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A conceptual framework for guiding the participatory development of agricultural decision support systems

E. Jakku, P.J. Thorburn *

CSIRO Sustainable Ecosystems and Sustainable Agriculture Flagship, Queensland Bioscience Precinct, 306 Carmody Road, St. Lucia QLD 4067, Australia

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ABSTRACT

Scientists develop decision support systems (DSSs) to make agricultural science more accessible for farmers and extension officers. Despite the growing use of participatory approaches in agricultural DSS development, reflection on this endeavour has largely focused on the 'doing' of participation or the 'problem of implementation' when DSSs have not been adopted by stakeholders. There has been little reference to relevant theoretical approaches to the social processes involved in 'participation' or 'implementation'. However, if DSS use is to reach its full potential, a more conceptually informed understanding of how stakeholders collaborate in the participatory development of DSSs is required. To contribute to this conceptualisation, we developed a framework based on three concepts drawn from the field of science and technology studies: technological frames, interpretative flexibility and boundary objects. The framework highlights the importance and value of social learning for participatory DSS development, which relies upon exploring the participating parties' different perspectives on the agricultural system represented in the DSS. Our framework provides a broad definition of success for participatory DSS development, placing greater weight on learning during the participatory process compared with subsequent use of the DSS by farmers and/or advisors. Two case studies of stakeholder collaboration to develop an irrigation scheduling DSS for sugarcane production were used to explore the relevance of the framework. The concepts in the framework were clearly displayed during the case studies. At the conclusion of the studies there were contrasting outcomes for the DSS. One group of farmers was keen to apply it in their ongoing irrigation management, while another saw little relative advantage in use of the DSS. In both instances co-learning occurred amongst case study participants, so the participatory process was clearly a success.

1. Introduction

The declining profitability of agriculture, increasing climatic variability and growing concerns over the environmental impacts of farming pose complex challenges for farm management in Australia (Keating and Carberry, 2010). These challenges have prompted a search for ways in which scientific knowledge can be incorporated into tools that can assist farmers in making farm management decisions. These tools include decision support systems (DSSs), which help make agricultural science more accessible to and useful for farmers (McCown, 2002). Agricultural DSSs are software applications, typically based on computer models that describe various biophysical processes in farming systems and how they respond to different management practices (e.g. irrigation, fertiliser, sowing and harvesting dates) and/or climatic variability (e.g. temperature and rainfall). For example, DSSs may aid the management of cotton crops (e.g. GOSSYM/COMAX; Hodges et al., 1998), optimise nitrogen fertiliser management (e.g. SUNDIAL; Smith et al., 1996; Gibbons et al., 2005), or assess the impact of seasonal climate variability on crop production (e.g. Whopper Cropper; Nelson et al., 2002: Yield Prophet®; Hochman et al., 2009).

Recently, the development of agricultural DSSs has shifted towards participatory approaches to both design and implementation (Carberry et al., 2002; Nelson et al., 2002; McCown and Parton, 2006). This shift towards participatory development of DSSs is part of a broader change in the way that agricultural innovations and interventions are viewed. Innovation is no longer regarded as a simple, linear process, wherein agricultural research and development creates technologies that are transferred via extension officers to farmers. Instead, agricultural innovation is recognised as "a complex, interactive process" of co-learning and negotiation (Klerkx and Leeuswis, 2008, p. 365). It is difficult to neatly categorise the range of participatory approaches used in research and development because there is marked variation in the degree of power sharing between scientists and stakeholders, and therefore the level of stakeholder participation and the modes of communication across these studies (McNie, 2007). Nevertheless, central to participatory approaches is the principle of involving stakeholders

* Corresponding author. Tel.: +61 7 3214 2316; fax: +61 7 3214 2308.
E-mail address: peter.thorburn@csiro.au (P.J. Thorburn).

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as active participants from the early stages of the research, rather than treating them as passive recipients of knowledge (Kloppenburg, 1991; Massey et al., 2006).

Within this context, an important role for information and communication technology tools (such as DSSs) lies in their potential to support social learning (Pahl-Wostl et al., 2007). Social learning broadly refers to the "processes of learning and change of individuals and social systems" (Pahl-Wostl and Hare, 2004, p. 194) and "acquisition of collective skills" (Voinov and Bousquet, 2010, p. 1272). Practitioners within the field of environmental assessment are increasingly recognising the value of social learning processes, focusing on how stakeholders interact, learn collaboratively and make collective decisions (Keen et al., 2005; Muro and Jeffrey, 2008; Ritzema et al., 2010; Lynam et al., 2010). Thus social learning principles and their emphasis on shared learning have strong parallels to participatory approaches (Measham, 2009). Within agricultural research there has been some recognition that DSSs can support social learning; for example Nelson et al. (2002) propose the term "discussion support systems" to capture the role that DSSs can play in facilitating dialogue about management practice between key players. However, appreciating the opportunity for participatory DSS development to support social learning means that 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.

