Sustainability as a governing principle in the use of agricultural decision support systems: The case of CropSAT

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Abstract

Precision agriculture (PA) is an important part of sustainable intensification, where information and communications technology (ICT) and other technologies are necessary but not sufficient for sustainable farming systems. Many agricultural decision support systems (AgriDSS) have been developed to support farmers to manage an increased amount of gathered data. However, the traditional approach to AgriDSS development is based on the knowledge transfer perspective, which has resulted in technology being considered as an isolated phenomenon and thus not adapted to farmers' actual needs or their decision making in practice. The aim of this study was to improve understanding of farmers' use of AgriDSS. The theoretical framework of distributed cognition (DCog) was used as a lense when investigating and analysing farmers' use of a software tool developed for calculation of variable rate application (VRA) files for nitrogen (N) fertilisation from satellite images called CropSAT. In a case study, the unit of analysis was broadened to the whole socio-technical system of farmer's decision-making, including other people and different kinds of tools and artefacts. The results reveal that CropSAT functions as a tool to support decision making and promotes social learning through the use of *enhanced professional vision*.

Keywords:

Precision agriculture, sustainable intensification, distributed cognition, agricultural decision support system, CropSAT, social learning

1. Introduction

Precision agriculture (PA) is a keystone in a sustainable intensification trajectory where information and communications technology (ICT) and other technologies are necessary for the sustainability of large-scale farming systems (Aubert et al., 2012). By definition, sustainable intensification has to harness the complexity of a wider range of agro-ecological and socio-technological processes and PA is an important piece of the larger picture. PA can be viewed as a management concept based on observing, measuring and responding to within-field variations in both temporal and spatial components. Several kinds of PA technology provide possibilities for crop farmers to recognise and handle variations to a much finer degree than before, and represent a paradigm shift in farming practices due to a change from considering the field as homogeneous to considering it as a heterogeneous entity (Aubert et al., 2012). Better adaptation of field measures to crop requirements decreases sub-optimal treatments, which in turn increases profitability due to higher efficiency in usage of inputs, better crop quality and a decrease in negative environmental impact.

It is widely acknowledged that farming is a complex, dynamic system, involving products and impacts that are difficult to measure, let alone predict and control (Woodward et al., 2008). At the very core of the agricultural transition towards sustainability is the individual decision maker (Matthews et al., 2008; Van Meensel et al., 2012). It should be stressed that it is the individual farmer who makes the strategic, tactical and operative decisions which bridge theory and practice, balancing the desirable with the feasible. It has been argued that various kinds of ICT systems can be a major contributor to the transition towards sustainability in agriculture (Aubert et al., 2012). However, in many of the available agricultural decision support systems (AgriDSS), a certain kind of ICT system developed to support farmers' decision making is for various reasons seldom used to its full potential (e.g. Aubert et al., 2012; Matthews, 2008; Thorburn et al., 2011). Briefly stated, the traditional and normative approach to AgriDSS development is based on the knowledge transfer perspective, which has resulted in many AgriDSS not being adapted to farmers' needs. In particular, Röling (1988) claims that the traditional view lacks a systemic perspective and fails to place the technology in the context where farmers will use it. As a result, available technology can be considered an isolated phenomenon and is therefore often is not adopted and situated in farmers' praxis (Röling, 1988).

Based on Röling's (1988) remarks, this study sought to acknowledge the link between environmental sustainability and ICT by addressing *sustainability through design* – how ICT systems in general, and AgriDSS in particular, can be used to promote and cultivate more sustainable behaviours (Hanks et al., 2008; Lindblom, Lundström and Ljung, 2014). This assumes that PA technologies are instrumental in supporting information-intense decision-making processes that are valuable for agro-ecological systems and for the diversity of farming systems. The overall aim of the study was to improve understanding of farmers' use of AgriDSS. The theoretical framework of distributed cognition (DCog) (Hutchins, 1995) was used as a lense when investigating and analysing farmers' use in practice of a software tool called CropSAT developed for calculation of variable rate application (VRA) files for nitrogen (N) fertilisation from satellite images. In a case study, the unit of analysis was then broadened to involve the whole socio-technical system of farmers' decision making, including other people and different kinds of tools and artefacts. CropSAT has received much interest from many farmers and it may become an important tool in farmers' adoption of VRA techniques. This study examined how CropSAT functions as a tool to support decision-making processes and promote social learning, which in the long run may create more sustainable farming practices.

