The potential of a multi-criteria Decision Support System in the adoption of agroecological practices

A case-study in Southern Sweden

Adeline Langlet

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Swedish University of Agricultural Sciences, SLU
Faculty of Landscape Architecture, Horticulture and Crop Production Science (LTV)
Department of Biosystems and Technology
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Adeline Langlet

Supervisor:	**Thomas Prade, SLU, Department of Biosystems and Technology**
Assistant supervisor:	Bindu Sunilkumar, SLU, Department of Biosystems and Technology
Examiner:	Georg Carlsson, SLU, Department of Biosystems and Technology

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Swedish University of Agricultural Sciences
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Department of Biosystems and Technology

Abstract

Our globalised food system is facing numerous challenges with food demand expected to increase due to a growing population, and crops increasingly threatened by climate change. In this context, Digital Technologies (DT) have been promoted as one of the solutions to increase productivity and enable a better use of resources, while reducing the impacts of agriculture on the environment. However, there is an uneven distribution of these technologies among farmers and types of farming, with DT being primarily designed and adapted to large-scale conventional farming systems. At the same time, farms following agroecological principles have demonstrated high productivity and resilience, suggesting an opportunity to leverage DT in supporting a transition toward these practices. Some tools can support the adoption of more sustainable practices, such as the multi-criteria Decision Support System *Soil Navigator*, capable of assessing and providing recommendations of farm management practice to improve soil functions such as primary productivity, nutrient cycling, water purification and regulation, climate regulation and biodiversity and habitat provisioning. In the present study, *Soil Navigator* was applied to a case-study farm located in the South of Sweden in Scania, with the objective of evaluating the relevance and applicability of its management recommendations and determining whether these could support a transition to an agroecological production system, within the farm socio-economic context. A secondary objective of this study was to gather the perceptions of the use of the tool and other DT in general from farmers, policy makers, researcher and farm advisers to identify the limitations, opportunities, barriers and enabling conditions for the broader adoption of DT in agriculture. The findings indicate that Soil Navigator has the potential to provide a comprehensive assessment of the soil's performance, while suggesting management of practices that can align with the farmer's socio-economic context and values. Some limitations were identified, including the lack of specificity and adaptation of the recommendations provided to the Swedish context and the initial time investment required for data collection. Improved integration with existing technologies, customisation of the user interface, and recommendations adapted to the Swedish context could enhance the tool's relevance and level of acceptation. This case study highlights the potential of DT to support agroecological transitions when designed according to the 10 elements of agroecology developed by the FAO. The principle of co-creation and sharing of knowledge proved to be particularly important and can be integrated into the development of solutions by adopting a participatory approach, involving farmers from their concept to their validation and promotion among established or newly created networks. Further research is recommended to assess the scalability of Soil Navigator across different farm types and agroecological transition stages.

Keyword: Agroecology, Digital Technologies, Decision Support System, Transition

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Abbreviations

Abbreviation	**Description**
AI	Artificial Intelligence
A-WEAI	Abbreviated version of the Women's Empowerment in Agriculture Index
C	Carbon
CAET	Characterisation of Agroecological Transition
CAP	Common Agricultural Policy
CH_4	Methane
CO_2	Carbon dioxide
CSA	Community Supported Agriculture
DEX	Decision Expert
DSS	Decision Support System
DT	Digital Technologies
EU	European Union
GPS	Global Positioning System
IoT	Internet of Things
N	Nitrogen
N_2O	Nitrous oxide
PAT	Precision Agriculture Technologies
RA	Regenerative Agriculture
SLU	Swedish University of Agricultural Sciences
SN	Soil Navigator
SOCLA	Latin American Society for Agroecology
TAPE	Tool for Agroecology Performance Evaluation

Foreword

When I joined the Agroecology Master Program in 2023, I must admit that my knowledge of Agroecology´s main principles was limited. The system thinking approach was however one of its concepts that appealed to me instantly. Having worked for several years in large agro-industrial groups and institutions, I had almost resigned myself to be constantly confronted to silo thinking and the “reinvention of the wheel”. Having witnessed numerous anomalies in our food systems during my personal and work experience, I sometimes questioned the way these were addressed, often by applying short-term corrective actions while the underlying causes were overlooked. These last two years spent studying the discipline, science and movement of Agroecology pushed me to apply critical thinking and to widen the lens through which we analyse these issues. I hope now that I can better comprehend their systemic nature.

The idea for this thesis came from my personal interest in anything related to data and new technologies, but also in response to a perceived distrust of digital technologies among Agroecology practitioners. While these are now embedded into our daily lives, their benefit and potential barely questioned, they still appear somehow incompatible with the adoption of agroecological principles. On the contrary, I was convinced that, when used in the proper manner, Digital Technologies have the potential to assist farmers establishing complex and sustainable agroecosystems. While looking for an experiment that could test this assumption, I came across the research from Schreefel et al (2022) titled “How to make regenerative practices work on the farm: A modelling framework”. In this study, the authors tested the use of decision support systems to estimate the impacts of regenerative practices adoptions on a conventional dairy farm. I found the approach of simulating the application of sustainable practices on a farm particularly interesting in the context of a transition process, as it enables the famer to visualise how their farm could perform under a different management. This study became therefore a significant source of inspiration for the methodology developed for my research.

By the end of my research, my perception of the role of Digital Technologies in agriculture became more nuanced. In my view, it highlighted the importance of system thinking, especially when dealing with disruptive technologies, and illustrated the applicability of agroecological concepts even in technological solutions design. I hope that reading this thesis will allow you to also realise the opportunities that Digital Technologies can bring, and that a synergy with agroecological values is not only possible but necessary to make their respective benefits more accessible.

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1. Introduction

With the world population expected to grow to 10.3 billion within the next 60 years, it is crucial to strengthen our global food system by reducing food waste and improving productivity, while limiting the environmental impacts of agriculture (United Nations 2024; Tamburino et al. 2020). This need is becoming all the more urgent as food production faces threats from climate change, particularly in developing countries which are expected to suffer the most from deterioration in cultivation productivity with estimated yield losses between 7% and 23%, due to elevated temperatures, higher atmospheric carbon dioxide levels, and changes in water availability (Srivastava 2019; Yuan et al. 2024). Sustainable intensification driven by technologies are increasingly regarded as the solution to future food security crisis, allowing a maximisation of productivity through a better use of resources (Godfray & Garnett 2014; Tamburino et al. 2020; Rose et al. 2021).

The adoption by farmers of technologies such as Artificial Intelligence (AI), Big Data, the Internet of Things (IoT), and drones could help them adapt their practices, and design farm agroecosystems that are more resilient toward climate change (Ma & Rahut 2024). In parallel, the adoption of agroecological practices, including crop diversification, animal integration, soil organic carbon management and water conservation has been shown to increase the resilience of agroecosystem towards extreme climatic events (Altieri et al. 2015). Unfortunately, the current Digital Technologies (DT) used in farming are designed with a low emphasis on the environmental and social aspects of sustainability, and rather focus on improving the economic outcome of large scale conventional agricultural systems (Barnes et al. 2019; Rose et al. 2021). In addition, while DT could assist in the design of complex agroecological ecosystems that rely on the integration of a high number of crops, the lack of digital tools adapted to organic and/or agroecological farms and the high initial investment constitute major challenges to their adoption by these farmers (Giagnocavo et al. 2025).

Developed as part of the European research project LANDMARK in 2019, which aimed at developing a framework for soil management to enable sustainable food production in Europe, Soil Navigator (SN) is a Decision Support System (DSS) made available in open access. It provides recommendations and guidance to promote sustainable practices adapted to a wider range of farmers and could serve as a potential tool for agroecological farms (Debeljak et al. 2019). Before going further into the presentation of this tool, this section provides a brief overview of the increasing role of DT in agriculture, followed by a presentation on how this study plans to explore the use of SN in promoting the adoption of agroecological practices.

1.1 Digital Technologies in agriculture

1.1.1 A brief history of Digital Technologies in agriculture

Technological advancements have reshaped agriculture practices over time with the domestication of animal and the use of mechanised tools (Ikram et al. 2023). In recent history, agriculture went through two consequential technological evolutions with the industrial revolution in the late 18th century, and the green revolution which introduced the extensive use of chemical fertilisers, high yielding variety seeds and large-scale mechanisation (Basu & and Scholten 2012; Kerridge 1969). Since then, modern technologies have enabled farmers to greatly improve efficiency, productivity and sustainability (Ikram et al. 2023). Some of the most prominent technologies were the emergence of precision agriculture technologies (PAT) in the 1960s in the USA, correlated with the development of new statistical tools capable of handling spatial variability of soil nutrients coupled with grid soil sampling methodologies (Franzen & Mulla 2015). Variable-rate fertiliser applicator started to appear on the market later in the 1980s and 90s thanks to progress in Global Positioning System (GPS) technologies, satellite imagery and sensors using near-infrared spectroscopy. But it was only in the 2010s that a real uptake could be observed in growers, especially for machinery traffic control systems and yield monitoring. Precision farming is now seen as a potential solution to a more efficient use of inputs, such as nutrients and water, to maximise the productivity of the farmlands, while conserving resources (Franzen & Mulla 2015).

Systems modelling developed for agroecosystems appeared approx. 60 years ago as a methodology aimed to understand and predict overall performance of complex agroecosystems. Using agricultural systems science, the models aiming at studying agroecosystems behaviour consider the interactions between components of a system with one another, and with their environment, such as between agricultural production, natural resources and human factors (Jones et al. 2017). They have been increasingly used to replace expensive field experiments to study and estimate agroecosystem response, to develop sustainable land management strategies. They are now the main components of DSS that can be found in most farm management software, capable of providing site-specific recommendations for pest management, farm financial planning, management of livestock enterprises and general crop and land management (Jones et al. 2017).

The 2020s have seen the arrival of the latest technologies and advancements in data analytics, AI, machine learning, digital modelling and cloud computing. Also seen as an alternative to maximise productivity in agriculture, they have the potential to bring transformative changes to the whole food supply chain, to the point of being called the 4th agricultural revolution (da Silveira et al. 2021).

1.1.2 What Digital Technologies are used in agriculture?

In literature, the term “Digital Technologies” can be used to define a wide range of solutions associated with smart farming, precision farming and DSS (Hilbeck et al. 2022). Precision farming includes tools focusing on managing in-field variations with the support of GPS localisation, with the aim to optimise the use of resources while maximising outputs (Hilbeck et al. 2022). Abiri et al (2023) describe DDS in agriculture as smart systems that assist decision-making responding to specific objectives with actionable recommendations to the farmer. These decisions are based on information such as raw data, documents, personal knowledge and/or models. DSS can be categorised as data-driven, model-driven, communication-driven, document-driven, or knowledge-driven. Smart farming, often seen as one of the key drivers in the 4^{th} agricultural revolution or “Agriculture 4.0”, and the next step after precision farming, combines various technologies such as IoT, AI data analysis, chatting communities, sensors, drones and robotics (Rose et al. 2021; McCaig et al. 2023). Generally, the principal objective of these technologies is to make farming more cost effective and sustainable while maintaining or improving farm productivity (McCaig et al. 2023).

In the context of this study, it was decided to use the term “Digital Technologies” as a more encompassing term to include all the technologies mentioned above.

1.1.3 How are Digital Technologies used in agriculture today?

The deployment of DT in agriculture brought significant changes to agricultural practices following the green revolution. Some of the positive impacts noticed are linked to the emergence of automation using IoT and AI, making farming operations more efficient. According to McCaig et al (2023), reducing the amount of repetitive and monotonous tasks can improve mental wellbeing, enabling farmers to spend more time on strategic decision-making. It also greatly affected labour organisation at the farm, with the use of robots for seeding, sowing, irrigation, fertilisation, crop spraying, collecting, and shepherding, having the capacity to replace a significant number of workers (Jha et al. 2019). In addition, precision agriculture has been shown to effectively increase profitability via a cost effective use of resources and increased yield (Chen et al. 2009; Cheng et al. 2023). A more comprehensive study carried out on a wide range of DT used in agriculture available on the market in Europe indicated that these demonstrated mainly favourable effects on productivity and income and reduced environmental impacts (Anastasiou et al. 2024).

Despite these benefits, it is still difficult to assess the level of uptake of these technologies in agriculture, with surveys and studies either based on qualitative information or on samples lacking farm types representativity. A survey from the consulting company McKinsey (Ferreira et al. 2022) carried out on 5,500 farmers across the world reports a very heterogenous level of adoption, with Western countries being at the forefront. The survey shows that respectively 62% and 61% of the farmers surveyed from the European and North American continents are currently using or willing to adopt at least one technology, while only 9% of farmers from the Asian and Indian regions responded positively. Technologies such as management software and remote sensing were seen as the preferred entry point into integrating DT in their farming systems, especially in Western countries. However, the representativity of the sample used for the survey could be questioned as no breakdown by farm types (conventional versus organic) was provided. Overall, Abiri et al (2023) estimate that even with the latest progress, the use of technologies like big data and analytics, wireless sensor networks, and cyber-physical systems is still limited. In most cases, their use is still at the developmental stage and tools developed have not yet been released for commercial use. While no recent survey has been conducted on the level of adoption of DT in farming in Sweden, farmers are perceived as early adopters of automation and monitoring system, but the rate of innovation in agriculture and food processing is still estimated to be lower than in other sectors (OECD 2018).

The growing body of literature studying the adoption of DT in agriculture is mainly focused on Precision Agriculture Technologies (PAT) and shows adoption rates that vary greatly in Europe, with the general consensus being that small-scale farmers tend to use PAT less. Despite being promoted within the European Union (EU) Common Agriculture Policy (CAP) 2023-27 strategy, these technologies are still favoured by large-scale farms, motivated by profitability and return and not really adapted to small-scale operations due to high investment costs (European Commission n.d.). These would rather use user-friendly automation systems, aiming at reducing the farmer's workload (Barnes et al 2019; Gabriel & Gandorfer 2023).

Scale is not the only factor influencing the adoption of DT in farming. The farm type also plays a significant role with DT perceived as being more adapted to conventional farming, mainly due to a lack of adaptability of the technology proposed (Giagnocavo et al. 2025). A study, funded and mandated by the European Union's Horizon Europe research and innovation programme, mapped the existing and emerging technologies in Europe used in agriculture in 2024 and indicated that almost all commercial products (98.1%) were also relevant to organic farming (Anastasiou et al. 2024). However, Hilbeck et al. (2022) observed that these DT were not specifically designed to support agroecological or organic systems, or to facilitate the transition to such systems. When DT providers promote digital products as being ‘also’ applicable in organic systems, it is often presented as a secondary benefit.

Despite the limited technological solutions made available to organic and agroecological farmers, recent studies show that there is potential for technologies to take a more significant role in the strengthening of these agroecosystems (De Marchi et al. 2022; Hilbeck et al. 2022; Bellon-Maurel et al. 2022). At the farm level, agroecological agroecosystems are characterised by a high level of integration between all the different elements i.e. crop plants, soil, soil organisms, insects, environmental conditions and management practices (Gliessman 2015). These systems rely on a delicate balance between the inputs and outputs, maintained by biological synergies between its components (Wezel et al. 2009). Examples of beneficial integration of technology mainly include the use of drones and GIS systems to enable precision farming for the application of organic amendments or support precise sowing and intercropping (Gatti & Zanoli 2022). For example, soil monitoring technologies using satellite imagery, drones and sensors to adapt fertiliser application were being cited as being adopted by a high proportion of organic farms in Czech Republic and Slovakia, used on 70% and 75% of organic farms, respectively (Petrovic et al. 2025). There are opportunities to adapt the principles of precision agriculture to agroecology further than nutrient managements, such as water management and precision livestock tracking. Another area showing promises is the use of multi-objective decision-making systems, capable of assisting the farmer in managing the diverse objectives on its farm, which often tend to be multivariate as spanning across the three dimensions of sustainability (Bellon Maurel et al 2022).

1.2 To Soil Navigator, a multi-criteria Decision Support System

The Soil Navigator tool provides a good example of how a Decision Support System can be used at the field scale on a farm. Developed as part of the European research project LANDMARK, aiming at creating a scientific framework for the quantification and management of soil performances, the tool, based on multi-criteria decision models, is capable of assessing five soil functions simultaneously and provide recommendations of management practice to improve these functions based on the end-user priorities (Debeljak et al. 2019). The soil functions assessed are:

1) Primary productivity
2) Water purification and regulation
3) Climate regulation and carbon sequestration
4) Biodiversity and habitat provision
5) Nutrient cycling

This tool was developed to fill to a gap in technological solutions on the market, which typically can assess only one function at a time and often focusing on the productivity performance of the soil. It was also designed in response to the observed low level of adoption of these tools, compared to the number available and accessible at the time SN was developed in 2019, linked with a lack of involvement of the end-users in their conception and design. The development and validation of SN included therefore the active participation of end-users identified as farmers and advisers, to increase trust and acceptance. In open access and presenting a simple user interface, it is advertised as being easily accessible and adaptable to multiple farm types (Debeljak et al. 2019).

In addition to providing an integrated assessment of the five soil functions, it also demonstrates the diverse trade-offs between these functions, often unknown to the farmers. For example, Bagnall et al. (2021) indicate that the perceptions of the relationship between soil health and crop yield range widely among farmers, likely because of underlying biophysical complexity as well as social and economic issues. These trade-offs and synergies can be complex to understand but this understanding is crucial for effective soil ecosystems (Zhao et al. 2022).

Being open access, having a user-friendly interface and requiring no prior training made SN an appropriate case for examining the role of digital tools in facilitating the adoption of agroecological practices.

