Cognition and Decision-Making in Adoption of Agricultural Decision Support Systems

The Case of Precision Agriculture

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Cover: CropSAT used for decision-making considering N fertilisation.
(photo: C. Lundström)

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Abstract

Precision agriculture (PA) has a central role to play in a sustainable intensification trajectory of agriculture, including increased yields and decreased environmental impact. Although grounded in advanced technologies this still implies that the individual farmer will have to develop knowledge that is complex, diverse and local. To manage adaptation to the within-field variation in large scale agriculture, so-called agricultural decision support systems (AgriDSS) are necessary. This thesis aims to 1) investigate farmers' naturalistic decision-making in their socio-technical system, aiming to increase their *situated knowledge* and *care* in critical, complex situations, and 2) investigate and present strategies to improve the development processes of AgriDSS. This is done by discussing the so-called *problem of implementation* of AgriDSS in practical precision agriculture. Aspects of the implementation dilemmas are considered within three research questions: 1) What characterises a socio-technical system that supports farmers' decision-making in complex and critical situations? 2) How can AgriDSS support farmers' decision-making and development of situated knowledge, in order to increase sustainability of their practices? 3) How can the development process for new precision agriculture technology, such as AgriDSS, be improved to decrease or go beyond the problem of implementation?

The research questions are addressed using the theoretical framework of distributed cognition (DCog) from the research field of cognitive science and using user-centred design (UCD) approach from the field of human-computer interaction. Two case studies were performed and the main contribution is the novel concept of *enhanced professional vision*, which states that both technology and intuitive experience-based knowledge are necessary in decision-making. Neither one of them is replaceable when an increased adaptation to within-field variation and complexity in farmers' care for their local situation is needed. The thesis also reveals the importance of social interactions for technology adoption and use: 1) during the participatory development process of AgriDSS; 2) for decision-making and learning when applying these technologies; and 3) to encourage farmers to use new technology to increase sustainability.

These findings have potential implications for farmers and advisors, by changing the dominating perspective in farm technologies from knowledge transfer to participatory approaches. The discussions provided here about expertise in relation to ICT, human beings and care in the trajectory of sustainable intensification will hopefully influence how farmers' experience and situated knowledge is acknowledged in future research and development (R&D). More studies on R&D in advisory work in relation to new technologies and strategies to facilitate their use, and social learning and decision-making among farmers are needed, as are improved possibilities for advisors to interact and exchange experiences and strategies relating to technology use.

Keywords: enhanced professional vision, agricultural decision support systems, farmers' decision-making, care, situated knowledge, distributed cognition, user-centred design.

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Sammanfattning

Lantbruket står inför stora utmaningar. Att möta samhällets krav på ökad produktion parallellt med bevarad eller helst stärkt miljönytta förutsätter innovationsförmåga. Hållbar intensifiering (ökad skörd på bibehållen areal i kombination med minimerad miljöbelastning) är ett koncept som används för att ange i vilken riktning vi måste röra oss i vissa produktionssystem. Oavsett produktionssystem så kommer krav på ökad hållbarhet att medföra att den individuella lantbrukaren behöver ha större *situerade kunskap* (erfarenhetsbaserad, intuitiv kunskap som är bunden till individen och lokalt anpassad) för att i större utsträckning kunna anpassa olika åtgärder efter platsbundna förutsättningar. Lantbruket står också inför en ökad osäkerhet i odlingsbetingelser på grund av klimatförändringar, vilket samtidigt kommer att kräva en större anpassningsförmåga. Här har precisionsodlingen en viktig roll att fylla, åtminstone i storskaligt lantbruk. För att tillämpa precisionsodling och anpassa olika åtgärder efter inomfältsvariationer i gröda och jord är olika typer av beslutsstödsystem nödvändiga. Idag utvecklas en mängd nya sådana inom precisionsodlingsområdet, men få används i praktiken, vilket inom forskningen kallats för *implementeringsproblemet*.

Denna avhandling har som målsättning att bidra till lantbrukares utveckling av *situerad kunskap* och därmed deras *omsorg* i praktiken (*care*: här definierat som resultatet av allt agerande som får teknik och information att bidra till hållbarhet i det praktiska lantbruket). Detta sker genom att undersöka vad som egentligen döljer sig i begreppet implementeringsproblemet vid utveckling för hållbar intensifiering av lantbruket. Målen är att: 1) från lantbrukares perspektiv undersöka deras naturalistiska beslutsfattande (beslutsfattande i verkligheten) i komplexa, kritiska situationer, samt 2) förbättra utvecklingsprocessen av nya beslutsstödsystem och på detta sätt undvika implementeringsproblemet. Detta ska göras genom att besvara följande tre forskningsfrågor: 1) Vad karaktäriserar ett socio-tekniskt system som stöder lantbrukares beslutsfattande i komplexa, kritiska situationer? 2) Hur kan beslutsstödsystem stödja lantbrukares beslutsfattande och utveckling av situerad kunskap med syfte att öka hållbarheten i lantbruket? 3) Hur kan utvecklingsprocessen av nya beslutsstödsystem förbättras för att på bästa sätt stödja lantbrukarna i deras produktion? För att besvara dessa forskningsfrågor har jag använt mig av det teoretiska ramverket distribuerad kognition (DCog) från forskningsområdet kognitionsvetenskap samt den teoretiska ansatsen användarcentrerad design (UCD) från forskningsområdet människa-datorinteraktion. Det viktigaste bidraget från den teoretiska analysen och de två fallstudierna är introduktionen av det nya konceptet *utvidgad professionell blick* (*enhanced professional vision*), som är en kombination av *professionell blick* (*professional vision*) och *teknikmedierat seende* (*tool mediated seeing*), dvs. kombination av teknik och situerad kunskap. En erfaren lantbrukare kan ses som expert på sin egen gård och sina fält, med stor erfarenhetsbaserad och intuitiv kunskap som inte kan ersättas av teknik. Såväl expertis som omsorg är beroende av situerad kunskap och detsamma gäller den samordningsförmåga som är en central kompetens som en lantbrukare måste ha i sitt dagliga arbete. Teknik kan stödja expertis, omsorg och samordningsförmåga, men inte ersätta den, därför behövs en kombination av teknik och situerad kunskap för att öka lantbrukets hållbarhet. Avhandlingen visar också på vikten av sociala sammanhang i relation till ny teknik: 1) under

utvecklingsprocessen av nya beslutsstödsystem, genom att olika grupper av slutanvändare medverkar under hela utvecklingsprocessen och tekniken på så sätt anpassas redan från början till slutanvändarnas behov; 2) för beslutsfattande och lärande under praktisk användning; samt 3) för att motivera lantbrukare att ta till sig och använda ny teknik.

Förhoppningen är att resultaten från detta arbete ska påverka forskares, lantbrukares och rådgivares praktiska verksamhet, genom att förändra synen på hur kunskap utvecklas. Från så kallad informationsförmedling (knowledge transfer) som är enkelriktad från en utvecklare till en mottagare och som underförstått innebär att någon annan än slutanvändaren vet vad som är relevant att veta eller göra, till helt deltagarstyrda strategier där utvecklare och olika kategorier av slutanvändare deltar och bidrar med sina respektive erfarenheter och behov i en gemensam lärprocess. Förhoppningen är också att denna avhandling ska bidra till att lantbrukares erfarenhet och situerade kunskap ska värderas högre i framtida forskning och utveckling. Detta genom att en diskussion uppstår om expertis och förhållandet mellan teknik och människor, samt vikten av att stödja lantbrukares utveckling av situerad kunskap och därmed sin förmåga och vilja att bidra till ökad hållbarhet. Avhandlingen visar att rådgivare är nyckelpersoner för hållbar teknikanvändning i lantbruket, men deras kompetens vad gäller teknik behöver utvecklas för att möta ett ökat behov från allt kompetentare lantbrukare. För att det storskaliga lantbruket ska utvecklas i en riktning mot hållbar intensifiering är precisionsodling och nya beslutstöd nödvändiga. Men utvecklingen av nya beslutsstöd måste göras i samverkan med olika grupper av slutanvändare och bättre strategier för att stödja användning, socialt lärande och beslutsfattande i relation till ny teknik bör beaktas under hela utvecklingen.

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My appreciation also goes to the farmers and advisors whom I followed, observed and interviewed during this project. Thank you for all your patience and for giving me the possibility to share your practice. You will all stay anonymous for ethical reasons.

The project was funded within the thematic programme BioSoM (Biological Soil Mapping) at the Swedish University of Agricultural Sciences.

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when needed! And all the rest of you, my lovely family and friends – thank you for being there, making me enjoy life and go on! It has been a process of ups and downs and your being there and supporting me have been tremendously valuable. The only thing I feel a bit sorry about is that I could not join my father's fishing trip to Norway, in order to complete this thesis. Finally, I want to thank our little dog Polly, who entered my life during the last month of this work and forced me to take walks in the wood and laugh at all her silly frolics, even though I felt I did not have the time. Thank you all!

Christina Lundström, September 2016

Theory weary, theory leery
Why can't I be theory cheery?

Tom Ericson

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Lindblom, J., Lundström, C. & Ljung, M. (2016). Next-generation decision support systems for farmers: Sustainable agriculture through sustainable IT. *Farming Systems Facing Global Challenges: Capacities and Strategies 1*, Berlin: IFSA Europe, pp. 49-57.

II Lundström, C., Lindblom, J., Ljung, M. & Jonsson, A. (2015). Some considerations about the development and implementation process of a new agricultural decision support system for site-specific fertilisation. *Precision Agriculture* 15, pp. 437-444.

III Lindblom, J., Lundström, C., Ljung, M. & Jonsson, A. (submitted). Promoting sustainable intensification in precision agriculture: Considering the ICT development process for site-specific fertilisation. Invited submission to the journal *Precision Agriculture*; the manuscript is currently under review.

IV Lundström, C., Lindblom, J., Ljung, M. & Jonsson, A. (2016). Sustainability as a governing principle in the use of agricultural decision support systems: The case of CropSAT. Paper presented at the *IFSA Symposium*, 12-15 July, Newport, Shropshire, UK.

V Lundström, C. & Lindblom, J. (2016). Considering farmers' situated expertise in using AgriDSS to foster sustainable farming practices in precision agriculture. Paper presented at the *13th International Conference on Precision* Agriculture (ICPA), 31 July-31August, St Louis, Missouri, USA, pp. 1-15.

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Contribution of Christina Lundström to Papers I-V:

I Took part in formulating the idea, planning the work and writing the manuscript, together with the co-authors.

II Was the main author and developer of the idea and planned and performed the studies. Wrote the manuscript together with the co-authors. Presented the results at a conference.

III Took part in formulating the idea, planning the work and writing the manuscript, together with the co-authors.

IV Was the main author and developer of the idea and planned and performed the field work. Selected sequences to be included in the manuscript, analysed the data and wrote the paper together with Lindblom, in consultation with other co-authors. Presented the results at a conference.

V Was the main author and developer of the idea and planned and performed the field work. Selected sequences to be included in the manuscript, analysed the data and wrote the paper together with Lindblom, in consultation with the co-author. Presented the results at a conference.

Abbreviations

AEC	Agricultural Extension Communication
AgriDSS	Agricultural Decision Support Systems
BioSoM	The thematic project Biological Soil Mapping
CPS	Crop Production Software
CS	Cognitive Science
DCog	Distributed Cognition
EC	Environmental Communication
HCI	Human-Computer Interaction
ICT	Information and Communications Technology
N	Nitrogen
NDM	Naturalistic Decision-Making
PA	Precision Agriculture
PD	Participatory Design
POS	Precision Agriculture Sweden Network
R&D	Research and Development
RQ	Research Question
UCD	User-Centred Design
VI	Vegetation Index
VRA	Variable Rate Application
YNS	Yara N-sensor

Preface

For me, this thesis work was a step in life that I had considered for a long time while working at the university, but which I was stimulated to take on encountering this particular area of interest. My background is as a crop production agronomist, with an associated interest in sustainability and precision agriculture (PA), but with an even greater interest in human beings, their thinking and performance in practice. Coming from a suburban childhood with much time spent in the countryside, I dreamed of a future life on a farm. I studied agronomy and through that met my life companion, a farmer. I have lived on a farm for almost twenty years and spent the early part of my working time within the County Administration Board, focusing on water quality issues connected to acidification. I later moved to working with fertilisation issues at the Swedish Board of Agriculture and with precision agriculture at SLU in Skara. In 2005, I took a teacher training course, which resulted in projects concerning outdoor teaching and schoolchildren's knowledge of food production and farming in society. Those projects were conducted as naturalistic inquiries based on interviews and participatory observations. In parallel, I worked as a coordinator in the Swedish network on precision agriculture (POS), and I have personally experienced a frustration among researchers about the limited interest in precision agriculture technology among farmers. However, the experiences of and connections with practice, research, pedagogy, advisory work, and administration has constituted a good base for this work, by providing me an understanding of different perspectives and world views that needs to be bridged in order to increase sustainability in agriculture.

1 Introduction

In a sustainable intensification trajectory for agriculture, the aim is to increase food production on existing farmland and decrease the environmental impact, using context-dependent strategies that consider both social and natural scientific knowledge (Garnett *et al.*, 2013). In such a trajectory, different stakeholders, including individual farmers, will need to develop situated knowledge that is *complex, diverse* and *local* (Leeuwis, 2004). Precision agriculture strategies aiming to adapt field measures to within-field variation in different soil and crop properties have a role to play in simultaneously increasing yield and decreasing environmental impact, at least in large-scale agriculture. To manage such adaptation to within-field variation, various kinds of information and communications technology (ICT)[1] systems in general, and so-called agricultural decision support systems (AgriDSS) in particular, are necessary, in combination with machinery that can perform the required measures.

The aim of this thesis was to act as a bridge between farmers' experience-based *situated knowledge* in a sustainable intensification trajectory in agriculture, and the use of AgriDSS in order to develop farmers' *care* in practice in precision agriculture, in the sense used by Krzywoszynska (2015). This was done by addressing the so-called *problem of implementation* and *gap of relevance* (McCown, 2002) in precision agriculture regarding the practical use of AgriDSS. I am aware of the criticisms of these two concepts within some areas of agricultural research due to their relation to the *knowledge transfer* perspective. Nevertheless, I have chosen to use them, due to the interdisciplinary nature of this thesis work, since they are accepted and commonly used within the field of precision agriculture. The intention in the work was to problematise the concept of *implementation* and the *knowledge transfer* perspective.

The starting point for the research described in this thesis was three statements by Röling (1988) criticising the implementation concept. He argued that:

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[1] The concepts of IT and ICT are used interchangeably in this thesis.

- Technology is often seen as an isolated phenomenon
- Technology is not adapted to the needs of farmers
- The traditional view of knowledge transfer lacks a systemic perspective and does not put the technology in the context in which it belongs.

In order to address the *problem of implementation* pertaining to precision agriculture with Röling's statements in mind, two central aspects of precision agriculture appeared to be appropriate goals: 1) An improved understanding of farmers' naturalistic decision-making in their socio-technical system[2] and 2) an investigation into how new and emerging AgriDSS could be developed, with emphasis on making them usable and credible by the end-users, with a greater fit in the decision-making milieu in which they would be used. In order to acquire knowledge concerning these two aspects, I turned to research fields outside agriculture to seek and introduce convenient theories and methodologies.

In relation to the first of the two aspects pf PA, I turned to the theoretical framework of distributed cognition (DCog) from the research field of cognitive science (CS) to increase our understanding of farmers' naturalistic decision-making in their socio-technical system. By using the DCog framework, cognitive processes such as social interactions, interactions between internal processes and artefacts[3] and interactions over time are demonstrated and can be more easily interpreted and explained. To address the aspect of developing new usable AgriDSS, I turned to the research field of human-computer interaction (HCI) and the user-centred design (UCD) approach, which provides methods for user-centred ICT development processes. By introducing these methods in the precision agriculture domain, in relation to AgriDSS use and development, I sought to contribute to farmers' development of experience-based *situated knowledge* and *care* in a sustainable intensification trajectory. However, in raising farmers' interest and engagement in AgriDSS within precision agriculture, challenges remained in terms of addressing the so-called *problem of implementation* and the *gap of relevance.* This required a revision of views on how knowledge is created and what learning and communication might mean.

The project was funded within the thematic programme Biological Soil Mapping (BioSoM) at the Swedish University of Agricultural Sciences and was performed in two parts during 2010-2012 and 2013-2015. BioSoM (www.BioSoM.se) sought to examine the whole process concerning soil-borne

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[2] In this thesis the concept socio-technical system is considered similar to socio-material systems and other similar concepts, unless otherwise stated.