Despite the growing use of participatory approaches DSS development in agriculture, studies of DSS development have largely focused on the 'doing' of participation in development (such as for instance Carberry et al., 2002; Foale et al., 2004), the 'problem of implementation' (Matthews et al., 2008; McCown, 2002), or the cognitive structure of individual farmer's learning and decision making (McCown et al., 2009). These studies have identified important lessons about participatory DSS development. However, they make limited reference to the theoretical approaches within the social sciences that have explored the social processes involved when different social groups interact to develop new technologies. Such approaches exist within the field of science and technology studies (STS). STS is a multidisciplinary field that examines science and technology as complex enterprises that take place in specific contexts, shaped by, and in turn shaping, social processes, relationships and practices (Bowden, 1995; Law, 2008). Within STS, science and scientific knowledge is "an actively negotiated, social product of human inquiry" (Cozzens and Woodhouse, 1995, p. 534) and technology is "a social product, patterned by the conditions of its creation and use" (Williams and Edge, 1996, p. 866). STS provides a collection of conceptual approaches for thinking about science and technology in sophisticated ways (Hess, 1997). While some analysts have applied actor network theory, a perspective from STS, to examine agricultural research and development (de Sousa and Busch, 1998; Higgins, 2006; Juska and Busch, 1994; Murdoch, 1995), the broader STS field has remained largely untapped by those interested in the participatory development of agricultural DSSs.

This paper aims to help provide a stronger theoretical understanding of the social processes underpinning participatory DSS development, in an agricultural context. In it we describe three concepts drawn from STS that can add value to understanding agricultural DSSs and combine them in an analytical framework explaining the social processes involved in participatory DSS development. Our framework emphasises that learning is a valuable outcome that can occur when scientists, extension officers and farmers collaborate, and may help deliver this outcome in the future. We illustrate these concepts with two case studies of participatory development of a DSS that was designed to help sugarcane farmers to optimise limited irrigation water supplies.

2. Conceptual framework

2.1. Background and context

We combined the concepts of technological frames, interpretative flexibility and boundary objects in a framework (Fig. 1), to describe the social processes of participatory DSS development and help identify different outcomes that may result when farmers, extension officers and scientists collaborate to develop a DSS. The overall structure of our framework was inspired by the social learning framework developed by Claudia Pahl-Wostl and her colleagues as a means to support participatory planning in water and river basin management. They identified the social learning processes that can emerge when multiple parties collaborate to achieve context-specific outcomes (Pahl-Wostl and Hare, 2004; Pahl-Wostl et al., 2007; Pahl-Wostl, 2009). They define recognise the importance of "communication, perspective sharing and development of adaptive group strategies for problem solving" (Pahl-Wostl and Hare, 2004, p. 194) in social learning.

Our framework recognises that DSS development is often a multi-party (farmers, advisors/consultants, researchers, etc.) group process conditioned by the external social, cultural, political, economic and/or biophysical context. These factors range from macro-level economic and political factors, such as world markets, through to micro-level social and cultural factors, such as farming traditions, and individuals' educational backgrounds and attitudes towards risk, as well as constraints that the biophysical environment places on the farming system (Doorman, 1991; Ang et al., 2001). Within this broader context, participatory DSS development usually commences as a result of various parties, typically farmers, extension officers and scientists, recognising that there is a problem or an issue within a particular agricultural system that could be addressed if they work together to develop an appropriate DSS (McCown et al., 2009).

2.2. Technological frames and interpretative flexibility

The concepts of technological frames and interpretative flexibility help to describe the influence that context and social processes have upon participatory DSS development. Technological frames and interpretative flexibility are concepts that have emerged from the social construction of technology branch of STS. Studies of the implementation and early use of a new information technology have built on Bijker's (1987, 1995) work on the social construction of technology, to define a technological frame as "...the subset of members' organisational frames that concern the assumptions, expectations and knowledge they use to understand the technology" (Orlikowski and Gash, 1994, p. 178). This includes perceptions of the nature and role of the technology itself, as well as the "specific conditions, applications and consequences of that technology in particular contexts" (Orlikowski and Gash, 1994, p. 178). Thus the concept of technological frames provides a structured approach to analysing the ways in which specific social groups make sense of a particular technology.

