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A conceptual framework to support adaptation of farming systems – Development and application with Forage Rummy

G. Martin *

INRA, UMR 1248 AGIR, Castanet Tolosan F-31326, France

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ABSTRACT

The context of agricultural production, climate change in particular, increasingly requires adaptations to the structure and management of farming systems. As a result, farmers need to develop their adaptive capacity. To support this process, agricultural research has developed two main approaches: hard approaches that are mainly science-driven and rely on simulation models, and soft approaches that rely fully on stakeholders' knowledge. Both approaches present several drawbacks to achieve relevance to real-world decision-making and management. In this article, I elaborate a conceptual framework hybridizing hard and soft approaches to develop farmers' adaptive capacity. First, based on the literature, I define the requirements (systemic, situated, integrating multiple perspectives, etc.) for research approaches aimed at developing farmers' adaptive capacity. According to these requirements, I clarify the scope for hybridization of hard and soft approaches. For instance, hard approaches enable integration of up-to-date scientific knowledge while soft approaches ensure local relevance, thanks to stakeholders' knowledge. However neither approach is able to synergize the two knowledge types (scientific and empirical). Building on this analysis, the proposed conceptual framework relies on participatory group (researchers and stakeholders) modeling workshops. During these workshops, stakeholders are involved in an iterative process consisting of designing and evaluating candidate adaptation solutions using boundary objects encapsulating scientific and empirical knowledge. An application example of the conceptual framework is presented with Forage Rummy. Playing this board game, farmers' groups use their empirical knowledge to select and combine sticks and cards representing forage crop and grassland production and animal feeding, production and reproduction from a range of possibilities to design a livestock system. The system designed is instantaneously evaluated using a spreadsheet informing among other things about the matching of forage production and animal feeding requirements. Past workshops show that Forage Rummy stimulates farmers' discussions and knowledge exchange about farming practices. By supporting collective thinking about adaptation of livestock systems to changes in the production context e.g. climate change, it develops farmers' adaptive capacity.

1. Introduction

Under the influence of various factors (climatic, economic, social, etc.), the context of agricultural production is increasingly changing and erratic (Gilbert and Morgan, 2010; IPCC, 2007). With the support of agricultural consultants, farmers keep trying to adapt their farming systems to this context in order to preserve the sustainability, in particular the production ability, of such systems (Darnhofer et al., 2010; Fleming and Vanclay, 2009; Reidsma et al., 2009). Adaptation refers to a process, action or outcome in a system in order for the system to better cope with, manage or adjust to experienced or expected events e.g. climatic (Smit and Wandel, 2006). The pace, scale and even the direction of contextual changes being plagued with uncertainties (Thompson and Scoones, 2009), it is particularly difficult for farmers to make decisions about adaptation measures.

To address this adaptation challenge, technology transfer has long been dominant in agricultural research and development. It consisted of the development and promotion of ready-to-use technical adaptation packages with limited consideration for the peculiarities of farming systems and contexts (Darnhofer et al., 2010). Nowadays, these approaches are no longer of interest to effectively manage potential contextual changes such as climatic risks (Howden et al., 2007). Indeed, the occurrence and impacts of contextual changes are increasingly variable between farms within a single region (Reidsma et al., 2007). Hence the effectiveness of farming system adaptation and the connected preservation of the sustainability of farming systems require flexibility, since there are

* Tel.: +33 5 61 28 54 52; fax: +33 5 61 28 54 52.
E-mail address: guillaume.martin@toulouse.inra.fr

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no single problems and no single adaptation solutions (Magne and Ingrand, 2004; Vanclay, 2004).

Over recent years, along with the development of adaptation science (Meinke et al., 2009) and unlike the technology transfer approach, approaches seeking to develop farmers' adaptive capacity have increasingly been developed (Darnhofer et al., 2012; Klerkx et al., 2012b; Speelman et al., 2014). Adaptive capacity refers to farmers' "ability to design and implement effective adaptation strategies, or to react to evolving hazards and stresses so as to reduce the likelihood of the occurrence and/or the magnitude of harmful outcomes resulting from climate-related hazards" (Brooks et al., 2005). Adaptive capacity and the corollary concept of adaptive management (Pahl-Wostl et al., 2007) build upon farmers' local knowledge as well as farmers' learning about oneself, the farming system and its environment (Newsham and Thomas, 2011). It consists of continually improving management strategies and practices by learning from the outcomes of implemented strategies and practices.

As elaborated by Darnhofer et al. (2012), agricultural research accommodates two approaches to promote learning and, as a result, adaptive capacity of farmers. (i) The hard approach (e.g. Hansen, 2005) views farming systems as real entities existing as such with defined boundaries and goals. It relies on analysis and modeling of data from physical, chemical, physiological and ecological processes. Farmers are seen as optimizers seeking for combinations of best technical means to manage their farming systems. (ii) The soft approach (e.g. Ison et al., 2007) views farming systems as social constructs with negotiated boundaries and goals. The core concern is farmers' perceptions of their environment and their adaptation options. Farmers' strategies are seen as the product of human interaction, learning, conflict resolution and collective action.

As stated by several authors (Darnhofer et al., 2012; Martin et al., 2011c), both hard and soft approaches have drawbacks. For instance, due to mathematical complexity and inflexibility (Jones et al. 1997), the hard approach is criticized for being unable to cope with different production and management contexts and for relying on 'black box' models lacking transparency (Leeuwis, 2004; McCown et al., 2009). The consequence is that applications of the hard approach are regarded as unintelligible and as a result neither salient nor legitimate by most farmers. On the other hand, quantitative analysis and up-to-date scientific advances are neglected by the soft approach (Sellamna, 1999). Moreover, the soft approach hardly enables exhaustive exploration of the whole space of adaptation options. Applications of the soft approach may thus lack scientific credibility.