[3] In this thesis I do not distinguish tools from artefacts and use them both in the sense of artificial devices which are designed to serve a representational function in the cognitive system (Norrman, 1991).

diseases, from soil sampling to detection of pathogens, control and strategies for decrease in occurrence and on to practical use in agriculture. In this licentiate project, I took a critical look at the *problem of implementation* considering AgriDSS in precision agriculture, in order to apply those experiences in the area of biological soil mapping.

1.1 Aim and purpose

The overall purpose of this thesis is to contribute to farmers *situated knowledge* and *care* in a sustainable intensification trajectory in agriculture, by investigating what the research field of PA names as the *problem of implementation* and the *gap of relevance* in relation to AgriDSS. Precision agriculture aims to increase yield, crop quality, farm viability and efficiency in input use, in parallel with reduced environmental impact, through better within-field adaptation to crop and soil properties. With this in mind, the aims of the thesis were to: 1) take into account farmers' perspective when investigating their naturalistic decision-making in the socio-technical system, aiming to increase their *situated knowledge* and *care* in practice in critical, complex situations, and 2) investigate and present strategies/recommendations to improve the development processes of AgriDSS in order to develop AgriDSS that are considered usable and credible by the end-users and fit into the decision-making milieu where they will be used.

1.2 Research questions

To reach the aims of the thesis the following three research questions (RQ) were formulated:

RQ 1: What characterises a socio-technical system that supports farmers' decision-making in practice in complex critical situations?

RQ 2: How can AgriDSS support farmers' decision-making and development of *situated knowledge*, in order to increase sustainability in their practice?

RQ 3: How can the development process of new precision agriculture technology as AgriDSS be improved in order to decrease the *problem of implementation* and the related *gap of relevance*?

1.3 Research approach: the road taken

1.3.1 My point of departure

Coming from a natural sciences background, the research topic investigated in this thesis was a reaction to my personal experience of the *problem of implementation* of precision agriculture technology and an understanding of the need for a wider and changed perspective. The point of departure for my research was a world view captured in the words of Röling (1997, p. 249): *natural systems are governed by causes, people are guided by reasons - predicting human behavior on the basis of causes has consistently led to failure*. In precision agriculture research, the focus has long been on technical aspects, *i.e.* developing and proving the advantages of different technologies. However, human properties and social aspects in the whole chain from technology development, advisory work, decision-making, learning and usage in practice have been neglected to a great extent, with the field remaining wedded to the normative perspective of knowledge transfer (McCown, 2002). Another important aspect is that researchers have focused on technology as an isolated phenomenon, while farmers always have a whole *farming system* to consider (Röling, 1988). Therefore, my ontological point of departure was not a reductionist paradigm to study causalities, but rather an ontological approach based in the interpretive paradigm, following Röling's (1997) advice about working with subjectivity instead of objectivity, using a holistic approach. Hence, the overarching aim was to gain a better understanding of farmers' decision-making and learning in their socio-technical system, *in the wild*[4], where a knowledge gap has been identified (IV; Rossi *et al*., 2014; Mackrell *et al*., 2009; McCown *et al*., 2009; Matthews, 2008; McCown, 2002).

People change their behaviour when they have reasons for doing so and as long as they have a choice. Such reasons cover a wide spectrum, from fear or incentives to attitudes, values or knowledge, depending on the individual and the situation. The objective *reality* is thus not received by an individual; rather, it is *constructed* in relations and interactions with others and with the natural world (Patton, 2015; Röling, 1997). Accordingly, this thesis takes the view that reality is socially constructed and that all humans have their own interpretation of the world, which also means that there is no objective truth, except as physical laws. Instead, different individuals create their own interpretation of their *world* and the researcher's task is to reveal different interpretations of an object, task or

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[4] "*In the wild*" denotes a difference compared with traditional cognitive science in studying situations in its natural context, instead of performing studies in the laboratory.

phenomenon by individuals and groups (Rodela *et al.*, 2012). While knowledge is seen as socially constructed, the researcher aims to identify and understand different interpretations and determine whether and how they interact with each other and the object of interest. Accordingly, to support farmers in the agricultural transition towards sustainable intensification, there is a need for a different approach that meets the necessity to understand and manipulate causalities in the natural world. In so doing, it is important to avoid the style of communication that is common within conventional agriculture according to Carolan (2016, p. 15) and is *more interested in telling than listening, in directing rather than following and in effecting rather than learning to be affected.* Thus, the aim should not be to find a so-called objective truth, but rather to contribute to our understanding of human learning and decision-making in its socio-technical context to avoid the *technology fix* (Black, 2000) and the *knowledge transfer* perspective, by highlighting the importance of precision agriculture technology in order to frame farmers' development of *situated knowledge* and *care*, but embedded in a social learning context from development to use in practice.

1.3.2 An interdisciplinary approach

The work performed in this thesis was interdisciplinary, spanning five major research fields of study (Figure 1) and the literature reviewed was wide-ranging, flowing across disciplines. The adoption of the phrase *field of study* here is deliberate in order to imply that these five fields of study are not all claiming the status of a discipline, nor are they equally advanced in their development. For our purpose here it is sufficient to acknowledge that they are overlapping fields of study and areas of research endeavour. It is with understanding that, the word discipline has been used in this section. These five fields of study were: environmental communication (EC), agricultural extension communication (AEC), precision agriculture (PA), cognitive science (CS) and human-computer interaction (HCI). However, I was aware of the potential risks of using an interdisciplinary approach, since I cannot claim to be a specialist in all of these fields, their specific terminologies and theories. Although at first glance the different fields may not seem to have much in common, they offer highly complementary rather than alternative views which can help gain deeper and broader insights into achieving sustainable intensification in agriculture. Therefore, each field is briefly described below.

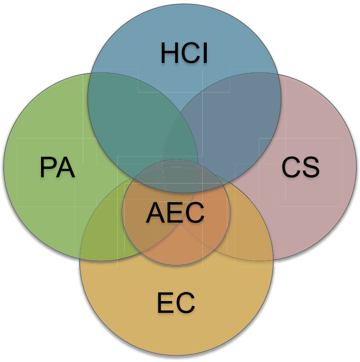

Figure 1. This work spanned five fields of studies: environmental communication (EC), agricultural extension communication (AEC), precision agriculture (PA), cognitive science (CS) and human-computer interaction (HCI). The diagram does not include interrelations between the fields.

Environmental communication (EC) (Cox & Depoe, 2015), which is rather new field, dating back to the 1960s (Hansen & Cox, 2015), is part of a large, not yet identified, field of communication theory regarding communication on issues considering environment or natural resources (Craig, 1999). It is situated at the nexus of nature and culture, focusing on communication and human relations to nature and natural resource management (Milstein, 2009).

Agricultural extension and communication (AEC) (Leeuwis, 2004; Nitsch, 1994; Röling, 1988) as a field of study and professional practice originating from the era when universities as knowledge centres started to *extend* their findings to end-users and practitioners, predominantly in agriculture, food, forestry and such other production contexts and in health and community development. The desire to teach common people, in a tradition of knowledge transfer, in what ways and how they could improve their practice characterises this field. Historically, the underlying motivation in agricultural contexts has been to increase food production, though in the present era the mission of agricultural extension and communication is well beyond that purpose and, through a long critique of the knowledge transfer paradigm, has now incorporated other perspectives, notably the human dimension and its many aspects and qualities.

Precision agriculture (PA) (EIP-AGRI FOCUS GROUP, 2015; Aubert *et al*., 2012) has the ambition to use sensors and other kinds of technology, *e.g.* global positioning systems (GPS) and often other geographical data, to adapt different farming measures to within-field variation in different parameters. The aim is to increase crop yield and quality, improve farm profits by more effective use of inputs and decrease the environmental impact (http://www.precisionsskolan.se/). To this end, precision agriculture provides possibilities for crop farmers to recognise and handle variations in the soil or crop to a much finer degree than ever before, thus increasing sustainability by decreasing sub-optimal treatments that usually may lead to negative environmental impact and an increase in profitability due to higher efficiency in usage of inputs and higher crop quality.

Cognitive science (CS) (Lindblom, 2015; Rogers, 2012; Bechtel *et al.*, 1998; Hutchins, 1995) is an interdisciplinary research field focusing on the mind and its processes. It investigates the nature, task and function of cognition, including areas such as learning, decision-making, perception, problem solving, language and memory. The traditional foundation states that cognition can be understood as representational structures and computational procedures (*e.g.* Rogers, 2012; Bechtel *et al.*, 1998; Pylyshyn, 1984). Here, cognitive science is used as a theoretical foundation to increase understanding of farmers' decision-making in their socio-technical context, focusing on naturalistic decision-making (NDM) (Orasanu & Connolly, 1995) and distributed cognition (DCog) (Hutchins, 1995), new advances in the cognitive science field.

Human-computer interaction (HCI) (*e.g.* Issa & Isaias, 2015; Hartson & Pyla, 2012; Rogers, 2012) is a rapidly developing field that in itself is interdisciplinary, involving computer science, informatics, interaction design, graphics and cognitive psychology. Initially, the main focus was on human-computer interaction *per se*, but that is not solely the case nowadays. Instead, the focus has widened to designing and developing simple, intuitive and transparent user interfaces that are usable, efficient and credible, by which people easily can express themselves through various computationally enhanced tools and media. Human-computer interaction is used as an umbrella term for a field which overlaps with many others, *e.g.* academic disciplines and design practices. In this thesis, there was an identified need to scrutinise and understand how ICT systems, such as AgriDSS, can be better adapted to the end-users' needs, both by the design processes and strategies for development.

1.3.3 Theoretical framework

In order for agriculture to consider, handle and confront future challenges, there is an identified need for new knowledge, perspectives, strategies and technology (Jordan & Davis, 2015; Garnett *et al.*, 2013; Leeuwis, 2004). Farmers' complex socio-technical system involves technical aspects and cognitive, organisational and social components. Therefore, I have chosen to turn to the above-mentioned fields of study to widen the technical, biological and natural science knowledge developed within the field of precision agriculture, to bring cognitive and human-centred issues to agricultural science and farming practice. Environmental communication constitutes the basis for the work by providing theories and perspectives on interactionism and constructivism when dealing with several issues with regard to natural resource management. Both environmental communication and agricultural extension communication are important for the social learning aspects and for diffusion of innovation to farmers' socio-technical context.

Farmers' decision-making has traditionally been studied using theoretical frameworks from economic science, similar to the traditional approach within cognitive science, which has resulted in limited understanding of their situated and naturalistic decision-making process that encompasses the whole socio-technical system. In order to acquire more knowledge of how farmers' decision-making occurs in its socio-technical context *in the wild*, I turned to the new advances in cognitive science, in particular the DCog framework (Hutchins, 1995), and NDM (Orasanu & Connolly, 1995). They have more in common and share the ontological and epistemological bases of interactionism and constructivism that are the pillars of agricultural extension communication, and contribute by widening the unit of analysis to include technology and other tools and artefacts in the decision-making process. To conclude, there is a need for improved knowledge on convenient strategies for design and development of ICT systems, where the research area of human-computer interaction (HCI) (Issa & Isaias, 2015; Rogers, 2012) can significantly contribute. In this work, HCI provides established knowledge and processes to design and develop ICT systems that are usable, efficient, and credible through consideration of the user-centred design (UCD) approach, which may also benefit agriculture in general and precision agriculture in particular.

1.3.4 Methodology

A qualitative approach using naturalistic inquiry was adopted, which in this thesis was taken to be interchangeable with qualitative inquiry. Naturalistic inquiry is characterised by observations conducted in natural settings (Lincoln & Guba, 1985) and focuses on deep and detailed descriptions of actions, behaviours, conversations, activities and interpersonal interactions from fieldwork (Patton, 2002). In naturalistic inquiry, the context is incorporated in the analysis, because it is considered important for the interpretation of the meaning of a situation (Patton, 2002; Lincoln & Guba, 1985). Furthermore, in naturalistic inquiry the quality of the data combined with sound conclusions are the most important aspects to achieve scientific rigour (Patton, 2002). Patton (2002, p. 243) claims that *the validity, meaningfulness and insights generated from the qualitative inquiry have more to do with the information richness of the cases selected and the observational/analytical capabilities of the re-*

searcher than with sample size. Thus, the quality of the analysis lies in the performance of the study itself. In naturalistic inquiry, ethnography-inspired data collection techniques are commonly used and combined. The ethnographic approach involves the study of cultural perspectives and patterns in their natural settings over time.

To answer the research questions posed in this thesis (*cf.* section 1.2), two case studies were performed. A case study can use both quantitative and qualitative methods, but in this thesis only qualitative methods were used. The first case study was influenced by the *workplace study* methodology (Luff *et al*., 2000) with the focus on farmers and their opinions and needs, mostly using participant observation, video-recording, field notes and ethnographic interview as data collection techniques. The second case study mostly took a conceptual approach, using design methodology to investigate pros and cons in initiating a shift in ICT system design methodology for precision agriculture, where the theoretical part was used as a lens in analysing and discussing the data collected.

Workplace studies investigate and analyse people and technology in action and in what ways different tools and artefacts are used in practical organisational conduct (Heath *et al*., 2000). Such studies are important to understanding of natural systems and contribute valuable information about design, usage and evaluation of different technologies. A number of theoretical approaches to study practical actions in the workplace have been suggested in the literature, *e.g.* activity theory (Rogers, 2012), situated actions (Suchman, 1987) and the theoretical framework of DCog. According to Heath *et al*. (2000, p. 307) "*...Distributed Cognition* [DCog] *has provided the vehicle for a body of ethnographic work and an array of findings concerning the ways in which tools and technologies feature in individual and co-operative activity in organizational setting*". According to those authors, Hutchins (1995) has provided some of the most illuminating and influential research regarding workplace studies with his study of ship navigation. Accordingly, there are relations and equalities between the methodology for workplace studies and the theoretical framework of DCog.

2 Background

2.1 Setting the scene

Agriculture is facing immense challenges to fulfil different societal goals and values, including a need for increased food production and environmental concerns such as biodiversity and climate change, among others, in order to reach higher levels of sustainability in the domain. Sustainable development has been defined by the Brundtland Commission (World Commission on Environment and Development, 1987) as *development which meets the needs of the present without compromising the ability of future generations to meet their own needs*. It also calls for convergence between the three pillars of: economic development, social equity and environmental protection (Drexhage & Murphy, 2010). Sustainable intensification of the agriculture sector aims to increase food production from existing farmland while minimising the environmental impact, in order to secure the needs of both present and future generations (Garnett *et al*., 2013). Sustainable intensification in agriculture means: 1) Increased food production, 2) increased food production on existing farmland area, since there is roughly no more land to exploit, 3) decreased environmental impact by radical rethinking of production and 4) development of context-dependent strategies for sustainable intensification considering both social and natural sciences knowledge (Garnett *et al.*, 2013).

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 (*e.g.* Woodward *et al*., 2008). Accordingly, history has shown that there is no agricultural development model that is generally applicable (Leeuwis, 2004). To increase sustainability in agriculture, the strategy will not be a question of adaptation to any global policy or initiative, but will instead require a never-ending local decision-making process depending on the fundamental characteristics of the system of interest, as well as its sensitivities and vulnerabilities (Schlindwein *et al.*, 2015). Thus, to move agriculture along a more sustainable trajectory, a wide range of approaches, conventional, high-tech, agro-ecological and organic, must be assessed and tested in relation to physical and social contexts (Garnett *et al.*, 2013). Leeuwis (2004) expresses this as different stakeholders requiring a focus on development of situated knowledge that is *complex, diverse* and *local.* Schlindwein *et al.* (2015) claim that agricultural adaptation to climate change will be a question of adjusting *practices*, *processes* and *capital*, in parallel with changes in *social* and *institutional structures* and altered *technological* options. An agricultural transition progress will clearly require integration of different major approaches within research and development to face and consider a wider range of complexity than before, and find more diverse solutions or strategies, more closely adapted to local situations (Jordan & Davis, 2015). In this thesis, the focus was on farmers' socio-technical system in relation to strategies for management of complexity arising due to within-field variation in different factors. It considered both the individual decision maker and the situation that should be handled, starting with the basic conviction that there is a need for better adaptation of different farming measures to within-field variation in order to increase yield, crop quality and farm viability and decrease the environmental impact, which are the common goals in precision agriculture (http://www.precisionsskolan.se/). In the next section, I discuss the farmer as the focal actor in agricultural transition and precision agriculture technology as support for handling within-field variation in soil and crops, starting with the farmer.