2. Background

2.1 Decision-making in agriculture

Farm management and farmers' decision making are usually analysed using theoretical frameworks from economic science (Gray et al, 2009). As a result, the focus is often on the decision event and not on the decision-making process (Öhlmér et al., 1998; Gray et al., 2009; Lindblom and Lundström, 2014). Decision making is a cognitive ability and traditional normative views on cognition in the area of cognitive science have similarities to the normative perspectives on decision making applied in economics, by viewing cognition as the result of internal, individual processes (e.g. Pylyshyn, 1984). However, studies of farmers' decision making in their complex practice have revealed that this kind of description is inconvenient, because it fails to explain decision making in a complex, dynamic and ill-defined context (Gray et al., 2009; Lindblom et al., 2013; Lindblom and Lundström, 2014). Instead, it is important to increase understanding of how farmers actually make decisions, considering their complex socio-technical context, using descriptive theories such as naturalistic decision making (NDM) (Lindblom et al., 2013).

NDM theories emerge from different theoretical and methodological approaches based on decision making 'in the wild', in which studies are performed in situations where humans make decisions in dynamic and complex domains (Klein, 2008). The individual´s experiences and knowledge are taken into account and time pressure and high uncertainty are also included (Orasanu and Connolly, 1995). Although NDM focuses on decision making by experts 'in the wild', the unit of analysis is still only the individual, while contextual factors such as technology and other actors are excluded. According to Lindblom et al. (2013), NDM is an appropriate approach to investigate farmers´ decision making. However, it lacks a systemic perspective within the complex socio-technical system, and therefore the unit of analysis needs to be broadened from the individual to include the social and material context. For this purpose, the theoretical framework of DCog can be a convenient way forward (Lindblom et al., 2013; Lindblom and Lundström, 2014).

2.2 DCog: Broadening the unit of analysis

The theoretical framework of DCog was introduced by Hutchins (1995) in response to more individual models and theories of human cognition. From a DCog perspective, human cognition is fundamentally distributed in the socio-technical environment that humans inhabit. DCog takes a systemic perspective and discards the idea that the human mind and its environment can be separated (see Lindblom, 2015 for further details). Hence, DCog views cognition as distributed in a complex socio-technical environment and cognition, including decision-making and learning processes, is viewed as the creation, transformation and propagation of representational states within a socio-technical system (Hutchins, 1995). An important aspect of the systemic view is that cognition is seen as a culturally situated activity that should be studied where it naturally occurs, i.e. 'in the wild'. The DCog framework differs from other cognitive approaches in its commitment to two theoretical principles (Hollan et al., 2000). The first principle concerns the boundaries of the unit of analysis for cognition, which is defined by the functional relationship between the different entities of the cognitive system. The second principle concerns the range of processes considered to be cognitive in nature. In the DCog view, cognitive processes are seen as coordination and interaction between internal processes, as well as manipulation of external objects and the propagation of representations across the system's entities.

When these principles are applied to the observation of human activity *in situ*, three kinds of distributed cognitive processes become observable (Hollan et al., 2000): (1) *Across* the members of a group, (2) *between* human internal mechanisms (e.g. decision making, memory, attention) and external structures (e.g. material artefacts, ICT systems, social environment), and (3) distributed *over* time. Different kinds of representations are central to the unit of analysis in DCog. Hollan et al. (2000) argue that representations should not only be seen as tokens that refer to something other than themselves, but also as being manipulated by humans as physical properties. Hence, humans shift from attending to the representation to attending to the thing being represented. An example used in Hutchins (1995) is the navigational chart, which is used for offloading cognitive efforts (e.g. memory, decision making) to the environment and for presenting information that has been accumulated over time. An important insight in this example is the relationship between the external structure (the chart as a representation) and the internal structure (the biological computation). Hence, by studying the external material and social structures, properties about the internal, mental structures are revealed and become observable. In other words, by studying cognition with this larger scope in mind, it is clear that the functional cognitive system has cognitive properties that cannot be limited to the cognitive abilities of the individual.