So far, in agricultural science, despite practical examples (e.g. Van Paassen et al., 2007) no third way has emerged that combines the merits of the hard and soft approaches to compensate for their drawbacks, with the aim of promoting learning and hence the adaptive capacity of farmers. In this article, I elaborate the conceptual foundations of such a third way, located at the interface between the hard and soft approaches. In Section 2, based on the scientific literature, I define a set of requirements for approaches aimed at developing the adaptive capacity of farmers. In Section 3, based on these requirements, I evaluate the benefits and drawbacks of the hard and soft approaches, and point out opportunities for hybridizing the two approaches. In Section 4, I present the conceptual foundations of such a hybridization and an application example, i.e. Forage Rummy (Martin et al., 2011a). The whole work is discussed in Section 5.

2. Requirements for research approaches aimed at developing farmers' adaptive capacity

As stated by Cash et al. (2003), effectiveness of scientific information and intervention in influencing societal learning and action and hence farmers' adaptive capacity and adaptations of farming systems depends on three main features: credibility, salience and legitimacy. "Credibility involves the scientific adequacy of the technical evidence and arguments. Salience deals with the relevance of the assessment to the needs of decision makers. Legitimacy reflects the perception that the production of information and technology has been respectful of stakeholders' divergent values and beliefs, unbiased in its conduct, and fair in its treatment of opposing views and interests" (Cash et al., 2003).

Table 1
Determinants of salience, credibility and legitimacy for research approaches aimed at developing farmers' adaptive capacity.

	Problem reframing stage
Salience	Situated approach
	Systemic approach
Credibility	Up-to-date and multidisciplinary scientific knowledge
	Scientific methods for design and evaluation of candidate solutions
Legitimacy	Transparency
	Multiple perspectives

Based on the scientific literature, a number of determinants can be identified for salience, credibility and legitimacy respectively (Table 1). Applied to the enhancement of farmers' adaptive capacity, I consider that salience is conditioned by three features of the research approach: it has to include a (i) problem reframing stage, and has to be (ii) situated and (iii) systemic. In order to be credible, the research approach has to use (iv) up-to-date and multidisciplinary scientific knowledge and (v) scientific methods for design and evaluation of candidate solutions for adaptation of farming systems. Finally, legitimacy is a function of (vi) the transparency of the research approach for stakeholders and the extent to which it (vii) integrates the multiple perspectives of researchers and stakeholders such as farmers.

(i) As stated by Pretty (1995), there is no single correct understanding of problem situations. These understandings are framed by individual interpretations that themselves depend on knowledge and beliefs acquired during life. A typical pitfall for research approaches aimed at enhancing farmers' adaptive capacity is to take definitions of problem situations for granted, i.e. without questioning the problems farmers face and how they are handling them now (Cox, 1996). This may lead to lack of structure in problem situation definitions because farmers' goals and constraints, knowledge underpinning decisions as well as farming system states are uncertain, contested or even unknown (Groot and Rossing, 2011; McCown, 2002). Ill-structured problems are critical in that they affect how the solution space is defined (White et al., 2010). At a very early stage of a project, problem reframing is thus essential to ensure that researchers and farmers share the same definition of the problem situation (Pahl-Wostl and Hare, 2004).

(ii) Farming is definitely a "situated" activity – characterized by a diversity of climatic, spatial, social, institutional and economic conditions defining constraints at different levels (Giller et al., 2008). As a result, farmers have situated management practices and situated management problems (McCown et al., 2009). For this reason, research approaches aimed at enhancing farmers' adaptive capacity have to be social and locally-specific, that is flexible enough to accommodate simultaneously the conditions of any farming context (Pretty, 1995; Sellamna, 1999).

(iii) While research and scientific information generally rely on reductionist approaches, farmers have no alternative to a holistic management approach (Meinke et al., 2006). Indeed, their decisions are influenced by on-farm observations and information as well as by factors such as policy, legislation, knowledge availability, infrastructure, funding, and markets. Adapting a farming system is therefore a balance between new technical practices and new organizational procedures (Klerkx et al., 2012b). Research approaches have to be systemic in order to integrate this complexity across its different agronomic, ecological, economic, sociological, and spatial dimensions, hierarchical levels and scales of analysis (Giller et al., 2008).

(iv) Acknowledging the complexity of the adaptation issue requires an interdisciplinary approach, integrating concepts and methods from natural (agronomy, ecology, animal science) and social (sociology, management science, economics) science (Giller et al., 2008). In addition, the adaptation issue is confronted with uncertainty about the pace, scale and direction of contextual changes and about the response of nature to such changes. Research approaches aimed at enhancing farmers' adaptive capacity thus have to take advantage of up-to-date scientific knowledge about this issue.

(v) Research approaches should not neglect the fundamental principles of science, namely "systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses" (The Oxford English Dictionary – 2nd ed., 1989). These principles apply to all stages of the research approach. Filtering and assimilating data can rapidly be overwhelming (McCown, 2002). The same applies to exploring the solution space through the design of candidate solutions for adaptation of farming systems, and their evaluation, which involves characterization of their relevance and level of uncertainty.

(vi) As stated by Giller et al. (2008), transparency is key when working with stakeholders such as farmers. This means that research approaches aimed at enhancing farmers' adaptive capacity have to be clear about the knowledge and procedures used, on the assumptions being made, on the meaning and interpretability of the results and on their uncertainty (Jiggins and Roling, 2000; Matthews et al., 2010).

(vii) When dealing with complex issues such as adaptation of farming systems, several authors have claimed that the contribution of science lies in bringing together pluralistic knowledge and perspectives (Bammer, 2005; Pretty, 1995). Hence participation of stakeholders such as farmers in research approaches is essential to adequately integrate the diversity of backgrounds, values, knowledge, representations, goals, interests and opportunities (Sterk et al., 2009). Farmers are no longer viewed as adopters of scientific recommendations but rather as experts capable of bringing new perspectives upon adaptation of farming systems (Röling and Wagemakers, 1998). Then "scientists must improve their understanding of the farmer and his practice and vice versa" (McCown, 2002).

