schaller, N., Sempore, A., 2012. Validating a whole farm modelling with stakeholders: evidence from a west African case. *J. Agric. Sci.* 4, 159.
- Antle, J.M., Basso, B., Conant, R.T., Godfray, H.C.J., Jones, J.W., Herrero, M., Howitt, R.E., Keating, B.A., Munoz-Carpena, R., Rosenzweig, C., Tittonell, P., Wheeler, T.R., 2017. Towards a new generation of agricultural system data, models and knowledge products: design and improvement. *Agric. Syst.* 155, 255–268.
- Antonenko, P.D., Dawson, K., Sahay, S., 2017. A framework for aligning needs, abilities and affordances to inform design and practice of educational technologies. *Br. J. Educ. Technol.* 48, 916–927.
- Bernhard, E., Recker, J.C., Burton-Jones, A., 2013. Understanding the actualization of affordances: A study in the process modeling context. In: *International Conference on Information Systems (ICIS 2013)*. Università Bocconi, Milan.
- Berthet, E.T.A., Barnaud, C., Girard, N., Labatut, J., Martin, G., 2016. How to foster agroecological innovations? A comparison of participatory design methods. *J. Environ. Plan. Manag.* 59, 280–301.
- Blazy, J.M., Tixier, P., Thomas, A., Ozier-Lafontaine, H., Salmon, F., Wery, J., 2010. BANAD: a farm model for ex ante assessment of agro-ecological innovations and its application to banana farms in Guadeloupe. *Agric. Syst.* 103, 221–232.
- Botha, N., Turner, J.A., Fielke, S., Klerkx, L., 2017. Using a co-innovation approach to support innovation and learning: cross-cutting observations from different settings and emergent issues. *Outlook Agric.* 46, 87–91.
- Bower, M., 2008. Affordance analysis - matching learning tasks with learning technologies. *Educ. Media Int.* 45, 3–15.
- Bower, M., Sturman, D., 2015. What are the educational affordances of wearable technologies? *Comput. Educ.* 88, 343–353.
- Burton-Jones, A., Grange, C., 2013. From use to effective use: a representation theory perspective. *Inf. Syst. Res.* 24, 632–658.
- Castella, J.C., Trung, T.N., Boissau, S., 2005. Participatory simulation of land-use changes in the northern mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. *Ecol. Soc.* 10, 32.
- Cerf, M., Jeuffroy, M.-H., Prost, L., Meynard, J.-M., 2012. Participatory design of agricultural decision support tools: taking account of the use situations. *Agron. Sustain. Dev.* 32, 899–910.
- Christen, B., Kjeldsen, C., Dalgaard, T., Martin-Ortega, J., 2015. Can fuzzy cognitive

- mapping help in agricultural policy design and communication? *Land Use Policy* 45, 64–75.
- Cortez-Arriola, J., Groot, J.C.J., Améndola Massiotti, R.D., Scholberg, J.M.S., Valentina Mariscal Aguayo, D., Titttonell, P., Rossing, W.A.H., 2014. Resource use efficiency and farm productivity gaps of smallholder dairy farming in north-West Michoacán, Mexico. *Agric. Syst.* 126, 15–24.
- Cortez-Arriola, J., Groot, J.C.J., Rossing, W.A.H., Scholberg, J.M.S., Améndola Massiotti, R.D., Titttonell, P., 2016. Alternative options for sustainable intensification of smallholder dairy farms in north-West Michoacán, Mexico. *Agric. Syst.* 144, 22–32.
- Crane, T.A., 2010. Of models and meanings: cultural resilience in social-ecological systems. *Ecol. Soc.* 15.
- Cvitanovic, C., McDonald, J., Hobday, A.J., 2016. From science to action: principles for undertaking environmental research that enables knowledge exchange and evidence-based decision-making. *J. Environ. Manag.* 183 (Part 3), 864–874.
- Delmotte, S., Barbier, J.-M., Mouret, J.-C., Le Page, C., Wery, J., Chauvelon, P., Sandoz, A., Lopez Ridaura, S., 2016. Participatory integrated assessment of scenarios for organic farming at different scales in Camargue, France. *Agric. Syst.* 143, 147–158.