1.3 Soil as an entry point into the adoption of agroecological practices

Soil health is crucial to maintaining productivity and ensuring food security by supporting crop yield, agroecosystems resilience and farmer profitability (Bagnall et al. 2021). It is the basis of our food production system, with an estimated 95% of the food production relying directly or indirectly on soils (FAO 2015). Soils also provide a wide range of ecosystem services to society, as summarised by Shulte et al (2014) and as incorporated into the SN framework. These services include primary productivity, water purification, carbon sequestration, habitat for biodiversity and recycling of nutrients. As the cornerstone of global food security, maintaining soil health can offer a pathway toward the adoption of sustainable agricultural practices.

Practices following regenerative agriculture (RA) concepts place soil health as one of the fundamental principles. Going back to the origins of RA, Giller et al. (2021) report how Richard Harwood, an agronomist and Director of Rodale Research centre, an institute at the forefront of the regenerative movement in the 1980s, summarised the RA philosophy in 10 points, with soil playing a central role, particularly in points 2 and 3:

2. "Agriculture should increase rather than decrease soil productivity, by increasing the depth, fertility and physical characteristics of the upper soil layers."
3. "Nutrient-flow systems which fully integrate soil flora and fauna […] are more efficient and less destructive of the environment and ensure better crop nutrition. Such systems accomplish a new upward flow of nutrients in the soil profile, reducing or eliminating adverse environmental impact. Such a process is, by definition, a soil genesis process."

While there is still no common scientific definition of regenerative farming, Schreefel et al. (2020) identified similar themes across the different definitions proposed in the literature. These themes converged on the enhancement and improvement of soil health, underscoring its importance as an objective of RA. Later in a separate study, Schreefel et al. (2022) further demonstrated how the soil functions used as soil performance indicators in Soil Navigator can actually reflect regenerative agriculture principles: a) improve economic prosperity and "primary productivity", b) improve nutrient cycling and "nutrient cycling", c) improve water quality and "water purification and regulation", d) alleviate climate change and "climate regulation", and e) improve soil health and "biodiversity and habitat provision" (Schreefel et al. 2022). Their findings suggest that using Soil Navigator to assess and improve soil health can serve as an entry point for the adoption of regenerative practices on a farm.

It is important to acknowledge that RA principles do not always fully encompass those of agroecology. RA can indeed be perceived as reprising the agronomic components of agroecology such as "soil and ecosystem restoration, reliance on biological interactions and ecosystems services, integration of domestic plants and animals, efficient used of the photosynthetic potential of annual and perennial combinations" (Tittonell et al. 2022). However, RA places less emphasis on socio-economic dimensions of sustainability and tends to question the current agricultural model less, overlooking the political dimensions of agroecology (Schreefel et al. 2020; Tittonell et al. 2022; Aguilar & Paulino 2025). This distinction is also reflected in the findings from Schreefel et al. (2022), which demonstrate how the adoption and transition toward RA depends on their capacity to contribute positively to other sustainability aspects such as farm profitability and farmer's wellbeing.

By promoting sustainable practices to improve soil health and providing recommendations in line with regenerative principles, the SN tool has the potential to support farmers in either increasing the agroecological level of their farm or provide an entry point toward a transition process. It is however essential to also evaluate the impacts these recommendations would have on socio-economic indicators to ensure a comprehensive approach that include all dimensions of sustainability.

1.4 Objectives and research questions

The aim of this study will be to explore the potential of the Soil Navigator tool as a Decision Support System in promoting the adoption of sustainable practices and its contribution toward increasing the agroecological level of farm. This will be achieved by applying the tool on a case-study farm located in Scania, South of Sweden, and assessing its effectiveness in providing solutions to enhance soil health, as well as its user-friendliness and the overall perception by the farmer. To assess the relevance of the tool in the farm context, the secondary objective of the thesis is to evaluate the impacts of the implementation of the suggested practices on socio-economic factors at the farm level.

The research findings will contribute to addressing the following questions:

1) Would the use of this tool facilitate the adoption of more sustainable farming practices and increase the agroecological level of the farm?
    a. What would the expected impacts of applying the proposed solutions be on the farm socio-economic context?
    b. What are the barriers in the use of digital technologies, and the tool as perceived by the farmer and stakeholders in contact with farmers?
    c. What factors would facilitate the adoption of the tool in the farm context?

2. Methods

In order to fulfil the research objectives, a methodology was developed to replicate the process that a farmer would have gone through with an adviser to collect the data and information required to run SN. The recommendations of management practices obtained are then reviewed and evaluated to determine the best approach to increase the desired soil health function according to the farmer's priority. It was also deemed important to capture the views of the farmer and various stakeholders regarding the tool, placing them within the wider context of the current use of DT in farming. Given the different elements required, the work was divided into separate tasks represented in Figure 1.

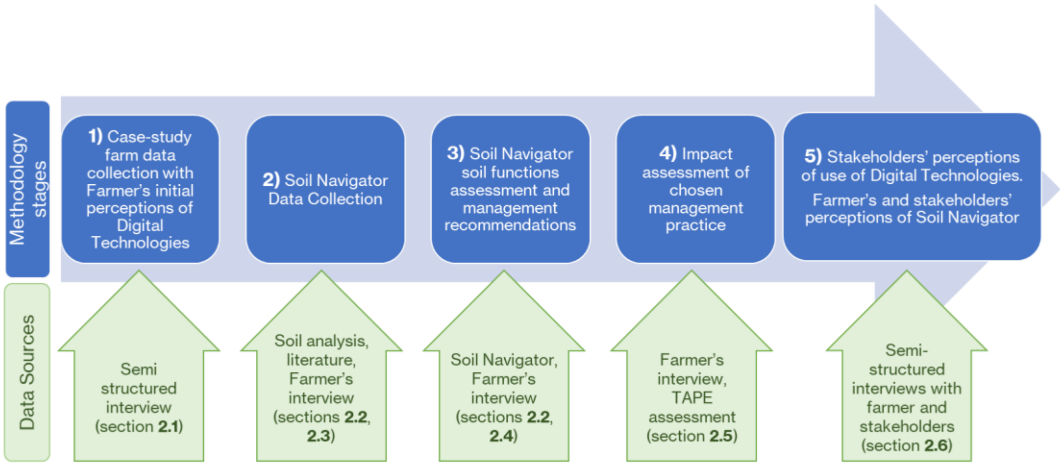

Figure 1: Diagram describing the methodology framework divided into stages. Data collection methodologies are represented by the green arrows.

The first phase consisted of the experimental application of the DSS on a case-study farm to assess the relevance and capacity of the tool (stages 1 to 4 in Figure 1). The second phase of the data collection included the collection of the perceptions of the use of DT in agriculture in general, and SN in particular, by the farmer, and stakeholders such as researchers and advisers via carrying semi-structured interviews (stages 1 and 5 in Figure 1). Data sources and methodology tools used at every stages are indicated by the green arrows and refer to the associated sections where these are further described.

2.1 The case study

A semi-structured interview was carried out to collect the main information on the case-study farming system. This method was chosen as it allows for a more conversational questioning of the farmer across specific themes. It was also expected that this interview method, considered as a better way to learn about someone's motivations, would assist in observing the farmer´s attitudes towards his practices and environment (Walsh 2019). The interview guide (Appendix 1) was developed based on the Hawkesbury Peanut Model system analysis to help identify the main elements of the farming system and determine the main topics to assist in collecting information (Bawden et al 1984).

2.1.1 Case-study farm

The farm selected for this case study is a 60 ha organic farm located in Scania, producing hemp seeds, that are sold as is or further processed into oil, and other crops such as emmer wheat, green peas, rye and various vegetables. The farm is certified organic by the certification system KRAV (KRAV 2024) since 1999, the farmer took over the farm from their parents in 2005 and started to sell vegetables online and produce hemp in 2007.

The main farm activities:

The farm gets the greater part of its income from the production and distribution of vegetables boxes through a Community Supported Agriculture (CSA) subscription, working all year round. The organic vegetables are either produced on the farm or sourced from various suppliers in Europe during winter. In addition to the production of hemp products such as seeds and flour and other crops for human consumption, the farm activities also include a shop used to sell the farm products and other food products locally sourced, a café, and facilities available for rentals.

Cropping system:

The cropping area occupies 40 ha across 6 fields, of which 5-10 ha are dedicated to the production of vegetables for the CSA scheme, and 20 ha of pasture for the grazing of horses and goats, mainly kept as pets. On the arable land, the farm operates a seven-year crop rotation as follows: hemp, vegetables, green peas, emmer wheat, ley grass (“*vall”* in Swedish) used as fodder for the animals (Jordbruksverket 2025), flower mix used for greening measures and lastly rye. The farm also processes hemp seeds from five local organic producers to complement its own production. While compost and cow manure sourced from local farms are used as fertilisers, as a rain-fed cropping system, the main input costs identified by the farmer were crop seeds and diesel.

The farm environment:

The farm is located close to habitations and surrounded by natural reserves and another inactive farm. The farmland also includes two wetland areas that the farmer maintains to preserve the biodiversity of the farm’s agroecosystem. The soil texture is mostly sandy, with glaciofluvial sediments from the ice age, but most of the land is covered with fluvial sediment, which the farmer deemed low in nutrients but favourable for the growth of vegetables (Figure 2) (SGU 2020).

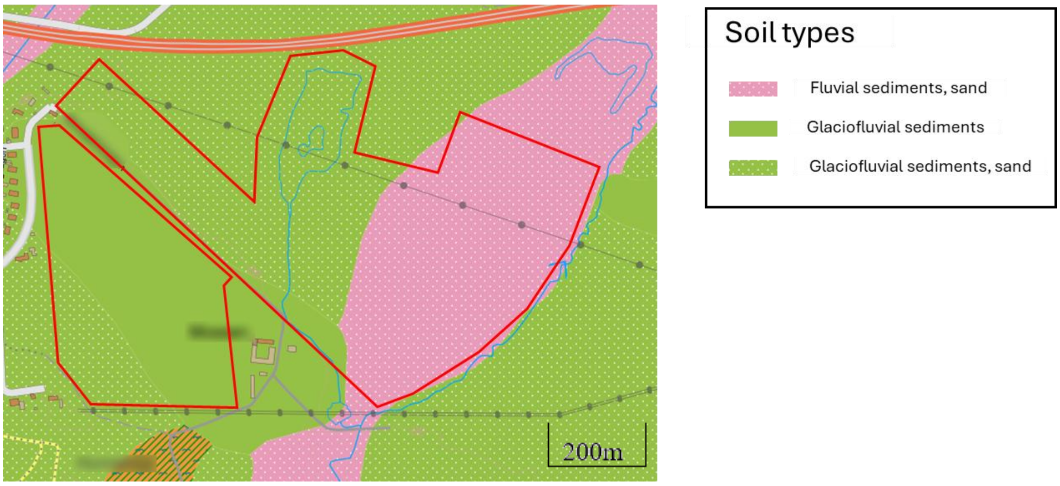

Figure 2: Soil map of the farm area delimited by red lines. Anonymised and modified from Jordarter©SGU.

Main values and prospects:

Initially, the farm was converted into organic farming by the previous owners as an absolute condition *"to produce food in a non-toxic environment, to preserve [the farm for] future generations, and care for the soil"*. The current owner would like to further develop and diversify their business to *"further engage with the public and raise awareness on where food is coming from, using art and music"*. Their plans include the creation of five business units corresponding to different activities on the farm: 1) a cropping system following regenerative principles, 2) a café serving organic foods, 3) the organisation of cultural events, 4) the development of a range of products derived from hemp seeds, and 5) the continuation of the online CSA subscriptions. In addition, they aim to create a *"biodiversity oasis"*, with the objective of attracting a variety of endemic plants and insects.

The farmer identified several future challenges that could hinder the continuation of their activity: a) the potentially increased vulnerability of the agroecosystem to drought due to climate change, b) a lack of funding to expand their business, and c) changes in regulations that may reduce support for organic farming as government priorities shift.

2.2 Description of the multi-criteria decision support system Soil Navigator

In this section, the basic functions and design principles behind the DSS Soil Navigator modelling tool are described. As a multi-criteria DSS, SN is designed to qualitatively assess and provide farm management recommendations to improve five key soil functions at the field level (Debeljak et al. 2019). While the tool was not validated in Sweden, the assumption was made that its use was still valid and relevant for the pedoclimatic conditions of the Southern Sweden region. This is based on the fact that the pedo-climatic conditions were similar between a continental climate in Danmark, where the tool was validated, and the South of Sweden (Metzger et al. 2005).

2.2.1 The five soil functions

The tool assesses five key soil functions, as these are considered to play a critical role in the provision of ecosystem services in an agroecosystem, and for the production of goods and services (Schulte et al. 2014). Table 1 lists their definition as described in the LANDMARK project and SN context.

Table 1. Soil functions definitions as cited in "Glossary of terms for use in LANDMARK", Shröder et al. (2018).

Soil function	Definition
Primary Productivity	The capacity of a soil to produce plant biomass for human use, providing food, feed, fibre and fuel within natural or managed ecosystem boundaries.
Water Purification and Regulation	The capacity of a soil to remove harmful compounds from the water that it holds, and its capacity to receive, store and conduct water for subsequent use, and the reduction of consequences of prolonged droughts and risks of flooding and erosion.
Climate Regulation	The capacity of a soil to reduce the negative impact of increased greenhouse gas (i.e., CO_2, CH_4, and N_2O) emissions on climate, among which its capacity to store carbon.
Nutrient Cycling	The capacity of a soil to receive nutrients in the form of byproducts, to provide nutrients from intrinsic resources or to support the acquisition of nutrients from air or water, and to effectively carry over these nutrients into harvested crops.
Biodiversity and Habitat	The multitude of soil organisms and processes, interacting in an ecosystem, making up a significant part of the soil's

natural capital, providing society with a wide range of cultural services and unknown services.

2.2.2 Soil Navigator structure

The SN DSS's structure is divided into two main parts: the first part is designed to assess the five soil functions i.e. primary productivity, water purification and regulation, climate regulation, soil biodiversity and nutrient cycling, and in the second, soil management practices are identified and recommended to improve these functions, according to the assessment in the first part and the user's goals and priorities (Debeljak et al. 2019). These two sets of outputs are the results of input information related to a farm field going through decisions models (Figure 3).

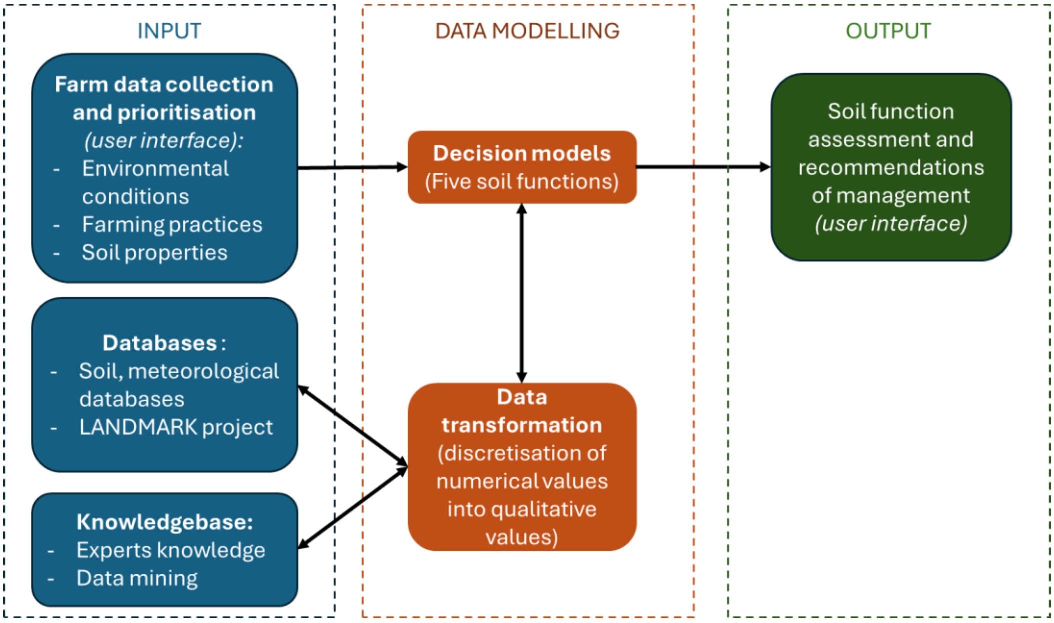

Figure 3: Simplified methodological structure of Soil Navigator (adapted from Debeljak et al. 2019)

Via the user interface accessible on the SN website (Soil Navigator n.d.) the end user enters information related to the farm field i.e. farm location, farm management, climate, topography and soil characteristics. Other sets of information necessary to the assessment and recommendations consist of: a database collating soil and meteorological databases; soil, environment and management data collected as part of the LANDMARK project; and a knowledge base, developed with groups of scientists from the LANDMARK project, as well as empirical data using data mining and machine learning from previous studies (Trajanov et al. 2015, 2018; Bondi et al. 2018; Debeljak et al. 2019).

From these data, the decision models are then able to assess the five soil functions and generate recommendations aiming at improving the functions prioritised by the end user (Debeljak et al. 2019).

2.2.3 Data input and transformation

The models use three categories of data input to assess the soil functions: environmental conditions (climate and topography), soil properties (chemical, biological, and physical properties) and current farming practices (e.g., crop management, soil amendments, fertilisation) (Debeljak et al. 2019). The user interface displays fields for data entry that are conditional to the farm type and management practices selected. In the case of an organic crop farm, there are a total of 70 data points to be filled in per field, of which 29 relate to soil properties (Table A2).