Three important dimensions of technological frames can help with analysing the way in which people make sense of a new technology: (i) the nature of technology, which refers to people's images of the technology and their understanding of its capabilities and functionality; (ii) the technology strategy, which refers to people's views of why their organisation acquired and implemented the technology; and (iii) the technology in use, which refers to people's understanding of how the technology will be used and the likely or actual conditions and consequences associated with such use (Orlikowski and Gash, 1994). We have used these three dimensions of technological frames as a useful guide for structuring

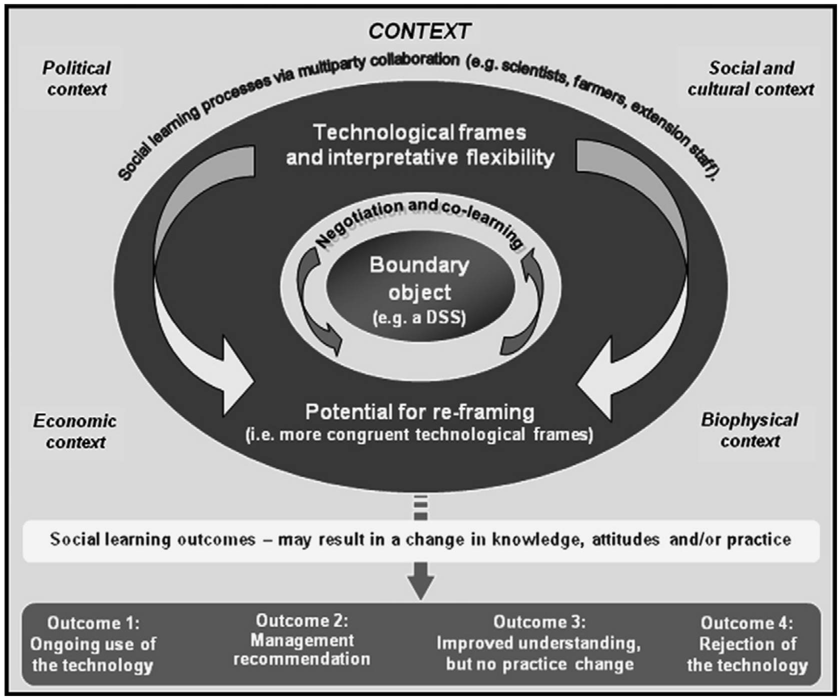

Fig. 1. Framework illustrating the context, social learning processes and three potential social learning outcomes of participatory DSS development, through reference to the three key concepts of technological frames, interpretative flexibility and boundary objects.

interviews to determine different actors' perceptions of the design and implementation of a DSS (see Section 3.2).

The technological frames held by different actors may be similar or disparate. The practice of holding similar technological frames is referred to as congruence (Orlikowski and Gash, 1994). Incongruent technological frames occur when stakeholders hold disparate expectations or assumptions about key aspects of the technology. Incongruence can create difficulties in applying a technology, since it can lead to conflicts over the use and value of the technology (Orlikowski and Gash, 1994). Incongruent technological frames occur due to the interpretative flexibility of technologies, i.e. the way in which an object can mean different things to different people (Hess, 1997). When applied to technologies such as DSSs, the concept of interpretative flexibility emphasises that a DSS will mean different things to the various stakeholders involved its development. For instance, the scientists, extension officers and farmers involved in developing a DSS will have different interpretations of the meaning of that DSS and the issue that it is designed to address. Because participatory DSS development involves pursuing (through cycles of negotiation) co-learning that values both local and scientific knowledge, we suggest that managing interpretative flexibility and searching for increasingly congruent technological frames through re-framing interpretations of the DSS, or the issue it addresses, is a key objective of participatory DSS development.

2.3. Boundary objects

Our conceptual framework (Fig. 1) conceptualises a DSS as a boundary object, providing a common point of reference through which stakeholders in DSS development can collaborate and co-learn. The concept of a boundary object originated in the STS sub-field of the sociology of scientific knowledge. Boundary objects are defined as "plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" (Star and Griesemer, 1989, p. 393). For example, the research of Cash (2001, p. 441) has demonstrated the potential for cropping, hydro-geologic and economic models to act as boundary objects in agricultural extension, since the "farmers and water managers were able to test different management scenarios they viewed as credible, and scientists were able to produce scientific outputs that were policy relevant and robust with respect to local data."