2.3 Decision support systems (DSS): Failure and success factors in AgriDSS

A DSS is an ICT system that supports either a single decision maker or a group of decision makers in making more effective decisions when dealing with unstructured or semi-structured problems. The DSS supports one or more activities in a decision-making process in order to complement and 'support' decision makers rather than to replace them. Furthermore, a DSS can either support the decision maker in an ongoing decision situation, or it can prepare the decision maker to perform better in the future through decision training (Alenljung, 2008). By using a DSS, individual productivity, decision quality and problem solving can be improved and interpersonal communication and learning can be facilitated. In addition, using a DSS can improve decision-making skills and increase organisational control (Alenljung, 2008).

The main efforts made to bridge the gap within the current agricultural knowledge and innovation system (AKIS) include implementing new advisory concepts, re-organising advisory services and developing AgriDSS. Many AgriDSS have been developed, but not used to any wider extent, mainly as a result of the normative way of development based on the perspective of knowledge transfer, where knowledge is produced by research and end users are looked upon as passive receivers (e.g. McCown, 2002; Matthews, 2008; Thorburn et al., 2011; Aubert et al., 2012). Accordingly, there is a need for functional and usable AgriDSS that promote sustainable farming practices by providing proper and credible representations of complex situations that clarify and support farmers' decision making without losing the complexity at hand. An AgriDSS must therefore match farmers' naturalistic decision making and challenge their learning without replacing their 'gut feeling' (Hochman and Carberry, 2011). In addition, it has to support farmers' experimentation with options rather than present optimal solutions, because when farmers are handling messy, real-world problems they tend to satisfy current needs rather than optimising performance. Many researchers point out that an AgriDSS is a useful tool for the ongoing transfer of scientific knowledge and 'best practices', claiming that the single unifying predictor of success or failure is the extent to which users are involved and participate in the design and development processes of the AgriDSS (e.g. Woodward et al., 2008; Jakku and Thorburn, 2010; Hochman and Carberry, 2011; Van Meensel et al., 2012). Another important aspect of participation approaches is social learning among stakeholders involved in the development and use processes (e.g. Jakku and Thorburn, 2010; Hochman and Carberry, 2011).

3. Method and performance

3.1 The case study

During spring 2015, a *workplace study* was performed (Luff et al., 2000). The study adopted a qualitative approach, using ethnographical data collection techniques, and the collected data were triangulated from participant observation, video-recordings and semi-structured interviews. The study was conducted with four purposively sampled farmers in western Sweden. The selected farmers had previous experience of using ICT-based crop production software (CPS) and demonstrated an interest in PA technology.

3.2 Setting the scene

During 2013-2014, a new AgriDSS for N fertilisation, CropSAT (www.cropsat.se), was developed by the Precision Agriculture Sweden (POS) network (www.precisionsskolan.se/). CropSAT uses satellite images for calculation of vegetation index (VI) (Qi et al., 1994) and VRA files for N fertilisation in cereals. During 2015, a high-fidelity prototype of CropSAT was made available on the internet for use, free of charge, thanks to funding by the Swedish Board of Agriculture. To support farmers in their N fertilisation strategy, a minimum of three satellite images were published during the period April-June 2015. The recommended strategy for fertilising wheat is to apply N two or three times during spring (Albertsson et al., 2015).

To calculate a VRA file in CropSAT, the user visits its website and selects a field and a satellite image. As a result, the VI is calculated and shown in Google Maps. To receive a VRA file, the user must decide the level of N fertilisation within five VI classes, which are estimated automatically from the satellite data (Figure 1a) and used to calculate VRA files for N for the field. The VRA information is transferred to the tractor and spreader via a USB stick.