To ensure that the models are fed with data in a suitable format, input data go through data transformation including data discretisation, where numerical values are converted into qualitative values, derivation of synthesised input attributes, and attribute harmonisation (Figure 3) (Debeljak et al. 2019). To ensure data format consistency, the end user must select the correct ranges of values displayed as input options in SN when providing numerical information such as yield, precipitations, or soil pH for example.

2.2.4 Decision models

The decision models used to score all five soil functions are based on qualitative multi-criteria decision models to allow their simultaneous assessment. These were built using Decision Expert (DEX) integrative technology, a hierarchical, rule-based multi-criteria decision modelling method, which for SN was based on attributes related to each soil function with a set of nominal values represented by a “low”, “medium”, “high” scale for example (Bohanec 2022). These are then sorted into a hierarchical organisation resembling a decision tree, with high-level attributes nominal values depending on lower-level attributes nominal values. Figure 4 below shows as an example the top part of the climate regulation soil function attribute hierarchical organisation. A detailed version of the decision model structure developed for the climate regulation soil function is provided in Appendix 3.

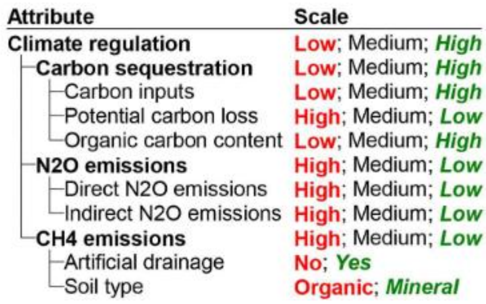

Figure 4: Top part of the hierarchical organisation of attributes related to the climate regulation and carbon sequestration soil function. The attributes values are ordered, with red values representing negative impact and green values positive impact on the overarching attribute (Debeljak et al. 2019:5).

The combination of hierarchical organisation and decision-rules enables to not only assess the soil functions but also to evaluate the impact of alternatives (by changing the value of one of attribute values for example) by providing what-if analyses. An example of what-if analysis integration rules used to assess nitrous oxide (N_2O) emissions is given in Table 2.

Direct N2O emissions	Indirect N2O emissions	N2O emissions
High	High	**High**
High	Medium	**High**
High	Low	**High**
Medium	High	**Medium**
Medium	Medium	**Medium**
Medium	Low	**Medium**
Low	High	**Medium**
Low	Medium	**Low**
Low	Low	**Low**

Table 2: Integration rules for the integration of direct and indirect N_2O emissions into N_2O emissions (adapted from Debeljak et al. 2019:5).

This analysis is used to select soil management measures aiming to improve the final score of a soil function if required.

By using the DEX methodology, the models are also able to manage missing values, using probabilistic or fuzzy distribution of attribute's values (Debeljak et al. 2019).

2.2.5 Outputs

From the information on the farm's field, the tool assesses the five soil functions performance, giving them a score of "low", "medium" or "high". The end user then has the possibility to set the soil performance improvement ambition for each field by indicating on the user interface the desired level of performance (“low”, “medium” or “high”) as well as a level of importance (from “very low” to “very high”) for each soil function. This allows the end user to prioritise between the soil functions and enables the model to select management practices aiming to improve the most important function, while ensuring the other soil functions are not negatively impacted. After selecting the desired state and priority for each soil functions, the end user is given a list of management recommendations that aim to improve the specified soil functions for the analysed field (Debeljak et al. 2019).

2.3 Soil Navigator data collection

As indicated in section 2.2.3, in addition to environmental and farm management practice information, a great part of the data collection consisted in gathering soil characteristics data. These were collected either from the interviews with the farmer, from the literature, or from open data sources such as weather data provided by the Swedish Meteorological and Hydrological Institute for climate data for example (SMHI n.d.). Some of the soil characteristics were provided by the farmer from previous soil testing results as part of a soil mapping carried out in 2016 by a third-party laboratory. However, these were not sufficient to inform all soil characteristics data points and related to only two fields out of a total of six currently used at the farm. Due to this limitation, it was decided to focus the experiment on these two fields and complete the soil characteristics data with additional soil sampling and analysis.

2.3.1 Soil sampling

The soil sampling was carried out in on the 6th of February 2025 at 9am on two fields, identified as 7A and 7B, following a protocol provided by the Swedish Board of Agriculture (Jordbruskverket 2010). The weather conditions during the sampling were sunny with an average temperature of 3°C. Sample points were predetermined to ensure that there was one sample point per hectare for each field (Figure 5):

Figure 5: Soil sampling map representing the sample points for fields 7A and 7B and their identifiers. Generated with the application Google My Maps (2025) prior to soil sampling.

For each sample points, 10 subsamples were randomly taken in a radius of 3 to 5 m surrounding the geolocation of the sample point, at a depth of 0-25cm. This depth was recommended by the SN tool for soil analysis. These subsamples were mixed in a plastic bag, sealed then stored at 4 °C within a few hours after sampling.

For the analysis of the bulk density, one sample was taken per sampling point, following the core method, using a volumetric cylinder pressed into the soil (Gatea et al. 2018). The soil collected inside the cylinder was then carefully transferred into a plastic bag, sealed and stored at 4 °C within a few hours after sampling.

2.3.2 Soil analysis

The additional soil analysis performed to complete the soil characteristics data are listed in Table 3. Counts of earthworms, nematodes, microarthropods and enchytraeids are also required to provide exhaustive soil biology information. However due to the sampling being performed during the period of low activity for earthworms, and time constraints for analysing the soil richness and abundance in nematodes, microarthropods and enchytraeids, it was decided to rely on the total bacterial and fungal biomass as indicators of soil biology (Lavelle 1988). To do so, a phospholipid fatty acid (PLFA) and neutral lipids fatty acid (NLFA) analysis was attempted to measure the total microbial biomass (Li et al. 2025).

Table 3. List of soil characteristics data input with respective source and methodology used for the data collection

Data field	Source	Data Collection Methodology
Soil type	Farmer	Interview
Soil texture	Farmer	Interview
Clay content	Soil analysis February 2025	The Cornell Framework 2017, protocol adapted from Kettler et al. (2001).
Soil crusting/capping	Farmer	Interview
Thickness of organic layer	Farmer	Interview
Potential rooting depth	Farmer	Interview
Groundwater table depth	Farmer	Interview
Soil organic carbon	Soil Navigator	The soil organic carbon content was estimated by dividing the soil organic matter content by 2 (Soil Navigator n.d.)
Soil organic matter	Soil analysis February 2025	The Cornell Framework 2017, protocol adapted from Broadbent (1965).
Soil bulk density	Soil analysis February 2025	Gatea et al. (2018)
Drainage class	Farmer	Interview
Soil pH	Soil analysis August 2016	
Cation exchange capacity	Previously available data	Markinfo (2002)
Soil C:N ratio	Soil analysis February 2025	Chevalier et al. (2017)
Soil N:P ratio	Soil analysis February 2025; Soil analysis August 2016	Chevalier et al. (2017)
Plant available P	Soil analysis August 2016	
Plant available K	Soil analysis August 2016	
Plant available Mg	Soil analysis August 2016	
Salinity	Soil analysis February 2025	The Cornell Framework 2017, protocol adapted from Rhoades 1982.
Bacterial biomass	Soil analysis February 2025	PLFA/NLFA analysis (Li et al. 2025)
Fungal biomass	Soil analysis February 2025	PLFA/NLFA analysis (Li et al. 2025)
Earthworm richness	*Not measured*	
Earthworm abundance	*Not measured*	
Nematode richness	*Not measured*	
Nematode abundance	*Not measured*	
Microarthropod richness	*Not measured*	
Microarthropod abundance	*Not measured*	
Enchytraeid richness	*Not measured*	
Enchytraeid abundance	*Not measured*	

As the SN tool requires a single value per attribute per field, the average of the soil analysis results across all samples was calculated after removal of outliers using a z-score test (Senthamarai Kannan et al. 2015).

Not all results from the additional soil analysis were used in the tool. Due to incorrect storage conditions used for the samples, the PLFA/NLFA analysis generated results on soil microbial biomass that were deemed not representative of the actual microbial biomass of the field at the time of sampling. It was therefore decided to not use these results as data input in SN and rely instead on the tool's capacity to handle missing values. Missing biodiversity data were replaced in this case by values from linear prediction models based on other attributes present in the model, regression analysis carried out in previous studies in the Netherlands and France, and other spatial models (Rutgers et al. 2018).

2.3.3 Other data points

The other data points related to the agroecosystem, farm management and environment were collected either from interviews with the farmer or from literature. References used to inform these data inputs are listed in Appendix 2.

2.4 Soil Navigator outputs

2.4.1 Assessment and optimisation of soil functions

After referencing all the available data points on the SN web application, the tool was initially run a first time to provide an assessment of the five soil functions. Using a participatory approach, the results of the assessments were discussed with the farmer to determine which function would need improvement. The farmer then ranked the soil functions by priority. This ranking was used to select the objectives and constraints for each soil function, which were then inputted into the optimisation model. The results provided a list of management practices to implement on the field to improve the selected soil functions.

2.4.2 Scenarios tested

Two scenarios were tested, corresponding to different sets of data inputs with varying level of completeness to evaluate the effect they would have on the assessment and optimisation steps:

- Scenario 1: A complete data set using additional soil analysis, excluding soil biodiversity information.
- Scenario 2: A data set without the additional soil analysis, relying only on results from the previous soil analysis from 2016, mandated by the farmer as part of regular soil mappings.

Table 4 lists the SN data input fields related to soil characteristics used in each scenario. Due to the unavailability of bacterial and fungal biomass indicators, these were left blank in both scenarios.

Table 4. List of soil characteristics data input and respective sources used under each scenario. An "x" is indicated when the data field was left blank.

Data field	Scenario 1	Scenario 2
Soil type	Farmer	Farmer
Soil texture	Farmer	Farmer
Clay content	Soil analysis February 2025	Soil analysis August 2016
Soil crusting/capping	Farmer	Farmer
Thickness of organic layer	Farmer	Farmer
Potential rooting depth	Farmer	Farmer
Groundwater table depth	Farmer	Farmer
Soil organic carbon	Soil analysis February 2025	Soil organic matter/2
Soil organic matter	Soil analysis February 2025	Soil analysis August 2016
Soil bulk density	Soil analysis February 2025	x
Drainage class	Farmer	Farmer
Soil pH	Soil analysis August 2016	Soil analysis August 2016
Cation exchange capacity	Literature	Literature
Soil C:N ratio	Soil analysis February 2025	x
Soil N:P ratio	Soil analysis February 2025; Soil analysis August 2016	x
Plant available P	Soil analysis August 2016	Soil analysis August 2016
Plant available K	Soil analysis August 2016	Soil analysis August 2016
Plant available Mg	Soil analysis August 2016	Soil analysis August 2016
Salinity	Soil analysis February 2025	x
Bacterial biomass	x	x
Fungal biomass	x	x

2.5 Estimation of the socio-economic impacts of practices recommended by Soil Navigator

The methodology used to evaluate the impacts the implementation of the practices suggested by SN would have on socio-economic factors consisted in establishing a baseline prior to the application of these practices. Their impacts were then assessed either quantitatively or qualitatively based on a set of indicators.

The baseline assessment was carried out using the Tool for Agroecology Performance Evaluation (TAPE), which evaluates the current level of transition of the farm to agroecology (FAO 2019). The TAPE tool also allows for the assessment of the agroecological level of other key aspects of the agroecosystem, such as diversity, synergies or resilience and provides a more comprehensive evaluation of the overall impacts on the farms' environmental, social and economic sustainability.

The assessment follows a stepwise approach, based on two core steps evaluating the agroecosystem against a set of defined criteria (steps 1 and 2), and completed by a preliminary description of the farm systems and context (step 0) (FAO 2019):

- Step 0: Description of the farm production systems, household, and environment.
- Step 1 - Characterisation of Agroecological Transitions (CAET): scoring of the farm agroecosystems against a set of indicators based on the 10 elements of agroecology, using a descriptive scale (Table 5).
- Step 1bis – Transition typology: scores from the CAET assessment are aggregated to provide an overall score expressed as a percentage, representing the stage the farm is in the transition process. As a guide the following categorisation was used:
    - Score < 50 percent: non-agroecological system
    - Score from 50 to 70 percent: in transition to agroecology
    - Score > 70 percent: advanced agroecological system
- Step 2 - Core performance criteria: assessment of the performance of the farm system based on 10 core criteria (Table 5). Indicators such as farm net income, productivity and added value, were used to evaluate the impacts of the practice recommended by SN on the farm economic factors.

Table 5: List of indicators used for steps 1 and 2 of the TAPE assessment, CAET and Core performance criteria (FAO 2019)

Characterisation of Agroecological Transitions Indicators	Core performance criteria
Recycling	Secure land tenure
Responsible governance	Productivity
Synergies	Income
Diversity	Added Value
Co-creation and sharing of knowledge	Exposure to pesticides
Resilience	Dietary diversity
Human and social values	Women's empowerment
Culture and food tradition	Youth employment
Efficiency	Agricultural biodiversity
Circular and solidarity economy	Soil Health

The farm was evaluated against all the indicators indicated in Table 7 apart from the core criteria “Dietary diversity”, which was deemed irrelevant for the context of this study. In addition, the TAPE assessment can be completed by participatory interpretation of the results. In this study, the findings were shared and discussed with the farmer to evaluate the relevance of the analysis and assess the potential impacts of adopting the practices recommended by SN on the initial assessment.

The data and information required to carry out the TAPE assessment were gathered through several interviews with the farmer. When quantitative data were unavailable, a qualitative assessment was carried out with the farmer for the establishment of the baseline, and for the assessment of the impacts of the recommended practice on the CAET indicators and core performance criteria.

2.6 Semi-structured interviews on the use of Digital Technologies in farming in Sweden

To answer the first research question “What are the barriers in the use of digital technologies and the tool as perceived by the farmer and advisers?”, semi-structure interviews were conducted with five interviewees, who had regular contact with farmers as part of their profession, and/or with knowledge of existing digital technologies used in agriculture in Sweden. The interviewees profiles were the followings:

- A researcher specialised in precision agriculture technologies,
- A farm adviser working with organic farmers,
- A farm adviser specialised in regenerative farming working with conventional and organic farmers,
- A policy analyst from the Swedish Agricultural Board,
- Two project managers from the Swedish Agricultural Board in charge of advisory services and of farm management applications and tools made available to advisers and farmers.

The objective of these interviews was to collect data on the perceptions on the current level of uptake of DT in general in farming in Sweden, identify risks and barriers to the use of DT in farming, and gather feedback on the Soil Navigator DSS. For the purpose of the interviews, the term Digital Technologies was defined as “electronic tools used for data collection, storage, processing or communication”.

The interview guide included open and closed questions and was organised around main themes and follow-up questions. This method was used to allow the exploration of the themes identified, while providing a structure to ensure consistency between the interviews (Kallio et al. 2016). The first part of the questionnaire (Appendix 3) focused on general DT perceptions and was developed using key themes used in a survey from the study “A multi-stakeholder perspective on the use of digital technologies in European organic and agroecological farming systems” from Giagnocavo et al (2025). Some of the themes were the perceived adaptation and adoption of DT to non-conventional farms, barriers to the use of DT in farming, opportunities and risks associated with the use of DT in farming.

In the second part of the interview, the tool was presented to the interviewees, following the different steps taken with the farmer, with presentation of the user interface and the final display of soil functions scoring and management recommendations. The aim of the presentation was to gather the interviewees’ point of view on the relevance of the tool in a farming context in Sweden, as well as identify its perceived benefits, limitations, and potential improvements.

The interview guide used was different from that for the farmer, where the general perceptions of DT were collected before using the tool. The final interview with the farmer included similar questions on general perceptions of the tool as with the other interviewees but included questions to determine if the use of the tool changed this general perception.

All interviews were recorded with the interviewee’s prior consent. Audio recordings were used to complete and verify the accuracy of the notes taken during the interviews, and to generate the transcripts for the citations used in this report.

3. Results

3.1 Perceptions of Digital Technologies in agriculture

3.1.1 Farmer

Current level of use and awareness of Digital Technologies in farming:

The farmer has been using DT to sell their products online for 20 years but does not use them to assist in the farm operations. They are aware of precision farming techniques used to track animals that are using GPS for example but not necessarily of other types of DT available to farmers such as farm management systems or DSS. They do not get a lot of information on these kinds of tools since they are not part of the *"right"* farm networks, as in those associated with larger conventional farms. While they see the potential of combining AI and new technologies with regenerative farming, they feel unprepared to adopt these currently, partly due to a lack of confidence in their ability to upskill themselves and would therefore have someone else using these such as an advisor.

Benefits and opportunities:

The farmer estimated that the main benefits they get from DT for now came from the use of social networks and e-commerce platforms. These were seen as very beneficial to reach out directly to consumers and to find new business opportunities. This observation is in concordance with the farmer's current focus on raising consumer awareness on current issues with the food system and promoting more sustainable practices. They also identified several areas where DT could be advantageous, particularly in automating farming operations to respond to current issues. The examples given were:

- Installing an automated irrigation system that would be connected via wireless technologies (Wi-Fi), to mitigate drought risks during the summer months.
- Addition of a robot powered by solar panels to weed the vegetable garden. This wish came from the need to reduce physical labour and the difficulty to hire personal to assist on the farm during the summer months.

Risks:

The perceived risks associated with highly digital farming systems were the vulnerability of connected technologies to external threats, such as hacking. The farmer was also concerned about perceived potential effects of wireless networks on the biodiversity on the farm leading to some suspicion regarding its impacts. Ethical and sustainability issues related to technology were also highlighted. The high energy consumption associated with AI was a concern since it required significant resources, which might lead to overreliance on less sustainable energy sources. They also emphasised the need to ensure that technologies are produced ethically, especially in relation to child labour to avoid using tools *“based on kids producing equipment in a foreign country”*.