DSSs may act as boundary objects by creating a connection between the stakeholders involved in their development, while remaining flexible enough to be used by the different parties for their own purposes. The co-learning that the DSS-as-boundary object can facilitate involves a re-framing of beliefs, assumptions and expectations regarding the problem (i.e. more congruent technological frames), which allows the parties involved in this process to arrive at an increasingly shared understanding of the problem. Acknowledgment of this co-learning potential of the DSS-as-boundary object helps to deal with differences in technological frames and therefore manage interpretative flexibility within the participatory development of DSSs.

2.4. Potential social learning outcomes of participatory DSS development

Our framework highlights four social learning outcomes, which may result if there is a change in knowledge, attitudes and/or practices during the participatory DSS development process. They are separated for analytical purposes, but should be viewed as points on a continuum of possibilities. In the first case, the participatory process results in a DSS 'product' that fulfils a particular need and therefore is used subsequent to the development process. Further cycles of negotiation may be necessary to modify the DSS for this routine role (e.g. through making the software interface more user-friendly). Once the DSS is ready for routine use, emphasis shifts from co-learning to making the DSS available for ongoing use by farmers and their advisors. This enables Outcome 1 (Fig. 1), whereby a DSS is able to influence farmers' management decisions through its continued role in problem solving.

Alternatively, the cycles of co-learning can lead to a more detailed understanding of the problem and its context. It is possible that this understanding will result in the development of a new and widely applicable management practice that can become a management recommendation, independent of the DSS (i.e. Outcome 2, Fig. 1).

However, it is also possible that the participatory process does not result in a management recommendation. The parties involved may find that their understanding of the problem has improved, but either there is no need for change, no scope for change, and/or no relative advantage (Rogers, 1995) associated with the change: Consequently practice change does not occur (i.e. Outcome 3, Fig. 1).

Finally, practice change may not occur because of rejection of the DSS technology and/or the different beliefs, assumptions and/or expectations the various parties being to the participatory process (i.e. Outcome 4, Fig. 1).

3. Details of the case studies

3.1. Background and initiation

In Australia, most sugarcane is irrigated, but irrigation water supplies are generally inadequate to fully irrigate the crop. Thus maximising effectiveness of the limited water supplies is a widespread problem in sugarcane production. Maximising effectiveness can be achieved by scheduling irrigation to alleviate crop water stress as much as possible; i.e. not irrigating until the crop has extracted all the readily available water from the soil, but irrigating before the crops suffers severe water stress. To achieve this optimal timing requires knowledge of crop water use, soil water holding capacity, soil water content, the weather and previous irrigation. Crop-soil models can be used for irrigation scheduling provided they have an accurate representation of the relevant crops and soils, and utilize data on the crop's management history, recent weather and availability of irrigation water. There have been a number of irrigation DSSs developed for sugarcane (Inman-Bamber et al., 2005; Webb et al., 2006; Singels, 2007). Adapting the strengths of these previous DSSs to create *WaterSense* (Inman-Bamber et al., 2007), a new DSS designed to better meet the demands of scheduling limited water supplies, was the focus of the case studies in this paper.

To initiate the case studies, two scientists presented their earlier work on irrigation DSSs (Inman-Bamber et al., 2005; Webb et al., 2006) to a group of local stakeholders in two sugarcane growing areas of Bundaberg and Mackay (situated on the north-eastern coast of Australia), to assess their interest in having a DSS available to assist with scheduling their irrigation. The stakeholders in each group consisted of farmers and extension officers. The scientists worked closely with these two groups over 4 years to develop *WaterSense* (Inman-Bamber et al., 2007).

3.2. Data collection

We used a case study methodology to collect rich qualitative data (Maxwell, 1996; Yin, 1994) on experiences of the farmers, extension officers and scientists who collaborated to develop *WaterSense*. Case study methodology involves empirical enquiry into a phenomenon within its real-life context, where the research goal is to collect rich data to expand and generalise theories (analytic generalisation), rather than enumerate frequencies or make inferences about a population based on data collected about a sample (statistical generalisation) (Yin, 1994). Our case study data came from semi-structured, in-depth interviews that we conducted with a cross-section of the key people involved, i.e. the local stakeholders and the scientists involved in the development of *WaterSense*.