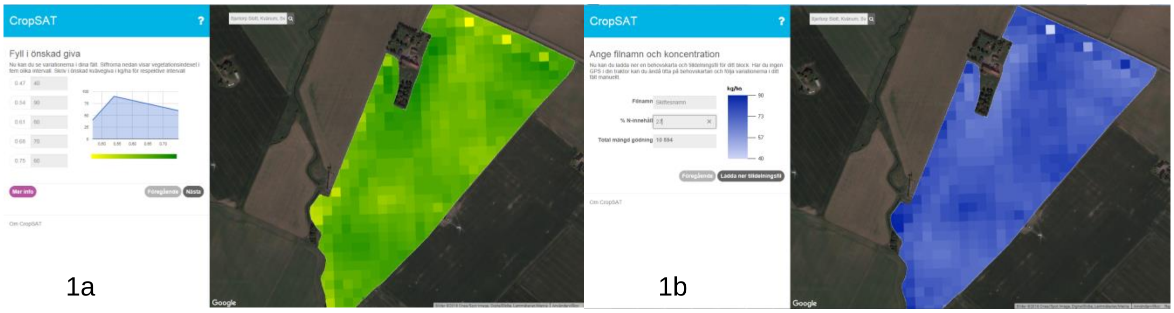


Figure 1 a) Vegetation index is displayed on Google Maps, where the user should enter five levels of N fertilisation compared with the coloured scale. B) VRA file ready to be entered into the fertiliser spreader via a USB memory stick.

To set the N levels for each VI class, the user is recommended to go out into the field and verify the N status with a so-called Spadmeter (https://www.konicaminolta.eu/en/measuring-instruments/products/colour-measurement/chlorophyll-meter/spad-502plus/introduction.html), or to simply estimate the need for additional N, based on observation of the canopy and prior experience. When new satellite images were published during spring 2015, the farmers studied the crop development on the actual farm using CropSAT. On some occasions, a VRA file was calculated and later used for variable fertilisation, and sometimes the images were used to get an overview of the status, or used in the decision-making processes regarding fertilisation with a Yara N-Sensor (YNS) (http://www.yara.se/crop-nutrition/Tools-and-Services/n-sensor/).

4. Findings: CropSAT used ‘in the wild’

Swedish farmers fertilise winter wheat one to three times during spring in order to optimise yield and protein content. They have a fertilisation plan for each field, and in this study all farmers used an ICT-based CPS for creating these plans. In the fertilisation plan, an average amount of N per field is specified, but can be adjusted due to a wide range of factors during the season. Farmers can use CropSAT or some kind of tractor-based N sensor to apply a variable rate of fertiliser, using the planned average amount of N as a basis. The units of analysis in these decision-making processes include a wide range of artefacts, e.g. CropSAT (images on VI and VRA files used in computers, mobile phones and Ipads), CPS (tables and field maps in computers, mobile phones and Ipads), paper-based field maps, calculator (in mobile phone), Spadmeter and notepads (Figure 2).

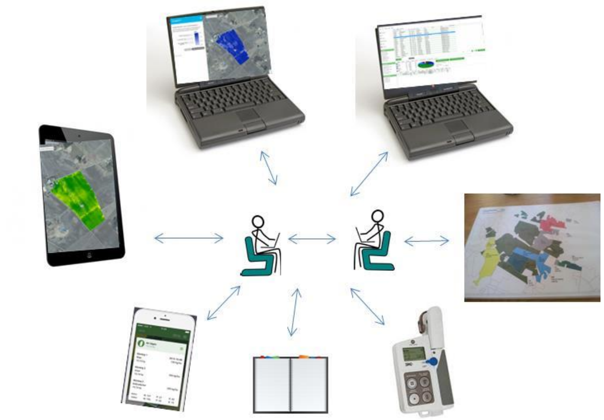


Figure 2. Unit of analysis of the DCog system, where cognitive processes are distributed: (1) *across* the members of a group, (2) *between* human internal mechanisms (e.g. decision-making, perception, memory) and external structures (material artefacts, ICT systems and social environment), and (3) *over* time.