3. Critical assessment of existing approaches

3.1. Hard approaches

3.1.1. Problem reframing stage

With hard approaches, the decisions to be made, the ends to be achieved and the means chosen are revealed by research on practical situations (Martin et al., 2013). The translation of goals, criteria, constraints and alternatives into a solution space is thus carried out by researchers. The problem identified is very specific and assumed to be stable. For instance, it consists of adapting farming systems to market shocks (Mosnier et al., 2009) and to variability of weather (Cabrera et al., 2006). The ability of researchers to specify a problem situation reflecting the constraints and opportunities faced by farmers is questionable (Cox, 1996). Moreover, in real-world practice, problems do not present themselves to the practitioner as given. They must be constructed: the goals are often unclear when a design project begins, and the requirements and constraints continue to change. Hence there is a risk of hard approaches leading to the production of inadequate representations of the problem situation and as a consequence, to a lack of salience and legitimacy.

According to Ison et al. (1997), a core principle with soft approaches is that problems do not occur in isolation but are part of interrelated networks of problems. Moreover, problems do not exist objectively. They are social constructs with negotiated boundaries and goals. Soft approaches therefore start with a problem definition stage involving stakeholders. The aim is to open up the problem and the solution space interactively (Bos et al., 2009). For instance, Groot Koerkamp and Bos (2008) involved farmers, people from the supply chain, advisors, egg trading companies and non-governmental organizations in order to analyze the problems related to hens' egg production in the Netherlands. Starting with a sustainability issue, the final version of the problem definition addressed detailed aspects of animal welfare, economic aspects and the societal image of agriculture. With soft approaches, the importance given to the problem reframing stage ensures their salience and legitimacy especially as problem definition can be revised during implementation of the approach.

3.2. Situated approach

Hard approaches rely on computer models representing plants, animals and even farming systems (e.g. Cabrera et al., 2006; Mosnier et al., 2009). Usually these models have been developed from scientific evidence. Therefore they are supposed to accommodate the peculiarities of different farming contexts. Yet it has been shown that computer models such as plant growth models do not always perform very well in reproducing yields when applied to new sites (Ewert et al., 1999; Palosuo et al., 2011) and at farm scale (Ewert et al., 2002). Critical issues relate for instance to inappropriate consideration of factors and processes determining yield variability over space and time (Challinor, 2009). In particular, it has been pointed out that the consideration of farm management needs to be improved (e.g. Martin et al., 2011b; Reidsma et al., 2009; Woodward et al., 2008). Inability of computer models to address social and local factors may compromise salience and credibility of hard approaches.

As soft approaches rely on stakeholders' contributions, they are situated in essence. Indeed, such approaches mostly rely on the facilitation of network building, negotiation and learning among various stakeholders in order to identify candidate adaptation solutions (Leeuwis, 2004). For instance, prior to fostering the search for locally relevant adaptations of land use, Webber and Ison (1995) conducted semi-structured interviews of local farmers and collective workshops with these farmers to define the problem situation. In this way, "knowledge is created and made meaningful by the context in which it is acquired, and learning is embedded in the daily experiences of the learners" (Sellamna, 1999). Therefore soft approaches accommodate any specific situation and their salience and credibility are not compromised.

3.3. Systemic approach

Computer models used in hard approaches are developed following a systemic approach. Corresponding scientific articles elaborate on the system boundaries, entities and interactions considered in these models (e.g. Cabrera et al., 2006; Mosnier et al., 2009). Still, by definition, models are simplified representations of real systems. Thus, as stated by Kalaugher et al. (2013) for the purpose of analysis of climate change adaptation options, computer models never include the full range of contextual changes applying to these systems, nor the full range of system entities and interactions. For instance, Dogliotti et al. (2005) neglects the dynamic interactions between the farmer and market prices that may result in changes in the crop rotations. Modeling is precisely a problem of clarifying model complexity, uncertainty, and imperfection. Thus, as long as model complexity, uncertainty, and imperfection are made explicit, credibility, salience and legitimacy may not be compromised.

Soft approaches are rooted in a number of systemic approaches such as the soft system methodology (Checkland, 1999). Therefore, as stated by Ison (2012), soft approaches pay particular attention to identification of system boundaries, to the issue of scale (system, subsystem and suprasystem), to the system elements and their interactions, to the system purpose and to the monitoring and evaluation of system performance. System analysis applied to dairy husbandry systems was performed in this way by Bos et al. (2009). Still, Ison (2012) recognizes that "what is or is not systems practice arises in the social dynamics or relations of those who concern themselves with the question". For this reason, Giller et al. (2008) noted that a number of soft approaches address only the local level and neglect higher-level constraints such as policy and regulations. In such cases, soft approaches may lack credibility, salience and legitimacy.

3.4. Up-to-date and multidisciplinary scientific knowledge

Because of their roots in physical and biological sciences, hard approaches benefit from the latest advances in these fields that are required to ensure scientific credibility. For instance, Cabrera et al. (2006) integrated up-to-date knowledge on the response of plants to manure application in order to address the environmental side-effects of farmers' adaptation to seasonal weather variability. Moreover, computer models constitute excellent repositories of multidisciplinary scientific knowledge. Indeed, they enable link concepts and models belonging to different disciplines to be linked. For instance, animal nutrition models can be coupled with econometric models (Mosnier et al., 2009). Therefore, hard approaches generally integrate multidisciplinary scientific knowledge, thereby preserving credibility, salience and legitimacy.

With soft approaches, there is no hierarchy between positions on an issue. "Every position deserves total respect and wins its legitimacy by the simple fact that it is a position" (Sellamna, 1999). Therefore, all knowledge is considered equally valid and capable of being negotiated. For instance, the design process described by Groot Koerkamp and Bos (2008) gives equal importance to the knowledge provided by citizens and by experts in the field in designing sustainable hens' egg production systems. As a consequence, up-to-date scientific knowledge, e.g. about the impacts of climate change on laying hens can be neglected even if of primary importance for the issue. The multidisciplinary nature of the knowledge used depends on the participants, including researchers, involved in the application of the research approach. Careful attention is required in their selection but this does not always happen (Barnaud and van Paassen, 2013). Hence a typical pitfall of soft approaches is to yield oversocialized views of farming systems (Röling and Wagemakers, 1998).