Barriers:

The principal barriers identified by the farmer were the lack of time to upskill themselves and the associated costs with acquiring these technologies. They also mentioned that investments done to adopt these might not be profitable in the long term.

Enablers:

According to the farmer, the factors that would facilitate the adoption of DT on their farm would be greater government support through subsidies. This would enable the farm to acquire the necessary equipment and employ someone to manage this part of the farm operations. Finally, while recognising that DT can be a useful addition to the farmer’s tool kit, they should be *“grounded into the farmer’s own interests”* to prevent adding to the existing administrative workload and to ensure the tool doesn't replace the farmer's observational skills.

3.1.2 Stakeholders

Different levels of uptake depending on the farm type:

The current level of uptake of DT in agriculture in Sweden is hard to assess but there is a clear disparity among farmers according to most of the interviewees. While a slight increase is perceived overall, it is mainly observed for large-scale conventional farms, especially regarding precision agriculture. Referring to survey data from a study from 2024, an interviewee noted that 80% of the total farmland in Denmark was managed using precision agriculture. Although the level of adoption in Sweden was considered slightly lower, the use of crop sensors, either using satellite data or mounted on tractor, was believed more widespread in Sweden, with approximately 50% of the area cultivated for winter wheat using these technologies for nitrogen management.

Respondents mentioned a variety of DT available to farmers in Sweden such as “VERA”, developed and maintained by the public organisation Greppa Näringen, that proposes a variety of technological solutions for general farm planning, plant nutrient balance, soil health assessment, with the application “Hur mår min jord?”, and carbon sequestration estimations (Greppa Näringen 2025; Greppa Näringen n.d.). Several commercial tools available on the Swedish market are mainly focused on precision farming and are either based on satellite imagery (Dataväxt), on sensors, handheld or installed on tractors (Yara), or actual soil sampling (Markkartering.se) (Dataväxt, n.d.; Yara 2025; Markkartering.se n.d.). However, apart from nitrogen handheld sensors which can be used as part of a consulting session, an adviser estimated that the level of use of these tools by organic farmers was rather low. In addition, it was generally perceived that the level of interest was higher among the new generation of farmers compared to older farmers, especially when these tools were integrated into their education programmes.

Benefits and opportunities offered by the Digital Technologies in farming:

With DT being part of their daily lives, some interviewees noted the inevitability of DT tool introduction into farming, with farmers expected to be more and more connected somehow. Some of the benefits mentioned included a gain in time and accuracy in the application of amendments or fertilisers on the field when using precision farming for example. One interviewee cited the example of the quick adoption of autosteering for tractor, enabling the farmers to manipulate machinery with greater precision, even allowing them to focus on other tasks while in the tractor.

DT were also mentioned for assisting in more efficient fertilisation planning, especially in complex mixed farming system with animals, as well as reducing costs of inputs and improving the quality of record keeping by transitioning from paper to digital formats. This transition was seen as particularly beneficial to farmers to accurately report to institutions such as Länstyrelsen, helping them comply with regulations or facilitating subsidies applications under the European Union (EU) Common Agriculture Policy (CAP). Finally, DT were considered "*important for farmers to operate within the law, so that they can take more responsibility for their action.*".

Digital Technologies that are mostly developed towards large-scale conventional farms:

Despite the variety of DT available to farmers, there is a consensus between the interviewees that these are mostly developed for and therefore adapted to large-scale conventional farms. One of the respondents expressed it the following way:

> *"It is farmers that are serious people, that have a lot of land and do things in a good way, that are mostly interested."*

Most of the models used in DT are developed for conventional farms, using parameters specific to this type of farming. Even if it is recognised by all interviewees that in principle these should be usable by all types of farmers, they might be too costly or provide inaccurate results if these are not used in the conditions they were developed for. One adviser took the example of green light spectrometers used to assess the biomass by measuring green light from pictures of the field. It was noted that these tools are specifically designed for winter wheat crops and may produce inaccurate results when interrow spacing is too wide, which can occur in organic farming compared to conventional arable farming. As a result, the biomass measurement may be lower due to the soil being visible on the picture.

It was also perceived by some interviewees that current DT used in farming do not handle diverse farming systems and soil variations. An example cited was the use of satellite imagery in precision farming or in carbon sequestration measurements, that were deemed not adapted to smaller farms. One adviser mentioned the lack of flexibility of these technologies towards diverse farming systems in particular:

"Everyone can use satellite imagery, but it is harder when there are lots of small areas on the farm. […] The more diverse a system, like vegetables growing for market gardening, the harder it is to get accurate measurement. It is easier for larger systems and monoculture rather than small scales, diverse farms."

This was explained by the level of resolution of satellite images that might be too low to capture variations on smaller fields, such as alley cropping in agroforestry or intercropping. Even when precision farming is based on actual soil measurements such as regular soil mappings, some advisers noted that the sampling requirements of one sample per hectare might not accurately capture the variation in soil characteristics.

There is however an effort to improve the accessibility of these tools to a wider range of farm types by either making some functions open access to farmers, and by involving different types of farmers earlier on in research and in the development of the tools as one of the interviewees commented:

"It is mostly conventional [farmers] so far but still we try to also work with organic farmers […], organic farmers are working more and more with technologies. We also try to do research with organic farms and farming practices. In principle, these techniques should not be limited to conventional. Conventional might be more into this but it may be changing a little bit".

Other efforts include updating the tools to offer a broader range of options, such as incorporating functions like a manure calculation function in "VERA" to cater for the needs of organic farming practices (Greppa Näringen 2025).

Barriers to the use of DT in farming:

Generally, interviewees observed that while most farmers in Sweden are interested in the opportunities offered by DT, a lack of awareness about available tools, coupled with a lack of time to learn and effectively use them, hindered their ability to adopt these technologies. Adapting an agroecosystem to the use DT requires indeed a lot of investment in time to familiarised itself with the tools, get training or advice to effectively use them, then regularly input data into models either from automated systems or manual data entry via web platforms or applications. As highlighted by all interviewees, in a context where farmers face a significant administrative burden and are already suffering from "*reporting fatigue*", these DT can be perceived as an additional workload. One adviser expressed it this way:

" Some of them [farmers] are already just running around trying to be profitable."

The costs associated with adopting these technologies was another important barrier identified. Precision farming and GPS tracking was one example mentioned, where a lot of capital was required to acquire necessary equipment, often making it inaccessible to smaller farms. Another example provided was the high costs of soil sampling and analysis, often required to run decision support systems for precision farming.

Finally, resistance to change, unfamiliarity with the tools, and a low level of trust were obstacles perceived as making the adoption of DT difficult. Some interviewees pointed out that there was still a portion of the farming population that did not use a computer, revealing a big training gap for these people. Furthermore, some solutions offered by private companies are available only in English, which for some interviewees clearly indicated that these companies targeted a specific profile of farmers.

Risks:

When DT are used incorrectly or not for the purpose they were designed for, it can lead to farmers applying recommendations that are not adapted to their farm. One example mentioned by interviewees was the risks related to the use of the same system to plan farming operations and for certification or regulation purpose, running the risk for the farmer to report inaccurate or even falsified data. Others identified the loss of accuracy in the interpretation of the data and getting misleading recommendations or results as an issue when using tools that may oversimplify a complex farming system. This was observed for instance when comparing the greenhouse gas emissions from two dairy farms in different contexts using the same tool, without considering specific characteristics such as cows being left to graze outside, which can affect the emission calculations. Issues can also occur when interpreting satellite imageries, where the level of resolution doesn't allow to account for small-scale variations in the field.

DT were also seen as being vulnerable to external perturbations such as a sudden loss of support or access to equipment or technologies, disturbances in satellite positioning systems, or the risk of having connected devices hacked or stolen. These were perceived as significant threats especially when agroecosystems become dependent on these technologies to operate normally. One interviewee illustrated this point mentioning farmers who adopted precision farming and autosteering that are now unwilling *"to go back"* after experiencing the benefits. On the other side, this dependency was interpreted by another interviewee as an overreliance on technical tools and a potential loss of connection to the soil. They articulated it as follows:

"The main risk is that you get one further step removed from the soil you are working with. They never stepped outside the tractor to check the soil, dig a hole and see how soil is doing, counting earthworms, and check if there is a plough pan. When the tool tells them to add more fertilisers, they do not know why for example"

This observation was linked to other issues related to the environmental costs due to overfertilisation, the loss of essential observation skills that are acquired mainly from experience and the feeling of *"not being part of nature"* anymore.

Finally, one adviser pointed out the risk for conflict of interests, particularly with private companies offering fertilisation measurement solutions while also selling fertilisers. This highlighted the need to have these tools independently validated to maintain trust levels.

Knowledge sharing, participatory development and validation are key to enable a wider use of DT in farming for all farm types

The interviewees identified a wide range of approaches and actions that could enable a wider use of DT in farming, from participatory approach and co-developing of solutions, to ease their access or get government subsidies.

The main lever to increase the uptake of DT in farming was a greater involvement of the final users of the tools i.e. the farmers, in the development, communication and sharing of the expertise and benefits acquired. It was indeed seen as critical condition to ensure that the solutions developed are trusted and adapted to practical conditions, as expressed by one interviewee:

"We expect farmers to be sceptical towards these techs. We need to develop tools that are properly tested and validated in a good way. Because farmers will ask a lot of questions. In research, it is important to have farmers and advisers involved to avoid misunderstanding things. Because they know the reality and have good input in product development and in communicating specific needs."

An adviser, involved in the development of a measuring tool based on satellite imagery pointed out the necessity of having the model and solution co-developed with farmers to ensure it reflect the real farm conditions. Similarly, this approach could also facilitate the communication of research results, where these could be applied directly and integrated into DT functions, making then accessible to farmers to use.

To increase the level of trust and uptake of DT in farming, it was also deemed critical to enable farmers to share their experience with one another, either via increased networking or actual demonstration at the farm. As one of the advisers pointed out *"farmers look at each other"*. Increasing sharing of knowledge can also be achieved by organising a safe platform for data sharing between farmers, a project one of the interviewees is currently involved in.

"It would be nice to let farmers see what other farmers are doing as well. Because it is interesting to them to know how they are doing in comparison to other farmers."

Having advisers involved in the process of promotion and training of these tools was unanimously perceived as essential to facilitate the adoption of DT. These actors are indeed considered as trusted individuals, on which the farmer can more easily rely on to get support if needed.

Open access, multipurpose and interoperability were the characteristics identified for DT to be more easily adopted on a farm. These features would notably help in reducing the time allocated to data entry in multiple systems. Transparency and open access would also enable to more efficiently use resources spend in their development and support the validation of these systems. This last point was mentioned by several interviewees, who emphasised the importance for both researchers and farmers to be able to validate the models behind the tools and the resulting recommendations. An adviser illustrated this with the example of satellite imagery interpretations, which required further assessment by farmers to confirm their accuracy. In conclusion, involving farmer in every step of the development of DT development was seen as a key enabler to increase their adoption.

3.2 Soil Navigator outputs

3.2.1 Soil analysis results

The results from the soil analysis carried out on the samples taken on fields 7A and 7B are provided in Table 6. Apart from one outlier in measurements of "Total Carbon (C) and Nitrogen (N) in dry weight" identified with a z-score test, all values obtained from the soil analysis across all samples were used in the calculation of the average values. Theses average values (Table 6) were then used as data input for the corresponding attributes or in their calculation. After consultation with the farmer, it was noted that the management practices applied on fields 7A and 7B were similar. It was therefore decided to consider the two fields as a single one for the analysis, and to use the average value across all the samples as data input into SN.

Table 6: Results from soil analysis performed in 2016 and 2025. Green shaded average values correspond to results obtained in August 2016; orange shaded to those obtained in February 2025.

Sample ID	pH	P (mg/100g dry soil)	K (mg/100g dry soil)	Mg (mg/100g dry soil)	Organic Matter (%)	Clay (%)	Density (kg/dm3)	Organic Matter (%)	Sand (%)	Clay (%)	Silt (%)	Electric Conductivity (µS/cm)	Total Nitrogen % in dry weight	Total Carbon % in dry weight
7A_1							1.32	2.72	70.0%	3.2%	26.8%	120	0.12	1.88
7A_2							1.31	2.10	74.7%	2.5%	22.9%	110	0.09	1.39
7A_3							1.26	2.31	83.0%	0.1%	16.9%	130	0.08	1.76
7A_4							1.40	2.48	76.4%	1.5%	22.1%	160	0.10	1.76
7A_5							1.37	2.20	72.3%	1.5%	26.2%	100	0.10	1.53
7A_6							1.44	2.26	68.6%	1.7%	29.8%	200	0.10	1.58
7B_1							1.32	2.21	81.8%	3.1%	15.1%	150	0.11	1.67
7B_2							1.35	2.36	78.4%	1.7%	19.9%	160	0.10	1.77
7B_3							1.25	2.19	81.2%	2.5%	16.3%	80	0.12	1.84
7B_4							1.42	1.54	87.6%	2.3%	10.1%	160	0.06	1.23
7B_5							1.40	1.60	90.3%	2.5%	7.2%	130	0.05	1.25
7B_6							1.36	1.15	90.5%	3.2%	6.3%	100	0.04	0.98
7B_7							1.42	1.03	91.6%	2.3%	6.1%	150	0.02	0.98
7B_8							1.33	1.43	87.8%	3.7%	8.5%	150	0.05	1.02
Average	**6.7 ****	**13.3****	**6.5****	**5.6****	**2.1***	**3%***	**1.35**	**1.97**	**81.0%**	**2.3%**	**16.7%**	**136**	**0.08**	**1.47**

* average over two values
** average over 12 values

Results from 2016 soil analysis
Results from 2025 soil analysis

The values were then used to select the correct range of values proposed for each attribute on the user interface as shown in Figure 6, representing the data entry form for soil characteristics.

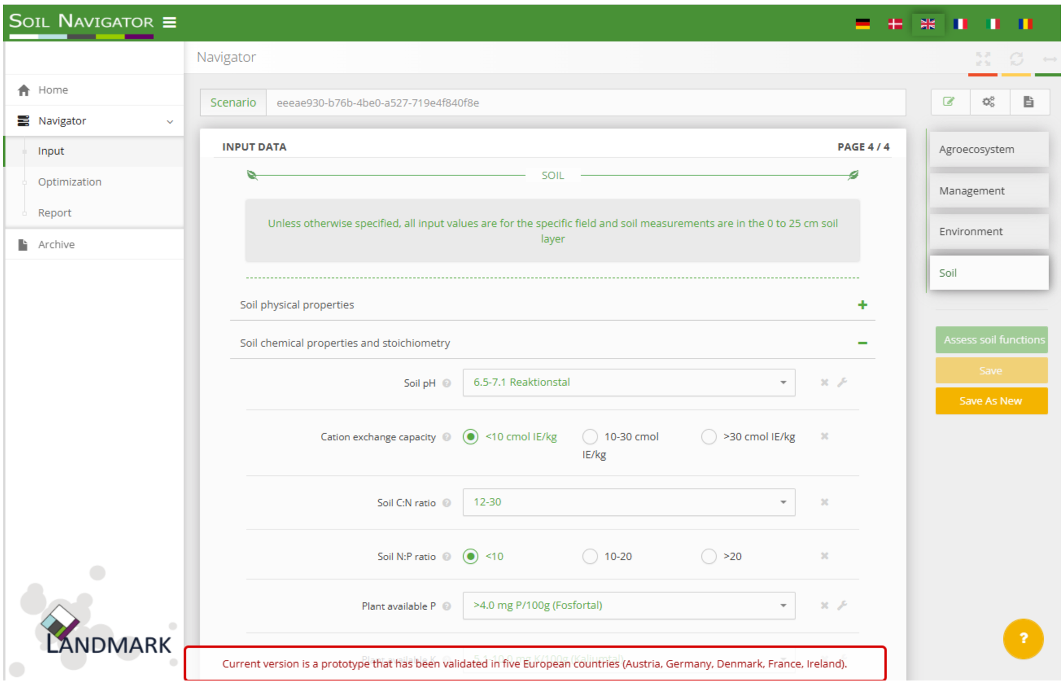

Figure 6: Data entry form for soil characteristics at the field level as displayed in the Soil Navigator online tool (screenshot taken 2025-03-27; Soil Navigator 2025).

The attribute values selected as data input into Soil Navigator are available in Appendix 2.

3.2.2 Soil functions scores

Impact of scenario on the assessment of soil functions

In both scenarios 1 and 2 (Table 4 section 2.4.2), the soil functions received the same assessment which scores to medium to high (Figure 7).

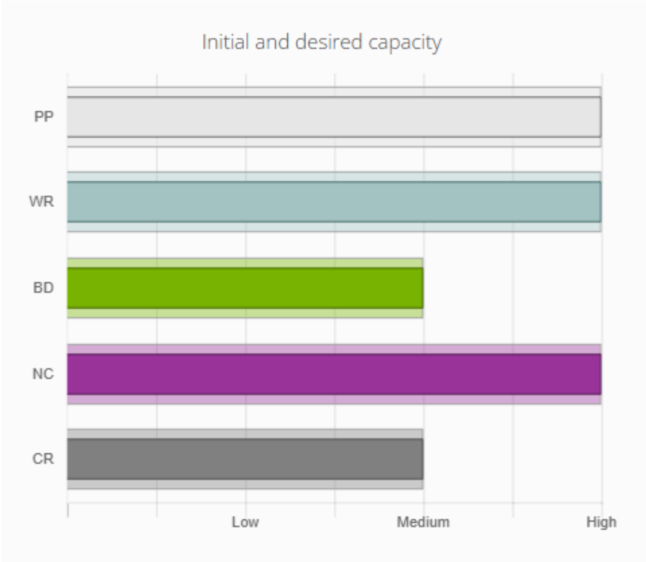

Figure 7: Screenshot from Soil Navigator showing the soil function assessment with PP: Primary Productivity; WR: Water Purification and Regulation; BD: Biodiversity and Habitat Provision; NC: Nutrient Cycling; CR: Climate Regulation (screenshot taken 2025-03-27; Soil Navigator 2025).