The images created in CropSAT are visual digital representations that display crop biomass complexity in a way that is difficult to achieve by walking or driving in the field. Below, descriptions and analyses of some selected brief episodes that illustrate decision-making processes within the distributed cognitive system are presented. In the first episode, CropSAT is being used as a decision support tool for calculation of VRA files (section 4.1). In the second, CropSAT is being used as a coordination mechanism in the decision-making process for crop production (section 4.2).

4.1 CropSAT as a decision support tool for creation of VRA files

It is widely recognised that farmers know that crop yield varies within fields. When looking at the satellite images in CropSAT, farmers with long experience of their own fields easily recognise and explain much of the visualised variation in crop biomass. In this particular episode, an experienced farmer in his 50s using CropSAT for the first time took a closer look at one of his fields of winter wheat. He had 15 years of experience of using VRA files and YNS. He compared and contrasted his acquired knowledge of the characteristics of the particular field with the satellite image displayed in CropSAT. He then said: "*Well, this [field] is a bit poorer, you could say ... it's farther away from the old farmhouse, so over time it almost certainly got less manure, and besides the soil is lighter up here". "So it looks like I expected... I could have drawn [the map] myself".*

It should be noted that the bird's eye view of the variation in crop biomass is difficult to observe while merely walking in the field. Consequently, fertilising correctly with regard to variations in the field is impossible without support from technology. The CropSAT image provides another kind of representation format that visualises the within-field variation with more clarity than could be achieved with the human vision system alone. As such, the image reveals details and differences that the *professional vision* (Goodwin, 1994) of an experienced farmer cannot "see" clearly due to biological characteristics of the human colour vision system. *Professional vision* is a socially organised way of seeing and understanding events that are of interest in the domain and to the social group (Goodwin, 1994). The major challenge is that the farmer has to act upon this variability by setting the five levels of N fertilisation in relation to the variation in crop biomass.

Figure 3. Telephone support to set N levels in CropSAT. The farmer pointed at the image while speaking to his advisor.

In the next episode, a younger, university-educated farmer with shorter farming experience had some difficulties in grasping how to use the CropSAT images. He had recently invested in PA technology in his farming business and he was a skilled user of various ICT systems. In the particular episode described here, he was re-planning the amount of N fertilisation in a particular field with winter wheat. He had previously set the average level to a standardised amount together with his advisor in the CPS. It is obvious that deciding on the five levels of N in practice was not an easy task for him and therefore he needed some assistance from his advisor. He phoned his advisor and the conversation went as follows: '*Hi ... we're sitting here with the files for variable rate application and vegetation index and I'm wondering about what doses to use, or how much I should vary it ... for wheat ... yes the main dose for wheat is given as 80 kg N per hectare and then ... yes, you get a beautifully coloured map, but the question is how much variation you need to use'.*

During the discussion, the farmer repeatedly pointed to different aspects on the screen, e.g. N levels, the VI scale or different parts of the field (Figure 3). He and the advisor had a long and intense discussion concerning how to set the five levels of N. CropSAT challenged his common work practice, i.e. fertilising with the same amount throughout the whole field or using the YNS. When his work practice altered, he was hesitant about deciding the levels and sought support from his advisor. In this episode, the satellite image ceased being a representation of the field and became the field itself. The information provided by the image was shared between farmer and advisor and functioned as a coordination mechanism in their conversation. After the call, the farmer decided the fertilisation levels on three additional fields and calculated VRA files to be used on the same day. It should be emphasised that the guidance received from the advisor supported the farmer in deciding the N levels for the other fields, but he was still not confident concerning his way of reasoning about the fertilisation strategy.

4. 2 CropSAT as a coordination mechanism in the decision-making process for crop production

In these two episodes, an experienced farmer in his 50s was initially discussing fertilisation with his advisor. The first episode started after they had been walking in the fields and were sitting in the farm canteen to discuss the current situation and the decisions to be made. They used CropSAT to get an overview of the fields and compare the satellite images displayed with their first-hand experiences of the fields. As shown in the first episode in 4.1, they had some difficulties in interpreting the satellite images, which resulted in intense discussions (Figure 4).