3.5. Scientific methods for design and evaluation of candidate solutions

As suggested by Bergez et al. (2010), hard approaches can be divided into four steps: (i) designing a set of candidate solutions for adaptation of farming systems, either randomly created or provided by the user; (ii) simulation of the solutions in farming contexts; (iii) evaluation of the solutions; (iv) comparison and choice of the most satisfactory solutions and if necessary, iterative improvement by looping back to the first step. In order to maximize scientific credibility, design of candidate solutions should ideally explore the whole solution space. This is the case with most hard approaches. For instance, Dogliotti et al. (2005) generate all possible combinations of crop rotations prior to exploring which one best suits the farmer's objectives. Moreover, quantitative and qualitative evaluation of candidate solutions and computer models is required (Crout et al., 2009). Hard approaches (for instance Mosnier et al., 2009) tend to favor the former at the expense of the latter.

With most soft approaches, the methodology for problem definition is documented in detail (see for instance Webber and Ison, 1995). This emphasis on problem finding has led to little formalization of the problem-solving stage, i.e. the design and evaluation of candidate solutions. In this respect, the reflexive interactive design methodology (Bos et al., 2009) is an exception. It implies a structured design process with a set of principles and steps to follow. For instance Groot Koerkamp and Bos (2008) explain how they linked stakeholders' needs and requirements identified in the systems analysis stage through the definition of key functions that drive the design of sustainable hens' egg production systems. The systems designed were evaluated through scoring according to the requirements previously defined. Still, soft approaches are limited by human capabilities that restrict the design and evaluation to a small set of candidate solutions within the whole solution space. Interesting solutions may then be ignored, thereby compromising scientific credibility.

3.6. Transparency

Good modeling practice involves transparency of the model and its outputs (Crout et al., 2009). Part of it is usually achieved through scientific publications that describe the system boundaries, entities and interactions considered in these models. Still, most models (e.g. Dogliotti et al., 2005; Mosnier et al., 2009) are constructed in such a way that they cannot be easily understood by stakeholders (Jiggins and Roling, 2000). Even for researchers, 'the risk of getting lost in [their] complexity [. . .] is ever present' (Cacho et al., 1995). Despite efforts to explain the output of hard approaches (e.g. Rossing et al., 1997), most such approaches are like a 'black box', lacking transparency. As a consequence, as already stated by several authors (McCown et al., 2009; Woodward et al., 2008), they may not be regarded as salient and legitimate.

A core principle of soft approaches is transparency (Barnaud and van Paassen, 2013). Scientists intervening in such approaches have to be clear about the uncertainty associated with the knowledge they provide, or about the likelihood of their predictions (Leeuwis, 2004). Scientists also have to clarify their role and if necessary, specify the way in which it differs from the one of facilitators and communication workers (Leeuwis, 2004). Thanks to these transparency efforts, soft approaches are often considered salient and legitimate by stakeholders such as farmers.

3.7. Multiple perspectives

With hard approaches, there is not much participation of intended users or other stakeholders (e.g. Mosnier et al., 2009). Exceptions concern collaborative participation during analysis and conceptualization of the problem situation, with the involvement of stakeholders during definition of goals and identification of management constraints (Rossing et al., 1997; Van Calker et al., 2006). As a result, most hard approaches do not suit the decision-making style of farmers (Cox, 1996). Moreover, these approaches merely "[ignore] broader issues of power, economics, politics and all that determines social phenomena" (Sellamna, 1999), which might compromise their salience and legitimacy.

Among Pretty's (1995) six elements for alternative systems of learning and action, one is to seek multiple perspectives. This is a central objective of soft approaches in which reality is considered to be socially and culturally constructed and subject to multiple interpretations (Sellamna, 1999). In the example provided by Groot

Koerkamp and Bos (2008), a diversity of actors is always involved. Such collective and interactive settings often enable the complexity of the world to be tackled more holistically (Pretty, 1995). Still, as pointed out by several authors (Barnaud and van Paassen, 2013; Giller et al., 2008), soft approaches have failed to address power issues, conflicts and politics. Such failures have tended to marginalize the powerless (Barnaud and van Paassen, 2013; Sellamna, 1999). Recent recommendations on the topic (Barnaud and van Paassen, 2013; Leeuwis, 2000) may help to improve the already satisfactory salience and legitimacy of soft approaches.

3.8. Potential for hybridizing hard and soft approaches

In accordance with Pahl-Wostl's (2005) proposal for the field of environmental science, the assessment established in Section 3 shows that the hard and soft approaches exhibit complementarities (Table 2). For instance, whereas computer models used in hard approaches are unable to address social and local factors, stakeholders' contributions promoted by soft approaches may help to accommodate wider sets of specific situations. In the field of agricultural science, hybridization of hard and soft approaches can benefit the credibility, salience and legitimacy of research approaches aimed at developing adaptive capacity of farmers across the seven criteria defined in Section 2 (Table 2).

4. Hybridizing hard and soft approaches

4.1. A conceptual framework hybridizing hard and soft approaches

In order to hybridize hard and soft approaches, the proposed framework builds on the principles of adaptation science (Meinke et al., 2009), of integration and implementation science (Bammer, 2005), of participatory modeling (Voinov and Bousquet, 2010) as well as on the use of boundary objects in innovation systems (Cash et al., 2003; Klerkx et al., 2012a). In line with adaptation science,

Table 2
Critical assessment of hard and soft approaches aimed at developing farmers' adaptive capacity and intended benefits of their hybridization. + and – mean that the considered approach displays strengths and weaknesses respectively, as regards the criteria considered.