It indicates that in this case, the same assessment of the soil functions could be performed even with missing values on soil physical and chemical properties and stoichiometry.

3.2.3 Recommendations of management practice

Following the presentation of the soil functions scores, the farmer was given the possibility to choose which function they wanted to improve, providing the following order or priority (Table 7):

Table 7. List of soil functions with corresponding priority level as indicated by the farmer

Soil function	Farmer's priority level
1	Biodiversity and habitat provision
2	Nutrient cycling
3	Water regulation and purification
4	Climate regulation
5	Productivity

It is interesting to note that "Biodiversity and Habitat Provision" was being given the highest priority here. This reflects the farmer's objectives of maintaining a high level of biodiversity on their farm and the connection made between the biodiversity in the soil and the overall farm biodiversity. They also linked this function with the ability for the soil to better retain water, to *"produce its own nutrition"* and its perceived positive effects on soil carbon sequestration.

These priorities were then inputted into the tool, with the user setting the desired level for each soil function, and the level of “flexibility” i.e., whether it enabled the tool to provide recommendations that could lower or only improve the soil function performance. Figure 8 represents the user interface displayed to select the desired level of the “Primary Productivity” function and level of flexibility.

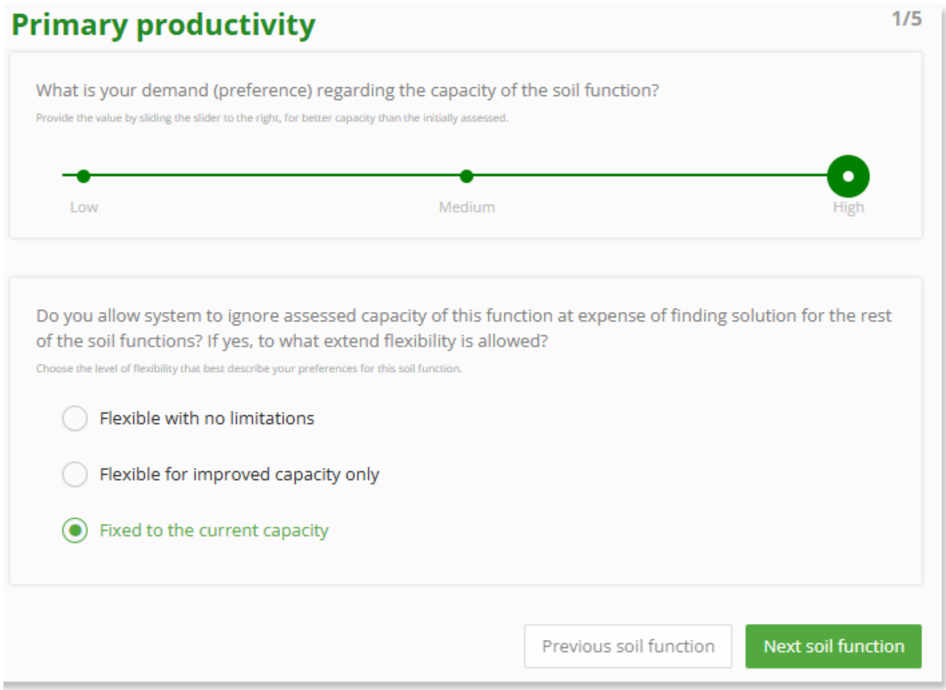

Figure 8: Screenshot from Soil Navigator showing the interface used to input the desired level of the “Primary Productivity soil function and the level of flexibility (screenshot taken 2025-03-27; Soil Navigator 2025).

Given the already high scores obtained for “Primary Productivity”, “Water Purification and Regulation” and “Nutrient Cycling”, their flexibility levels were set as “Fixed to the current capacity”. Following the priority order given by the farmer, we increased the desired “Biodiversity and habitat provision” capacity of the soil to “High”, with a level of importance set as “High” as shown in Figure 9. It is important to note that the option to set the level of importance of the soil function becomes available only when the desired level exceeds the previously assessed level.

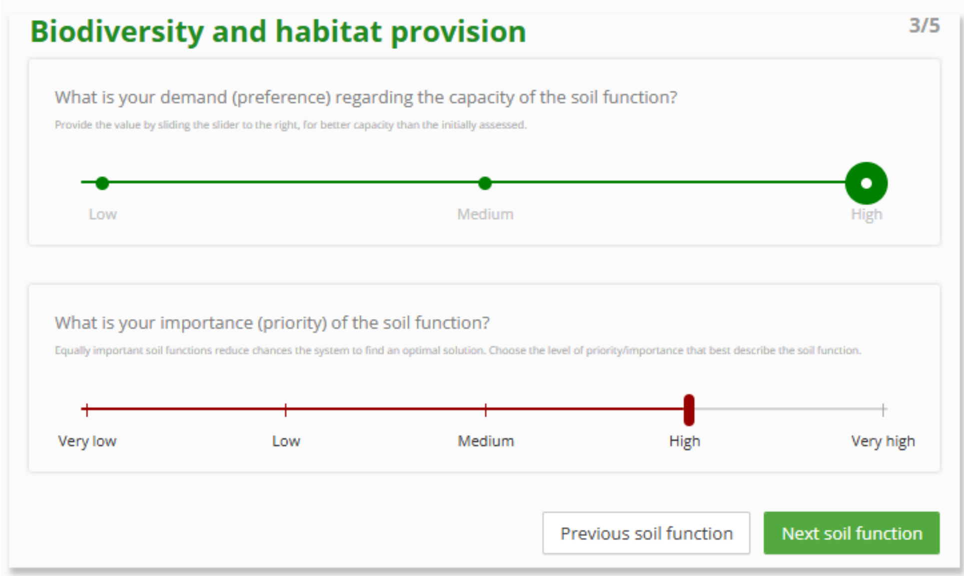

Figure 9: Screenshot from Soil Navigator showing the interface used to input the desired level of the "Biodiversity and habitat provision" soil function and the level of importance (screenshot taken 2025-03-27; Soil Navigator 2025).

The "Climate regulation" function, also originally assessed as "Medium" was left at "Medium" as a desired state, with a flexibility set at "Flexible for improved capacity only". In this case, the system doesn't allow to set a high level of priority for both "Biodiversity and habitat provision" and "Climate regulation", indicating that it couldn't find management practices able to increase these two capacities to the highest level. It demonstrated here a potential trade-off between these two functions, where practices found to positively impact one function could hinder the other.

After setting the level of priority for each soil function, the tool provided a list of recommendations aimed at improving the "Biodiversity and habitat provision" capacity of the field. These were generated following the decision model tree available in Appendix 5:

1) Increase soil Carbon/Nitrogen (C/N) ratio:
    a. Apply/increase solid manure or compost according to national fertiliser guidelines
       OR
    b. Introduce/increase catch crops/cover crops/green manure according to national guidelines
2) Increase soil Organic Matter:
    a. Reduce tillage frequency/intensity
3) Increase thickness of organic layer

As shown in Figure 10, these recommendations were suggested to increase the level of nutrients in the soil, considered as a critical factor that would positively impact soil biodiversity on the field.

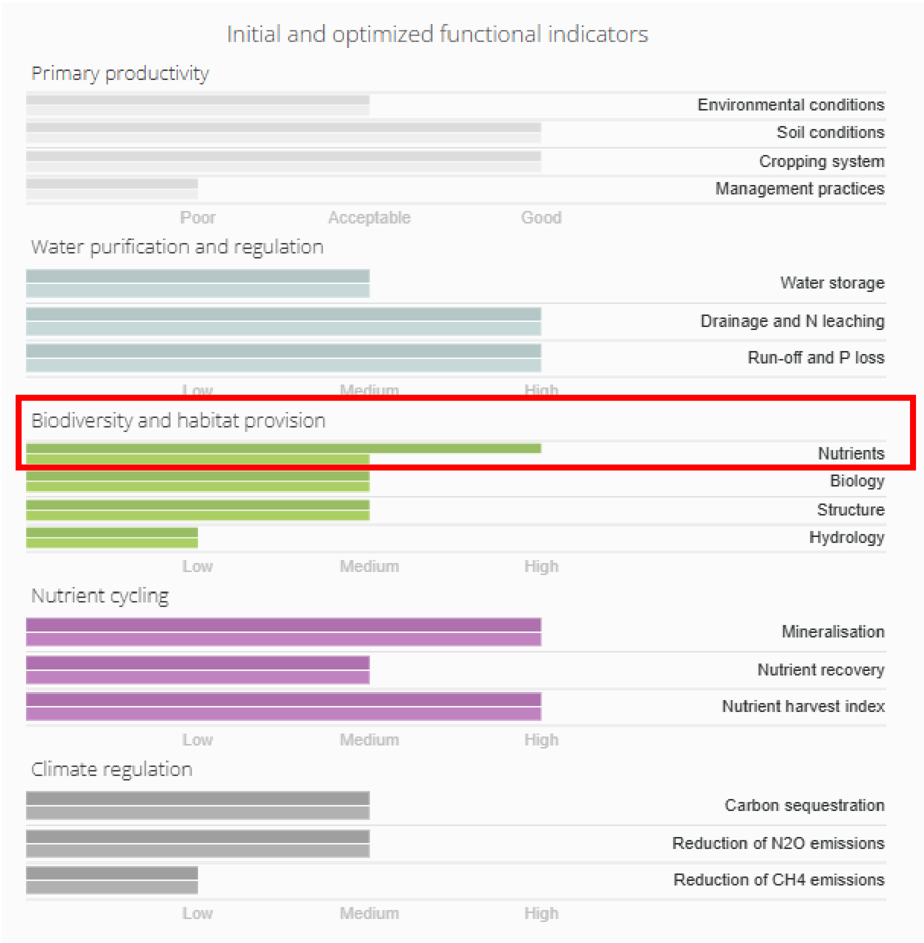

Figure 10: Screenshot from Soil Navigator showing the initial (light shaded bars) and optimised (dark shaded bars) soil functions indicators. Increasing the "Nutrients" indicator was expected to positively impact soil biodiversity (red rectangle) (screenshot taken 2025-03-27; Soil Navigator 2025).

While the assessment of soil function capacities was identical under scenario 2, the suggestions of practices provided with the same priority parameters were less specific, as it was only recommended to increase the thickness of organic layer. This indicates that with less precise information on the field soil characteristics such as C and N content, the model relied on more generic suggestions of practice aiming at increasing the level of nutrients to improve the soil biodiversity capacity.

In concertation with the farmer, it was decided to focus on the recommendation aiming at increasing soil C/N ratio by introducing a new catch crop/cover crops/green manure into the existing rotation. The reasons for this were that reducing tillage further would have been difficult to implement as the farmer already limited the use of tillage to manage weeds during the production of vegetables, which occurs every seven years. Increasing the amount of solid manure or compost was also dismissed since it was estimated that it would have a negative impact on the farm profitability by increasing costs of inputs.

When discussing the different options to follow the recommendation to "introduce/increase catch crops/cover crops/green manure" in the crop rotation, the farmer expressed the willingness to grow crops destined towards human consumption rather than animal feed. It was therefore proposed to simulate the addition of mustard in the crop rotation, either white mustard (*Sinapsis alba),* or brown mustard (*Brassica juncea*). This crop offers several benefits i.e. it produces seeds that can be used to produce mustard condiment, serves as an efficient catch crop due to its ability to develop deep roots rapidly, and helps to reduce pest pressure and diseases, particularly nematodes populations, which could be advantageous if carefully planned in the rotation (Jordbruksverket 2007). It also has the capacity to grow well in well-drained sandy soils with a neutral pH, conditions that are present in the analysed field (Madhusoodanan et al. 2004). However, the C/N ratio of mustard highly depends on plant growth stage and plant parts, with some experiments measuring mustard shoots C/N ratio between 6.6 to 9.9, 30 to 33 for straw, and a C/N ratio of 44 for roots (Brennan & Smith 2018; Dannehl et al. 2017; Gan et al. 2011). The actual effect of the addition of mustard in the rotation will therefore depend on the timing of plantation and its final purpose, be it as a cover crop planted during winter, or as a cash crop, with seeds harvested and residues left on the field.

Despite these uncertainties, the proposed recommendation appeared to offer more product diversification potential to the farmer, with the possibility to produce a high-value mustard condiment. The assumption was made that the addition of mustard in the crop rotation with the objective of harvesting would be applied on the whole farm, with crop residues left in the field. According to the literature, crop residues with C/N ratios above 30 tend to cause net immobilisation of soil mineral N (Muhammad et al. 2011; Trinsoutrot et al. 2000). Muhammad et al. (2011) further demonstrated that the extent of N immobilisation depends not only on the C/N ratio but also on the lignin content of the residues, with experiments indicating that cotton residues with a C/N of 29 and 21% lignin resulted in significant N immobilisation. Mustard straw having similar compositional characteristics, it can be expected that their residues may temporarily increase the soil C/N ratio (Jahan et al. 2014). This theoretical basis supports the assumption that such a practice would align with the of SN recommendation and would likely have a positive effect on soil biodiversity and overall soil health. However, soil C/N dynamics also depend on other factors such as soil pH, porosity, water content, bulk density, and microbial biomass, which can be further influenced by farm management practices (Li et al. 2022). Further expert knowledge would therefore be required to determine an optimised crop planning to obtain the desired effects of increasing soil C/N ratio.

3.3 Estimation of the socio-economic impacts of suggested practice

3.3.1 TAPE initial assessment

In this section, the results of the TAPE initial assessment are presented following the stepwise approach as described in section 2.4.1.

Step 0: Description of systems and context

The system assessed is the case-study farm. A description of the crop system and farm environment is available in section 2.1.

Step 1: Characterisation of Agroecological Transition (CAET)

From the information collected during the interviews, the farm was assessed against the 10 elements of agroecology as defined by the FAO (2018), using a scoring of semi-qualitative indices on a scale from 0 to 4 (FAO 2019). The detail of the scoring is available in Appendix 6 and the final scores obtained are represented in Figure 11 in a spider diagram.

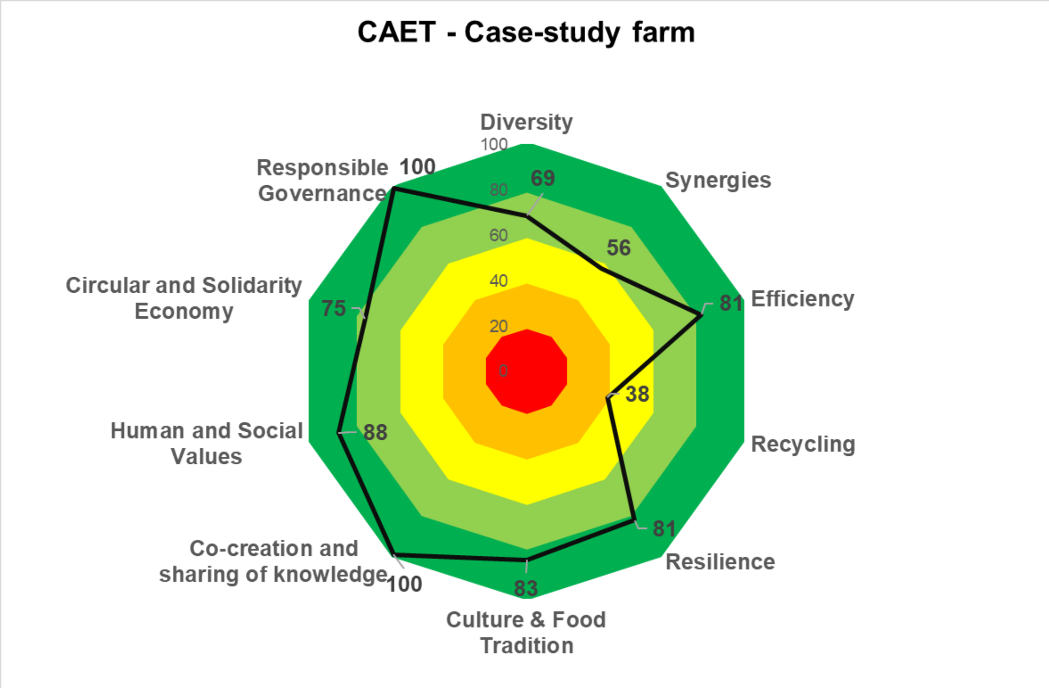

Figure 11: Spider diagram representing the scores obtained by the farm when assessed against the CAET criteria on a scale from 0 to 100%.

The farm system obtained particularly high scores (above 80%) across most of the elements of agroecology assessed: Responsible Governance (100%), Co-creation and sharing of knowledge (100%), Human and Social Values (88%), Culture and Food Tradition (83%), Resilience (81%) and Efficiency (81%). The excellent score in Co-creation and sharing of knowledge reflects the active participation of the farmer in a variety of networks and collaborations with farmers and local universities, as well as their efforts teaching and involving students in several projects on the farm. In addition, their commitment to promote regenerative farming and sustainable living values, as well as involvement in women's entrepreneurs' circles, explain the high score in Human and Social values. The farm's diverse activities and a perceived good level of assurance coverage contributed to its high level of resilience.