The main data came from 15 interviews conducted at the end of the DSS development process with the 12 local stakeholders (six in each region) engaged in the case studies at that time and the three scientists. Interviewees had regularly attended group meetings and were involved with the DSS development process. The interviews focused on experiences of collaborating through the stakeholder groups, perceptions of *WaterSense* (including whether the stakeholders used the DSS and if so, how they used it and what was their experience of using it, or what were the reasons they did not use it), and expectations about the potential for wider use of *WaterSense* within the sugarcane industry. Preliminary interviews with three local stakeholders and two scientists were also conducted in Bundaberg at the start of the DSS development process. The general topics covered in these interviews were perceptions of irrigation scheduling, initial impressions of *WaterSense* (including its strengths and limitations compared with current irrigation practice), and factors that might influence the potential use of *WaterSense*.

All 17 interviews were recorded and transcribed and then coded and analysed with the assistance of the qualitative data analysis software, *QSR NVivo* (QSR International, 2006, version 7).

4. Analysis of interviewee responses

4.1. Technological frames

The range of assumptions and expectations held by the farmers, extension staff and scientists about *WaterSense* revealed the technological frames that helped them make sense of this technology. In Bundaberg, the farmers framed *WaterSense* as a tool that could allow them to explore their options and possible scenarios for scheduling their irrigation. As one farmer from Bundaberg explained, his first impression of it was "a program that is going to…give us the best scenario on irrigation scheduling using what available moisture we have got and what rainfall events are going to happen." Another remarked that his first impressions of *WaterSense* focused on its potential to "clarify or reinforce how you think you are going to use your water."

In Mackay, one farmer summarised his initial expectations of *WaterSense* as "a useful tool [for] people like myself and most…growers [in this area who] have a limited water supply, [to] make the best use of it at the best time." Another Mackay farmer admitted that "we always had a big issue of where we needed to irrigate first and what our priorities were on our farm. …We tried to put as much on as quick as we could and that's how we irrigated." For this farmer, the value of *WaterSense* was that it had the potential to provide guidance on when to schedule his irrigation.

In contrast, the technological frame of the extension staff related to whether *WaterSense* would be 'user-friendly'. For instance, one of the extension staff noted that DSSs like *WaterSense* may be a "very useful thing for an extension officer or an adviser or someone working in the subject area", but might be less suited to a farmer. Similarly, another extension officer noted that from the beginning of the project, he was "aware that we were going to have to make [*WaterSense*] farmer-friendly and we were going to have to iron out some bugs and fill that gap between science and the people."

The scientists' technological framing of *WaterSense* was as a risk management tool for irrigators in the sugarcane industry. The scientists also viewed *WaterSense* as a possible catalyst for increased use of other technologies, for instance: "given that we're talking about a new type of tool…this will open up people's ideas about what other types of technology related to their own farm management or business management [they could] be using." The scientists also acknowledged that the simulation modelling, which *WaterSense* was based upon, represented a different way of understanding farming, since "the growers operate intuitively…they don't think in terms of models."

4.2. Interpretative flexibility

The interpretative flexibility of *WaterSense* was evident from the different technological frames held by the case study participants, i.e. from the range of ways in which the DSS was interpreted by those involved in its development. This was exemplified by the different interpretations held by the local stakeholders and scientists about how soils were categorised in *WaterSense*. In the preliminary interviews in Bundaberg, both the farmers and the extension staff expressed concerns about the level of detail in which the early versions of *WaterSense* defined the basic parameters (relating to water holding capacity) of soil types. One of the farmers argued that "that the classification for soils needs to be thrown out…because really most soils have low, medium or high water holding capacity so you don't need these ten different soils…the way the soil scientists name them."

The categorisation of soil types remained an issue in the main round of interviews at the end of the DSS development process, with difference between the names used by the farmers and scientists for soils. One of the scientists described the way in which he and the other scientists worked with the farmers and extension staff to negotiate these different views on soil naming, noting that "there's so many different names for different soils…[and the farmers] always had specific requirements on the correct [local] terminology to use. Also on what variables they actually wanted to see." One of the extension officers remarked that there were "some issues…in relation to soils" that meant that the development of *WaterSense* "will probably be ongoing." Similarly, one farmer observed that *WaterSense* would "work a lot better…if we can get a better idea of what our actual soil types are exactly like [since then] we'll have a better idea of whether to water them." The farmers' and extension officers' more contextualised understanding of their local soil types influenced how they viewed this key feature of *WaterSense*. This illustrates the way in which the abstract scientific knowledge that DSSs like *WaterSense* are based on has to be adapted to suit local needs, by incorporating local knowledge.