Criteria	Hard appr.	Soft appr.	Intended benefits of their hybridization
Problem reframing stage	–	+	Shared problem definition and mutual understanding between project participants
Situated approach	–	+	Integration of social and local specificities
Systemic approach	+	+	Elicitation of the complexity, uncertainty, and imperfection of the research approach to avoid mismatches between their resolution and their intended purpose
Up-to-date and multidisciplinary scientific knowledge	+	–	Integration of up-to-date scientific knowledge
Scientific methods for design and evaluation of candidate solutions	+	–	Formalized and exhaustive exploration of the solution space in order to yield not only reliable, but also socially robust solutions
Transparency	–	+	Communication about the research approach and especially the computer models being used
Multiple perspectives	–	+	Hybridization of knowledge and ideas provided by project participants

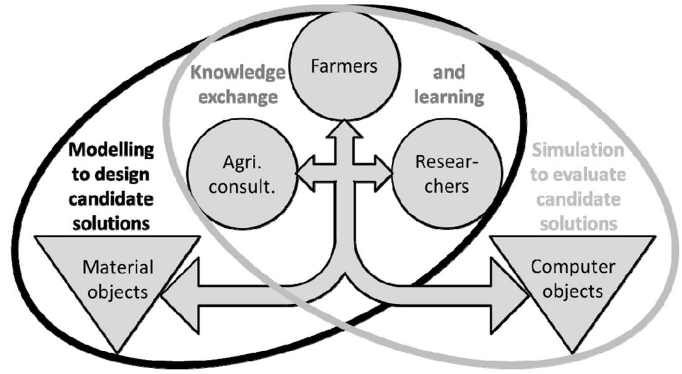

Fig. 1. Overview of the communication platforms underlying the proposed conceptual framework. Circles refer to people and triangles to boundary objects. Arrows represent interactions between people and between people and boundary objects. The text in bold characters is connected with the ovals and refers to processes involving people and boundary objects.

the proposed framework (Fig. 1) aims at "identifying and assessing threats [...] and opportunities and generating the information, knowledge and insight required to effect changes in systems to increase their adaptive capacity and performance" (Meinke et al., 2009).

These aims are achieved by implementing Bammer's (2005) principles to address complex societal issues: systems thinking and complexity science, participatory methods and knowledge management, exchange and implementation. Implementation of Bammer's (2005) principles takes the form of participatory group modeling workshops (Fig. 1). Such workshops are communication platforms (Klerkx et al., 2012b) involving researchers, agricultural consultants and farmers who collectively manipulate objects (e.g. cards and computer models) enabling simulation modeling of farming systems and their adaptation to new contextual challenges (e.g. climate change) and new farmers' objectives (e.g. transition to organic farming). Two synergistic benefits are sought: (i) knowledge production and exchange between participants in the workshops and (ii) integrated evaluation of candidate solutions to a given farming problem (Voinov and Bousquet, 2010).

As opposed to the provision of optimal or ready-made solutions, the idea is to support stakeholders trying to improve their understanding of the farming system complexity and its dynamics under various conditions and therefore their adaptive capacity. Following Voinov and Bousquet (2010), the researchers' role switches to facilitating and strengthening stakeholders' learning processes. Researchers have to identify local groups of farmers and agricultural consultants concerned with a similar problem situation. With each group, researchers have to set up workshops enabling these problem situations to be addressed. Hence they have to offer workshop participants ways of collectively defining problem situations and designing, evaluating and comparing collectively candidate solutions for adaptation of farming systems (Fig. 1; Giller et al., 2008) in an equitable and legitimate atmosphere (Barnaud and van Paassen, 2013).

As suggested by several authors (Jakku and Thorburn, 2010; Klerkx et al., 2012a), I conceptualize as boundary objects the objects manipulated (e.g. cards and computer models) in the communication platforms involving researchers, agricultural consultants and farmers. A boundary object is defined as "an entity shared by several different communities but viewed or used differently by each of them, being both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" (Star and Griesemer, 1989, p. 393). In the proposed conceptual framework, manipulated boundary objects are of two types: (i) material objects (e.g.

cards) enabling modeling, i.e. design of candidate solutions on a board game and (ii) computer objects (e.g. computer models) enabling simulation, i.e. evaluation of these solutions.

Material objects are intended to create a connection between workshop participants (Klerkx et al., 2012a). Material objects have to represent physical and functional entities managed by farmers in their farming activity such as grassland fields and herd batches. The type of objects to be manipulated can best be co-defined with agricultural consultants and farmers (Antona et al., 2003) in order to match their representation of a farming system and to ensure that their features are locally relevant to the problem situation. For instance, if the problem deals with self-sufficiency for forage in livestock farming systems, one type of object has to clarify the consequences of weather variability on forage production in the area where farmers and agricultural consultants participating in the workshop are operating. Manipulating these material objects and the information they encapsulate to design candidate solutions to their problem situations, farmers and agricultural consultants share knowledge, opinions and discuss the pros and cons of different solutions to the problem situation (Martin et al., 2011a; Speelman et al., 2014).

Computer objects are intended to provide integrated evaluation of candidate solutions designed by workshop participants in order to stimulate their reflections and discussions using relevant and objective biophysical and socio-economic up-to-date knowledge encapsulated in simulation models. Yet, scholars may be cautious and avoid using science-driven models not developed for participatory modeling (Voinov and Bousquet, 2010). Indeed, models have to stay systemic but simple (e.g. avoiding too many parameters), interactive (e.g. enabling live evaluation of candidate solutions) and usable (by at least some of the stakeholders). These goals can best be pursued by co-constructing models and calibrating them for local conditions with agricultural consultants and farmers (Antona et al., 2003). And in addition to the credibility usually approached through the predictive capability, evaluation of computer models used in participatory settings has to focus on salience (Crout et al., 2009).

Boundary objects provide them with a shared vocabulary that promotes transparency of the research approach and facilitates mutual understanding and knowledge sharing between researchers, agricultural consultants and farmers. Problem reframing and iterations between modeling and simulation, i.e. design and evaluation of candidate solutions, using material objects and then computer objects facilitate communication, cooperation and knowledge exchange between them (Fig. 1).