There are two elements that could however be improved. These are Recycling (38%) and Synergies (56%). The low score for Recycling can be explained by the fact that while all on farm residues are reused, none of the seeds are kept for the next crop seasons and the lack of water-saving equipment. The low level of integration of the farm crop system with trees and animals impacted the Synergies score.

Step 2: Core Performance Criteria

The performance of the farm system has been evaluated according to a set of 10 dimensions, deemed essential for producing sustainable food and contributing to the achievement of the related Sustainable Development Goals (SDGs) (FAO 2019). The results from the assessment are listed in Table 8. They are represented with a traffic light visualisation with green indicating a desirable state, yellow for acceptable and red for unsustainable. These have been obtained either from a combination of semi qualitative indicators as defined in the TAPE guidelines or from the farmer's own perceptions and observations when quantitative data was not available (FAO 2019).

Table 8: Results of core criteria of performance applied to the farm

Core criteria of performance	Results
Secure land tenure	The farmer has formal documentation showing them as holder of the land.
Productivity	The farmer's perceived their productivity as being acceptable and stable (crop specific costs of input unavailable).
Income	Farm net income per family worker > Median national income (SCB 2024)
Added value	Gross added value per family worker < 0.8 x national agricultural GDP per agricultural worker (World Bank 2024)
Exposure to pesticides	Organic farm – no use of pesticides.
Dietary diversity	(N/A) Not assessed.
Women's empowerment	A-WEAI score = 85% (detailed scoring available in Appendix 7)
Youth employment	Student number enrolled in agricultural program declining since 2020 (SLU 2025) and farmer's perceptions that it is more difficult to recruit youth on the farm.
Agricultural biodiversity	Gini-Simpson index = 72%
Soil health	SOCLA average score = 4 (detailed scoring available in Appendix 8)

Most of the core performance criteria were evaluated as in a desirable state, apart from "Added value" and "Youth employment". The reason "Added value" was rated as unsustainable while "Income" is considered as in a desirable state is because subsidies contributed to a substantial part of the farm income. These subsidies, when removed from the calculation of the "Added Value" resulted in a value per family worker significantly below the national agricultural GDP per agricultural worker.

Step 1bis: Transition typology

When taking into consideration both CAET (step 1) and core performance criteria scores (step 2), the farm appeared to already be in an advanced agroecological state according to the transition typology (FAO 2019): the average of all CAET elements provided an overall score of 77%, and most of the core performance criteria are in a desirable state. To advance further on the agroecological scale, the farm would need to improve its "Recycling", "Synergy" and "Added value" criteria.

3.3.2 Impact assessment of practices

The evaluation of the introduction of a mustard crop into the crop rotation as recommended by SN was conducted qualitatively due to the lack of detailed economic data relative to crop production. The potential impacts were discussed with the farmer, then assessed in relation to each of the 10 agroecological elements and core performance criteria.

The initial scenario envisaged with the farmer was to harvest and process the mustard seeds with the objective of producing condiment mustard as the final product. With the assumption that the same equipment used for hemp seed harvesting and cleaning could also be used for mustard seeds, most of the investments would be directed toward the purchase of equipment for processing the seeds into the final condiment mustard product. The potential impacts on agroecological elements and core performance criteria are listed in Table 9.

Table 9: Qualitative impact assessment of introducing mustard in crop rotation on the agroecological elements and core performance criteria. Note: only elements and criteria that were deemed affected by the change are listed.

Positive impacts	Negative impacts
Agroecological elements:	
Diversity: product diversity will increase due to the addition of a new product. **Resilience**: the increased diversity could positively impact the overall economic resilience of the farm in the long-term.	**Resilience:** Despite an increased diversity of activities, the short-term resilience might be affected if further investments are required to process the seeds, increasing the level of debts.
Core performance criteria:	
Soil Health: may improve when following Soil Navigator recommendation.	**Added Value** and **Income** may decrease if the costs of inputs are too high (machinery, labour and consumable).

Agricultural Biodiversity: will increase thanks to the addition of a new crop in the rotation.

While there are potential positive impacts on resilience and diversity, mainly due to the addition of a new source of income, the economic effects remain difficult to assess without conducting a detailed cost analysis and risk assessment. Overall, the recommendation would likely benefit the farm's environmental sustainability, but it was not possible to conclude on the impacts on the social and economic factors. A more cautious approach could be to send the mustard seeds to external processors in a first stage, to eliminate the need for further investments in seed processing equipment. This would reduce the costs of inputs and labour since the addition of the crop can be integrated in the existing crop rotation plan and wouldn't require additional time to produce the mustard condiment. In this case, the positive effects on economic sustainability could be realised, potentially progressing the farm further on the agroecological scale in the transition typology.

Further improvements that could increase the farm's agroecological state according to this TAPE assessment, while outside the scope of this study, would require significant changes in farm operation and management. These include a change in seed procurement and add water storage facilities in case of drought to increase the "Recycling" criteria, or practice mixed or intercropping, integrating animals and trees into the farm agroecosystem to improve synergy and diversity.

3.4 Perception of the tool

In this section key points and themes gathered during the semi-structured interviews are presented. It is important to note that none of the interviewees had previous knowledge of the tool prior to the interview, nor were they aware of tools with similar functionalities.

3.4.1 The farmer

The farmer had an overall positive perception of the tool and found it trustworthy and providing useful information. The soil function assessment was in line with their own observations and the recommendations were found useful as it provided interesting suggestions to improve the soil biodiversity function. However, they mentioned that the initial level of trust was mainly connected to the trust they had in the interviewer (the author of this study), which by explaining and conducting the data collection greatly facilitated the process for the farmer. They also acknowledged that, even if they were interested in soil health improvement and the tool had a clear and user-friendly interface, they would likely have needed some initial support to use the tool effectively. Additionally, the farmer's existing interest in soil health issues also made the time spent collecting data for the tool acceptable.

The farmer suggested some improvements to the tool that would increase its perceived benefits and acceptance such as, integrating the tool with their certification system to avoid having double data entry, being more specific on manure management practices recommendations, and have a Swedish translation. They indeed recognised that they had to translate the soil functions concepts to ensure they were selecting the right one to improve.

3.4.2 Other stakeholders

Following a short presentation of the tool, the interviewees were given the possibility to comment on several aspects such as benefits and limitations. The main advantages identified were the fact that the tool is offered in open access, is rather user-friendly which simplified its use and the need for training, and that it could be used by farmers and advisers to draw a baseline on the current state of the soil, as mentioned by one of the advisers:

"It could be a check for your soil, to show that you are a good farmer."

It was indeed mentioned that the tool could respond to an increased interest by farmers in soil health assessment, especially organic farmers. One adviser then pointed out that it could be used as an educational tool to raise awareness on these issues and start thinking about ways to improve your soil.

However, there was a consensus on the anticipated excessive time and effort required for the data entry, especially given the amount of information to input and potentially associated with high soil analysis costs. These were seen as a detrimental barrier to the use of the tool by farmers. In addition, a certain level of scepticism was shared among the interviewees when looking at the recommendations provided by SN. First, more insight into how the models behind the tool were built was required for some interviewees to ensure their validity. Secondly, these recommendations were generally deemed too broad, and potentially not adapted to the farm assessed, and to the climactic and cultural context in Sweden, since the tool hasn't been validated in the country. One adviser took the recommendation of reducing tillage as advised by the tool as an example to point out that this practice might not be adapted in farms with significant weed issues. This runs the risk of having a farmer applying irrelevant recommendations of practice, especially if the model is run on a limited data set.

The interviewees provided various suggestions to address the perceived limitations of the tool:

- Having an adviser accompanying the farmer when using the tool to either facilitate or oversee the data entry. They would also be able to provide practical suggestions in order to follow the recommended management practices identified by the tool.
- Getting recommendations that are more specific to the cultural and environmental Swedish context. Some interviewees indicated that given the amount of data provided to the tool, it should be able to provide more specific and practical suggestions, such as the type of crop to include in a rotation or the amount of manure to add on a field.
- Limiting the time dedicated to data entry by either integrate the tool with other systems already used by the farmer, or by having climatic data already filled out based on the farm geolocation and local weather stations for example.

4. Discussion

The results of this case-study provide nuanced answers to the established research questions. While SN appeared to be a tool easily accessible that provided interesting insights into a farm's soil health, several limitations have been identified during this study. The advantages of using such a tool on a farm, be it as a DSS or for educational purposes, is evaluated (4.1). The constraints, as recognised by the various stakeholders and associated with the use of the tool and in the broader context of the use DT in agriculture, are examined (4.2), and potential solutions to these challenges are discussed. Finally, before suggesting opportunities to improve the methodology used and complement this research (4.4), we will attempt to replace the use of SN and DT in general in a more holistic and agroecological context (4.3).

4.1 The potential of Soil Navigator

4.1.1 Raising awareness on soil health as an entry point toward the adoption of sustainable practices

Few of the DT and DSS tools cited by the interviewees as being the most used by farmers in Sweden are aiming at assessing soil health. Instead, these tools are focusing on either increasing the productivity and reducing input via precision farming, nutrient and fertiliser management, or estimating the soil carbon sequestration potential from satellite imagery. The Swedish Board of Agriculture, in collaboration with SLU, introduced the tool "Hur mår min jord?" (in English: "How is my soil doing?") in 2021. The tool, designed for farmers, is focusing on the soil structure as an indicator of soil productivity potential and a factor toward limiting the impacts on climate and the environment (Greppa Näringen n.d.). The ability of SN to assess five different soil functions simultaneously constitutes its main advantage over other tools such as "Hur mår min jord?", as it provides farmers with a comprehensive overview of the health and condition of their soil. Some adviser noted that SN could be beneficial to provide a baseline and a way for some farmers to assess their performance as well.

DSS and smart farming technologies in general offer farmers the opportunity to gain a deeper understanding of their farm systems (Eastwood et al. 2019). SN was indeed developed with the purpose of raising awareness about different soil functions and how they interact and are affected by management practices, soil characteristics, and environmental conditions. It allows the farmers to visualise the effect of the adoption of a specific management practice not only on primary productivity but also on the performance of other soil functions (Debeljak et al.

2019). As noted previously, preserving soil health can be considered as an entry point for regeneration and enhancement of the soil multiple ecosystem services. By taking soil health as a starting point for discussion, it enables the farmer to envisage the farm ecosystem sustainability through integration of sustainable practices and potentially initiate a transition process.

4.1.2 Multi-objective and trade-off management

Over the last six decades, numerous multi-objective and multi-criteria models have been developed to optimise farm agroecosystems. These have been seen as the solution to comprehend the complexity of interactions between its components of agricultural system (Jones et al. 2017). Research on these systems continues, and while many models and DSS are still focused primarily on farm productivity and optimising land use and inputs, some have also started integrating environmental sustainability (Cheng et al. 2023; Chin et al. 2024). However, these tools remain difficult to access and use as they require a deep understanding of the models and their parameters (Garofalo & Vonella 2025; Schreefel et al. 2022; Groot et al. 2012).

In contrast, SN offers open-access and a user-friendly interface, providing a clear visualisation of soil function performances. It allows a farmer to select different soil functions to improve, and based on these selections, the tool can determine the management practices that could enhance the prioritised soils functions, while considering the impacts on others. In addition, by giving the farmer the flexibility to choose the soil function they deem most important, the tool enables them to select practices that align with their farm system and values, as demonstrated in the case study where the farmer chose to prioritise soil biodiversity.

During the study it was observed that the tool couldn’t identify management practices capable of increasing simultaneously biodiversity and climate regulation, illustrating the trade-offs that exist between the soil functions. Given the complex and knowledge intensive nature of the agriculture industry, understanding the interactions between soil characteristics, management practices, environmental conditions, and soil functions can be challenging to visualise and comprehend (Tumwebaze et al. 2025). Farmers face trade-offs on multiple scales, whether it is at the crop level (e.g., grain production versus residues production), field level (e.g., grain production versus nutrient leaching and water quality), or farm level (e.g., prioritising one crop over another) (Klapwijk et al. 2014). The use of a DSS can facilitate the assessment of these interactions, synergies and estimate their impacts, while also considering the different trade-offs. Some examples of trade-offs SN is capable of managing are the potential negative impacts of increasing cycling of phosphorus on water quality, or the trade-offs between the increase carbon sequestration from the application of manure and the increase N_2O emission if this application is not managed appropriately (Debeljak et al. 2019). In this way the tool has the advantage of raising awareness on these antagonisms and synergies, helping farmers to assess and balance alternative management practices to reach the soil desired level of performance.

4.1.3 Impact on socio-economic factors

To be able to assess the relevance of the tool in a more holistic and agroecological context, it was important to place the analysis in the social and economic context of the farm. As noted by the interviewees and in the literature, one of the main economic benefits of adopting digital technologies, such as precision agriculture, is the increased profitability for farmers, as these are being proven to reduce labour intensity, increase productivity and resource efficiency (Gobrecht et al 2024). Labor reduction was also cited by the farmer as a potential benefit from automating weed management via the addition of a robot.

Since SN does not require specific equipment, the cost associated to its use was primarily related to soil analysis and to the adoption of the suggested management practices following the prioritisation of soil functions. Due to a lack of quantitative data on crop and field specific costs of inputs, profit and labour, only a qualitative assessment was performed on the impacts of adding a cover crop into the rotation. This recommendation was preferred here over the addition of manure or compost as this would have increased costs of inputs, which the farmer was unwilling to invest in. This illustrates that, while the tool provides general recommendations, it allows for customisation based on the farm's specific economic and environmental context, such as selecting practices that require lower investments. While the analysis did not provide definite conclusions on the socio-economic impacts, we can assume that long term economic resilience of the farm would improve by introducing an additional source of income. Ultimately, the recommendations aim at increasing environmental sustainability, soil resilience, and ecosystem services, which could positively impact the farm's economic sustainability in the longer term. In that aspect, the tool constitutes a valuable addition to the farmer's tool kit, supporting the farm's progress towards its agroecological transition.

4.2 Risks and limitations associated with the use of DT in farming

Despite the opportunities offered by the use of DT such as SN in improving farm systems efficiency, it is important to review the risks associated with the development of DT and deployment of smart farming. Several have been identified during this study, either from literature review, or from the interviews, and will be discussed in this section.

4.2.1 Environmental costs

One of the risks identified during the interviews regarding the use of DT in farming was the potential increase in electricity consumption to power components, and store, process and transmit data. It was assumed that this increase could lead to a greater reliance on fossil fuel to complement electricity from renewable sources, resulting in a net increase in energy consumption. This concern has been refuted by several studies showing that there is actually a negative relationship between digitalisation and overall energy consumption (Dzwigol et al. 2024). It is also generally expected that digitalisation effectively reduces the environmental impacts of the agricultural system due to efficiency gains, or the use of electricity instead of fossil fuel to carry out agricultural operations (Huck et al. 2024). However, most of the studies estimating the environmental impacts via life cycle analysis are limited to the use of precision farming in crop management and do not consider the full life cycle of these technologies from production, use, to the end of life (Huck et al. 2024). Including these stages in the use of DT would be needed to better assess their effect on mineral resources use, marine eutrophication, or ionising radiations for example. Rebound effects from the use of DT have also been observed, where the actual consumption of resources, such as electricity and water, exceeds the environmental benefits expected from the gains in efficiency obtained from using these DT (Peng & Qin 2024; Mehmeti et al 2016).

Due to a lack of quantitative data and a rapidly evolving sector, the environmental costs of the use of both hardware and software in agriculture are often overlooked and may vary in the future (Hilbeck et al. 2022; Huck et al. 2024). This implies that overall environmental impacts, either negative or positive, associated with the use of DT in agriculture are still difficult to evaluate but are likely underestimated. The principle of precaution as elaborated by Bellon-Maurel et al. (2022) may present a better approach toward mitigating these impacts. They propose in their study the concept of “frugality vs speculation”, where the resource needs for digitalisation are balanced against the global reduction of input into smart farming, calling for further consideration of this balance in the deployment of DT in farming and for more studies to ensure the associated environmental footprint is minimised.

4.2.2 Increased imbalance between farmers in the access to Digital Technologies

The same way DT has permeated every aspect of our daily lives, the digitalisation of agriculture, actively promoted by institutions, may seem inevitable.

Considered one of the key objectives of the EU CAP Policies 2023-27 with the aim to make agriculture more competitive and sustainable, it is currently supported via eco-schemes and subsidies mainly directed toward precision farming (European Commission n.d.; Jordbruksverket n.d.). However, the shift created by the 4th agricultural revolution has the potential to create disruptive changes across the whole food supply chain, increasing power imbalance between actors and social divide (Fielke et al 2019; Rose et al. 2021). While promoting greater sustainability, the deployment of DT in agriculture often dismisses the social and economic contexts where they are applied and dissociates the ecological sustainability from justice and socio-economic equity (Rosén et al. 2018). As observed by some interviewees and in the scientific literature, these technologies mainly tend to serve the interests of large-scale farms and the big actors from the agri-food industry (Aguilar & Paulino 2025). The relegation of social sustainability poses the risk of a greater marginalisation of those resisting new technologies or those who do not consider these tools to be adapted to their activities such as small-scale, organic or agroecological farming, and further increases existing power imbalances between farmers (Giagnocavo et al. 2025; Rose et al. 2021; Pappa 2024).