2.1.1 The farmer – the focal actor in agricultural transition

At the very core of the transition towards sustainable intensification in agriculture is the individual decision maker, making strategic, tactical and operative decisions bridging theory and practice and balancing the desirable with the feasible (Van Meensel *et al.*, 2012; Matthews *et al.*, 2008). Thus, the decisions made by every individual farmer will have positive or negative impact on sustainability in agriculture (Van Mensel *et al.*, 2012; Matthews *et al.*, 2008). Farmers' daily work activities are complex insofar as they require knowledge and consideration of a wide range of biological, technological, practical, political, legal, economic, ethical and social factors and circumstances (*e.g.* Lindblom *et al.*, 2013; Nitsch, 1994). According to Nitsch (1994, p. 30), the very core of farm management lies in *the ability to coordinate complexity under uncertainty*. The farmer needs to manage a wide range of competences to manage this complexity, including: 1) knowledge about the subject (crop production *etc.*), 2) skills in formal planning (the ability to keep economic records and make a budget), 3) practical skills (the ability to organise and to get farm tasks and chores done in time) and 4) orientation about the institutional environment (legislation, market conditions, agricultural policies and other institutional factors). However, this is not enough: *The crucial element is the ability to apply them in the coordination of the complexities of farming on a specific farm* (Nitsch, 1994, p. 32). *It is not a matter of doing everything right, rather it is a matter of making sure the right things are done* (Nitsch, 1990, p. 118). This kind of knowledge is personal and cannot be separated from the person who has it.

Sustainable agriculture has to become more flexible and adapted to its environment, by supporting and acknowledging the individual decision maker in their socio-technological context. Thus it is the individual farmer, with their personal and situated knowledge, who must achieve a significant part of the goals for agriculture. Technology is central, but must be used in the proper way in order to increase sustainability. Accordingly, issues about individual, technical and organisational development are important and sustainable agriculture will require farmers who can manage and co-ordinate more variable farming systems (Leeuwis, 2004).

Much of the adaptation of farming practice aiming to increase sustainability is optional for farmers. This makes adoption of new knowledge and technology more demanding, since farmers must be motivated to change their actions (Deci & Ryan, 2008). However, once accepted, the probability of higher quality in their actions in relation to sustainability is also increased. Deci and Ryan (2008) make a distinction between autonomous motivation and controlled motivation. Autonomous motivation is characterised as both so-called intrinsic and integrated motivation. Controlled motivation consists of both external and introjected motivation (for more information see Deci & Ryan, 2008). It is well known that autonomous motivation for a task leads to more effective performance. According to Deci and Ryan (2008), social environments where the individual interacts with others and feels relatedness, competence and autonomy could be effective contexts to increase individuals' motivation to learn and change.

Farmers' daily routine work is characterised by problem solving in various areas and of differing severity in a broad range of operations. External factors, *e.g.* weather, vary continuously, and the impacts on weather-dependent biological systems are difficult to explain and impossible to predict and control. Accordingly, exactly the same situation will never reappear and it is impossible to repeat an action to investigate different alternatives under exactly the same conditions in a certain field on a farm. It is also essential to consider that a solution to one part of the farming practice could create problems in another part of the same practice (Leeuwis, 2004). As a result, the individual farmer must often balance and make trade-offs between several, sometimes conflicting, environmental goals and weigh efficiency against environmental considerations. The continuous and ongoing act of comparing formal knowledge with self-experienced results, obtained during earlier years in different places, is made either consciously or unconsciously, creating new knowledge and rules of thumb in current farming practice (Lindblom & Lundström, 2014). During this knowledge development process, a broad range of different individual and social learning situations are of major importance in influencing the farmer. Hoffman *et al.* (2007; p.360) remarked that *farmers work in a kind of life-long longitudinal case study set-up*. They develop operating skills to *know that* action is required, *know what* to do, and also *know how* to solve a problem, even if it is clear to them that the actions they performed will probably not always be optimal (Baars, 2011).

Care and expertise in farming practice

According to Krzywoszynska (2015), experiential, situated knowledge is central for the delivery of the multiple *care* aspects that society is increasingly expecting and demanding from farmers and agriculture. *Care* in this meaning is not considered an obligation, a principle or an emotion, but *the result of all practices that make technology and knowledge work* and enable maintenance, continuation and repair of our farming world (Krzywoszynska, 2015; p. 290). The emphasis on *all practices* is important, because it expands the area of interest from specific interactions to a broader context (*e.g.* the whole farm) and could be compared with Nitsch's (1990) concept of coordination skills. Delivery of care is dependent on *expert situated knowledge,* which develops from experience in a practice and is constituted by *attentiveness*, *responsibility* and *competence* (Krzywoszynska, 2015). Good *care* requires *attentiveness*, *responsiveness* and *adaptation* to the always changing circumstances, as is the case in farming practice. However, those three are also elements of true competence, according to the Dreyfus model of skill acquisition, which states that an experienced individual with situated knowledge and expertise cannot be superseded by ICT systems in handling complex situations in real-life settings (Dreyfus & Dreyfus, 2005).

Dreyfus and Dreyfus (2005) offer a five-stage model of the cognitive activities involved in directed skill acquisition in real-life, complex situations (Table 1). It ranges from a novice, who follows rules or recipes, to an expert who applies sophisticated heuristics and uses experience and intuitive knowledge from earlier, similar situations to solve complex problems. Formulating rules from intuitive knowledge is both impossible and also a way of simplifying the situation, whereupon it is no longer considered expert knowledge. Dreyfus and

Dreyfus (2005) claim that increased experiences are followed by decreased concerns for assessments of isolated elements, cultivating a holistic perspective. Thus, a computer could follow explicit rules and perform better than a beginner, but could not rival an engaged expert whose experience-based, intuitive process is fast, holistic and accurate. Nevertheless, ICT systems are superior to humans when *e.g.* handling and computing big data or measuring properties that human senses cannot perceive. Consequently, ICT systems, as different kinds of cognitive artefacts with representational functions, could complement human abilities, promote different cognitive activities for which humans are poorly suited and enhance and support development of those cognitive skills which humans are biologically predisposed to process easily (Clark, 1999). Humans constantly process information, but the limited human capacity for attention and poor short-term memory are some central limitations for cognitive capacity.

Table 1. The Dreyfus and Dreyfus (2005) model of skill acquisition

Level	Description
Novice	Follows rules, regardless of context
Advanced beginner	On developing some experience, the advanced beginner can recognise meaningful additional aspects of the situation and the experiences, as well as rules used in performance.
Competent	A huge number of potentially relevant elements and procedures are recognised in the situation and the task seems overwhelming. In this step the performer learns how to determine which elements and procedures to consider important and which can be ignored. Moreover, each individual must decide for themselves in each situation what plan or perspective will be adopted, without being sure that it will be appropriate.
Proficient	To get to this level, the individual must be engaged. Now the performer's skill, as represented by rules and principles, is gradually replaced by situational discrimination accompanied by associated responses. The individual then sees what should be done rather than using any calculative procedure to select by alternatives, still making decisions.
Expert	The individual sees what needs to be done and can also immediately see how to achieve the goal. The expert reacts to a situation with an immediate intuitive situational response

To sum up, increased sustainability requires farmers to increase their *situated knowledge* based on experience from their practice. Without situated knowledge, there will be no development of *expertise* and, accordingly, no *care* will be delivered. The inter-dependences between *expertise*, *care* and *situated knowledge* are important in order to increase sustainability in agriculture (Mol *et al*., 2010). Increased sustainability in farming practice requires further acknowledgement and respect, as well as promotion and cultivation of farmers' *situated knowledge* (Krzywoszynska, 2015). An ICT system or an expert system can never perform as well as a human expert in handling complex situations (Dreyfus & Dreyfus, 2005). Applied in the agricultural domain, Nitsch (1990) claims that farmers' skills in coordinating the four areas of farm management: 1) Knowledge about the subject, 2) skills in formal planning, 3) practical skills and 4) orientation about the institutional environment are experience-based and intuitive, and cannot be replaced by a computer. However, computers can supplement and facilitate farm management, *e.g.* technology is essential in handling big data samples, measuring properties that cannot be detected by the human vision system and providing valuable, credible representations of complex situations that clarify and support actions without losing the complexity at hand, and hence support, but not replace, novices and experienced decision makers. Handling big data quantities and measurement of crop and soil properties are becoming increasingly important with better adaptation of field interventions to the within-field variations in different soil and crop properties. Consequently, precision agriculture is dependent on ICT systems in order to reach its aims of increased yield, crop quality, farm viability and efficiency in input use, in parallel with a decrease in environmental impact through better within-field adaptation to crop and soil properties.

In the next sub-section I will go on discussing PA and the *knowledge transfer* tradition in relation to PA technology.

2.1.2 Precision agriculture

During the past century, farm size and field size have both increased steadily, resulting in bigger farms as well as larger fields. *e.g.* in 1932 there were 428 600 farm companies in Sweden, of which 121 000 cultivated less than 2 hectares, whereas in 2010 there were 71 000 farm companies, of which only 3800 cultivated less than 2 hectares (Jordbruksverket & SCB, 2012). Due to this rationalisation, farmers are now cultivating larger areas and many small fields have been merged to larger units, often leading to an increase in within-field variation in soil properties and other factors important for crop growth. Thus increased complexity has often been incorporated within the individual field.

Precision agriculture represents a paradigm shift in permitting consideration of the field as a heterogeneous entity, allowing selective and more situated treatments, instead of as a homogenous entity treated on an average (Aubert *et al*., 2012). This paradigm shift provides several possibilities for crop farmers to recognise and handle variations in the soil or crop to a much finer degree than ever before, thus increasing sustainability through decreasing the use of sub-optimal treatments leading to negative environmental impacts and increasing profitability due to the higher efficiency in usage of inputs and higher crop quality (EIP-AGRI FOCUS GROUP, 2015; Aubert *et al.*, 2012). In order to do this, variations in the soil or crop must be estimated and interpreted, and available technology aiming to support that action must be accessible, credible and usable. It should be noted that the variation in *e.g.* crop biomass or soil properties is often well known by the farmer, but in rough terms, while it is still difficult to estimate without a bird's eye view or by the farmer's own visual perception system. Thus acting upon a variation without the use of technology is very difficult, if not impossible. Technology could therefore play a vital role as an enabler for farmers to make decisions better adapted to the needs of the crop in their farming practice. However, while the use of precision agriculture technology can improve decision-making, it will still not be *perfect* due to the complexity of the system (Marra *et al.*, 2003).

The emergence of precision agriculture technology has resulted in the development of many new agricultural decision support systems (AgriDSS) for practical farming, but so far the adoption rate has been rather low, leading many researchers in this field to discuss the so-called *problem of implementation* (*e.g.* IV; Rossi *et al.*, 2014; McCown *et al.*, 2009; Mackrell *et al.*, 2009; Matthews, 2008; McCown, 2002). As long as the adoption of new technology is optional for farmers, they will only adopt if the technology is considered *usable* and *credible* in their farming practice (Matthews, 2008). Thus, the *problem of implementation* can be explained at least partly by the process of how the majority of development of new technology has been conducted so far. According to Röling (1988), it can partly be explained by to the following aspects:

- The traditional view of knowledge transfer lacks a systemic perspective and does not put the technology in the context in which it belongs.
- Technology is often seen as an isolated phenomenon.
- Existing technology is not adapted to the needs of farmers.

Technology development is normally based on what researchers and developers (R&D) of AgriDSS consider *usable* and *credible*. This normative approach, based on the *knowledge transfer* perspective, has resulted in many AgriDSS that are not adapted to farmers' actual needs and practices, resulting in limited usage. They represent a *technological fix*, according to Black (2000). The limited uptake of AgriDSS in farming practice could be explained by the *gap of relevance* perceived or experienced by the end-users, *i.e.* the farmers (McCown, 2002). The *gap of relevance* and the *technological fix* have been acknowledged for some time in agriculture. However, the characteristics that make good decision support systems from an agricultural perspective and the experiences of these need to be determined.

2.1.3 Decision support systems

Information and communications technology (ICT) systems that support users in decision-making are called decision support systems (DSS) (Alenljung, 2008). The aim with DSS is to reduce effects of human decision-making weaknesses or cognitive limitations by facilitating user's ability to process huge amounts of information or expanding the perception or imagination of the decision maker. Decision support systems can support either a single decision maker or a group of decision makers in making more effective decisions when dealing with unstructured or semi-structured problems. Unstructured or semi-structured problems are problems with open ends and without clear solutions. Decision support systems can either support the decision maker in an on-going decision situation or can prepare the decision maker to perform better in the future through decision training. They can also improve individual productivity, decision quality and problem solving, as well as facilitating interpersonal communication, improving decision-making skills and increasing organisational control (*e.g.* Alenljung, 2008; Turban *et al.*, 2007; Power, 2002). By definition, DSS do not replace a decision maker, but rather support them in the decision-making process. They are interactive, which implies that there is an exchange between the system and the user. Decision makers must be able to confront a change in conditions, which is why DSS must be adaptive and flexible to meet user needs and capable of being modified by the user. As mentioned above, precision agriculture is dependent on ICT systems and AgriDSS to perform site-specific measures within a field.

Agricultural decision support systems (AgriDSS)

To date, agricultural researchers have used AgriDSS in a prescriptive manner, to transfer knowledge from science to practical work, aiming to increase farmers' acquisition of scientific knowledge to increase sustainability and facilitate diffusion of innovation (Thornburn *et al.*, 2011; McCown *et al.*, 2009; Leeuwis, 2004; Nitsch, 1994). During the past 30 years, research has produced a large number of AgriDSS, but most of them have not been used appropriately in practice (*e.g.* Rossi *et al.*, 2014; Aubert *et al.*, 2012; Eastwood *et al.*, 2012; Matthews, 2008; McCown, 2002). AgriDSS developers often come from a knowledge transfer tradition, but also normally consider just one issue, the technology, while the farmer must consider the technology in the whole complex situation of practice (Rossi *et al.*, 2014; Röling, 1988). Prost *et al.* (2012, p. 592) investigated end-users using the methodology of agronomic model development and concluded that there *is little scientific debate about the design methodology considered as a whole, and even less about the link with the intended use of the models being designed*. They took this as an indication that those questions are not regarded as central topics in the agronomic research community, even though the lack of use was considered a problem. The general belief appears to be not that agronomic researchers have failed to innovate in their design, but rather that they do not consider design questions as requiring discussion (Prost *et al.*, 2012).

Aubert *et al.* (2012) claim that factors influencing the adoption of innovations are tightly linked to work practices that are more complex than just the perspectives of technology acceptance or diffusion of innovations. One identified reason for the *problem of implementation* is the normative way of developing new technology, without consideration of the actual needs of the end-users (McCown, 2009). This often leads to development of AgriDSS that are not perceived as *useful* or having *ease of use*, and accordingly remain unadopted (Pierpaoliet *al.*, 2013; Aubert *et al.*, 2012). To be used, an AgriDSS must be credible for the end-user and fit into the decision-making milieu where it should be used (Matthews, 2008). There is an obvious gap between research and practice (Mackrell *et al.*, 2009) that McCown *et al.* (2009) defined as a *gap of relevance* which has to be bridged, or at least decreased, if farmers are expected to use developed AgriDSS. To bridge the gap of relevance, it is important to increase understanding of how individuals in complex situations actually make decisions, considering their whole complex socio-technical context. Most existing research on farmers' work practices is based on rationalistic assumptions rather than on empirical data from practice studies in real-life settings, although there are some exceptions (*e.g.* Lindblom & Lundström, 2014; Lindblom *et al.*, 2013; Bradford, 2009). Through a more thorough portrayal of how farmers make decisions, the criteria on which decisions are based and how precision agriculture technologies are applied in practical farming, it would be possible to suggest how the adoption process can be designed in order for the technologies to be valuable for farmers (IV; Lindblom *et al.*, 2013).