4.2. Example of hybridization with Forage Rummy

Forage Rummy (Martin et al., 2011a) is a board game supported by computer models that has been developed following a participatory systems approach involving agricultural consultants and farmers. To promote credibility and legitimacy, it integrates multiple perspectives through multidisciplinary scientific as well as empirical knowledge. It is intended to be used by agricultural consultants and/or researchers with small groups of 2 to 4 farmers during workshops lasting from 2 to 4 hours. The problem situation is defined with farmers prior to the workshops or at their very beginning and reframed during the discussions in the workshops in order to ensure salience. Workshops include collectively (to seek multiple perspectives and therefore favor legitimacy of Forage Rummy) and iteratively designing and evaluating livestock systems able to be adapted to new contextual challenges (e.g. climate change, volatility of input prices) and new farmers' objectives (e.g. transition to organic farming). Throughout these iterations, it aims at developing farmers' adaptive capacity by stimulating their reflections and discussions.

Forage Rummy is based on five boundary objects, four material objects and one computer object (Figs 2 and 3), enabling livestock systems to be designed and evaluated:

(i). The game board is divided into 13 four-week periods, i.e. one year, along the x-axis. Along the ordinate, the upper part is concerned with management of land use and consequently forage production within the farm. The lower part is dedicated to herd management and especially herd feeding. Seeking for salience, the game board supports a systemic representation of the key challenge faced by farmers, i.e. to adequately match animal feeding requirements with forage production across seasons.

(ii). For each combination of annual weather pattern (past or projected weather data, the years being selected with farmers), soil type, forage crop (permanent and sown grasslands, cereals,

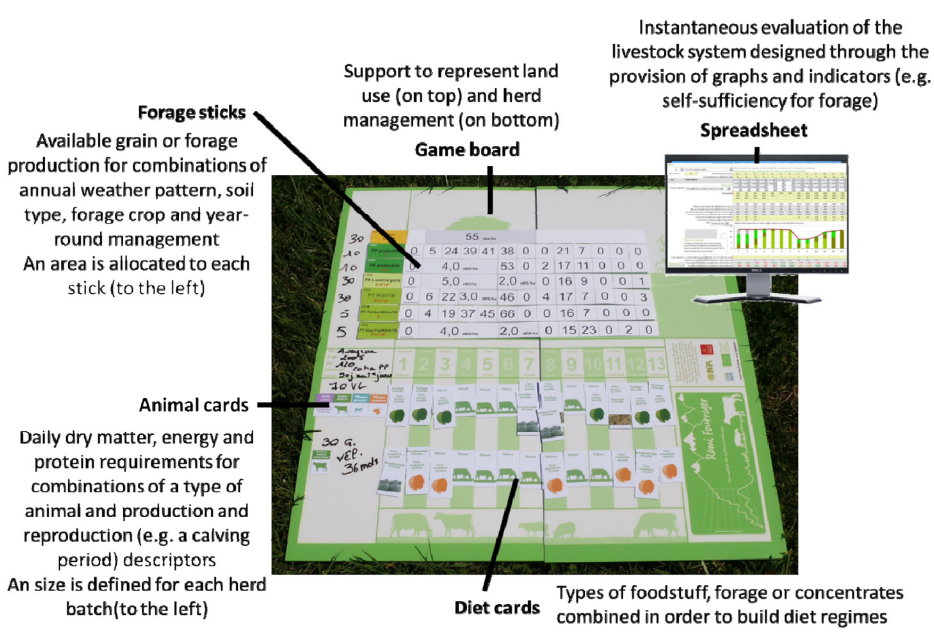

Fig. 2. Overview of Forage Rummy.

legumes, etc.) and year-round management (e.g. during year 2009, on a deep soil, an early and productive permanent grassland grazed six times a year), the game contains flattened sticks (that I call forage sticks) marked with the available grazed grass in kilograms per hectare and per four-week period across the calendar year or with the available yield through mechanized harvest once (for crops or grasslands harvested once) to several times a year (for grasslands). This way, the data used in the modeling process is transparent to the farmers and provides legitimacy to Forage Rummy. In order to ensure salience, Forage Rummy is situated. For each new application of the game, forage sticks are developed based on researchers', agricultural consultants' and/or farmers' expertise, or using crop models (e.g. Duru et al., 2009) incorporating up-to-date and multidisciplinary scientific knowledge (to provide credibility to Forage Rummy) parameterized with information provided by agricultural consultants and/or farmers (i.e. situated information to ensure salience of Forage Rummy). To represent land use and grassland and crop management, farmers have to select a limited number of forage sticks from among the whole set, place the sticks on the upper part of the game board and decide on the area to allocate to each stick.

(iii). Animal cards either display a type of animal (e.g. dairy cow, goat) and production (e.g. a milk production level) and reproduction (e.g. a calving period) descriptors. By combining animal cards one creates an animal and its year-round management (e.g. a herd batch of dairy cows producing 6000 kg of milk per year and calving in autumn). Based on these combinations, for each new application of the game, the daily dry matter, energy and protein requirements of this animal are defined across the thirteen four-week periods of the calendar year using databases as well as an animal production and feeding model (INRA, 2007) incorporating up-to-date and multidisciplinary scientific knowledge (to provide credibility to Forage Rummy) parameterized using situated information provided by agricultural consultants and/or farmers (to ensure salience of Forage Rummy). In order to ensure legitimacy of Forage Rummy, the resulting data are made available and thus transparent to farmers throughout the modeling process. To represent herd management, farmers have to create herd batches on the lower part of the game board. They have to select and combine animal cards to create a representative animal. Then, they have to specify a headcount for this type of animal on the game board. At most 3 herd batches can be created. The system applies to beef and dairy cow farms, meat and dairy sheep farms and goat farms.

(iv). Each diet card represents either a type of foodstuff, forage (e.g. grazed grass, hay, silage) or concentrate (e.g. soya meal). Each foodstuff is characterized by a fill value and energy and protein contents based on up-to-date scientific knowledge (INRA, 2007). To represent herd feeding management, farmers have to select and combine diet cards in order to build the diet regime of each herd batch across each of the thirteen four-week periods of the calendar year. These cards are placed on the lower part of the game board, aligned with the animal cards.