4.2.3 Loss of farmer's knowledge and connection to the land

A greater reliance of DT in farming without consideration for social sustainability may also change the nature of farm work. Already coined in 1973 by Bailey, the "one-man" farm concept aims at finding the optimum fully mechanised one-man farm, which nowadays would be supported by DT, and is still seen as the logical response to a declining farming population and a trigger to increase farm size (Bailey 1973). An illustration of this trend is the quick adoption of autosteering in tractors, which as mentioned by one interviewee enables the farmer to focus on different tasks while being in the field, a flexibility which they assumed the farmers would be reluctant to lose. It was also pointed out during the interviews that an overreliance on DT and measuring instruments on the farm may lead to the loss of critical observational skills, that are often learnt from experience. While some studies suggest that the addition of DT in farming might complement rather than compete with visual observation (Quddus et al. 2022; Silva et al. 2024), Rose et al. (2021) argue that they can lead to a disconnect between the farmer and the landscape, reduce work satisfaction and relegate the farmer experiential knowledge to the role of data collector to feed statistical models.

4.2.4 Hierarchisation of knowledge

Just as knowledge transfers shifted from being indigenous and between farmers within the community, to being driven by technology and experts during the green revolution, the rise of DT in farming could further this knowledge grab at the farmers' expense (Basu & Scholten 2012). Some advisers observed during the interviews that DT used by farmers can be complex and require specific training and/or the intervention of an adviser for guidance. The lack of skills in technologies is indeed considered the main barrier to the adoption of DT in farming (da Silveira et al. 2021). It was also noted that farmers are unlikely to train themselves due to the perceived gap of technological skills and lack of time. These factors increase the farmers' reliance on advisers, seen in this case as the expert users of such technologies.

On one hand, the reliance on advisers and extension services can be seen as an enabler in the adoption of DT, reducing inequality between farmers and promoting their use (Ma & Rahut 2024). On the other hand, as smart farming becomes increasingly effective at providing evidence-based decisions without human intervention, the role of the adviser is evolving to focus on assessing the value of technological solutions with the farmer (Eastwood et al. 2019). This positions them as an unavoidable intermediary between DT and the farmer and could ultimately further undervalue the farmer's experiential knowledge and observations skills. Even though SN was designed with a user-friendly and intuitive user interface, concerns about a potential misuse of the tool remain and highlight the need for an adviser to be involved in the decision-making process. This is illustrated in the study, where expert knowledge was deemed necessary to select appropriate crops and design an effective crop rotation plan to achieve the intended impact on the soil C/N ratio.

4.2.5 Data ownership

After questioning the repartition of knowledge, it is also important to discuss the ability of farmers to remain proprietaries of their information and data when using DT. This risk was raised during the interviews and is reported in several studies as being one of the main concerns for farmers (McCaig et al. 2023; Giagnocavo et al. 2025). This question is all the more important with the emergence of monopolistic actors and providers of DT, who might take possession of information related to the farm (Abiri et al. 2023). While the exchange of agricultural data should enable a greater adoption of DT by farmers, the governance of this data must be transparent and user privacy and ethics must be considered when developing these tools (McCaig et al. 2023). In that aspect, the open access offered by SN, facilitates the sharing of various farms' data while ensuring data anonymity, allowing farmers to review assessments from other farms. If tools are designed with the needs of farmers at the forefront, ensuring the secure and organised sharing of knowledge, it could empower farmers to regain control over their own information and expertise.

4.3 Co-development and knowledge sharing as a pathway toward the development of tools aligned with agroecological principles

Putting the social aspect back into the smart farming discourse is essential to ensure that the risks identified previously can be mitigated. With a focus on production efficiency via a smarter use of resources, water, land, inputs and labour, social component of sustainability are still overlooked when developing DT in agriculture (Rose et al. 2021). One way to refocus on these aspects could be to adopt a multi stakeholders' participatory approach that places the farmer's need at the centre and foster an environment beneficial for the co-creation and sharing of knowledge within farmers' communities.

4.3.1 Enabling the co-creation of Digital Technologies

The involvement of farmers and other end users in the design, development, validation and implementation of DT in farming was consistently recognised in both the interviews and several studies as an important enabler in their adoption (Rose et al. 2021; McCaig et al. 2023; Giagnocavo et al. 2025). It was particularly highlighted as a key factor in a survey of organic and agroecological farmers in Europe, especially the need to have "DT adapted to the farm's needs and capacities, as well as to organic production and/or agroecology approaches" (Giagnocavo et al. 2025). A "farm centric" approach would require to develop technical solutions that are embedded into a system that the farmer can trust, that protects data from unauthorised access, maintain privacy and interoperability (McCaig et al. 2023). To achieve this Rose et al. (2021) proposes a broader framework for what they call "responsible sustainable innovation", using an inclusive approach to co-innovation, where stakeholders are engaged in conversations on the future of farming. The themes discussed can be on whether this future includes DT, if these are relevant to address the issues, and anticipate production, environmental and social implications of the new technologies developed. This would ensure the proposed solutions can contribute to all aspects of sustainable agriculture (environmental, economic and social), and finally ensure benefits are realised, via support systems that are accessible and fit for purpose. In this framework, policies and government role should not be limited to facilitating the deployment and implementation of DT but should also play a big role in their validation, by ensuring there is a control of the tools' quality maintenance and management to ensure the fitness of the tools, sufficient training provided, and monitor the level of uptake across all farmers (Rose et al. 2021).

Representing one of the outcomes of a pan-European consortium of scientists, chambers of agriculture and policy makers, SN can be viewed here as an attempt at applying this approach. Multiple stakeholders and targeted end users like farmers and advisers were continuously involved in the development process, which helped in fostering a sense of trust and ownership toward the tool (Debeljak et al. 2019). Ultimately, the bottom-up and participatory approach enable DT to further align with this agroecological principle.

4.3.2 Sharing of knowledge and increasing awareness of Digital Technologies

One of key principle of agroecology is the sharing of knowledge. It is one of the 10 elements of an agroecological system as defined by the FAO (2018) and is seen as an enabler for integration of each aspects of agroecology as a science, a practice, and a social movement (Gliessman 2018). Adhering to this principle can be crucial in facilitating the adoption of DT in farming. This can be achieved through facilitating the dissemination of information, networks or collaborations between cooperative, farming communities and advisers to share equipment, exchange knowledge and improve training on DT (Ma & Rahut 2024; Giagnocavo et al. 2025). In the present study, the farmer acknowledged their lack of awareness of DT, attributing it to not being part of the "right networks", while other interviewees perceived these as being already well advertised in farmer´s usual networks. The lack of communication on the available tools toward organic and agroecological farmers and therefore lack of awareness was also identified as a barrier to the adoption of DT in the survey carried out by Giagnocavo et al. (2025). They noted that a positive attitude towards DT might be driven by previous knowledge, which can be reinforced by the creation of more collaborative networks.

Creating inclusive networks from the design, development and application of DT was perceived as the best way to improve their adoption. As suggested by some interviewees, these could take the form of farm visits or workshops, giving the possibility for farmers to see their application in practice in similar farms. When organised for a training purpose, these workshops could include areas for farmers to learn from each other's experiences and to interact with farmers who experienced a successful adoption of the technology (McCaig et al. 2023).

4.3.3 Toward the development of Digital Technologies in line with agroecological principles

Ultimately, developing DT aiming at supporting an agroecological transition should align with not just one but all 10 elements of agroecology, i.e. diversity, co-creation and sharing of knowledge, synergies, efficiency, recycling, resilience, human and social values, culture and food traditions, responsible governance, and circular and solidarity economy (FAO 2018; Hilbeck et al 2022). Taking the implementation of several ICT tools in Tanzania as an example, Hilbeck et al.

(2022) illustrate how to apply these principles to the development of DT in the following way:

1) *Diversity:* Provide a range of tools adapted to the varying level of digital access via locally relevant media and interoperability.
2) *Co-creation and sharing of knowledge:* Favour a bottom-up and participatory approach, which means recognising farmers as valued holders and creators of knowledge
3) *Synergies:* Benefit from synergies created by the building cohesion between different stakeholders that operate and exist in the socio-economic context, with the goal of enhancing rather than replacing face-to-face communication and collaboration.
4) *Efficiency:* Favour energy efficient technologies, relying on renewables sources and use these to their full potential.
5) *Recycling:* Recycle, reuse and repair technologies with the aim of extending their longevity and usefulness, and limiting the environmental impacts associated with their production and use.
6) *Resilience:* Design resilient and sustainable DT capable of adapting to changing socio-technical and environmental conditions such as unreliable internet connectivity for example. Avoid creating tools that increase the farmer's dependence on prepackaged solutions and reliance on external agricultural inputs.
7) *Human and Social Values:* Design tools that align with local ethical and cultural values.
8) *Culture and Food Traditions:* DT and methodologies should support locally relevant crops, agricultural practices and exchange.
9) *Responsible Governance:* Ensure DT are used properly by involving a wide range of local stakeholders. This could be achieved through governance frameworks that promotes partnership with different levels of government, organisations and institutions.
10) *Circular and Solidarity Economy:* DT should foster non-competitive modes of communication and collaboration where the well-being of farmers, communities, and ecosystems is seen as the priority.

Synergies already exist between technologies and agroecology. With agroecology aiming at adapting practices to the local context, working with the farm' environment and nature, DT should assist farmers in handling the complexity of these systems in combination with traditional knowledge. To achieve this, it would require reaching a balance between the complexity of agroecological systems and the need to simplify models, as well as between the level of details of the data and processing and storage needs to develop flexible and energy efficient tools (Bellon-Maurel et al. 2022). Appropriate DT could assist in the acceleration of the agroecological transition at the farm and at the territory level, with landscape management, circular economy, collective management of natural resources, being the focus of dedicated DT (Bellon-Maurel et al. 2022).

As part of the Digitalisation for agroecology (D4AgEcol), a project aiming at identifying appropriate digital tools and technologies to provide knowledge for the transition to agroecological farming, an online repository has recently been made available and lists various digital tools in development or on the market that could contribute to agroecology (D4AgEcol 2025). This platform, by ranking the tools against criteria following the 10 agroecological principles as described by the FAO, constitutes a valuable resource for farmers looking for DT that can support a transition process or the adoption of more sustainable practices. Nevertheless, given the already observed disruptive effects of DT in the agricultural industry, it is crucial that elements of agroecology are taken into consideration early in their design, with functionalities serving these principles, as opposed to DT designed for high input industrialised systems that are made accessible to organic farming practices as a collateral benefit.

With its open access and participatory development approach, SN allows farmers to choose practices that align with their values, priorities, and socio-economic context. Although not explicitly stated by the developers as a primary objective, these characteristics allow farmers to better align their agroecosystem with the principles of agroecology. The resilience of the tool could however be questioned since despite being developed in 2019, it never went beyond the prototype stage. This lack of further development raises concerns regarding it long-term viability, especially if the system is not maintained. Eventually, to enhance the practical implementation and acceptance of Soil Navigator, the tool would need to be adapted to the specific local environment and context in Sweden and be supported by a community of practice.

4.4 Discussion on method and further studies recommendations

During the data collection and analysis, several methodological aspects were identified as areas for improvement in future research. These are discussed in the following section.

4.4.1 Data collection

The data collection phase was recognised as potentially representing a barrier to the use of the tool. Even if SN can handle missing values, it was preferred to collect as much information on the farm fields as possible as suggested on the tool user interface: *"[...] missing input data will decrease the soil navigator's accuracy and so we encourage you to try to fill out everything as best you can."* (Soil Navigator 2025). This implied that due to limited data availability on soil chemical characteristics, the analysis had to be limited to two fields and completed with additional soil sampling and analysis, which increased significantly the time dedicated to the data collection. As mentioned by several interviewees, this approach was unlikely to be adopted in a real-life situation as it would be either too time consuming or too costly to conduct soil analysis, especially those aiming at measuring microbial biomass. This is in addition to the analysis required for conducting a soil mapping which provides most of the soil characteristics information and can cost up to 600 SEK per sample (Eurofins 2025).

Some suggestions have been proposed by interviewees to facilitate the data collection by either implementing an automatic population of data fields by linking the tool with localised weather data or by relying on other indirect methods to access soils characteristics information. There are also alternative data sources on soil characteristics such as open-sources soil maps, the digital soil map developed by SLU in collaboration with the Geological Survey of Sweden (SGU) (SLU 2024) being an example, or remote sensing technologies relying on satellite imagery, drones or sensors installed on tractors (Lausch et al. 2019; Abdulraheem et al. 2023). These could present less invasive methods and less costly sources of data.

While the tool provides a certain degree of flexibility in terms of data completeness, we observed that the accuracy of the recommendations improved with a more exhaustive data set. This raises questions about the validity of the soil biodiversity function assessment, using data derived from statistical model based on diagnostic horizons, which categorises soil types, to replace the missing values (FAO 2006; Rutgers et al. 2018). Further trials could include a sensitivity analysis on the effect of the addition of soil biodiversity data on the soil function assessment and recommendations to improve it. In addition to making the rules used for the assessment of the soil's functions more transparent, such trials could also provide an educational opportunity for farmers involved.

Finally, the lack of quantitative data on the farm's crop system such as field and crop specific yields, inputs quantity and costs, made the evaluation of the potential impacts of the adoption of the recommendations on socio-economic factors challenging. These data would have been required to carry out costs analysis to establish a baseline and estimate the effect of adding a new crop on the farm profit and labour demand. This is the reason why a qualitative method of assessment has been selected instead.

4.4.2 Potential bias from the farm selected for the case-study

It could be argued that the farm selected for this case-study, being an organic farm promoting regenerative practices, was already inclined to recognise the importance of soil health in an agroecosystem. As noted by one of the interviewees, this could have positively influenced the level of acceptance and trust in the tool and its recommendations. DT tools are indeed better accepted when they already align with the values of the farmer (Giagnocavo et al. 2025). Therefore, we could expect different perceptions and acceptance of SN if the experiment had been conducted on a different type of farm such as a large-scale conventional farm.

4.4.3 Soil Navigator's limitations

As mentioned previously, the specificity of the suggestions of practices depended on the amount of data provided to the tool. However, even when using all data available on the field, most of the interviewees found the suggestions too broad and generalised. This highlighted the risk that, without expert guidance, a farmer may implement a recommendation that could have detrimental effect on the soil functions they aimed to improve. In this study, for example, while incorporating mustard into the rotation could theoretically raise the soil C/N ratio, expert knowledge was still required to develop a crop planning and an implementation strategy tailored to the farm's ecosystem to ensure the desired effect on soil C/N ratio are actually realised. The loss of soil characteristics variations at the field level was also pointed out as an information gap. Because the tool needs aggregated data points in the form of an average at the field level, it overlooks intra-fields differences and does not consider the field size. This limitation highlights the lack of precision in applying the same management practice across the whole field. An interviewee also noted that farming type such as agroforestry were not taken into consideration by the tool. In some cases, agroforestry can indeed positively affect soil health by increasing biomass and soil organic matter content (FAO 2005). Adding this option would provide a wider range of recommendations adapted to this type of agriculture.

Some interviewees suggested to provide more specific information on current farm management practices such as the tillage type and depth to refine the assessment and recommendations. While this could increase the specificity of the suggestion, it would also increase the difficulty and time required for the data collection. This highlights the need to reach a balance between the level of details required at inputs, the model's capacity to handle it, and the level of details expected for the outputs. As the tool was developed using a participatory approach with end users involved in the design, implementation and validation of the tool, it is expected that the level of detail provided was deemed satisfactory by most of the users involved. Additionally, it could be argued that the more general nature of the recommendations actually allows for more flexibility in their application. This could be beneficial for educational purposes and encourage discussions between the farmer and the adviser about which management practices could be adapted to the farm's environmental and economic context.

4.4.4 Recommendations for further studies

The analysis had to be limited to two fields due to the lack of soil characteristic data on the other fields. This offers the opportunity to scale up the experimentation to a whole farm agroecosystem in future studies, enabling a more comprehensive analysis of the suggestion of practices at the field level and of how these could be integrated to assess their impacts on socio-economic factors and agroecological criteria. Applying this methodology to different types of farmers would help assessing the potentials of the tool in promoting the adoption of sustainable practices and supporting a transition process, especially if the case-study farm is considered at an early stage of agroecological transition. This could also provide insights into perceived bias in the acceptance of the tool, as well as explore how the tool could be integrated with different DT already in place at the farm. In addition, the educational value of the tool could be assessed by evaluating the level of knowledge and awareness of the farmer of the different soil functions and the associated trade-offs.

Finally, the models used in SN have the particularity of incorporating expert knowledge and databases for the design, integration rules definition, validation and calibration stages. These models also rely on estimations and extrapolations when certain values are not available, based in part on statistical models from data sets based in other areas in Europe, such as soil biodiversity statistical models developed from data from the Netherlands and France (van Leeuwen et al. 2019). Furthermore, with the tool providing the same assessment of the soil functions regardless of the completeness of the soil characteristics data, the precision and models behind this scoring could be questioned. More detailed information on the integration rules used in the data models would be required to understand which specific data point led to the observed scoring. This provide the opportunity for experts familiar with the Swedish context to reassess the validity of the integration rules and databases in light of the latest research developments, to provide assessments and suggestions more likely to be adopted by a Swedish farmer.

5. Conclusions

By experimenting the use of the multi-criteria DSS Soil Navigator on a case-study farm, this study demonstrated that when DT are designed in accordance with agroecological principles, especially the co-creation of knowledge, they can support the adoption of more sustainable agricultural practices. By taking the soil as the base to establish a baseline and generate recommendations for enhancing soil health according to the farmer's priorities, SN preserves the farmer's autonomy in decision-making by allowing them to select which soil functions to prioritise. While the experiment enabled to assess the soil functions and get recommendations of management practice for only one field, the tool was still able to provide interesting insights for the farmer into how their soil performed. However, the effective implementation of the SN recommendation would have required expert agronomic knowledge through the involvement of an adviser for example. In addition, a more detailed cost analysis would be necessary to thoroughly assess the impact of introducing a new crop into the rotation on farm profitability, labour requirements and overall economic sustainability. Despite data limitations, it was still possible to infer the long-term benefits of such recommendation on the farm's diversity of activities and resilience, supporting a further progression along the agroecological transition, even in a farm already advanced in this process.