According to Marra *et al.* (2003), adoption of new technology is not a question of diffusion of information or knowledge transfer. Instead, it is an active choice by the decision maker to adopt new technology and therefore a kind of ongoing learning process. Adoption is often a kind of substitution process, where the decision maker chooses to substitute one kind of technology with another kind hopefully better suited for the farmer's intended purposes. However, taking the view of the end-user as a passive receiver for new technology has resulted in a focus on spreading the knowledge about the innovation, instead of concentrating on the end-user's perspective. According to the diffusion of innovation theory, diffusion is a process where an innovation is communicated through different channels over time (Rogers, 2003). Before adoption, the individual considers the perceived advantage, compatibility, trial ability, complexity and observability compared with the technology it supersedes. The perceived relative advantages do not necessarily have much to do with *objective* advantages (Aubert *et al.*, 2012; Matthews, 2008; Rogers, 2003). High compatibility, trial ability and observability normally increase adoption, while high complexity decreases it. Aubert *et al.* (2012) claim that possibilities to obtain perceived high-quality information and support, as well as farmers' and their employee's knowledge of the technology, are important reasons behind successful adoption. Other reasons for the low adoption rate of AgriDSS by farmers are *e.g.* a perceived lack of confidence, poor user interface design, tedious data input requirements, low adaptation to the farm situation, no frequent information update, lack of incentive to learn and adopt new practices, and fear of having to change advisor (*e.g.* Rossi *et al.*, 2014; Van Meensel *et al.*, 2012; Eastwood *et al.*, 2012; Kerr, 2004). Van Meensel *et al.* (2012) also point out that some AgriDSS terminology and functions are not adapted and even irrelevant to the intended users and their activities.

Two additional important criticisms have been made of diffusion of research. One is the *pro-innovation bias*, *i.e.* the normative way of looking at adoption as the correct decision, based on the view that an innovation does not need to be re-invented or rejected. This leads to individuals being blamed for not adopting, *i.e.* the *individual blame bias* (Rogers, 2003). Both are related to the *knowledge transfer* and *technology push* perspective. They both assert that somebody other than the end-user knows what is usable and credible in practice, in line with the assumption of the so-called *problem of implementation* which also attributes a perceived problem to the user, not the developer. In addition, success in technology transfer or dissemination tends to focus on the number of adopters, not the long-term, cross-domain and cross-scale consequences (Wigboldus *et al.*, 2016). Altogether, a common focus in precision agriculture literature has been to identify different groups of farmers, resulting in the knowledge that age, educational level and innovativeness are important factors for adaptation (Aubert *et al.*, 2012).

However, a well-designed AgriDSS is a useful tool for farmers' possibilities to access scientific knowledge and *best practices* within the field of precision agriculture. Parker and Sinclair (2001) claim that the single unifying predictor of success or failure of an AgriDSS is the extent to which users are involved and participate in the design and development process. Accordingly, participatory approaches in development processes of AgriDSS have proven to be a success factor in many cases (Van Meensel *et al.*, 2012; Prost *et al.*, 2012; Cerf *et al.*, 2012; Hochman & Carberry, 2011; Thorburn *et al.*, 2011; Jakku & Thornburn, 2010; Matthews *et al.*, 2008; Măruşter *et al.*, 2008; Reed, 2008; Woodward *et al.*, 2008; McCown, 2002; Parker & Sinclare, 2001). Moreover, Van Meensel *et al.* (2012) and Jakku & Thornburn (2010) stress the importance of participatory approaches for the successful development of AgriDSS, as well as the role and relevance of social learning by the stakeholders involved in the participatory AgriDSS development process. However, instead of developing an AgriDSS as a straight operational tool to help farmers making decisions, many researchers highlight the possibilities to use an AgriDSS as a social learning tool during development and during usage, which can facilitate discussions and learning among different stakeholders with different interests and perspectives (*e.g*. Hochman & Carberry, 2011; Thornburn *et al.*, 2011; Jakku & Thorburn, 2010; McCown, 2009, 2002; Matthews *et al.*, 2008). Therefore participatory development processes involving different stakeholders are important for developing AgriDSS situated to the decision-making practice, on the one hand, and to a social learning context, on the other. From this perspective, the lack of participatory approaches is the core of the problems of implementation identified for most AgriDSS. Agricultural science should focus on developing adaptable *prototypes* and *principles*, instead of absolute *technical packages* and *solutions* (Hoffman *et al.*, 2007).

Models are now a major tool in agricultural research (Prost *et al.*, 2012). However, models for research and models convenient for support of action may be quite different. Schlindwein *et al.* (2015) refer to two metaphors describing adaptation to an unsecure situation for agriculture in relation to climate change and crop models. The first, conventional, metaphor is *adaptation as fitting into*, where both the situation and what is to be adapted are known in advance. This metaphor is considered to decrease the uncertainty in the system of interest. The second metaphor is *adaptation as co-evolution*, which can be seen as a process of learning and development, which does not have to change the level of uncertainty, but rather the way uncertainty is handled. Situations with high complexity often do not follow deterministic rules, so for instance crop models should not be used in the way they are normally intended, as some kind of expert system. Instead, crop models and other similar models should be used as one among many tools for the practitioner to learn from during adaptation to new situations

(Schlindwein *et al.*, 2015). If learning is considered as creation of knowledge through transformation of experiences (Kolb, 1984), Schlindwein *et al.* (2015) claim that it is the experiences of the use of crop models, not the models in themselves, that need to be changed. Thus, many AgriDSS could be used, or perhaps should be used, as learning tools embedded in advisory or other social learning contexts to be exploited in a proper way. When considered as independent AgriDSS or expert systems, they often do not live up to the users' expectations in terms of credibility, usability or decreasing uncertainty. Therefore, they are not taken up to any further extent. Thus, reconsideration of models or AgriDSS would provide important opportunities to involve different stakeholders in the learning process and to frame a change from *goal-orientated thinking* towards *thinking in terms of learning* (Schlindwein *et al.*, 2015).

With increased complexity in agriculture, it is desirable and even necessary for advisory services to adapt their strategies according to the kind of technology or knowledge that is accepted and used in practice. Payne *et al.* (2016) established nine advisory approaches from successfully accomplished projects, of which four are presented in Table 2 (for more information, see http://www.redmeatextension.co.nz/). The approaches presented encompass strategies from *technology push* to *co-production* models involving farmers, advisors and researchers in different successfully accomplished projects. Important characteristics are complexity, observability, compatibility *etc.*, which are factors also noted within the diffusion of innovation theory (Rogers, 2003) and mentioned in section 2.4.2.

Table 2. Extension strategies for technology (Payne et al., 2016)

Category	Characterisation
Technology push	Non-complex issues Observable impacts Technology compatible with existing farm management Easy to implement on the farm Utilises advisors and technical support agents as the main knowledge providers through field days, demonstrations, trials, media *etc*.
Transfer for fit-for-purpose technologies	Starting point is farmers' needs and constraints Technology adapted to farmers' needs Non-complex issues Not immediately observable results Low awareness among farmers about the problem Easily tested Not immediately observable benefits Change in farm practice is required
Co-development with researchers and farmers	Problems jointly identified by farmers and researchers Farmers' participation to ensure technology fit for purpose Benefits not immediately observable and limited compatible with existing farm management Non-complex to complex issues Technology adapted to farmers' needs, but requires robust testing and data collection in on-farm trials to demonstrate benefits and ensure fit-for purpose Farmers and researchers develop, test and demonstrate the technology
Co-development with farmers, advisors and researchers	Problems jointly identified by farmers, advisors and researchers Problem-focused approach to implement fit-for-purpose technologies Advisors are involved, as farmers have difficulties implementing the technology alone Complex technology without immediately observable benefits and low awareness by farmers Difficult to test on farm and limited compatibility with existing farm management Focus on jointly development, testing and demonstrating fit-for-purpose technologies by farmers, advisors and researchers

In Sweden, there are obvious differences in farmers' adoption between different types of AgriDSS within the area of precision agriculture (Lindblom *et al.*, 2014). Assisted steering systems, for example, have been quickly adopted, while AgriDSS considering variable fertilisation have only been adopted to a limited extent. Looking at the different categories and their characterisations in Table 2, the reason becomes rather obvious. In the case of assisted steering systems, the advisory approach used has been *technology push*. In this case the approach was in accordance with the technology that would be implemented, according to Payne *et al.* (2016). However, in the case of many other precision agriculture technologies, they would fall into the category of *co-development with farmers, advisors and researchers*, but the advisory approach used (if any) would still be acknowledged as *technology push*. In those cases, either the low adoption is attributable to an inconvenient advisory or development strategy, or the low adoption rate is a result of farmers not prioritising the problem that the AgriDSS is designed to solve. As one farmer interviewed in another project said when considering why he did not use variable rate application (VRA) files: *They are not the lowest-hanging fruit – good drainage and soil structure and boom sprayers are more important.*

2.2 Theoretical background

2.2.1 Finding an alternative to the *knowledge transfer* perspective

As mentioned in the previous chapter, the perspective of *knowledge transfer* in relation to new technology has been widely criticised (Aubert *et al.*, 2012; Eastwood *et al.*, 2012; Rossi *et al.*, 2012; Matthews, 2008; McCown, 2002; Röling, 1997). *Knowledge transfer* is associated with one perspective of communication. There are two main traditions in communication (Klöckner, 2015): 1) The dialectic tradition, to which the transfer of knowledge tradition belongs, also relates to traditional cognitive science and the *computer metaphor of mind* (Card *et al.*, 1983). According to the dialectic perspective, truth can be determined by logical argumentation. 2) The dialogic tradition, which claims that communication is an exchange of information between people, leading to social construction of meaning; environmental communication research in Sweden is related to this tradition, as are different approaches of interactive cognition and distributed and situated approaches of cognitive science applied in naturalistic settings (see section 2.2.4).

Environmental communication (EC) is an applied research field which considers natural resource management from a constructivist perspective using communication in order to have positive environmental impact (Oepen, 2000). Environmental communication considers communication as a two-way social interaction process to create a common understanding, enabling the people concerned to understand key environmental phenomenon and their interdependencies, as well as to act upon the problems in a competent way. Accordingly, environmental communication does not focus on information dissemination or knowledge transfer, but rather on a shared vision of a sustainable future and capacity building in social groups to deal with or prevent environmental problems. According to environmental communication, people are not convinced to change behaviour due to one-way communication of scientific knowledge and ecological concerns. Rather, emotions and socialisation are central, which is why two-way communication towards shared meaning and win-win situations are considered much more practicable strategies (Oepen, 2000).

Agricultural extension communication (AEC) has a considerably longer history than environmental communication and a more ambivalent tradition to the constructivist perspective on communication (Leeuwis, 2004; Nitsch, 1994). One important reason is that the tradition of agricultural extension is very old and can be traced back to ancient Mesopotamia, Greece and Egypt (Leeuwis, 2004). The term extension originates from when universities started to *extend* their work beyond their campus to teach common people. In this tradition, the knowledge transfer perspective was introduced, with an educated sender from the university telling a receiver something that would improve their practice. This tradition builds on a conception that science is the engine of modernisation and development and that other people should be able to take advantage of new scientific findings. In agriculture, this transfer of knowledge was long performed in connection with the need for increased food production and there was a belief that rational scientific insights and procedures would automatically contribute to beneficial development for farmers, agriculture and society (Leeuwis, 2004). However, experiences from recent decades show a much more complicated picture of reality. Scientific knowledge has led to increased production in major areas of the world, but accompanied by serious problems in relation to at least environmental issues. In addition, science has long produced innovations and recommendations of limited use for many farmers (Leeuwis, 2004).

Consequently, there is an urgent need for reconsideration of extension in the light of moving agriculture along a more sustainable trajectory. Leeuwis (2004) claims that change is needed in extension that: 1) shifts from focusing on the individual to see extension as a range of services fostering new strategies for co-ordination, 2) changes from pre-defined patterns to generative dimensions, 3) indicates that there is a dual component in change, material/technical and social/organisational, 4) widens extension beyond decision-making and emphasises the importance of social learning and negotiation and 5) redefines extension as a two-way or multiple-way process including farmers, advisors, researchers and other stakeholders to contribute their perspectives and insights. In doing this, extension is redefined from *knowledge transfer* to *communication for rural innovation* (Leeuwis, 2004).

This redefinition marks a change in epistemology, in particular assumptions about the nature of knowledge and of knowing, which has a major influence on people's world views (Bawden, 2010). Salner (1986) defines learning within the individual as a development process taking place at three levels progressively: 1) dualism[5], 2) multiplicity and 3) contextual relativism. At the first level, dualism, learners separate themselves from the external world. Knowledge is located in the external world, waiting to be explored and there is an objective *truth* to discover. This kind of learner has a tendency to see things in black or white, right or wrong. At the second level, the learner has recognised more aspects of the world and realised that different people have different opinions and thoughts. Suddenly, the single truth is missing and is replaced by a multiplicity of world views where everything is equally right or equally wrong, so making decisions becomes much more complicated. At the third level, the learner needs to commit to a decision and then recognise that the truth is not in the external world or within him- or herself. Instead, the truth is dependent or relative, according to the context or the situation. Complex and critical situations within farming are issues without definite answers and therefore individuals within the agricultural domain would need a learning approach according to what Salner (1980) describes as contextual relativism. Many farmers probably already have this kind of learning approach in many aspects of their farming practice. However, considering contextual relativism makes the *knowledge transfer* perspective problematic, while when looking at communication as well as learning as social creation of meaning, the idea of *knowledge transfer* becomes impossible (Blackmore, 2010).

2.2.2 Technology development using participatory approaches

Departing from the knowledge perspective requires a change in epistemology, as noted above, but also new methodological strategies. Since agricultural research mainly still uses the *knowledge transfer* tradition in development of AgriDSS, I turned to the research field of human-computer interaction (HCI) to investigate whether it has theories and methodologies that would be useful in agriculture. Human-computer interaction is commonly characterised as: […] *a discipline concerned with the design, evaluation and implementation of*

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[5] This use of the concept dualism should not be confused with the way it is used in philosophy and cognitive science from a general perspective, i.e. separating the mental from the physical.

interactive computing systems for human use and with the study of major phenomena surrounding them (The ACM SIGCHI Group, 1992). Generally speaking, HCI as an interdisciplinary field focuses on the various ways in which humans interact with ICT, and many textbooks have successfully highlighted the central principles in analysis, design and development for achieving usability of these human-technology interactions (*e.g*. Issa & Isaias, 2015; Benyon, 2014; Hartson & Pyla, 2012; Rogers *et al*., 2011; Dix *et al*., 2004; Preece *et al*., 2002). It should be pointed out that designing usable ICT systems is not always straightforward, as the many poorly designed ICT systems show. One of the challenges of HCI design is to keep up with technological developments and to ensure that these are adapted for the best possible human benefit. However, software developers often have a poor understanding of HCI issues, and therefore it is of major importance that HCI specialists explicitly address their knowledge of how to think in terms of future users' needs, values and supportable tasks and how to translate that knowledge into a functional and usable ICT system, which fits well for the needs and capabilities of the target group of users (*e.g*. Issa & Isaias, 2015; Hartson & Pyla, 2012; Rogers *et al*., 2011; Preece *et al*., 2002).

During the early 1980s, the focus was on HCI *per se*, but that is no longer the case. Now, the focus is on developing simple, intuitive, transparent user interface designs, by which people can easily express themselves through various computational enhanced tools and media. Human-computer interaction and interaction design is nowadays used as an umbrella term for a wide and growing field which overlaps with many other fields, both academic disciplines and design practices.

Various ICT systems have become important tools in the work and everyday life of many individuals. Lately, a discussion on sustainable ICT systems has been introduced, and ICT development has been addressed considering both *sustainability through design* (how ICT can be used to promote more sustainable behaviours) and *sustainability in design* (how sustainability can be the governing principle of the ICT itself) (Hanks, 2008). A sustainable ICT is characterised by longevity, simplicity, accessibility, responsiveness and adaptability, among others (Misund & Høiberg, 2003). In precision agriculture, ICT systems are critical for increasing sustainability by supporting farmers' decision-making considering adaptation of measures to the within-field variation in different parameters (Rossi *et al*., 2014; Aubert *et al*., 2012).

To achieve the goals of HCI in general, and AgriDSS in particular, a number of design methodologies can be utilised. These generally have the following characteristics in common: 1) User involvement throughout the whole design process, 2) integration of different kinds of disciplines and expertise, 3) conducting effective formative and summative usability evaluations, and 4) managing an iterative system design process (*e.g*. Issa & Isaias, 2015; Rogers, 2012; Hartson & Pyla, 2012; Rogers *et al*., 2011; Benyon, 2010; Dix *et al*., 2004; Preece *et al*., 2002). Since the mid-1980s, several methodologies have become an important issue in the design of ICT systems, in order to achieve good usability. The concept of usability has been well defined in ISO 9241-11, which describes an engineering approach where usability is specified in terms of measurable usability attributes and characterised as *the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use*. However, good usability does not appear by itself, since it has to be systematically and consciously designed and evaluated. In order to integrate usability and to involve HCI professionals in ICT development, a need for design methodologies for usability is put forward by many scholars and practitioners.