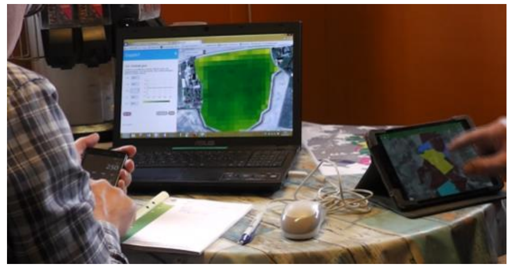
4 a  4 b 

Figure 4 a) Discussions about within-field variation in crop biomass due to soil compaction at the first meeting. b) Different tools and artefacts used in the distributed cognitive system.

In the next episode, the task was to decide how to fertilise seven fields of winter wheat. Instead of using CropSAT to calculate VRA files, the intention was to use the YNS to spread N. The motivation for this way of working was that YNS provides a more detailed picture of the biomass variation and consequently the amount of N can be distributed more precisely. During this meeting, all tools and artefacts displayed in Figure 4b were available and the satellite image taken three weeks earlier was used for comparing how much N had been utilised by the crop. Before the meeting, the advisor had used a Spadmeter in the fields to measure the need for additional N fertilisation based on the canopy greenness. These measurements were used as a point of reference in the ensuing discussion.

The role of the advisor is of major importance when introducing new technology in advisory services. In this particular case, the advisor acted as a role model in his ways of using the available tools and artefacts, advocating a ‘willing and able’ approach that influenced the farmer. However, the different digital representations of the fields in various ICT systems offered additional, but artificial, perspectives on the fields that differed significantly from first-hand experiences when walking in the fields. The key question was how to correctly utilise and combine the different representations and the acquired tacit knowledge, in order to develop a more sustainable farming practice.

The available digital representations from CropSAT initiated new kinds of discussions about the fields and current farming practices that were not possible previously due to the lack of detailed representations of with-in field variation in biomass at the time of fertilisation planning. The only option available previously to obtain an overview of the field was to walk through it or to measure with-in field variation in biomass with some kind of field sensor (but without fertilising). However, the enhanced detail in the digital representations that was available with less effort than using a field sensor triggered and facilitated comparisons between different factors, e.g. VRA files for phosphorus fertilisation and the satellite image. For example, the farmer and advisor discussed how variation in soil characteristics and phosphorus values could explain the with-in field variation in biomass. The farmer said: *’We used that variable rate application file last year there. We fertilised according to P content with it '. 'I am so fascinated by this, it’s completely insane*’. On the one hand, the new digital representations provided more detailed information than before, which in turn provided additional support for making decisions regarding fertilisation. On the other hand, the additional information may result in a more complex decision-making process, since the farmer lacks prior experience in how to interpret and use the added information, i.e. the digital representations have to be interpreted, compared and situated in the farmer’s decision-making context, resulting in an ongoing social learning process involving both practitioner and advisor. In other words, the perspective of *professional vision* is intensified through the so-called process of *tool-mediated seeing* (Goodwin and Goodwin, 1996). *Tool-mediated seeing* is characterised as seeing aspects relevant for a task only through the use of tools and artefacts, i.e. the satellite images in CropSAT. In this particular situation, this was done through interpreting the digital representations of the within-field variations in biomass.

Let us now return to the decision on how to decide the average amount of N and then calibrate the YNS to fertilise winter wheat for the last time in the spring. CropSAT offers the possibility to compare and discuss the development of the crop and its N uptake in relation to earlier fertilisation. In order to accomplish these tasks, the farmer and advisor first compared the earlier satellite image with the current image, discussing intensively how to interpret the images and then explaining what has happened in the field (Figure 5). They agreed that the crop had developed satisfactorily and that the winter wheat fields were looking good.

Figure 5. The farmer explaining differences in biomass variation between two different images, an older image on the left side and the present image on the right.