4.3. WaterSense as a boundary object

WaterSense acted as a boundary object during its development, because it enabled the farmers, extension staff and scientists to collaborate, even though they held diverse perceptions of its function and some of the issues it addressed (e.g. soil types). How *WaterSense* became a boundary object is evident in the words of one of the Bundaberg extension officers, who noted that the value of the industry group meetings lay in "bridging that gap between what was seen to be pretty good science, but making sure that it was paddock useable. [*WaterSense*]… could've been developed in an office in Townsville and it could've been spat out on a disk, and I don't think anybody would've used it. [It was]…the process of developing it and taking the science to the people and the people to the science and bringing the two together [to create something]…useful to the grower at his level rather than the scientist at his level".

The iterative and participatory nature of these meetings was essential. For instance, one of the Bundaberg extension officers explained the benefits of the negotiation that was central to the DSS development: "I think the best thing was it was addressing a specific need and we had the flexibility that we could change things slightly as we were going along, as we were starting to learn more and more about what the research was telling us but also more about what the issues were for the growers as well and trying to fine tune them what we were doing at the research level. …It was a participatory process. It was fairly dynamic. It allowed us to move at the same time." For one of the scientists, the direct feedback from the farmers "allowed the grower to be involved in every step of the way…to actually be part of the design of it [rather than] being shown the package [at the end and told]…to take it and leave it." Another of the scientists made a similar observation, remarking that "I remember one bloke in Bundaberg getting up on the whiteboard and he said, look, I understand what you've done, [but] that's not what we want. If you do it like this – and he drew a picture on the board. If you do it like that, we will use it. And we did it like that."

The farmers reinforced the value they placed on the collaboration facilitated by *WaterSense* acting as a boundary object. For instance, one of the farmers commented; "I feel like we were listened to." He went on to add that this was in contrast to past experiences, where "some ideas are put up and growers may not have had much input into what they wanted, what they expected out of it. I feel we got a fair bit of input into what we expected of [*WaterSense*]." The farmers' genuine involvement in the development of *WaterSense* was important for developing a sense of shared ownership of the technology.

WaterSense also acted as a boundary object in the Mackay group. The Mackay farmers commented on how they felt involved in the development of *WaterSense*, with one farmer remarking that: "It's not like someone standing up there lecturing us and telling us what we had to do and you do this or do that. They were consulting with us ourselves and…I'm pretty sure that they'd all say that they've learned and…they've gained from the whole experience." The farmers from the Mackay group also observed that the collaborative approach used in the project helped establish their trust and confidence in the scientists and in *WaterSense*. As one farmer admits, "When we started out I was little bit sceptical of [the scientists]. …The relationship has just grown through the whole project and we've got respect for each other, that's for sure." Through its role as a boundary object, *WaterSense* allowed the parties in each region to explore their diverse assumptions about irrigation and in doing so learn from each other, which allowed all parties to gain a better understanding of irrigation and the consequences of different irrigation strategies.

While the cycles of negotiation around *WaterSense* clearly improved it as a piece of software, they also resulted in co-learning amongst all involved in the DSS development process. A farmer from Bundaberg remarked that through his involvement he had "a massive increase" in his knowledge of irrigation: "…this last 3 years involved with the group…my knowledge in water use and in particular in the cane industry, has improved massively: …soil characteristics, cane physiology, its usage, water application systems and their efficiencies, even just evaporation characteristics, delivery scheduling." The increased knowledge was not confined to the farmers. The increased understanding the scientists gained from their involvement with the farmers was obvious to the farmers: "I like the idea that they [accepted] our data too… Scientists tend to want to look at irrigation on a wide scale thing and … they looked at it as us in Mackay and they took all our research and I think that's why they've got it fairly accurate; they didn't use it on like a broad thing. [Using] all our data … that … on our soil types, … rainfall and on [the] equipment that we [use] to irrigate with" (Farmer, Mackay).

Respecting each other's contributions was a key feature underpinning the co-learning that resulted from *WaterSense* acting as a boundary object: "The right ingredients to have in these sort of projects is respect from the different parties involved, so the researcher has a respect that the issues at the grower level or extension level can feed back into the research project and also there's got to be a respect from the grower and the extension officer to say that the research findings are relevant to them as well... When you respect those parts you have a successful collaborative-type project and I think that [this project] had those ingredients" (Extension officer, Bundaberg).

4.4. Outcomes of the development of WaterSense

Most of the participants in our case studies noted that they wanted to continue using *WaterSense* to help guide their irrigation scheduling decisions, a result consistent with Outcome 1 in the framework (Fig. 1). As one Bundaberg farmer explained, without *WaterSense* "you have to drive around every [farm] block at a certain time of day, morning and afternoon, and say mid morning and mid afternoon, to observe those crops and see what they're doing, whereas [with] *WaterSense*, you just pull a screen up." In the words of another Bundaberg farmer, *WaterSense* "takes a lot of the guesswork out of" irrigation scheduling. Similarly, one Mackay farmer explained that prior to the working with *WaterSense* he didn't understand about "...different soil types [and that on some soil types you needed to] start irrigating 2 weeks after [the last irrigation, but] others [are] different... I've only just got into it...I haven't got the whole farm under [*WaterSense*]. We've had one block then we're going to do another block this year."