The interdisciplinary field of HCI research offers a large amount of interesting user-centred design (UCD) methodologies, showing user involvement to be a critical factor in successfully developing ICT systems in general (Harris & Weistroffer, 2009). The result of employing UCD methodology when designing and developing an AgriDSS is a more efficient, satisfying and usable experience for the user, which is likely to increase user acceptance, learnability and confidence of the system (Hartwick & Barki, 2001). Generally speaking, UCD may be described as a practice, craft, framework, philosophy, discipline, or a methodology for design by involving users in the design process, and integrating UCD with other ICT development activities (Andreasson *et al*., 2015).

In general, UCD methodologies consist of three major iterative phases: the *analysis phase*, the *design phase* and the *evaluation phase*. Generally speaking, the purpose of the analysis phase is to understand the need of the intended users and the context of use, while the design phase involves the creation of a conceptual design concept, the interaction pattern, the *look and feel* of the product and prototyping to realise different design alternatives. The evaluation phase focuses on verification and refinement of the design solution (Andreasson *et al*., 2015). According to Andreasson *et al*. (2015), two of the most commonly used UCD methodologies are *user-centred systems design* (UCSD) (Gulliksen *et al*., 2003; Göransson *et al*., 2003) and *participatory design* (PD) (Bjerknes *et al*., 1987).

User-centred systems design is a method that focuses on usability through the entire ICT system life cycle. Gulliksen *et al*. (2003) addressed a lack of shared definition for the approach and identified 12 key principles of UCSD. These principles are based on both theory and experience from software development projects and revolve around users and understanding their needs. The key principles involve a clear user focus with user involvement, iterative and incremental system development with early and continuous prototyping, and evaluations performed in the context of use. Consequently, UCSD consists of three major phases: requirements analysis, evolutionary systems development (which is both iterative and incremental), and implementation. Gulliksen *et al.* (2003) stress the importance of a carefully considered transition process where the introduction must be planned, where user education and training is performed and the need for necessary support and instruction manuals is identified (for further details, see Gulliksen *et al*., 2003; Göransson *et al*., 2003).

A more radical UCD approach is the *Scandinavian model of participatory design* (SMPD) emerging within the system development field among a group of Scandinavian researchers focusing on the democratisation of working life (Bjerknes *et al*., 1987). The SMPD approach is characterised as attempting to actively engage different kinds of users and stakeholders (they all are seen as equal partners) in the ICT design process, in order to ensure that the product designed fulfils their needs and is useful. The approach also stresses the importance of processes and procedures of design and is more responsive to stakeholders' and users' cultural, emotional and way of working practices and learning (Bjerknes *et al*., 1987).

In sum, the UCD and SMPD methods have the vision of ensuring high usability, *i.e.* adapting the system to the *end-users'* and *stakeholders'* needs and goals, which significantly increases the possibility of satisfied users and AgriDSS success. The final AgriDSS is not an end in itself; rather, it can be considered a *means* to the end of providing good usability and supporting the actual tasks for the intended users.

In the last part of this theoretical background, I return to the individual farmer and their socio-technical system, in order to present theories that can be used to investigate farmers' naturalistic decision-making in their socio-technical system.

2.2.3 Decision-making, farmers' decision-making and theories considering such processes *in the wild*

Decision-making is a cognitive ability and the scientific literature on decision-making is huge and dates back to the 19th century. Research on decision-making as a cognitive phenomenon is comprehensive, and has been pursued from several different perspectives over the decades, with cognitive psychology marking the beginning of the empirical study of individuals making decisions. According to Alenljung (2008), decision-making can be studied organisationally, collectively or individually. The major focus in this thesis is individual decision-making, which can be considered from different approaches, *i.e.* normative, prescriptive and descriptive theories (Alenljung 2008). In short, normative theories describe how decisions should be made rationally (*e.g.* Kahneman & Tversky, 2000; Plous, 1993) and are often called classical decision-making theories. Normative theory studies are often conducted in laboratory settings to achieve a high degree of control. The intention is to predict future behaviour in well-defined tasks (Bradford, 2009). Prescriptive theories concern how people can be helped and trained to make better decisions, via the use of checklists and evaluation tools (Alenljung, 2008). Descriptive theories concern how people actually make decisions, where the study of decision-making in natural environments, *naturalistic decision-making* (NDM) (Orasanu & Connolly, 1993) has emerged, since it was considered difficult to mimic the complexity of the situation that occurs in daily life in controlled settings.

Naturalistic decision-making refers to research studying decision-making in dynamic, complex, real-life situations involving *e.g.* time-pressure, high stakes or a high degree of uncertainty, thus leaving an artificial environment. Naturalistic decision-making theories refer to different theoretical and methodological approaches based on decision-making *in the wild*, which means studying people making decisions in dynamic and complex domains. The individual's experiences and knowledge are taken into account and also for example time pressure and high uncertainty (Orasanu & Connolly, 1995). Although NDM focuses on decision-making by experts *in the wild*, the unit of analysis is still only the individual and contextual factors such as technology and other actors are not included.

According to Alenljung's overview of the area (2008), decisions can commonly be considered from different levels and time scales, and are often described as being conducted from operational, tactical and strategic levels of decision-making that can be either short- or long-term. Strategic decisions have greater impacts and are more consistent due to being conducted over a longer time horizon. Tactical decisions affect the strategic level, but are primarily about getting the business to function efficiently and effectively based on decisions at the strategic level, and have therefore a shorter time horizon. The lowest operational level involves the different tasks carried out mainly on a daily basis, *i.e.* from a short-term perspective. It should be noted that the information requirements and the decision-making processes vary for the different levels. The actual decision situation may also have varying degrees of structure, as some are well structured while others are unstructured, and some effort has to be made to grasp what the decision situation is actually about (Alenljung, 2008).

Studying decision-making in agriculture

Historically, advisory work and knowledge transfer in agriculture have taken a normative approach to decision-making, which has not been successful in this kind of complex domain and has also gained much criticism for its underlying assumptions on the nature of human actions/cognition. The farmers' work and commitment to their business are often closely linked with their own identity, which explains why the farmer's *life world* is involved in decisions and the complex farming situation can be the reason why learning does not take place or why certain kinds of decisions are not made (Schneider *et al.*, 2010). Farm management research has a tradition of using theoretical frameworks adopted from economic science with the focus on quantitative methods and mathematical modelling to describe farmers' decision-making (Gray *et al.*, 2009). This way of considering decision-making makes it nothing more than a series of well-defined options from which the decision maker chooses objectively and transparently. That perspective has resulted in a focus on the decision result, instead of the process behind decision-making, and it has tended to forget the farmer, as a human being, in farm management. Another important aspect of farmers' decision-making is that farm management is not about making a single decision: on the contrary, it is an ongoing cyclic process of planning, implementation and control (Gray *et al.*, 2009) on all three levels: strategic, tactical and operational. Consequently, the conventional, normative way of describing and explaining farmers' decision-making has failed to consider how decisions are made in practice, since it fails to explain decision-making that is complex, dynamic and ill-defined (Lindblom *et al.*, 2013; Gray *et al.*, 2009; Öhlmer, 1998). Öhlmer *et al.* (1998), among others, pointed out the need for revision of the approaches used in research to investigate and describe farmers' decision-making. According to Lindblom *et al.* (2013), to get the holistic perspective necessary to understand how farmers make decisions within their complex socio-technical system, the unit of analysis needs to be expanded from the individual to include their socio-technical context or *life world*.

2.2.4 Distributed cognition: a theoretical framework to study socio-technical systems

Distributed cognition (DCog) developed during the mid-1990s out of a criticism within traditional cognitive science regarding the plan-based, individualistic conception of human conduct (*e.g.* Lindblom, 2015; Heath *et al.*, 2000). The theoretical framework of DCog was introduced by Hutchins (1995) in response to more individual models and theories of human cognition and is a descriptive, systemic perspective that presents an understanding of the complex and temporally interplays of the body, the world and the brain as a whole phenomenon (Clark, 1998). From a DCog perspective, human cognition is fundamentally distributed in the socio-technical environment that the individual inhabits. Through its system perspective, DCog discards the idea that human mind and environment can be separated and states that cognition should instead be considered as a process, rather than as being contained inside the mind of the individual. Hence, DCog views cognition as distributed in a complex socio-technical environment, while cognition, including learning and decision-making processes, is seen as *creation*, *transformation* and *propagation* of representational states within a socio-technical system (Hutchins, 1995). A representational state can be what is expressed in utterances, written or drawn in symbolic language or notification systems, embodied interactions through movements and gestures that carry meaning, or information that is available via artefacts and tools used (*e.g.* displayed or stored in an ICT system or a speedometer). By observing and analysing what is happening within the information flow of whole systems, ongoing cognitive processes are externalised and visualised. An important aspect of the system view is that cognition is seen as a culturally situated activity, and should be studied where it naturally occurs, *i.e. in the wild*. The DCog framework differs from other cognitive approaches by 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 (see Figure 2). The second principle concerns the range of processes that is 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 DCog 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 and social environment), and (3) distributed *over* time.

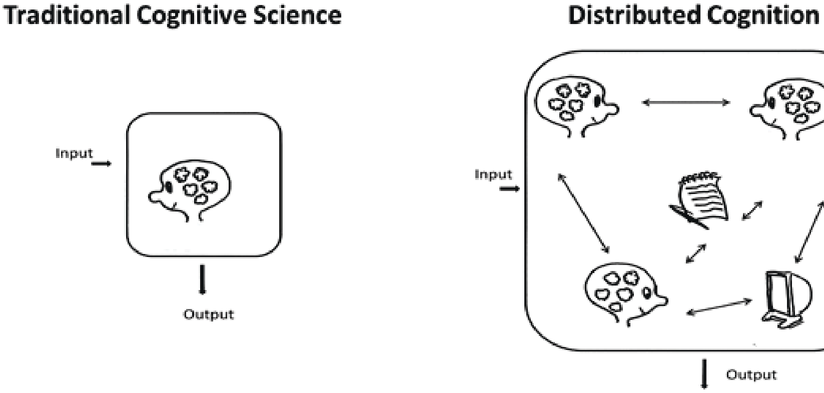

Figure 2. From a traditional cognitive science perspective (left), the unit of analysis is narrowed to inside the individual's head, while from a distributed cognition perspective (right) the unit of analysis is expanded to be distributed across people and artefacts where cognitive processes are the result of the functional relationships of the entities of the cognitive system.

Different kinds of representational states are central to the unit of analysis in DCog, as cognition is seen as coordination, transformation and propagation of representational states within a system. Hollan *et al.* (2000) take the stance that representations are not only tokens that refer to something other than themselves, but are also manipulated by humans as being physical properties. Humans shift from attending to the representation to attending to the thing represented, which produces cognitive outcomes that could not have been achieved if representations were always seen as representing something else. An example given by Hutchins (1995) is the navigational chart. The chart is used for offloading cognitive effort (*e.g.* memory, decision-making) to the environment and to present information that has been accumulated over time. Furthermore, Hutchins (1995) describes the navigational chart as an analogue computer where all the problems solved on charts can be represented as equations and solved by symbol-processing techniques. An important insight in this example is the relationship between the external structure (the chart as a representation) and the internal structure (the computation in the head). The relationship between the external and the internal constructs cultural meaning, and is part of the same cognitive ecology. By identifying processes, properties and breakdowns in a functional system, the focus is mainly on dynamic aspects of activity (propagation of knowledge through the functional system), rather than static entities (for instance power and role structures within an organisation) (Rogers & Ellis, 1994). Hence, by studying external, material and social structures, properties of the internal mental structures are revealed and become observable.

Human cognition embraces many cognitive processes, including learning and decision-making that can be revealed by applying the theoretical framework of DCog in various situations and contexts. Hutchins's (1995) definition of learning from a DCog perspective is formulated as "*adaptive reorganization in a complex system*". He describes learning as simultaneous coordination of many different media within a complex functional system and claims that the proper unit of analysis for learning or cognitive change includes the whole socio-technical environment that humans inhabit. Distributed cognition takes a systemic perspective and discards the idea that the human mind and its environment can be separated (Lindblom, 2015). Hutchins (1995) does not try to describe any mental mechanisms with which the behaviours of the representations can be modelled. According to Hollan *et al.* (2000), the environment that encloses people in their everyday life could be viewed as a reservoir of resources for learning, decision-making, problem solving and reasoning. By interaction with such external resources, internal representations and computational actions could be identified by their visible functional properties.

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. Therefore, the system-level view makes DCog a fruitful approach for studies of complex socio-technical systems, where different parts of the system provide different but complementary contributions that allow concerted action, which was pointed out by Röling (2002) as lacking in agriculture. In other words, the study of external, material and social structures reveals properties about an individual's internal, mental structures, like decision-making and learning. Hence, by studying cognition with this larger scope in mind, it is clear that the functional cognitive system has properties that cannot be limited to the cognitive abilities of the individuals. Using DCog as a theoretical framework provides the researcher with an approach that offers a systemic perspective on *e.g.* farmers' socio-technical context to describe and study farmers' decision-making (Lindblom *et al.*, 2013) from the systemic perspective that many agricultural researchers have demanded for years (*e.g.* Öhlmer *et al.*, 1998; Röling, 1988).

Distributed cognition has been shown to work well when applied in HCI research, through involving technology in the unit of analysis, instead of putting it outside (Rogers, 2012). The theoretical framework of DCog has been applied in many different and complex domains, including ship navigation (Hutchins, 1995), critical care environments (Patel *et al.*, 2008) and information fusion (Nilsson *et al.*, 2012). Therefore, it is reasonable to believe that it will also work properly in the agricultural domain, where many farmers' everyday life, or *life world*, includes social interactions and interactions with ICT systems, together with other tools and artefacts.

2.2.5 Summary

This thesis considers the sustainable intensification trajectory in agriculture, with a required increase in yield and input efficiency, in parallel with decreased environmental impact. Sustainable intensification will require increased adaptation to the local situation and consequently experienced farmers with *situated knowledge* in order to secure good *care* in their farming practice. In this context, precision agriculture has a role to play, by providing AgriDSS and other technologies in order to adapt field measures to within-field variation in crop and soil. Hitherto, many different AgriDSS have been developed in precision agriculture, but not used in practice to any wider extent, owing to the *problem of implementation*. Central to the *problem of implementation* is limited knowledge about farmers' naturalistic decision-making in their socio-technical system and a knowledge transfer approach in research that does not consider the needs of the farmers in development processes of new AgriDSS. This background chapter presented alternative approaches to the knowledge transfer perspective, from environmental communication and agricultural extension communication contexts. Instead of taking the dialectic world view, as in the *knowledge transfer* perspective, searching for the truth out there somewhere, the dialogic world view is that meaning is socially constructed and thus dependent on the situation in which it is situated. Many other research fields outside agriculture share this constructivist world view. One example is the user-centred design methodology in the field of human-computer interaction, which aims to increase usability in ICT systems mainly by involving end-users through the whole development process. This methodological approach is presented as an alternative strategy to the traditional *knowledge transfer* approach in AgriDSS development in precision agriculture. Finally, the theoretical framework of DCog was presented as one possible approach to study farmers' naturalistic decision-making in their socio-technical system, since DCog views cognition as creation, transformation and propagation of representational states within a socio-technical system. By observing and analysing the flow of information within the whole system, ongoing cognitive processes are visualised and can be interpreted. Following this short summary of the background to the thesis and its theoretical foundations, the next chapter will approach the empirical part of the work, by introducing the research design.

3 Research design

In order to investigate the *problem of implementation* and *gap of relevance* considering farmers' decision-making and adoption of precision agriculture technology and use, two empirical case studies were conducted. Both related to a new Swedish AgriDSS called CropSAT within a broader unit of analysis:

- The first case study, which took the form of a workplace study, investigated and analysed farmers' usage of CropSAT, either alone or together with advisors, when making decisions on how to fertilise winter wheat in practice.
- The second case study investigated and discussed the ICT development process for site-specific fertilisation, using first-hand experiences from participation in the Swedish network on Precision Agriculture (POS) regarding the development of CropSAT.

In order to answer the three research questions (*cf.* section 1.2), a qualitative, naturalistic inquiry in two parts was conducted, as the two case studies (naturalistic inquiry is used interchangeably here with qualitative inquiry). A naturalistic inquiry involves observations performed in natural settings (Lincoln & Guba, 1985) focusing on deep and detailed descriptions of actions, behaviours, conversations, activities and interpersonal interactions from fieldwork (Patton, 2002). It studies situations in the real world without manipulating or controlling them and is open to whatever emerges (Patton, 2015). In a naturalistic inquiry the context is incorporated into the analysis, because it is considered important for the interpretation of the meaning of a situation (Lincoln & Guba, 1985; Patton, 2002). Furthermore, choosing a naturalistic inquiry, the quality of the data combined with sound conclusions are the most important aspects to achieve scientific rigor (Patton, 2002). Patton claims that *the validity, meaningfulness and insights generated from the qualitative inquiry have more to do with the information richness of the cases* *selected and the observational/analytical capabilities of the researcher than with sample size* (Patton, 2002, p. 243). Thus, the quality of the study lies in the performance of the study itself.