(v). Throughout the game, farmers' choices regarding the forage sticks and their area allocation, the herd batches and their size as well as their diet are entered into a computer spreadsheet. This spreadsheet automates the calculations of indicators and graph building used for evaluation of the livestock system designed. For instance, graphs illustrate the extent to which animal feeding requirements are covered over each four-week period with the livestock system designed. It also holds data, among other things, about feeding costs as well as self-sufficiency for forage, concentrates, straw, energy and protein. In addition to providing a scientific method for evaluation of the livestock systems designed and therefore ensuring credibility of Forage Rummy, the spreadsheet hastens the process whereby players visualize whether forage production adequately matches animal feeding requirements across seasons and eventually decide whether to continue with additional design and evaluation loops.

Fig. 3. Example of a workshop using Forage Rummy and involving one scientist (facilitator), one agricultural consultant and three farmers. Farmers have represented a livestock system on the game board and are visualizing the graphs and indicators provided by the spreadsheet to stimulate their discussions.

In the course of the game, across the structured design process, researchers and/or agricultural consultants ask questions to stimulate thought and interaction between players and to ensure the salience and legitimacy of livestock systems designed. The input data and output indicators are available to the players at any time during the game, be it on the forage sticks or in the spreadsheet (Fig. 3). If necessary, researchers and/or agricultural consultants explain their meaning and farmers can even decide to modify input data, e.g. a yield on a forage stick, in order to better represent their farming context. This may ensure transparency and therefore legitimacy of Forage Rummy.

4.3. Application of Forage Rummy with farmer groups

So far, Forage Rummy has been applied in up to 50 workshops that have involved more than 200 farmers. As an example, I will describe a workshop that took place in Brittany in 2012. Two farmers (MC and BN), one agricultural consultant and one researcher were involved. The initial problem perceived by one farmer (MC) was his high feeding costs. For this reason, he wanted to increase the area of grassland on his farm. When introduced to the boundary objects of Forage Rummy adapted to their farming conditions, farmers fixed crop yields and decided to make corrections to the costs per ton for several types of forage in order to better match their conditions.

Using the various boundary objects, farmers reproduced MC's current farming system and verified that graphs and output indicators provided by the spreadsheet matched their measurements and observations. Then they started to revise the current system by increasing the area of grassland. This led to problem reframing: through discussions with the other farmer, MC realized that his problem did not only concern his high animal feeding costs but several other aspects such as his high milk production per cow that required costly cropping activities (silage maize mainly) and high levels of concentrates purchased off-farm. Thus, MC understood that the adaptation he wanted to test involved increasing the area of grassland on his farm as well as decreasing milk production per cow, increasing cow headcount, adjusting animal diets and land use. He claimed that he had to choose between defining milk production per cow and animal diets according to land use or defining land use and animal diets according to milk production per cow.

Candidate solutions designed by the farmers were evaluated for two types of weather, one year with favorable conditions and one year with a drought during spring. During this process, farmers discussed and argued, for instance about the best species mix to sow. After several iterations of design and evaluation of candidate solutions, one solution was considered to be satisfactory for both types of year by both farmers. Their evaluation relied on indicators provided by the spreadsheet (animal dry matter, energy and protein requirements coverage rate, self-sufficiency for forage, animal feeding costs, etc.) and on other criteria such as animal welfare resulting from their self-evaluation. Using the spreadsheet, MC found out that by increasing the area of grassland in his farm, he could decrease his feeding costs and save 35€ per ton of milk produced.

In the oral and written evaluation of the workshop, both farmers claimed that they appreciated playing Forage Rummy for two main reasons: discussing and exchanging ideas and doing simulations. In particular, MC said that he felt better prepared to increase the area of grassland on his farm and that the workshop had been the opportunity to prepare this adaptation. This echoes Brooks et al.'s (2005) definition of adaptive capacity: throughout the workshop MC improved his ability to design and implement adaptation strategies and to react to evolving hazards and stresses. This was the result of knowledge co-production between farmers and agricultural consultants as already observed in very different contexts (Newsham and Thomas, 2011; Webb et al., 2013). The two farmers did not know each other prior to the workshop and they agreed to keep in touch with each other about their practices. On the other hand, the agricultural consultant greatly valued the fact that farmers had been the main actors in the design of solutions and considered that consequently, they had found the appropriate solution.

Based on the evaluations provided by farmers and agricultural consultants, the 50 or so workshops carried out so far have produced similar outcomes to those described in the example. Replying to open questions (e.g. what did you like about playing Forage Rummy?), two thirds of farmers replied that they had liked to get a better understanding of the adaptation challenge at the farm scale and to share knowledge about most promising adaptation practices with their colleagues. Thus they appreciated having played Forage Rummy and made suggestions for future workshops. For instance, one farmer concluded a workshop by saying: "this winter, we have to lock ourselves away for one day to test and discuss a diversity of configurations for our farms." Negative comments were scarce and referred to the use of a game for a serious issue such as agricultural production, and to inaccurate crop and grassland yields on the forage sticks. In the latter case, yields were consistently modified according to farmers' knowledge of their local farming context.

5. Discussion

The aim of this article was to develop a conceptual framework combining the benefits of the hard and soft approaches in order to promote learning and hence the adaptive capacity of farmers. To this end, I have produced four main types of output: (i) a set of requirements for research approaches aimed at developing the adaptive capacity of farmers, (ii) a critical assessment of existing approaches, (iii) a conceptual framework combining the respective assets of the hard and soft approaches and (iv) an application of this conceptual framework called Forage Rummy.

The set of requirements for research approaches aimed at developing the adaptive capacity of farmers is original. Several authors (Matthews et al., 2008; McCown, 2002) have addressed the requirements of decision support systems in effecting adaptation of farmers' decisions and practices. None has addressed the whole research approach and the implementation process of a decision support system such as a computer model. Yet, this article shows that some aspects of the implementation process, such as the inclusion of a problem reframing stage, are crucial. Moreover, authors suggested several requirements such as credibility (Matthews et al., 2008), perceived usefulness and ease of use (McCown, 2002). But none proposed a set of requirements structured according to their respective impacts on the determinants of effectiveness of research approaches in influencing farmers' adaptive capacity, i.e. salience, credibility and legitimacy (Cash et al., 2003), as I propose in this article.