- 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. *Eur. J. Agron.* 82, 292–307.
- Dodouras, S., James, P., 2007. Fuzzy cognitive mapping to appraise complex situations. *J. Environ. Plan. Manag.* 50, 823–852.
- Dogliotti, S., García, M.C., Peluffo, S., Dieste, J.P., Pedemonte, A.J., Bacigalupe, G.F., Scarlato, M., Alliaume, F., Alvarez, J., Chiappe, M., Rossing, W.A.H., 2014. Co-innovation of family farm systems: a systems approach to sustainable agriculture. *Agric. Syst.* 126, 76–86.
- Dolinska, A., 2017. Bringing farmers into the game. Strengthening farmers' role in the innovation process through a simulation game, a case from Tunisia. *Agric. Syst.* 157, 129–139.
- Dung, L.C., Hoanh, C.T., Le Page, C., Bousquet, F., Gajasen, N., 2009. Facilitating dialogue between aquaculture and agriculture: lessons from role-playing games with farmers in the Mekong Delta, Vietnam. *Water Policy* 11, 80–93.
- Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.A., Justes, E., Journet, E.P., Aubertot, J.N., Savary, S., Bergez, J.E., Sarthou, J., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. *Agron. Sustain. Dev.* 35, 1259–1281.
- Farrié, B., Joven, M., Launay, F., Moreau, J.C., Moulin, C.H., Piquet, M., Taverne, M., Tchakérian, E., Thénard, V., Martin, G., 2015. Rangeland rummy – a board game to support adaptive management of rangeland-based livestock systems. *J. Environ. Manag.* 147, 236–245.
- Fazey, I., Bunse, L., Msika, J., Pinke, M., Preedy, K., Evely, A.C., Lambert, E., Hastings, E., Morris, S., Reed, M.S., 2014. Evaluating knowledge exchange in interdisciplinary and multi-stakeholder research. *Glob. Environ. Chang.* 25, 204–220.
- Flichman, G., Allen, T., 2015. Bio-Economic Modeling: State-of-the-Art and Key Priorities. International Food Policy Research Institute (IFPRI).
- Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P., 2011. Solutions for a cultivated planet. *Nature* 478, 337–342.
- García-Barrios, L.E., Speelman, E.N., Pimm, M.S., 2008. An educational simulation tool for negotiating sustainable natural resource management strategies among stakeholders with conflicting interests. *Ecol. Model.* 210, 115–126.
- Geertsema, W., Rossing, W.A.H., Landis, D.A., Bianchi, F.J.J.A., van Rijn, P.C.J., Schaminée, J.H.J., Tschamke, T., van der Werf, W., 2016. Actionable knowledge for ecological intensification of agriculture. *Front. Ecol. Environ.* 14, 209–216.
- Gibson, J., 1979. *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston.
- Giller, K.E., Leeuwis, C., Andersson, J.A., Andriess, W., Brouwer, A., Frost, P., Hebinck, P., Heitkönig, I., van Ittersum, M.K., Koning, N., Ruben, R., Slingerland, M., Udo, H., Veldkamp, T., van de Vijver, C., van Wijk, M.T., Windmeijer, P., 2008. Competing claims on natural resources: what role for science? *Ecol. Soc.* 13.
- Giller, K.E., Titttonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijokya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agric. Syst.* 104, 191–203.
- Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. *Science* 327, 812–818.
- Gray, S., Chan, A., Clark, D., Jordan, R., 2012. Modeling the integration of stakeholder knowledge in social-ecological decision-making: benefits and limitations to knowledge diversity. *Ecol. Model.* 229, 88–96.
- Groot, J.C.J., Rossing, W.A.H., 2011. Model-aided learning for adaptive management of natural resources: an evolutionary design perspective. *Methods Ecol. Evol.* 2, 643–650.
- Groot, J.C.J., Oomen, G.J.M., Rossing, W.A.H., 2012. Multi-objective optimization and design of farming systems. *Agric. Syst.* 110, 63–77.