For the naturalistic inquiry, a case study approach was chosen. A case study is a qualitative method which studies human actions *in the wild*, aiming to describe detailed systemic information to facilitate a holistic analysis (Patton, 2002). A case study can be conducted in order to explore a bounded system or systems over time by sampling in-depth data from multiple sources of information that are rich in context (Patton, 2015). A case, or the bounded system, can be an individual, a programme, an event, a phenomenon or an activity. Stake (2000) defines three main types of case studies: intrinsic, instrumental and collective instrumental. An intrinsic case study is investigated in order to understand that particular case in detail. When performing instrumental case studies, the actual case facilitates understanding of other cases and aims to provide an insight or at least a generalisation to other cases. Collective instrumental case studies are extended too many cases that manifest common characteristics, where the individual case may or may not be known in advance. In this thesis two instrumental cases were studied, in order to gain an insight into farmers' decision-making and learning in practice and make some generalisations. One of these cases was a workplace study (Luff *et al.*, 2000). Both case studies were conducted with an ethnographic approach, which involves studying cultural perspectives and patterns in their natural settings over time.

3.1 Case study one

In case study one, four collective cases were used and the analysis was conducted as a multiple case study from a workplace perspective (Luff *et al.*, 2000). The case consisted of four crop production farmers who showed interest in precision agriculture technology. The study was conducted during 2015 in south-west Sweden and the AgriDSS involved was CropSAT (www.CropSAT.se). Workplace studies investigate and analyse people and technology in action and observe the ways in which different tools and artefacts are used in practical organisational conduct (Heath *et al.*, 2000). Workplace studies are important to understanding natural systems and contribute valuable information about design, usage and evaluation of different technologies. Ethnographic data collection techniques were used and the collected data were triangulated from participant observations, video recordings and semi-structured interviews (Patton, 2015). All farmers were purposefully sampled in order to gain as much information as possible and understand the phenomenon in depth (Patton, 2015). Although the number of farmers was small, and therefore the results are not readily generalisable, such small samples can provide much learning if they are chosen in an appropriate way (Stake, 2000). Two farmers, Farmer 1 and Farmer 2, were identified via contacts with the local advisory service, while I had interviewed Farmer 3 earlier for another reason and found him interesting due to his intention to start to use CropSAT as an alternative to the Yara N-sensor. The reason was that he had bought Yara N-sensor services from another farmer in the past, but now had difficulties getting access to the service in this way and had too little acreage to be able to buy one of his own. Farmer 4 was invited to participate after attending a meeting about precision agriculture technology at which he proved to be very experienced and interested in this technology and wanted access to better field images to learn more about his fields. Three of the four farmers (Farmers 1-3) employed a personal advisor on crop production, which was the same individual in the case of Farmers 2 and 3. This was not intentionally planned, but happened because the farmers seemed interested in the topic and they also presented differences in farming experience, farm size and farming strategies.

The selected farmers had different levels of previous experience of using ICT-based crop production software and precision agriculture technology, but they all demonstrated an interest in this technology in general and in CropSAT in particular. The workplace study was performed on each farm, mainly through participant observations and ethnographical/contextual interviews which all were video-recorded. Every farmer was visited three times during spring and one time in the following autumn, for a follow-up session. Every visit lasted 1-3 hours. In some cases the farmer was alone and in other cases an advisor, colleague or an employee also took part. The meetings were generally held in the farmer's office, farmhouse kitchen or staff lunch room. In order to understand what could happen before such meetings, Farmers 2 and 3 and their advisor were accompanied on field sessions on two occasions before the computer session started. The computer sessions were conducted during farmers' ongoing work, which influenced both questions and answers in the interviews. It also made it impossible to arrange and decide how those sessions were conducted, that is why they were different on the farms involved. The observations, video recordings and interviews were transcribed and resulted in 135 pages of material. The transcripts were read through several times to find interesting episodes that could be further analysed. Those selected episodes were then more fully analysed, taking inspiration from the DCog theoretical framework (Hutchins, 1995). This resulted in descriptions of the propagation, distribution and information flow of different representational states in terms of work practices, decision-making, learning and procedures in the socio-technical system (Rogers, 2012). When an episode was chosen, the transcript and video recording were used together to make more detailed notations on the different cognitive processes that appeared.

3.2 Case study two

Case study two was conducted during 2014 and mostly involved a conceptual approach that investigated pros and cons in theory and practice when initiating a shift in ICT system design methodology for precision agriculture from a more technology-centred approach to a more user-centred approach in the design, implementation and diffusion of an AgriDSS (www.CropSAT.se) for computation of variable rate application (VRA) files for site-specific fertilisation. The empirical data were based on experiences collected at meetings and discussions within the Swedish network of Precision Agriculture (POS), for which acted as coordinator. The intention with this purposive sampling was that as coordinator within the network, I had good insights into what has happened so far within precision agriculture in Sweden, since the vast majority of the professionals involved in R&D on precision agriculture technology in Sweden are part of the POS network. The aim with case study two was mainly to frame the development process conducted so far, based on experiences of the approaches stressed in the human-computer interaction literature, which was rather unknown in this agricultural domain. By using theories, approaches and strategies from the human-computer interaction discipline, much unnecessary work can be avoided, as the agriculture domain then does not need to go through the learning process conducted in other domains when trying to develop credible ICT systems for precision agriculture. The collected data were analysed by content analysis (Patton, 2002) and iterative discussions during the writing-up process. It should be noted, however, that more empirical data were collected in case study one, whereas case study two focused on content analysis using human-computer interaction theory and the approaches advocated as a lens to analysis and discuss the empirical data.

3.3 CropSAT: a new AgriDSS in precision agriculture

During 2013-2014 a new AgriDSS for nitrogen fertilisation was developed, by the POS network (www.precisionsskolan.se), called CropSAT (www.cropsat.se). CropSAT uses satellite images to calculate a vegetation index (VI) (Qi *et al.*, 1994) and VRA files for nitrogen 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 from the Swedish Board of Agriculture. To support farmers in their nitrogen fertilisation strategy for winter wheat, a minimum of three satellite images were published during the period April-June 2015. The recommended strategy for fertilising winter wheat is to apply nitrogen 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 vegetation index is calculated and shown in Google Maps. To receive a VRA file, the user must decide the level of nitrogen fertilisation within five vegetation index classes, which are estimated automatically from the satellite data (see Figure 3a) and used to calculate VRA files for nitrogen for the field (see Figure 3b). The VRA information is transferred to the tractor and spreader via a USB stick.

3a

3b

Figure 3. a) Vegetation index displayed on Google Maps, where the user must enter five levels of nitrogen fertilisation based on the coloured scale. b) A VRA file ready to be entered into the fertiliser spreader via a USB memory stick.

To set the nitrogen levels for each vegetation index class, the user is recommended to go out into the field and verify the nitrogen 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 nitrogen based on observation of the canopy and prior experience. When new satellite images were published during spring 2015, the farmers included in the present analysis studied crop development on their actual farm using CropSAT. On some occasions, a VRA file was calculated and later used for variable fertilisation. On other occasions, the images were used to get an overview of the status or used in the decision-making process regarding fertilisation with an Yara N-sensor (http://www.yara.se/crop-nutrition/Tools-and-Services/n-sensor/). The data collected were analysed using DCog lens (Hutchins, 1995).

4 Summary of papers

4.1 Paper I: Next-generation decision support systems for farmers: Sustainable agriculture through sustainable IT

Paper I took the standpoint that AgriDSS could be a major contributor in achievement of a viable farm economy with less negative environmental impact. Current AgriDSS available to farmers, advisors, experts and policy makers are not used to their full potential, since the adoption of these systems is low. The reason is at least partly that existing AgriDSS are based on what scientists and system developers consider necessary. Paper I used user-centred design methodology in order to identify the core problems identified for most AgriDSS, because user-centred design puts the farmers' experience in focus and involves them early on and continuously in the design process. Next-generation AgriDSS must simultaneously enable stakeholders to gain access to the best knowledge available, and involve them in the process of developing the user interface design of the ICT system. To use existing and future information efficiently, user-centred design and participatory approaches are therefore considered to be crucial and need to be a part of the transition towards sustainable agriculture.

4.2 Paper II: Some considerations about the development and implementation process of a new agricultural decision support system for site-specific fertilisation

The starting point for Paper II was that precision agriculture enables important contributions toward more sustainable agriculture, by providing possibilities to adapt farming measures to within-field variation. Many farmers have the necessary technology to operate site-specifically, but they do not use it in practice, and consequently available ICT systems are not used to their full potential. Paper II discussed how to reduce the so-called problem of implementation in order to improve the ongoing development process of the internet-based fertilisation AgriDSS, CropSAT. The aim was to apply a participatory design approach when developing the AgriDSS further. The paper identified some pitfalls when starting to use a UCD approach in the development and implementation process, as well as some suggestions on how to reduce them. The main pitfalls and the suggestions considering how to solve them are summarised in section 5.3 and described in detail in Paper II.

4.3 Paper III: Promoting sustainable intensification in precision agriculture: Considering the ICT development process for site-specific fertilisation

Paper III was an extended version of Paper II and accordingly it used the same basic assumptions considering precision agriculture technology and its possibilities to provide improved sustainability in agriculture. Since Paper II was peer-reviewed and is published in the proceedings from the 10th European Conference on Precision Agriculture, while Paper III has been submitted (December 2015) to the scientific journal *Precision Agriculture*, I chose to include both in this thesis. Paper III also addressed the issue of how to increase AgriDSS adoption, based on the knowledge that participatory approaches during the design and development process are one of the most important factors to frame technology use. The development of sustainable ICT systems through theories and methodologies from the fields of HCI and UCD was presented and the ongoing Swedish project for development of a CropSAT was used as an example to frame the issue. The Swedish project intended to apply a UCD approach on the further development of the AgriDSS, and some pitfalls on starting to use this way of working were identified, together with some suggestions on how to reduce them through co-learning processes. The main results are summarised in section 5.3 and described in detail in Paper III.

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

Paper IV departed from the assumption that ICT and other technologies are necessary, but not sufficient, for sustainable farming systems in a sustainable intensification trajectory for agriculture. The aim of the study was to improve understanding of farmers' use of AgriDSS in practice. The theoretical framework of DCog was used as a lens when investigating and analysing farmers' use of the CropSAT software tool for calculation of VRA files for nitrogen fertilisation from satellite images. In a case study, the unit of analysis was broadened to the whole socio-technical system of farmers' decision-making, including other people and different kinds of tools and artefacts. Paper IV examined how CropSAT could function as a social learning tool and mediate discussions, as well as supporting more sustainable decisions and actions. When using CropSAT, farmers' *professional vision* was developed through *tool-mediated seeing*. As CropSAT reinforced farmers' professional vision by visualisation of the biomass variation in the crop, the use of the AgriDSS resulted in improved knowledge of the field. By a combination of the concepts of professional vision and tool-mediated seeing, a new concept concerning the ability to improve farmers' professional vision by the use of an AgriDSS was identified. The new concept was called *enhanced professional vision* and shows how the use of AgriDSS can support human cognitive abilities by visualisation of complexity in the crop, which the human vision system cannot reveal. This *enhanced professional vision* is important in a future where farmers' local and situated knowledge is crucial to increase sustainability in agriculture. The results obtained are summarised in section 5.1 and described in detail in Paper IV.

4.5 Paper V: Considering farmers' situated expertise in using AgriDSS to foster sustainable farming practices

The starting point for Paper V was the insight that more sustainable agricultural practices require experienced farmers with situated knowledge in order to handle variable farming systems adapted to the local situation. The study examined farmers' use of AgriDSS in relation to their situated expertise and fertilisation of their fields. The theoretical framework of DCog was applied in investigating and analysing farmers' use of the CropSAT tool. The results revealed that CropSAT could function as a tool supporting, social learning, decision-making and development of situated expertise. This situated expertise is connected to a farmer's professional vision. By *tool-mediated seeing* connected to CropSAT use, farmers' *professional vision* can be improved and developed to *enhanced professional vision* and consequently situated knowledge. Experienced farmers are experts on their fields and their situated knowledge and *enhanced professional vision* are central for the development of *care* in the farming practice. Care itself is defined as the totality of practices that make knowledge and technologies work in a sustainable direction, based on attentiveness, competence and responsibility and it is crucial for the everyday impact of the individual farmer's practice. The results obtained are summarised in section 5.1 and described in detail in Paper V.

5 Findings

The main findings from the work performed in this thesis that are pertinent to the research questions are presented in this chapter. They are organised according to the research questions posed (Table 3). More detailed results from the studies can be found in Papers I-V.

Table 3. Overview of the appended papers and their relation to research questions (RQ) 1-3

	Papers				
Research question	I	II	III	IV	V
RQ1	X	X	X		
RQ2				X	X
RQ3				X	X

RQ 1: What characterises a socio-technical system that supports farmers' decision-making in practice in complex critical situations?

RQ 2: How can AgriDSS support farmers' decision-making and development of *situated knowledge* in order to increase sustainability in their practice?

RQ 3: How can the development processes of new precision agriculture technology such as AgriDSS be improved in order to decrease the *problem of implementation* and the related *gap of relevance*?

5.1 What characterises a socio-technical system that supports farmers' decision-making in practice in complex critical situations?

Papers I-III demonstrated that precision agriculture can enable important contributions to more sustainable agriculture and identified various factors for success and pitfalls in current approaches. With these lessons in mind, approaches within distributed cognition were used in field work. In case study one and Papers IV and V, DCog-inspired analysis revealed that the socio-technical system concerning the decision-making on nitrogen fertilisation for winter wheat could be rather complex and composed of many artefacts (see Figure 4). The unit of analysis in the decision-making processes of Farmer 1 included a wide range of artefacts, *e.g.* CropSAT (images on vegetation index and VRA files used in computers, mobile phones, and tablets), crop production software (tables and field maps in computers, mobile phones and tablets), paper-based field maps, calculators (in mobile phone), Spadmeter, and notepads, discussed together with Farmer 1 and his advisor (Figure 4).

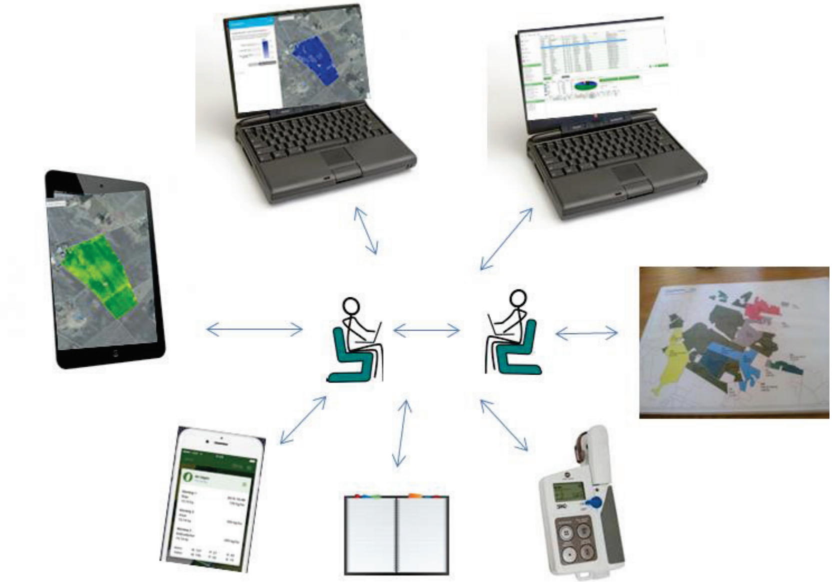

Figure 4. The unit of analysis of the distributed cognitive (DCog) system, where cognitive processes are distributed: (1) across the members of a group, (2) between human internal mechanisms (*e.g.* decision-making, perception, memory) and external structures (material artefacts, ICT systems, social environment), and (3) over time (Hutchins, 1995).

However, the chosen technology strategy seemed to depend on what kind of computer programs and devices the farmer was already familiar with, whether the advisor was present or not and the extent to which the farmer played an active part in technology use during advisory sessions. The four farmers in this study performed differently. Farmer 3 let the advisor take care of the computer while watching, Farmer 2 handled the computer himself, Farmer 1 took an active part in technology use, but with an iPad, and Farmer 4 did not buy any advisory services and did not use CropSAT.