However, there were some farmers, especially in Mackay, who felt there was no need to change their current practice. For one Mackay farmer, *WaterSense* "pretty well coincided with what I intended to do anyway. There was a remarkable correlation there. But it served to reinforce my ideas [and was like]...getting another opinion." Another farmer commented that "even though [he] didn't know how to use [*WaterSense*] physically, the information and education [he] got from it is something that will stand [him] in good stead whether...or not [he uses *WaterSense*]. The experience and the information gained is something that will stop with [him] all the time." For these farmers, the benefits that *WaterSense* might deliver were outweighed by the perceived costs associated with its set up and ongoing use. This result is consistent with Outcome 3 in the framework, where those involved find their understanding of the problem has improved but perceived no relative advantage (Rogers, 1995) associated with the change or further use of the DSS.

There were also some farmers in Mackay, who felt there was no opportunity to change their current practice. Irrigation on some farms in the regions is constrained by limited irrigation water availability and/or on-farm infrastructure. One farmer said; "with only a small amount of [irrigation] water, the good that [*WaterSense*] actually does, is not worth a lot to me in real dollar terms. I'm inclined to not worry too much about it. I just do the best I can and that's that." Another felt the opportunities to use *WaterSense* were limited: "...its lack of infrastructure I would say. ...we can't actually irrigate it to the scheduling [*WaterSense* produces] because we just can't get around the property." The response of these farmers is consistent with Outcome 4 for the framework (Fig. 1).

Our framework recognises that contextual factors influence the process and outcomes of participatory DSS development, and there were several contextual factors that could limit the ongoing use of *WaterSense*. One of the Bundaberg farmers noted that his long-term use of *WaterSense* might depend on the subscription costs if the DSS is commercialised. Access to irrigation water was another factor. In Bundaberg for example, irrigation allocations are dependent on levels in water storages. One farmer explained that: "If we don't get good rainfall, we won't have any water in our storages to [irrigate with and] use [*WaterSense*] anyhow..." Likewise, irrigation water availability was an issue in Mackay. Another factor that constrained the application of *WaterSense* for some farmers in Mackay was irrigation infrastructure, as described above. Thus while many farmers reached Outcome 1 (Fig. 1) during the case studies, in time they may move to a different outcome. However, provided their actions are consistent with Outcomes 2 or 3, their involvement with *WaterSense* should still be considered a success.

5. Discussion

The key lesson of our case studies of the participatory development of *WaterSense* is that, by acting as a boundary object, a DSS can foster social learning among farmers, extension officers and scientists. The role of DSSs as boundary objects in participatory DSS development has strong parallels to the emphasis within social learning approaches on setting up dialogues for mutual sharing of perspectives (Bouwen and Taillieu, 2004) and cooperation across boundaries (Mostert et al., 2008). Our analysis of the multiple technological frames held by these parties is also consistent with the emphasis on framing and re-framing within social learning approaches (Bouwen and Taillieu, 2004; Maurel et al., 2007). Thus, the literature on social learning approaches provides some useful principles that can help improve the outcomes of participatory DSS development.

Social learning principles that are relevant to participatory DSS development include shared ownership of the task, mutual benefit and open communication (Bouwen and Taillieu, 2004), recognition of interdependence between stakeholders, interaction between all stakeholders, development of trust, respect for diversity and critical self-reflection (Mostert et al., 2008; Pahl-Wostl and Hare, 2004). These social learning principles suggest that the process and outcomes of participatory DSS development can be enhanced by paying closer attention to the way in which the multiple stakeholders share their perspectives and work together as a group to solve problems, drawing on their different kinds of knowledge (Bouwen and Taillieu, 2004).