- Halbrendt, J., Gray, S.A., Crow, S., Radovich, T., Kimura, A.H., Tamang, B.B., 2014. Differences in farmer and expert beliefs and the perceived impacts of conservation agriculture. *Glob. Environ. Chang.* 28, 50–62.
- Hartson, R., 2003. Cognitive, physical, sensory, and functional affordances in interaction design. *Behav. Inform. Technol.* 22, 315–338.
- Hermans, F., Sartas, M., van Schagen, B., van Asten, P., Schut, M., 2017. Social network analysis of multi-stakeholder platforms in agricultural research for development: opportunities and constraints for innovation and scaling. *PLoS One* 12, e0169634.
- Hyler, D., 2009. *Visual Tools for Transforming Information into Knowledge*, 2nd ed. Corwin Press, Thousand Oaks.
- van Ittersum, M.K., Ewert, F., Heckelee, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkin, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E., Wolf, J., 2008. Integrated assessment of agricultural systems - a component-based framework for the European Union (SEAMLESS). *Agric. Syst.* 96, 150–165.
- Jakku, E., Thorburn, P.J., 2010. A conceptual framework for guiding the participatory development of agricultural decision support systems. *Agric. Syst.* 103, 675–682.
- Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: a review of bio-economic farm models. *Agric. Syst.* 94, 622–636.
- Janssen, S.J.C., Porter, C.H., Moore, A.D., Athanasiadis, I.N., Foster, I., Jones, J.W., Antle, J.M., 2017. Towards a new generation of agricultural system data, models and knowledge products: information and communication technology. *Agric. Syst.* 155, 200–212.
- Jones, J.W., Antle, J.M., Basso, B., Boote, K.J., Conant, R.T., Foster, I., Godfray, H.C.J., Herrero, M., Howitt, R.E., Janssen, S., Keating, B.A., Munoz-Carpena, R., Porter, C.H., Rosenzweig, C., Wheeler, T.R., 2017. Toward a new generation of agricultural system data, models, and knowledge products: state of agricultural systems science. *Agric. Syst.* 155, 269–288.
- Kirschner, P., Strijbos, J.-W., Kreijns, K., Beers, P.J., 2004. Designing electronic collaborative learning environments. *Educ. Technol. Res. Dev.* 52, 47.
- Klerkx, L., van Bommel, S., Bos, B., Holster, H., Zwartkruis, J.V., Aarts, N., 2012a. Design process outputs as boundary objects in agricultural innovation projects: functions and limitations. *Agric. Syst.* 113, 39–49.
- Klerkx, L., Van Mierlo, B., Leeuwis, C., 2012b. Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. In: Darnhofer, I., Gibbon, D., Dedieu, B. (Eds.), *Farming Systems Research Into the 21st Century: The New Dynamic*. Springer, Netherlands, pp. 457–483.
- Kok, K., 2009. The potential of fuzzy cognitive maps for semi-quantitative scenario development, with an example from Brazil. *Glob. Environ. Chang.* 19, 122–133.
- Kolb, D., 1984. *Experiential Learning: Experience as the Source of Learning and Development*. Prentice Hall, New Jersey.
- Kosko, B., 1986. Fuzzy cognitive maps. *Int. J. Man-Mach. Stud.* 24, 65–75.
- Kragt, M.E., Pannell, D.J., McVittie, A., Stott, A.W., Ahmadi, B.V., Wilson, P., 2016. Improving interdisciplinary collaboration in bio-economic modelling for agricultural systems. *Agric. Syst.* 143, 217–224.
- Le Gal, P.Y., Dugué, P., Faure, G., Novak, S., 2011. How does research address the design of innovative agricultural production systems at the farm level? A review. *Agric. Syst.* 104, 714–728.
- Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckelee, T., Berentsen, P., Lansink, A.O., Ittersum, M.V., 2010. FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. *Agric. Syst.* 103, 585–597.
- Maier, J.R.A., Fadel, G.M., 2009. Affordance based design: a relational theory for design. *Res. Eng. Des.* 20, 13–27.
- Markus, M.L., Silver, M.S., 2008. A foundation for the study of IT effects: a new look at DeSanctis and Poole's concepts of structural features and spirit. *J. Assoc. Inf. Syst.* 9, 609–632.