The observations revealed that the advisor played an important role in adoption and use of CropSAT. Their support in handling the technology and suggestions considering new practices and their confident handling of the tool seemed to encourage the farmers to use it themselves. Thus, it seems as though the advisor can have a crucial role in introducing new technology to the farmer in this more informal learning situation. Farmer 3, who was very competent in the use of computers, called his advisor on the phone and used CropSAT as a communication tool when discussing levels of nitrogen fertilisation. Thus it should be pointed out that in this situation the image became the field instead of being a representation of it, while the farmer pointed at the image when discussing. This means that he acted as though her were looking at the field itself, rather than a map of the field. In this case CropSAT mediated a discussion and functioned as a coordinating mechanism. Since CropSAT is internet-based, the farmer and the advisor could use the tool and, independently of each other, try different levels of nitrogen and look at the same or different images, while sitting in their own offices. This function as a coordinating mechanism in discussions became obvious also in other situations regarding CropSAT.

Farmer 1 let the advisor take care of the computer in the beginning, but when he became more experienced he took a more active part and used his iPad in parallel with the computer used by the advisor. One important reason for this way of acting was that this farmer used an internet-based crop production programme. Accordingly both that programme and CropSAT were available for the farmer and his advisor at the same time and thus the farmer could contribute information in parallel with the advisor's use of the same programme. The other tentative reason was that he and I met alone between two advisory meetings. At that occasion my attendance provided social interactions in relation to CropSAT use, when the farmer operated the AgriDSS during our discussion. At the following meeting, he seemed to be more active in using the different tools and gave the impression that he was able to contribute more, or in other words he was no longer a *CropSAT novice* in relation to the advisor. The advisor functioned as a role model for Farmer 1 when using the different tools and artefacts. By advocating a willing and able approach to the different devices, he influenced Farmer 1 in using the AgriDSS and learning occurred within the cognitive system.

The relationship between Farmer 1 and his advisor seemed very straightforward, relaxed and in a mood of accepting each other's competences. When comparing two images from different dates during spring, they noted a part of the field with low biomass. Then the advisor said: *Salt from the road destroys the clay colloids, resulting in soil compaction* and the farmer answered: *We stored straw bales here, which they picked up with a truck.* The fact that this little conversation ended with the advisor acknowledging the farmer's answer by responding *Of course* revealed two things. They both had important knowledge and experience that could bring the discussion forward and they also accepted without any comments that this was the case. The social interaction and the relations between the actors, it could be claimed, are important characteristics for a well-functioning social relation, which in turn could be important for the information flow and propagation of information in the socio-technical system.

Farmer 4, who did not use CropSAT but had an Yara N-sensor, became interested in CropSAT after talking to a Yara N-sensor expert, who suggested other applications for the AgriDSS, apart from fertilisation. Accordingly, this expert entered the cognitive system and advocated AgriDSS use by giving instructions considering an alternative strategy for AgriDSS use, and the farmer became interested and learning occurred. Farmer 4 and his partner farmer were eager to find new ways of interacting socially that could help them develop their crop production. They were not satisfied with the existing advisory service in the area, so they did not use it. Instead, they had started a learning group of their own with corresponding colleagues. However, while satisfied with that, they still wanted an advisor who would work closely with their company. Consequently, they described a lack of high-quality professional partners in their cognitive system. In a situation when Farmer 4 and his partner farmer were comparing maps from different AgriDSS, it became obvious that they wanted a professional advisor to take responsibility for handling the data and facilitating interpretation of the data, in order to learn more about their fields and about how to use the technology more efficiently. By looking at maps in retrospect, the participants reflected on the results and, consequently, reflective learning could take place. However, without an attending advisor who could facilitate the use of the different AgriDSS and interpretation of the data, limited learning occurred, except that it could be interesting to evaluate the maps in retrospect if it was possible. Later on, those two became nostalgic about when they started their farming company with a group of partner farmers. *In those days we sat until two in the morning ... but now we have been doing this for 15 years so maybe the trigger is not as strong as it was to begin with.* His partner farmer agreed: *We have done so many years now that we have become blind to it ... we must bring in new eyes!* Thus these companions had previously been able to act as learning facilitators for each other, but now needed new social interactors/partners who could contribute more information, ideas and strategies about how to improve their farming practices, preferably with the help of usable and credible AgriDSS

An AgriDSS must be adapted to farmers' needs and practice (*e.g.* Aubert *et al.*, 2012; Jakku & Thorburn, 2012; Prost *et al.*, 2012; Matthews, 2008), but the social context and possibilities to get profitable social interactions in relation to AgriDSS use seemed crucial to get it accepted and used. Beyond high-quality social interactions, correspondence between different AgriDSS and representations of the field seemed to be important in encouraging use of different AgriDSS in retrospect as a basis for discussion and learning. Aubert *et al.* (2012) stress the importance with compatibility among tools, and in this thesis too this emerged as an important factor in order to improve learning. When the representations of the fields (*i.e.* the maps) did not correspond, it became impossible to make reliable interpretations to compare and learn from. My impression was that if representations from different AgriDSS had been better adapted for comparisons of the results, they would be more interesting for farmers to use in retrospective analysis and thus valuable learning tools. Moreover, social and technical aspects of the socio-technical context seem to be crucial for how usable, credible and interesting an AgriDSS is as a basis for decision-making, discussion and as a learning tool. However, advisory services, as individual advisors or as facilitators of learning groups, have a very important role to play.

5.2 How can AgriDSS support farmers' decision-making and development of *situated knowledge* in order to increase sustainability in their practice?

In case study one (Papers IV and V), this issue was addressed by studying how farmers make decisions in a critical situation, fertilisation of winter wheat, using an AgriDSS. The interviews with the farmers revealed that the decision-making process on nitrogen fertilisation starts already in autumn the year before harvest. Then, farmers often decide an average nitrogen level for every field. That level is adjusted one to three times in spring depending on the crop quality, intended use and what the plant stand looks like after winter (Albertsson, 2015). CropSAT was used in this process of making adjustments. The images created in CropSAT were visual digital representations of the field that displayed crop biomass complexity in a way that is difficult to achieve by walking or driving in the field. Fertilising *correctly*, so to speak, with regard to variations in the field is impossible, since there is a long period between fertilisation and harvest, when many things can happen. However, with technological support it can be improved, *e.g.* by adapting the amount of N fertiliser to the variation in biomass amount as late as possible before stem elongation, improving fertilisation efficiency (Albertsson, 2015). Visualisation of the current variation in biomass with the satellite images showed variation that an experienced farmer was already aware of, but it would be difficult or even impossible to estimate the differences in biomass by human vision, let alone act upon them.

The CropSAT image provided different kinds of representation formats that visualised the within-field variation with more clarity than could be achieved with the human eye and it provided a possibility to apply nitrogen fertiliser adapted to the variability in biomass. When looking at the satellite images in CropSAT, farmers with long experience easily recognised and explained much of the visualised variation in crop biomass and revealed their *professional vision* (Goodwin, 1994). One farmer said this about a 30-ha field he had farmed for 30 years: *This bit is more or less gravel esker ... the ground rises here... it must rise by at least a few metres. Then there's a ridge here and a little hollow there... and of course it's all lighter soil ... there's heavy clay here. It's exactly what the field looks like ... here it's really fertile and nice... here it's really ... exceedingly good ... it's good there too, but not as good as it looks here ... but it will come... because of course the soil is still cold.*

Hence, CropSAT provided representations of the field, elucidating a complexity impossible to obtain with the human vision system, by what Goodwin and Goodwin (1996) call *tool mediated seeing*. The aspects of the complexity, some of which were already known and some which were not, allowed the farmer to add the revealed complexity at the representations from CropSAT to his own *professional vision* (Goodwin, 1994) based on experience, to increase his situated knowledge about the field. This combination of the experienced farmers' *professional vision* based on experience and the *tool mediated seeing* from CropSAT contributed to the new concept developed in Papers IV and V, called *enhanced professional vision.* In a sustainable intensification trajectory of agriculture, farmers need to adapt their practice more after the local situation (Leeuwis, 2004). However, they also need to improve their *care* in practice, where care is the sum of all practices that make technology and knowledge work (Krzywoszynska, 2015). The concept of *enhanced professional vison* elucidates how use of an AgriDSS can provide possibilities to support farmers' learning, decision-making and development of situated knowledge and care in a socio-technical system.

Farmer 4 wanted more and different (not calculated/interpreted) kinds of information than CropSAT could provide. He wanted regular field images in order to get representations of the field, to get a bird's eye view as well as a detailed representation, in order to recognise small differences in crop development to learn from: *It would start in April and you could get one of these once a week and then you could go down and zoom in and see exactly and then* *you could follow the field and see this here. Now it's 25 mm here ... so you see this ... how this ... it's like ... on my farm I can know a bit, but you get a whole different ... you get this here von oben... you can't compare them.* The partner farmer, who was not as interested, added: *Yeah... but then it's too late*. Farmer 4 replied: *Yeah, but even if it's too late you can draw a certain conclusion and you can maybe do something next time*. Thus they verbalised two perspectives of *situated knowledge* in this conversation. The partner farmer wanted to have access to information to act upon and use for decision-making, whereas Farmer 4 focused on the possibilities to learn by reflection through access to a bird's eye view of the fields. Farmer 4 could not verbalise what exactly he wanted to see, but he was strongly convinced that he should learn more about the fields in order to make better decisions in the future, drawing conclusions from his prior experiences combined with information displayed in new images. This line of argument could be interpreted as an example of expertise development. According to Dreyfus and Dreyfus (2005), an expert is deeply engaged and evaluates situations in relation to many other experienced situations. Farmer 4 had identified an opportunity to get access to new representations of his fields to evaluate them and increase his situated knowledge and professional vision (Goodwin, 1994), without being able to externalise in words what he really wanted to see.

The major challenge in using CropSAT was that the farmer had to act upon the variability by setting the five levels of nitrogen fertilisation in relation to the visualised variation in crop biomass. In this cognitive decision-making process, social interactions with the willing and able advisor, reflecting on older CropSAT images from the same year as well as other representations (soil maps) from the fields, were valuable and functioned as coordinating mechanisms during the decision-making process. In some cases, Spadmeter measurements and experiences from the field on the same day (farmers or advisors or both) as well as from history (farmers) also added valuable aspects on the process. Altogether, the farmers made their final decisions using the functional entities in the whole cognitive system, where CropSAT constituted one part.

To sum up, CropSAT can reveal information on the object of interest to both provide representations of complex situations by *tool mediated seeing* (Goodwin & Goodwin, 1996) and facilitate action, learning and decision-making about nitrogen fertilisation. However, setting the levels of nitrogen or using CropSAT for evaluation in retrospect in combination with other representations was difficult in those processes, and high-quality social interactions were crucial. CropSAT supported farmers' *professional vision* by providing possibilities for *tool mediated seeing* of complex situations and it resulted in *enhanced professional vision*, which supported the development of the farmer's *situated knowledge* and *care*.

5.3 How can the development processes of new precision agriculture technology such as AgriDSS be improved in order to decrease the problem of implementation and the related gap of relevance?

Case study two was initiated out of frustration concerning the limited practical use of different AgriDSS in Sweden and other parts of the world, the so-called *implementation problem* in the field of precision agriculture. This research question was considered in Papers I, II and III. To find strategies to avoid the *problem of implementation*, a need for more knowledge about farmers' naturalistic decision-making in combination with improved characteristics of the development process of the next generation's AgriDSS seemed crucial. Different actors, such as farmers, advisors, scientists, suppliers and policy makers, all contribute to the development of present-day agriculture. The question was how a further development of an AgriDSS could consider different kinds of requirements set by different actors in today's agricultural knowledge and innovation system. Case study two revealed the answer.

An AgriDSS that supports sustainable development of today's agriculture needs to be sustainable in itself. It must be adaptable, flexible and user-centred (Hanks, 2008). There is also an increased focus on the need for participatory approaches in ICT (*e.g.* Gulliksen *et al.*, 2003; Göransson *et al.*, 2003; Bjerkenes *et al.*, 1987), AgriDSS and sustainable agriculture in general (*e.g.* Schlindwein *et al.*, 2015; Cerf *et al.* 2012; Prost *et al.*, 2012; Jakku & Thorburn, 2010; Hoffmann *et al.*, 2007; Leeuwis, 2004; McCown, 2002). Participatory approaches have the potential to be the common ground in future integrated initiatives (Jakku & Thorburn, 2010). To tap existing potential when developing and implementing new technologies in agriculture and trying to improve both environmental performance and farm viability, there is probably a need to change approach and integrate different instruments in a joint or collaborative process of learning and decision-making (Hoffman *et al.*, 2007; Leeuwis, 2004).

Based on case study two, user-centred design (UCD) and participatory design methods in ICT systems design, as well as participatory approaches and social learning processes, share some common characteristics. These include: stressing the importance of understanding the context/s in which the activities take place, getting to know the people involved, establishing a dialogue of mutual sharing of different perspectives, and working together to reach common goals and develop an artefact that promotes *sustainability through design*. It is worrying that design questions, involving different agricultural models that are thought of as AgriDSS in practice, are not regarded as central topics in the agronomic research community, even though their lack of use is considered a problem (Prost *et al.*, 2012). According to Prost *et al.* (2012), this problem has arisen because agronomic researchers do not consider design questions to require discussion.

Accordingly, there is an increased focus on the need for participatory approaches in the design and development processes of sustainable agriculture in general (Leeuwis, 2004) and of ICT and AgriDSS in particular (Jakku & Thorburn, 2010). To handle participation by different stakeholders within a proposed development process, some necessary methodological support is available in the UCD approach (Issa & Isaias, 2015). Initially a group of relevant stakeholders consisting of end-users such as farmers, advisors and some researchers should be recruited, to meet on a regular basis. Furthermore, there is a clear need for a human-computer interaction (HCI) specialist in the role of a facilitator to act as an intermediate link between different participants, in order to create common ground and reach consensus within the established development team. By introducing aspects from a user-centred/participatory design approach, there would be improvements in such a development process, but there are also some pitfalls to consider. The most important pitfalls that were identified are presented below (see Papers II and III for further results):

- Non-familiarity with addressing usability work and specific work activities and processes in participatory design
- General lack of discussion on the usefulness of usability work during the analysis, design and evaluation phases, as well as lack of practical experience of usability work
- Introducing new ways of working that aim to foster knowledge exchange and equal impact.

This list provides a good starting point for the forthcoming work process in a technical development team and its additional members (*i.e.* the intended end-users of their AgriDSS). Some actions that are being considered to reduce the pitfalls are (for further results see Papers II and III):

- Recruiting farmers and advisors as end-users that are early adopters and *willing and able* to participate in this kind of user-centred/participatory design project

- Choosing a user advocate/HCI specialist, with responsibility for mediating between end-users and technical developers to lead the user-centred/participatory design work activities
- Fitting the developed AgriDSS into the existing farming ICT system context, for example, farmers' plant production system or official extension services.

The intention is that the user-centred/participatory design approaches will make it easier to bridge the gap between theory and practice in precision agriculture. The stakeholders involved may reach an increased understanding of the implementation problem through a social co-learning process. In the progressive development of an AgriDSS, the design and development team drives a social co-learning process themselves. Coming from different disciplines, with a broad spectrum of several kinds of experiences and knowledge, it has been recognised that some common concepts are used in slightly different ways, and subsequently the need for co-learning and negotiation is obvious. To conclude, applying a user-centred/participatory design approach when developing an AgriDSS will lead to innovative and more applicable farm management practices which would increase the use of AgriDSS and frame sustainability in agriculture.

6 Discussion and conclusions

The overall aim of this thesis was to examine the next phase in the sustainable intensification trajectory within agriculture, where farmers' *situated knowledge* and *care* are central when requirements for adaptation to the local situation and complexity increase. The starting point was the so-called *problem of implementation* and the *gap of relevance* considering farmers' limited use of AgriDSS in precision agriculture, which was discussed here in relation to Röling's (1988) three remarks:

- Technology is often seen as an isolated phenomenon
- Technology is not adapted to the needs of farmers
- The traditional view of knowledge transfer lacks a systemic perspective and does not put the technology in the context in which it belongs.

In order to avoid the criticism expressed by Röling (1988) and others (Cerf *et al*., 2012; Prost et al, 2012; Jakku & Thorburn, 2010; Leeuwis, 2004; McCown, 2002), this thesis turned to research fields outside precision agriculture to answer research questions concerning farmers' decision-making, their socio-technical system and AgriDSS development strategies.