Conceptualising a DSS as a boundary object, to facilitate social learning between farmers, extension officers and scientists, resonates with calls for a shift in thinking about the role of agricultural DSSs, and our conceptual framework adds value to this debate by drawing more thoroughly on STS concepts. In their reflection on the role and development of agricultural DSSs, Matthews et al. (2008) briefly allude to the potential for DSSs to act as boundary objects within a deliberative, inclusive process. The potential of DSSs to act as boundary objects is also implicit in several analyses of DSS development in agriculture. For instance, Hearn and Bange (2002, pp. 53–54) recognise the way in which participatory DSS development "has facilitated communication between farmers and scientists" by providing a "meeting point where farmers and scientists can explore" questions related to farm management. This point is also reflected in Nelson et al.'s (2002) use of the term "discussion support system". Similarly, Stone and Hochman (2004, p. 11) emphasise the importance of the relationship between scientists and farmers in the development of DSSs and highlight the value of DSSs in terms of "providing a focal point and form for communication between farmers and scientists rather than the main basis of the relationship." Moreover, Walker's (2002) call for a reappraisal of the role of DSSs is based on recognition of the value of DSSs for fostering co-learning. The role of DSSs as boundary objects is also implicit in many types of stakeholder-based environmental modelling (Voinov and Bousquet, 2010). Our framework provides a more conceptually informed explanation of the social processes underpinning participatory DSS development in agriculture, and takes a step in addressing the "social dimension" of the stakeholder-based environmental modelling process (Voinov and Bousquet, 2010, p. 1279). Our framework also complements the focus on individual learning within McCown et al.'s

(2009) cognitive model of farmer decision making, by providing additional insights into the broader social context and processes that influence this individual learning, which may help enhance social learning outcomes.

Our framework recognises that DSS development is situated within many contextual factors, some of which will be barriers to use of DSSs by stakeholders. The barriers imposed by contextual factors to farmers adopting innovations are well known (Rogers, 1995). More specifically for DSSs, McCown (2002) identified socio-technical barriers to the use of DSSs by farmers and subsequently explored the cognitive structure of farmers' learning and decision making to better identify opportunities for DSS intervention (McCown et al., 2009). As noted in the Introduction, overcoming these barriers focuses on the 'problem of implementation'. In our case studies, *WaterSense* was not presented as a 'finished product' to be implemented by farmers, and so some of these problems were not immediately relevant (although they were clearly identified by farmers, as shown above). Past experience with DSSs in agriculture (McCown, 2002) suggests that farmers or advisors who were using *WaterSense* at the end of the case study (i.e. who reached Outcome 1, Fig. 1) may subsequently have ceased using it in the face of various barriers, resulting in a different Outcome finally being achieved in terms of our framework. However, such a focus on 'use of the DSS' overlooks the potential value resulting from stakeholders and scientists interacting with the DSS and, importantly, each other. The value of these interactions is clearly shown in a companion study (Thorburn et al., 2011), where none of the farmers or advisors involved intended to use the DSS after the case study, but most reported fundamental changes in their view of the problem examined.

So, application of our framework helps expand the definition of 'success' in participatory DSS development in agriculture, closer to that common in stakeholder-based environmental modelling (Pahl-Wostl et al., 2007; Voinov and Bousquet, 2010). Instead of defining the success of DSSs primarily in terms of their function as tools to be used by industry stakeholders in an ongoing, routine manner, our framework recognises that a DSS may become redundant once it has fulfilled its function as a tool for co-learning. However, this is a successful outcome when it leads to a clearer understanding of the problem and, possibly, a changed management recommendation based on this understanding. Successful DSS development should be viewed as a participatory process leading to improved understanding and practice, irrespective of whether or not this involves ongoing DSS use.

6. Conclusion

Our framework combines the concepts of technological frames, interpretative flexibility and boundary objects from science and technology studies with social learning principles, to provide an explanation of the social processes in the participatory development of DSSs. The framework emphasises that, when deployed as a boundary object, a DSS encourages social learning between the farmers, extension officers and scientists involved in its development. Our case studies of the irrigation scheduling DSS *WaterSense* showed that, by acting as a boundary object, *WaterSense* was able to help bridge gaps between these parties through an iterative and participatory cycle of discussion and feedback. This involved acknowledging and respecting the different perspectives held by these parties (i.e. interpretative flexibility) and then taking up the opportunity to work together towards a shared understanding (i.e. arriving at more congruent technological frames). Appreciating the way in which a DSS can act as a boundary object recognises how cooperation among these multiple stakeholders can occur, despite the fact that these people can hold diverse perceptions of the DSS or the issue it is designed to address. Instead of defining the success of DSSs solely in terms of ongoing use, the participatory development of a DSS should be evaluated in terms of its ability to foster co-learning and improve practice. Our framework provides those involved in the development of agricultural technologies with new conceptual insights to reflect on their practice. In doing so, our framework contributes to enabling more effective participatory technology development and application processes, and helps DSSs be more effective in guiding sustainable farm management.

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