- Martin, G., 2015. A conceptual framework to support adaptation of farming systems – development and application with forage rummy. *Agric. Syst.* 132, 52–61.
- Martin, G., Felten, B., Duru, M., 2011. Forage rummy: a game to support the participatory design of adapted livestock systems. *Environ. Model. Softw.* 26, 1442–1453.
- Matthews, K.B., Rivington, M., Blackstock, K., McCrum, G., Buchan, K., Miller, D.G., 2011. Raising the bar? – the challenges of evaluating the outcomes of environmental modelling and software. *Environ. Model. Softw.* 26, 247–257.
- McCown, R.L., 2001. Learning to bridge the gap between science-based decision support and the practice of farming: evolution in paradigms of model-based research and intervention from design to dialogue. *Aust. J. Agric. Res.* 52, 549–572.
- Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., Michon, C., 2017. Designing coupled innovations for the sustainability transition of agrifood systems. *Agric. Syst.* 157, 330–339.
- Murungweni, C., van Wijk, M.T., Andersson, J.A., Smaling, E.M.A., Giller, K.E., 2011. Application of fuzzy cognitive mapping in livelihood vulnerability analysis. *Ecol. Soc.* 16.
- Norman, D., 2013. *The Design of Everyday Things: Revised and Expanded edition*. Basic Books, New York.
- Özesmi, U., Özesmi, S., 2003. A participatory approach to ecosystem conservation: fuzzy cognitive maps and stakeholder group analysis in Uluabat Lake, Turkey. *Environ. Manag.* 31, 0518–0531.
- Özesmi, U., Özesmi, S.L., 2004. Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecol. Model.* 176, 43–64.
- Pacilly, F.C.A., Groot, J.C.J., Hofstede, G.J., Schaap, B.F., van Bueren, E.T.L., 2016. Analysing potato late blight control as a social-ecological system using fuzzy cognitive mapping. *Agron. Sustain. Dev.* 36, 35.
- Prost, L., Cerf, M., Jeuffroy, M.-H., 2012. Lack of consideration for end-users during the design of agronomic models. A review. *Agron. Sustain. Dev.* 32, 581–594.
- Ravier, C., Jeuffroy, M.-H., Meynard, J.-M., 2016. Mismatch between a science-based decision tool and its use: the case of the balance-sheet method for nitrogen fertilization in France. *NJAS* 79, 31–40.
- Raymond, C.M., Fazey, I., Reed, M.S., Stringer, L.C., Robinson, G.M., Evely, A.C., 2010. Integrating local and scientific knowledge for environmental management. *J. Environ. Manag.* 91, 1766–1777.

- Reed, M.S., Fazey, I., Stringer, L.C., Raymond, C.M., Akhtar-Schuster, M., Begni, G., Bigas, H., Brehm, S., Briggs, J., Bryce, R., Buckmaster, S., Chanda, R., Davies, J., Diez, E., Essahli, W., Evelyn, A., Geeson, N., Hartmann, I., Holden, J., Hubacek, K., Ioris, A.A.R., Kruger, B., Laureano, P., Phillipson, J., Prell, C., Quinn, C.H., Reeves, A.D., Seely, M., Thomas, R., van der Werff Ten Bosch, M.J., Vergunst, P., Wagner, L., 2013. Knowledge management for land degradation monitoring and assessment: an analysis of contemporary thinking. *Land Degrad. Dev.* 24, 307–322.
- Rose, D.C., Sutherland, W.J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., Dicks, L.V., 2016. Decision support tools for agriculture: towards effective design and delivery. *Agric. Syst.* 149, 165–174.
- Rossing, W.A.H., Zander, P., Josien, E., Groot, J.C.J., Meyer, B.C., Knierim, A., 2007. Integrative modelling approaches for analysis of impact of multifunctional agriculture: a review for France, Germany and the Netherlands. *Agric. Ecosyst. Environ.* 120, 41–57.
- Salvini, G., van Paassen, A., Ligtenberg, A., Carrero, G.C., Bregt, A.K., 2016. A role-playing game as a tool to facilitate social learning and collective action towards climate smart agriculture: lessons learned from Apuí, Brazil. *Environ. Sci. Pol.* 63, 113–121.