Farmers' decision-making is an ongoing process and observation of decision-making can be difficult (II; Gray *et al*., 2009). However, by choosing to study the use of CropSAT in practice in case studies, it was possible to observe when decisions were prepared, discussed and made in relation to technology use and the importance of social interactions between farmers and advisors became significant. By use of the theoretical framework DCog, many interesting aspects of the socio-technical system were visualised, interpreted and understood. However, the analysis was performed on a somewhat general level, in order to identify the most important features of the system. To understand central processes in more detail, deeper analysis would be necessary but was beyond the scope of this thesis. The findings presented here are relevant for many areas within agriculture that are involved in developing technology or knowledge that is complex and without immediately observable benefits or low awareness by the farmers (Payne *et al.*, 2016). While this research concerned an AgriDSS for nitrogen fertilisation, it can be argued that the results can also be used in *e.g.* the area of biological soil mapping or a new service in practice such as mapping of soil-borne pathogens (Wallenhammar *et al.*, 2016)

When the farmers looked at the satellite images in CropSAT for the first time, their *professional vision* (Goodwin, 1994) was revealed. The images also provided new information from the field without decreased complexity, which resulted in *tool mediated seeing* (Goodwin & Goodwin, 1996) among the participants. By developing the concept of *enhanced professional vision,* (see Papers IV and V), this work will contribute to our understanding of how an AgriDSS can support farmers' development of situated knowledge and care in order to increase sustainability. Information and communications systems or AgriDSS can complement human abilities by promoting different cognitive activities for which humans are poorly suited, and enhance and support development of those cognitive skills which humans are biologically predisposed to possess (Clark, 1999). An AgriDSS can, for instance, complement human cognitive abilities by handling big data and visualising complexity that the human vision system cannot perceive. In contrast, expertise considering complex real-life situations is based on intuitive knowledge developed from experience, which is still a human quality (Dreyfus & Dreyfus, 2005). A role-based computer can never be as good as an experienced person in handling complex real-life situations, which is important to remember. Thus, agriculture needs both technology and experienced actors, at least in large-scale agriculture, and they can only replace each other to a certain extent. Therefore usable and credible technology is important, but expert systems aiming to replace the decision maker are not desirable. AgriDSS can support farmers in four out of five important areas of farm management (*cf.* section 2.1.1), but the farmers' crucial coordination skill cannot be replaced by an AgriDSS. Instead, experienced farmers' situated knowledge would be acknowledged in order to support the important base for good care in farming practice (Krzywoszynska, 2015). To achieve those usable and credible AgriDSS, using participatory methodologies and involving the end-users during the process is crucial (Cerf *et al.*, 2012; Jakku & Thorburn, 2010).

An increasing number of researchers within the field of agriculture emphasise the need for communication strategies other than knowledge transfer (*e.g.* Van Meensel *et al.*, 2012; Blackmore, 2010; Jakku & Thornburn, 2010). By taking a constructivist perspective on AgriDSS development and use, in combination with the introduction of UCD methodology in precision agriculture, important aspects of development strategies in order to improve usability were identified in this thesis. This kinds of changes would be desirable, doable and even necessary in order to develop AgriDSS that could be considered usable and credible by farmers. However, working together is probably always challenging, even though the people involved share the same goals. There will always be different opinions about the best way forward, claims that are challenged, convenient methods, what concepts should be used or what a specific concept really means. This thesis is one good example of that, by involving people from environmental communication, precision agricultural, agricultural extension and education and cognitive science, all with different research traditions, experiences and theoretical backgrounds in one possible approach. However, this thesis is also an example saying that it is possible. This work is not perfect, nor revolutionary, but seeks to bridge and increase understanding of some fundamental, important issues and it can be claimed that it has provided some initial and significant pointers in that direction. In the following sections, I present the main contributions from this thesis to the knowledge fields discussed here, the concern for scientific rigour and the limitations in the work, some implications, major conclusions and finally suggestions for future work.

6.1 Contributions of the thesis

The main contributions arising from this work in this thesis were:

- Introduction of the concept of *enhanced professional vision*. This concept emerged from the empirically based combination of *professional vision* (Goodwin, 1994) and *tool mediated seeing* (Goodwin & Goodwin, 1996), where technology supports farmers' development of *situated knowledge*.
- Empirical evidence indicating that both technology and intuitive experience-based knowledge are necessary to achieve a sustainable intensification trajectory for agriculture. Neither of these is replaceable, in at least large-scale farming practice, where increased adaptation to within-field complexity in farmers' *care* for their local situation is needed.
- Addressing results that elucidate that farmers' development of *situated knowledge* and *care* is not opposed to the use of ICT (technology).
- A demonstration that participatory approaches are crucial for farmers' development of *situated knowledge* and *care* in relation to technology. Social interactions are important: 1) during the development process of an AgriDSS, where participatory approaches would contribute to better usability and credibility by input from end-users early in the process and,

in addition, embed the AgriDSS in advisory work from the beginning, 2) for decision-making and learning during practical use, and finally 3) to motivate farmers to use new technology.

- Introduction of a research approach enabling issues from the agricultural domain to enter the research field of IT (and *vice versa*), where case studies of the agricultural domain are limited.
- Studies that suggest how the fields of precision agriculture and environmental communication could be bridged in research activities. Precision agriculture is based on a conventional *technology transfer* paradigm in both research and practice (and thus is not used for handling questions of learning and social interactions), while the field of environmental communication is anchored within the interpretative, learning paradigm (and not used for handling the relation between humans and technology in real-life situations, *in the wild*). By use of the theoretical framework DCog, the unit of analysis was widened to embrace both social interactions and technology.
- Depiction of how the so-called *problem of implementation* and the *gap of relevance* can be described by using theories and methodologies from other research fields and applying them in a precision agriculture context:
    - Applying user-centred design methodologies to propose appropriate strategies in AgriDSS development
    - Applying the theoretical framework DCog in precision agriculture, which was shown to be useful in elucidating farmers' socio-technical system by increasing understanding of cognitive processes where technology is included in the unit of analysis
    - Applying a theoretical approach that has applications in environmental communication and systemic agricultural research.

6.2 Scientific rigour and limitations of the research

The most important limitations in the research were: 1) The small numbers of farmers and advisors included, and 2) the pros and cons considering AgriDSS development described in case study two not being applied to a real AgriDSS development process. It would have been interesting to follow a process that used user-centred design methodology to complement the conceptual work.

The most important reason for the low number of participants in the workplace study was that such investigations are time-consuming in performance and analysis. However, it would have been to increase the range of farmers and advisors included, from which interpretations could have been made and conclusions drawn. Concerning the advisors, it was not optimal that two of the farmers engaged the same advisor. That decreased the possibilities to observe the advisor's impact on technology use by providing social interactions and technology adaptation to the needs of the individual farmer. The main reason for this was an ambition to find interesting farmers. However, as the work developed and the importance of the advisors was identified, a greater number of subjects would have been preferable in order to find a wider range of advisor strategies.

In spite of those limitations in the work, it can be claimed that important knowledge was revealed, in line with earlier discussions and presentations of findings. When discussing the rigour of my research below, I draw upon Lincoln and Guba's (1989) four criteria for qualitative research: *credibility*, *transferability*, *dependability* and *conformability*.

Credibility corresponds to validity in quantitative research and regards the match between the description and the explanation. To increase credibility, some strategies are important. Shenton (2004) addresses the Lincoln and Guba (1989) criteria and highlights a couple of guidelines. Using appropriate research methods is important and by using triangulation of data collection techniques, the degree of rigour can be enhanced. In this thesis I believe that the data collection techniques used were appropriate and in the workplace study I used triangulation of the data. In addition, four of the appended papers have been presented at conferences and two have been peer-reviewed prior to publication in conference proceedings. The researcher's familiarity with the study area is also important, as is their background, qualifications and experiences. Due to my long experience from the POS network (see Preface) in combination with personal experiences from living on a farm and experiences from using the methodology of ethnographic, naturalistic inquiry and the data collection methods of observations, video recordings and interviews, I would claim a respectable level of credibility for my work. What I did not do was to sample the informants randomly, which Shenton (2004) advocates. However, Patton (2002) argues for purposeful sampling techniques in order to achieve information richness. The path taken in this thesis was aligned with Patton's thoughts. In case study one, I decided to select the farmers purposively, since it was taken that having four farmers would be too few and that it was important to find interested individuals with differences in their farming situations. Before starting this work, I also took part in a pilot project (Lindblom & Lundström, 2014) aiming to investigate farmers' decision-making, to learn more about, theory, methodology and data collection technics in such processes.

Transferability is the external viability in quantitative research and concerns the possibilities to generalise from the findings (Shenton, 2004; Lincoln &

Guba, 1989). Stake (2000) claims that although every case is unique, it is also an example from a wider group and the prospect of generalisation should not be immediately rejected. Stake also argues that while knowledge from one case is not generalisable to all others, there is much to learn from a case and by making broad descriptions the readers can draw conclusions of their own. In order to increase transferability I provide written descriptions of the empirical work and the analysis, but until another person conducts a similar study, it is not possible to judge if my work is transferable.

Dependability refers to reliability and the possibility to replicate the study. In order to facilitate replication of this study, I described the process in detail. How successful this may be will only be revealed when another researcher seeks to replicate the study. Shenton (2004) argues that the role of the researcher must be discussed. My experience from farming is rather long, but I am not a farmer and I have never been. I would argue that the greatest risk for me would be to think that I *know*, when I definitely do not. Experience is valuable in order to understand the context, but in the work of analysing and interpreting the data, I was very conscious about reflecting on my interpretations in relation to what the farmers reported. It was valuable to be able to return to video recordings and listen to the exact words, but also to consider the situation in which the words were said. I used this in order to reconsider and reflect on my interpretations.

Conformability refers to objectivity and means that results and interpretations should be based on the collected data and not made up by the researcher. Again, the possibility to follow the process by rich descriptions is important, and Shenton (2004) mentions the value of triangulation in this regard. Triangulation can consider methods, but I would claim that cooperating with other researchers in conducting and interpreting empirical data is another form of triangulation. In case study two the empirical material was limited, but we were two researchers who agreed on the implications. I presented examples from the video recordings and my interpretations of them to my co-authors and PhD colleagues at a university course as a step in the analysis work. I have also presented them at conferences.

6.3 Implications

This thesis work was conducted within the BioSoM project (www.BioSoM.se) to avoid an implementation problem in the developing area of biological soil mapping. Due to difficulties in finding appropriate cases to study within the BioSoM project, I chose farmers' use of CropSAT as the case. The soil analysis developed within BioSoM (Wallenhammar *et al.*, 2016) does not offer such place-based, complex decision situations to study. However, the results are not specific to farmers' use of CropSAT. On the contrary, I would claim that they are applicable to other AgriDSS as well as developed knowledge, in precision agriculture but also in other areas of agriculture. Increased effort and interest in relation to design and strategies for development of agricultural models and of AgriDSS is crucial in agronomic research developing new AgriDSS, in BioSoM for instance. I hope that this thesis can generate increased interest in extension research in general and in relation to AgriDSS in particular, as an important part of the larger task to increase sustainability in agriculture. In that work the theoretical framework of DCog would be valuable in order to provide a systemic approach on farmers' practice.

This work has implications for farmers' practice which I hope will result in a change in perspective in extension work and research from knowledge transfer to participatory approaches, by emphasising the importance of social interactions and learning during the whole process of AgriDSS development and use. Starting with advisory services, I hope that there will be more focus on R&D in relation to new technology and strategies to facilitate use, social learning and decision-making among farmers, but also improved possibilities for advisors to interact and exchange experiences and strategies in connection to technology use. Those kinds of implications will probably require changes in advisory practices in relation to ICT and AgriDSS, but since advisors have an important role to play, it is important that they reconsider and alter their actual work practices where necessary.

Finally, this thesis has implications for precision agriculture research. The discussion about expertise in relation to ICT, human beings and care in the trajectory of sustainable intensification will hopefully influence how farmers' experience and situated knowledge is acknowledged in future R&D. In Sweden the POS network has been successful in involving different stakeholders, but so far farmers and advisors have been involved to a limited extent. Involving farmers during the whole process would be considered more costly and time-consuming. However, if researchers and developers are willing and able and can be supported with doable strategies and facilitation support, such kinds of participatory design strategies would be possible and enriching for everybody involved.

6.4 Concluding remarks

Precision agriculture research clearly needs to change perspective from *knowledge transfer* to more *cooperative/participatory approaches*, in order to avoid a *technology fix* in the development of AgriDSS. There is also a need for increased discussion and interest in design in relation to use of AgriDSS. By using methodology from user-centred design to increase the user perspective and by involving different stakeholders from early in the development process, AgriDSS could be better adapted to different end-user requirements. Thus developers of AgriDSS need to follow Hoffmann et al. (2007) when claiming a changed perspective from absolute *technical packages* and *solutions* to adaptable *prototypes* and *principles* in combination with acknowledgement of farmers' experimentation. I would add that it is also essential to acknowledge experienced farmers' *situated knowledge,* in order to improve farmers' *care* in practice.

Technology development is underway in agriculture, as elsewhere in society, and it is crucial to bridge between farmers' expertise and experience-based knowledge and the possibilities provided by new technology. The engaged and experienced human being, e.g. the farmer, and not the role-based ICT system is the expert in complex, real-life situations such as crop production. Nevertheless, technology can contribute various kinds of digital representations that the human eye cannot perceive (tool mediated seeing) and other functions that support humans' cognitive abilities and thus increase the sustainability in decisions and actions taken. The concept of *enhanced professional vision* formulated in this thesis is important in showing that technology can support farmers in decision-making, learning and development of *situated knowledge* and that social interactions and farmers' expertise are crucial for technology development and use.

AgriDSS must be put in a broader context, both technically and socially. They must fit with the rest of the farmer's technical system and must be presented in social learning environments that provide social interactions, in order to motivate farmers to change their practice. Schlindwein *et al*. (2015) offer an important statement when claiming that it is the experience of a crop model, not the model itself that often is the problem. Used as a learning tool in social interaction with colleagues or advisors and adapted to the practice in which it should be used, crop models and other AgriDSS can be utilised as intended and become valuable in practice – if the design permits.

A change of perspective from *knowledge transfer* to more *cooperative approaches* must also be considered by advisors. With increasing farmer competence, the function of advisors as information providers needs to change to a role as social learning partner or a facilitator of social learning. Considering the rapid development of technology in agriculture, advisors should also widen their area of competence and embrace AgriDSS more fully. Being a crop production advisor already demands dual expertise as agronomist and social facilitator. Adding a third competence, technology, could be challenging for some advisors and force them outside their comfort zone. However, as this thesis showed, social interactions are critical for technology use and farmers' care development, and advisors have a crucial role to play in this.

Different AgriDSS should be considered part of a wider agriculture knowledge information system involving different kinds of ICT systems, tools, artefacts and social learning processes. There are three critical components when developing AgriDSS in precision agriculture: the *hardware*, the *software* and the *orgware*. Once all three are considered, AgriDSS could become increasingly important components in sustainable intensification of agriculture, by ensuring provision of scientific knowledge and encouraging development of farmers' situated knowledge to support their care in practice. Participatory approaches are essential to avoid knowledge transfer and technology fix and for improving social interactions in all parts of the agricultural knowledge and information system, within precision agriculture and beyond.

6.5 Future work

To further develop this area of research, farmers' and advisors' opinions and needs in relation to AgriDSS must continue to be investigated, from both a technical and social perspective. In addition, participatory approaches should be applied in new projects involving farmers, advisors and researchers aiming to: 1) Investigate good strategies for AgriDSS use in precision agriculture practice from a social learning perspective, 2) investigate how different AgriDSS can be technically merged or synchronised in order to provide good systems of applications and functions in wider farming socio-technical system, 3) investigate strategies for AgriDSS development using the UCD methodology, and 4) develop models for increased knowledge exchange between advisors, considering usage of precision agriculture technology in advisory work, in order to support them in providing farmers' high quality advisory services.

A future that requires more competent farmers will also require higher levels and different forms of competence among advisors. Accordingly, a central issue for the agricultural sector must be to secure access to high-quality extension services, with social skills and competence in agriculture and precision agriculture technology.

Finally, in order to move agriculture along a sustainable intensification trajectory, precision agriculture and new AgriDSS are crucial. Thus work on developing and adapting new technology to farmers' needs must continue in increased cooperation between different stakeholders from the agricultural domain and with acknowledgment of farmers' situated knowledge.

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