Based on the planned amount of N in the CPS, the measurements from the Spadmeter, earlier first-hand experiences and the satellite images (both older and present), the farmer and advisor decided the average amount of N for each field. In order to calibrate the YNS, the advisor pointed at the screen displaying the satellite image and then showing where to drive the tractor to cover the variation in crop biomass (Figure 6). Calibrating the YNS is not an easy task without support from the ICT system because it is necessary to select appropriate spots to optimise the calibration.

Figure 6. Image sequence where the advisor (right) is making a suggestion on where to drive the tractor to calibrate the YNS to grasp the within-field variation in biomass.

This example illustrates how the participants explored new ways of using the available technology, e.g. CropSAT and YNS. This involved using the CropSAT images as a means to calibrate the YNS, which was not the intended contribution of CropSAT. Although this usage of CropSAT was beyond the developers' intention, it still contributed to generating sustainable farming practices through ongoing learning processes. Thus, it can be claimed that the ICT systems function as social learning tools. Taken together, this adds another dimension to Goodwin's (1994) initial term *professional vision* and Goodwin's and Goodwin's (1996) term *tool-mediated seeing*, which can be denoted *enhanced professional vision.* This *enhanced professional vision* incorporated both the above terms, because these need to be combined when making decisions on the use of ICT support and tacit knowledge in PA.

The examples above show socially distributed cognition over time and how the whole socio-technical cognitive system, which in this case would include farmers, advisors and the available tools and associated artefacts, is capable of performing much more than the individual farmer could. In other words, the coordination of different representations (external and internal) is an emergent property of the system as a whole, not easily reduced to an evident property of a certain entity (human or artefact and tool). This systemic view is the central foundation of the DCog approach; the whole is more than the sum of the individual parts, as the whole socio-technical system demonstrates emergent properties. Thus, cognition is viewed as *creation*, *transformation* and *propagation* of *representational states* within a socio-technical system (Hutchins, 1995).

5. Discussion and conclusions

This study sought to characterise and illustrate the use of CropSAT in PA as a complex socio-technical system from a distributed cognition perspective, focusing on the use, mediation and integration of different forms of representations, tools and artefacts in this domain to improve understanding of farmers' use of AgriDSS. The results revealed how CropSAT functions as a tool to support decision-making processes and promote social learning, which in the long run may generate more sustainable farming practices through the use of an *enhanced professional vision*. It is evident that an AgriDSS such as CropSAT provides important information that could be used as a basis for learning about farmers' crop fields as a part of a larger learning system. The advisor has a central role in promoting the usage of different ICT systems to support and foster social learning processes about how to fertilise farmers' fields, which is a governing principle in the direction that we envision for sustainable farming.

The interest shown by both farmers and advisors indicates that CropSAT is an AgriDSS that shows potential to fit within PA. However, new technology needs novel social and organisational arrangements, such as rules, perceptions, agreements, identities and social relationships to function properly (Leeuwis and Aarts, 2011). Thus, advisory services have a central role to fulfil, to situate the ICT systems in the context of their usage, where they provide opportunities to be used to a wider extent than just for the calculation of VRA files. Thus, technology should not be considered an isolated phenomenon in PA, as pointed out by Röling (1998). There are also possibilities for the use of CropSAT leading to change in current farming practices from their goal orientation to a learning orientation, which in itself has been a much discussed theme within advisory work. Although some farmers are reluctant to use ICT, and instead *'rely heavily on intuitive judgment underpinned by experience'* (McCown, 2002), this study showed that more detailed representations of their fields provide added value. We therefore introduced the term *enhanced professional vision* to characterise the combination of *professional vision* and *tool-mediated seeing*.

The implication of this study is that CropSAT should be considered part of a wider AKIS, where different kinds of ICT systems, tools, artefacts and social learning processes constitute additional parts of the system. CropSAT provides a 'hardware' that still needs further improvement of the 'software', but the immature 'orgware' requires additional development and discussion. Once this has been achieved, we envision that CropSAT could be an important component in the trajectory of sustainable intensification in agriculture and enhance the professional vision of farmers.

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