The set of requirements defined in Section 2 has proved its relevance to draw up a critical assessment of existing hard and soft approaches and to characterize their respective benefits and drawbacks (Section 3). In the scientific literature, the hard and soft approaches have rarely overlapped. Although the development of participatory modeling has helped to overcome this problem over the last years, a literature review mirroring hard and soft approaches was missing. For instance, literature reviews about hard approaches in agriculture (Janssen and van Ittersum, 2007; Pearson et al., 2011) focused on the features of computer models which might be used for adapting farming systems and developing farmers' adaptive capacity. Again, these reviews ignored the whole process of implementation of these models. The suggested complementarities between hard and soft approaches in agricultural science are echoed in Pahl-Wostl's proposal (2005) for the field of environmental science.

Following Giller et al. (2008), the conceptual framework hybridizing hard and soft approaches proposed in this article implies a shift in thinking about scientific knowledge and its role in society. Researchers no longer provide recommendations that bypass farmers' decision processes but rather try to facilitate their adaptation decisions (McCown, 2002). Researchers therefore help agricultural consultants and farmers in carrying out their own experimentation to transparently design and evaluate scenarios of candidate solutions and stimulate the discussions induced. Researchers in the FARMSCAPE research program had a similar position in their practice of action research and that contributed to produce both scientific outputs and outcomes for farmers (McCown et al., 2009). In this configuration, boundary objects such as computer models play a key role in mediating between researchers, agricultural consultants and farmers. Particular attention has to be paid to their capacity to fulfill their function, i.e. promoting learning and as a result the adaptive capacity of farmers. Indeed, applied to computer objects, Jiggins and Roling (2000) noticed that "scientists' tendency to develop true models interferes with interactive learning".

Although the environmental science literature contains a wide variety of game-based approaches to improve environmental management (D'Artista and Hellweger, 2010; Hartig et al., 2010; Simon and Etienne, 2010; Worrapimphong et al., 2010), Forage Rummy is, as far as I know, the first example of a game combining material and computer objects aimed at promoting learning and hence the adaptive capacity of farmers. In past workshops, as shown in Section 4.3., it has proven successful in stimulating farmers' thinking and discussions and consequently their adaptive capacity. As already observed by McCown et al. (2009), knowledge produced through the sharing of farmers' experiences is not just subjectively meaningful, but it becomes scientifically rigorous. Through the iterations of design and evaluation of candidate solutions to their problem situations, farmers build their own personal knowledge and are more likely to use it as it is meaningful to their future.

Progress is needed on four main aspects to improve the proposed conceptual framework and its applications such as Forage Rummy: (i) an improved characterization of the uncertainty carried out by the material and computer objects, (ii) more extensive guidelines on the role of researchers, (iii) characterization and analysis of research outcomes, such as farmers' learning and improvement of their adaptive capacity and (iv) identification of the conditions required for the production of such outcomes.

(i) Uncertainty can be high when addressing complex systems such as farming systems and their adaptation to new global challenges and new farmers' objectives. Transparency being essential in participatory settings, an improved characterization of the uncertainty carried out by the material and computer objects is required (Wallach et al., 2013). This is particularly relevant when addressing local situations in the framework of situated approaches.

(ii) Building on recent insightful analyses (Barnaud and van Paassen, 2013), issues of power in participatory modeling have to be clarified. At the moment, as observed for most participatory approaches (Giller et al., 2008), when stakeholders have differing world views, their power relations are not explicitly addressed in the facilitation of the workshops.

(iii) Building on the literature in communication and innovation science (Van Mierlo et al., 2010) and science and technology studies (Newsham and Thomas, 2011), characterization and analysis of learning and improvement of adaptive capacity induced by the implementation of the conceptual framework has to be improved. Indeed, systematic evaluation of cognitive change or revision of mental models of participants in a Forage Rummy workshop would be insightful for the promotion of farmers' adaptive capacity. It could possibly be complemented with verifications of implementation of the adaptations developed in the course of the workshops.

(iv) An assessment of the conditions (main features of farming systems, problem situations, etc.) leading to learning and innovation induced by the implementation of the conceptual framework may help to achieve more context-relevant applications. For instance, the proposed conceptual framework is most suited to adaptation of farming systems towards agroecological practices involving the management of a diversity of biophysical resources (e.g. several types of crops) thereby generating a complex resource allocation problem.

6. Conclusion

As a response to the changing agricultural context, farmers need to develop their adaptive capacity. To support this process, I suggest that research approaches have to include a (i) a problem reframing stage, and have to be (ii) situated and (iii) systemic. They have to use (iv) up-to-date and multidisciplinary scientific knowledge and (v) scientific methods for design and evaluation of candidate solutions for adaptation of farming systems. They also have to (vi) be transparent for stakeholders and (vii) integrate the multiple perspectives of researchers and stakeholders. I have shown that neither hard approaches, building on analysis and modeling of data from physical, chemical, physiological and ecological processes, nor soft approaches drawing on farmers' knowledge fulfill these seven requirements. Yet, they display complementarities, suggesting potential for hybridization. For instance, whereas hard approaches may yield inadequate representations of problem situations, soft approaches always start with a problem reframing stage involving stakeholders in order to construct a shared problem definition. Building on these complementarities, I have elaborated a conceptual framework hybridizing hard and soft approaches that takes the form of participatory group (researchers and stakeholders) modeling workshops. During these workshops, researchers, agricultural consultants and farmers are involved in an iterative process consisting of designing and evaluating candidate adaptation solutions using boundary objects encapsulating biophysical and socio-economic knowledge. Implementation of Forage Rummy, a first application of this conceptual framework, with farmers' groups has confirmed the potential of this framework to develop farmers' adaptive capacity.

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