- Schindler, J., Graef, F., König, H.J., 2015. Methods to assess farming sustainability in developing countries. A review. *Agron. Sustain. Dev.* 35, 1043–1057.
- Schut, M., van Paassen, A., Leeuwis, C., Klerkx, L., 2014. Towards dynamic research configurations: a framework for reflection on the contribution of research to policy and innovation processes. *Sci. Public Policy* 41, 207–218.
- Schut, M., Klerkx, L., Rodenburg, J., Kayeke, J., Hinnou, L.C., Raboanarielina, C.M., Adegbola, P.Y., van Ast, A., Bastiaans, L., 2015. RAAIS: rapid appraisal of agricultural innovation systems (part I). A diagnostic tool for integrated analysis of complex problems and innovation capacity. *Agric. Syst.* 132, 1–11.
- Sempore, A.W., Andrieu, N., Nacro, H.B., Sedogo, M.P., Le Gal, P.Y., 2015. Relevancy and role of whole-farm models in supporting smallholder farmers in planning their agricultural season. *Environ. Model. Softw.* 68, 147–155.
- Soler, L.S., Kok, K., Camara, G., Veldkamp, A., 2012. Using fuzzy cognitive maps to describe current system dynamics and develop land cover scenarios: a case study in the Brazilian Amazon. *J. Land Use Sci.* 7, 149–175.
- Souchère, V., Millair, L., Echeverria, J., Bousquet, F., Le Page, C., Etienne, M., 2010. Co-constructing with stakeholders a role-playing game to initiate collective management of erosive runoff risks at the watershed scale. *Environ. Model. Softw.* 25, 1359–1370.
- Speelman, E.N., García-Barrios, L.E., 2010. Social Networks and Sustainable Land-Use Planning (Redes Sociales Y Ordenamiento Territorial Sustentable- RESORTES). Unpublished board game available from authors.
- Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Titttonell, P., 2014. Gaming for smallholder participation in the design of more sustainable agricultural landscapes. *Agric. Syst.* 126, 62–75.
- Srivastava, J., Shu, L.H., 2013. Affordances and product design to support environmentally conscious behavior. *J. Mech. Des.* 135, 101006–101008.
- Star, S.L., Griesemer, J.R., 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.
- Sterk, B., van Ittersum, M.K., Leeuwis, C., Rossing, W.A.H., van Keulen, H., van de Ven, G.W.J., 2006. Finding niches for whole-farm design models – contradictio in terminis? *Agric. Syst.* 87, 211–228.
- Sterk, B., Leeuwis, C., van Ittersum, M.K., 2009. Land use models in complex societal problem solving: plug and play or networking? *Environ. Model. Softw.* 24, 165–172.
- Sterk, B., van Ittersum, M.K., Leeuwis, C., 2011. How, when, and for what reasons does land use modelling contribute to societal problem solving? *Environ. Model. Softw.* 26, 310–316.
- Van der Wal, M.M., de Kraker, J., Kroeze, C., Kirschner, P.A., Valkering, P., 2016. Can computer models be used for social learning? A serious game in water management. *Environ. Model. Softw.* 75, 119–132.
- van Vliet, M., Kok, K., Veldkamp, T., 2010. Linking stakeholders and modellers in scenario studies: the use of fuzzy cognitive maps as a communication and learning tool. *Futures* 42, 1–14.
- Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. *Environ. Model. Softw.* 25, 1268–1281.
- van Wijk, M.T., Titttonell, P., Rufino, M.C., Herrero, M., Pacini, C., Ridder, N.D., Giller, K.E., 2009. Identifying key entry-points for strategic management of smallholder farming systems in sub-Saharan Africa using the dynamic farm-scale simulation model NUANCES-FARMSIM. *Agric. Syst.* 102, 89–101.
- van Wijk, M.T., Rufino, M.C., Enahoro, D., Parsons, D., Silvestri, S., Valdivia, R.O., Herrero, M., 2014. Farm household models to analyse food security in a changing climate: a review. *Glob. Food Secur.* 3, 77–84.