Some limitations and risks associated with the use of DT in agriculture and SN were identified during this study. These were mainly related to the disruptive effects DT can have on power and knowledge dynamics across the whole food supply chain. The role of intermediaries and DT enablers such as researchers and advisers should also be reassessed in light of increasing DT adoption and agroecological principles. This re-evaluation should place greater value on farmer's experiential knowledge gained from field work and their deep connection to the land. This cannot be achieved solely via a participatory approach but would require the application of all agroecological principles.

SN can be seen as an attempt to develop a digital solution that aligns more closely with these principles. Developed though a participatory approach and open access, the tool provides the flexibility and opportunities for farmer to make choices according to their values and socio-economic context, while raising awareness on the complex synergies, inter connections and trade-offs between the different soil functions. Scepticism expressed by some interviewees could be addressed by adapting the tool's recommendations to local conditions and cultural context and integrating it with existing technologies. This would increase SN's relevance as a practical tool within the farmer's decision-making process, especially for those at various stages of the agroecological transition, should they be at the beginning or further engaged in the process.

Ultimately, SN illustrates a pathway for integrating agroecological concepts into the design of digital tools. Even so, it is essential to recognise that DT are only one element within a broader transformative process. They should not be perceived as an endpoint for all agricultural challenges as relying too much on DT risks externalising and diminishing valuable local and experiential knowledge. Instead, DT should be considered as complementary tools within a larger strategy for addressing future agricultural and ecological challenges.

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Popular science summary

Can Digital Technologies help us grow food in a more sustainable way?

Digital technologies (DT) have been used in agriculture for more than 60 years. Starting with precision agriculture (application of fertiliser or seeds guided by GPS), these technologies can include a wide range of techniques from biomass sensors to **Decision Support Systems** (DSS), complemented with data modelling, artificial intelligence and the internet of things (IoT). Called "smart agriculture" or "agriculture 4.0", the inclusion of these technologies is often seen as the solution to solve problems in our food production system in order to increase productivity, yield and reduce the use of resources such as water or fertilisers. However, for now, very few DT can be used by farm promoting more environmentally practices such as organic or agroecological farming, even though these practices can offer solutions to current agricultural challenges. This study explored the use of a multi-criteria DSS tool called **Soil Navigator**, designed to assess the soil health of a farm field and consequently suggest farming practices to improve it. The objective was to see how useful the tool could be for a small-scale organic farm and whether it could support farmers to adopt more sustainable practices.

What is a multi-criteria Decision Support System tool?
When used in agriculture, it is a software that can estimate the impact of environment or farming practices on several farm operations such as pest management, cropping system and livestock management. Often based on complex data models, it relies on real life information to determine which practices can achieve several goals at the same time, like maximising productivity while maintaining biodiversity and limiting the use of resources.

The results from this experiment, conducted on a farm in the South of Sweden, demonstrated that the tool was able to provide interesting insights into the current state of the soil, scoring its performance in terms of productivity, nutrient cycling, water purification and regulation, climate regulation and carbon sequestration, and biodiversity and habitat provision. Based on this assessment, the farmer was able to choose which aspect of soil health to focus on and get relevant recommendations of farming practices to reach that goal. In this case, the farmer decided to improve the biodiversity of its soil while keeping the other soil functions stable, for which the tool advised to increase the level of nutrients by incorporating a catch crop or a cover crop. Besides educating the farmer on the importance of the different soil functions and how they are connected, the farming practices recommended are also expected to bring long-term benefits for both the environment and the farm's economic sustainability.

A lot of information and data need to be available on the farm for the farmer to get a relevant assessment of the soil and proper recommendations from Soil Navigator. This can reveal to be particularly costly due to expensive and time-consuming soil analysis. Furthermore, some farmers may not trust the tool completely since it relies on complex data models that are difficult to comprehend and validate. Interviews with various stakeholders working with DT in farming revealed that this lack of trust could be mitigated via involving farmers early in the design of these solutions to ensure their values and needs are considered. Following a co-creation approach and creating networks for farmers to share their experience is instrumental to increase the adoption of DT in agriculture. It is however important to note that the future of farming should not be driven solely by DT. These technologies should be viewed not as an end in themselves, but as tools to support farmers in addressing emerging environmental challenges.

Can Digital Technologies support agroecological practices?

Testing a Decision Support System on a small-scale organic farm

Digital Technologies offer valuable opportunities for famers to design agroecosystems that are more resilient to climate change, an outcome also linked to the adoption of agroecological practices. While these tools currently mainly support large scale conventional farming, they hold potential for synergy with agroecology and could facilitate a transition to more sustainable practices. This study explores the use of a Decision Support System, *Soil Navigator,* and its alignment with agroecological principles. Findings suggest that the tool can improve a farm's agroecological level, and identify opportunities to improve its relevance to the Swedish context though a participatory approach.

By allowing a maximisation of productivity through a better use of resources, Digital Technologies (DT) such as Precision Agriculture Technologies, drones or Decision Support Systems (DSS) are regarded as the solution to future food security crises. These tools are however mostly designed toward large scale conventional farming systems and lack emphasis on the environmental and social sustainability of farms agroecosystems, making them often unadapted to small scales farms or agroecological farming practices. Despite the lack of technological solutions tailored to alternative farming systems, DT could take a more significant role in their design and strengthening.

Developed to fill a gap in technological solutions aiming at assessing soil health and usable by multiple farm types, the DSS *Soil Navigator* (see **Box 1**) could illustrate a possible synergy between DT and agroecological principles. By taking the improvement of soil health as an entry point to the integration of regenerative agriculture practices, it could offer a pathway to the adaptation of existing agroecosystems to agroecological practices.

The objective of this study was to explore the potentials of *Soil Navigator (SN)* in promoting the adoption of sustainable practices and its contribution toward increasing the agroecological level of a farm. It aimed at assessing the impacts of using the tool on the socio-economic aspects of a farm and identify barriers and opportunities for its adoption.

This fact sheet is intended for students and researchers, summarising the research carried out as part of the Independent Project within the Master program in Agroecology, titled "The potential of a multi-criteria Decision Support System in the adoption of agroecological practices - A case-study in Southern Sweden".

Box 1. What is *Soil Navigator*?

Soil Navigator is a multi-criteria decision support system, developed in 2019 as part of the European research project LANDMARK. Based on Decision Expert (DEX) models, it uses qualitative multi-criteria analysis to assess the soil performance at the field level across five functions: primary productivity, water purification and regulation, climate regulation and carbon sequestration, biodiversity and habitat provision, and nutrient cycling. Based on this assessment, the tool allows end-users to choose a soil function to improve and provides tailored recommendations of management of practices, while considering potential trade-offs between the soil functions.

How can *Soil Navigator* support the adoption of agroecological practices?

To address this question, a stepwise approach was applied using the tool on a small-scale organic farm in Scania (see Figure 1):

Run *Soil Navigator*: Data and information on selected fields were collected via farmer' interviews and soil analysis. Following the assessment of the soil performance, the farmer

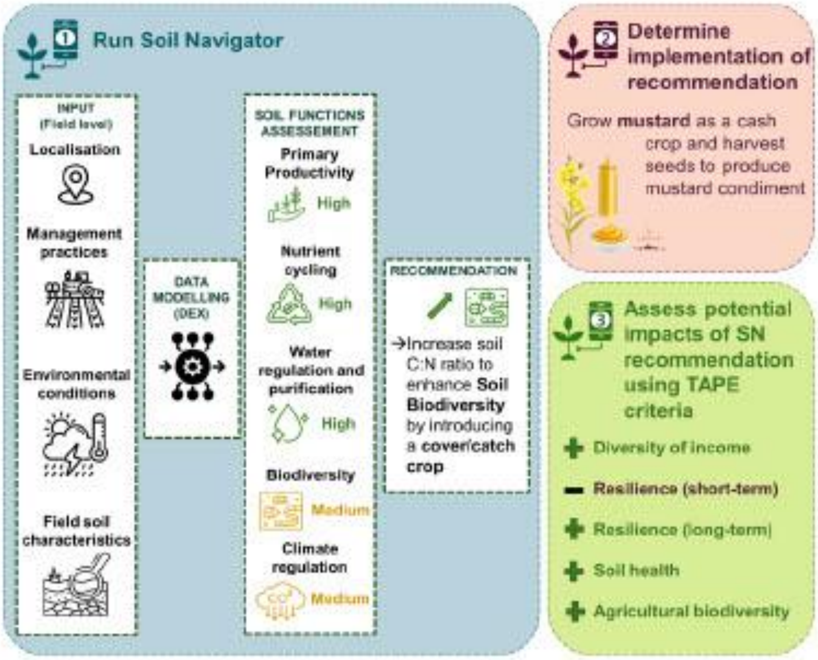

Figure 1: Process workflow of applying Soil Navigator to the case-study farm.

chose to improve the soil Biodiversity function, for which the tool suggested to increase soil C:N ratio by incorporating green manure, or cover/catch crop in the rotation.

2 In concertation with the farmer, it was suggested to add mustard to the crop rotation, as its straw and roots have a relatively high C:N ratio at maturity. The objective was to harvest the seeds and process them into mustard condiment.

3 The recommendation to add mustard in the crop rotation was assessed against agroecological criteria using the agroecological assessment tool TAPE (Tool for Agroecology Performance Evaluation). Following the establishment of a baseline, a qualitative assessment indicated that applying the SN recommendation could positively impact Diversity and Resilience elements (see **figure 2**), and improve soil health and agricultural biodiversity, leading to an overall increase of the agroecological level of the farm.

Potentials and limitations of *Soil Navigator*

SN has the potential to fill a gap in solutions aiming at assessing soil health in Sweden. Semi-structured interviews with stakeholders dealing with DT in farming revealed a lack of tools able to evaluate different soil functions simultaneously. Thanks to its open access and user-friendly interface, SN provides a clear visualisation of the soil performances (see **figure 3**) and potential trade-offs between the different functions. This way, it can assist farmers in selecting management of practices aiming at increasing the desired soil function without negatively impacting the others. By raising awareness on these issues, SN provides an entry point toward the adoption of more sustainable practices.

The recommendations generated by SN leave enough flexibility to the farmer to apply solutions adapted to the farm socio-economic context. In this study, adding a new crop had the potential to positively impact environmental and long-term economic factors.

However, SN requires a wide range of data to be able to provide relevant scoring and recommendations, making it time-consuming and potentially too costly for a farmer to use. In addition, the lack of specificity in the recommendations could lead to their misinterpretation. In this example, expert knowledge was still deemed necessary to ensure the chosen management practice had the desired effect on C:N ratio.

Figure 2. Spider Diagram representing the Characterisation of Agroecological Transition (CAET) scoring of the case-study farm.

Wider risks associated with the use of Digital Technologies in farming

Despite the wide range of opportunities offered by SN and DT in general, they also introduce disruptive changes that can amplify existsing power imbalance and

Figure 3. Screenshot from Soil Navigator showing the soil function assessment with PP: Primary Productivity; WR: Water Purification and Regulation; BD: Biodiversity and Habitat Provision; NC: Nutrient Cycling; CR: Climate Regulation (screenshot taken 2025-03-27; Soil Navigator 2025)

knowledge disparities between farmers. A lack of access to tools tailored to agroecological practices, and the erosion of experiential knowledge and connection to the land due to over-reliance on these tools, were identified as the main issues. These must be addressed to ensure that DT are used with consideration for social and environmental sustainability.

Soil Navigator as a case of co-creation and sharing of knowledge in agroecology

The agroecological principle of co-creation and sharing of knowledge offers a pathway to recentre the design of DT on the farmer's social and environmental values. By using a participatory development approach, SN illustrates a co-creation framework in which farmer's needs and knowledge inform the creation of a solution adaptable to diverse practices. Once deployed, the establishment of new networks, such as communities of practice, facilitate the sharing of knowledge, increase awareness, and promotes the adoption of DT among a wider range of farmers by showcasing successful implementations. Ultimately, to ensure DT address all dimensions of sustainability and remain inclusive, it is essential to integrate all ten agroecological principles throughout their design, deployment, and governance.

Future research

This study would benefit from an updated impact assessment of SN's recommendations using quantitative data and ex-ante analysis. Further participatory research could also help validate the models used by the tool and refine the recommendations to better suit the Swedish cultural and economic context.

Key message:

One of the main benefits of SN is its educational value. By raising awareness on soil health, ecosystems services and trade-offs, it can serve as an entry point into a transition process. In this case-study, SN had the potential to increase the overall agroecological level of the farm by supporting diversity and resilience over time. However, it remains data-intensive and requires expert input to collect and interpret SN suggestions effectively.

When designed in line with agroecological principles, especially the co-creation and sharing of knowledge, DT can also help addressing economic and social aspects of sustainability and constitute a valuable addition to the farmer's tool kit, supporting the farm's progress towards its agroecological transition.

Acknowledgements

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Background image AI generated using OpenArt from the prompt "agricultural fields from above"

References

Appendix 1 – Interview guide: Interview 1 with the farmer

Interview guide
Interview 1

1) Consent form and presentation of the thesis outline

2) Farm agroecosystem information

1. **Farmer's background (age, education, working experience)**
2. **History of the farm, main changes**
3. **Farming system**
   3.1. Activities
   3.2. Products (quantities)
   3.3. Number of fields and their size, map available?
   3.4. Main soil characteristics, previous soil analysis available?
   3.5. What is particular about the land? Topography, pollution, environment?
   3.6. Cropping system
      3.6.1. Which crops? Rotation systems? Which fields?
4. **Farm Outputs?**
5. **Inputs? Costs? Labour (working hours)?**
6. **Main current challenges with cropping system? Farm operations? (natural forces, socio-economic, evolutionary, cultural?)**
7. **Objective with cropping system? What would you like to achieve/improve in the next few years?**

3) Baseline perceptions of the use of Digital Technologies

8. **Do you use Digital Technologies (electronic tools used for data collection, storage, processes or communication) for your farm's operations and management?**
   a. If yes, which ones and what is their purpose?
   b. How often do you use them?
9. **What do you think are the main benefits from using DT on your farm?**
10. **Main opportunities? In which area of the farm management would it have the most benefits?**

Propose following if no suggestions: to help in transition, communication, farm design, management of resources, application of agroecological principles, income, optimisation of inputs and resources use? Gain of time?

1

11. Main barriers?

12. Risks?

Propose following if no suggestions: *adaptability of tool to organic farm, lack of collaboration to develop these tools, practices could seem not adapted, dependence on companies supplying the tool, privacy of data, appropriation of data, loss of management power, time, loss of local knowledge and connection to the land.*

13. **Drivers:** Would you see a benefit in using more DT and Decision Support Systems on your farm? If yes, what would be needed for you to use them? Most important factor (

Propose following if no suggestions: *training, subsidies, sharing of experience, tool access, user experience, participatory approach, etc.*

4) Presentation of the tool and data required

Appendix 2 – Soil Navigator data field list

Table A2: Soil Navigator data field list as displayed for an organic crop farm field, with associated data source and attribute value – (1/3)

Section	Sub-section	Data field	Data source	Value from case-study	Attribute value as entered in Soil Navigator
Agroecosystem	Agroecosystem	Country	(Metzger et al. 2005)	Danemark	Danemark
Agroecosystem	Agroecosystem	Climatic zone	(Metzger et al. 2005)	Continental	Continental
Agroecosystem	Agroecosystem	Land use	Farmer	Cropland	Cropland
Management	Farm management	Farming system	Farmer	Organic	Organic
Management	Farm management	Farm type	Farmer	Crop Production	Crop production
Management	Farm management	Tillage	Farmer	No tillage	No tillage
Management	Livestock management	Livestock density at farm level	Farmer	None	*Left blank*
Management	Crop management	Nb of crops in rotation	Farmer	7	>5
Management	Crop management	Current crop year n	Farmer	Hemp	Hemp
Management	Crop management	Previous crop (n-1)	Farmer	Grass mix	Rotational grass and grass/clover without norm, over 50% clover
Management	Crop management	Previous crop (n-2)	Farmer	Vegetable mix	Other vegetables
Management	Crop management	Previous crop (n-3)	Farmer	Pea	Pea
Management	Crop management	Previous crop (n-4)	Farmer	Emmer wheat	Spring wheat for bread
Management	Crop management	Number years with dedicated catch crops/cover crops/green manure (last five years - including present year)	Farmer	2 years	2 years
Management	Crop management	Number if years with crops residues left in the field in last five years	Farmer	3 after vegetables, hemp green peas	3 years/last five years
Management	Fertilization	Application of mineral fertilizer	Farmer	No	No
Management	Fertilization	Application of manure/compost/sludge	Farmer	Yes	Yes
Management	Fertilization	Manure application techniques	Farmer	Incorporation	Incorporation
Management	Fertilization	Type of manure/compost/sludge	Farmer	Solid manure	Solid manure
Management	Fertilization	Organic N fertilizer	Farmer	50-75 kg N/ha	50-75 kg N/ha
Management	Other amendments	Nitrification inhibitors	Farmer	No	No
Management	Other amendments	Liming	Farmer	No	No
Management	Other amendments	Other organic amendments	Farmer	Microbes, bucacci, compost tea trials	Yes

Table A2: Soil Navigator data field list as displayed for an organic crop farm field, with associated data source and attribute value – (2/3)

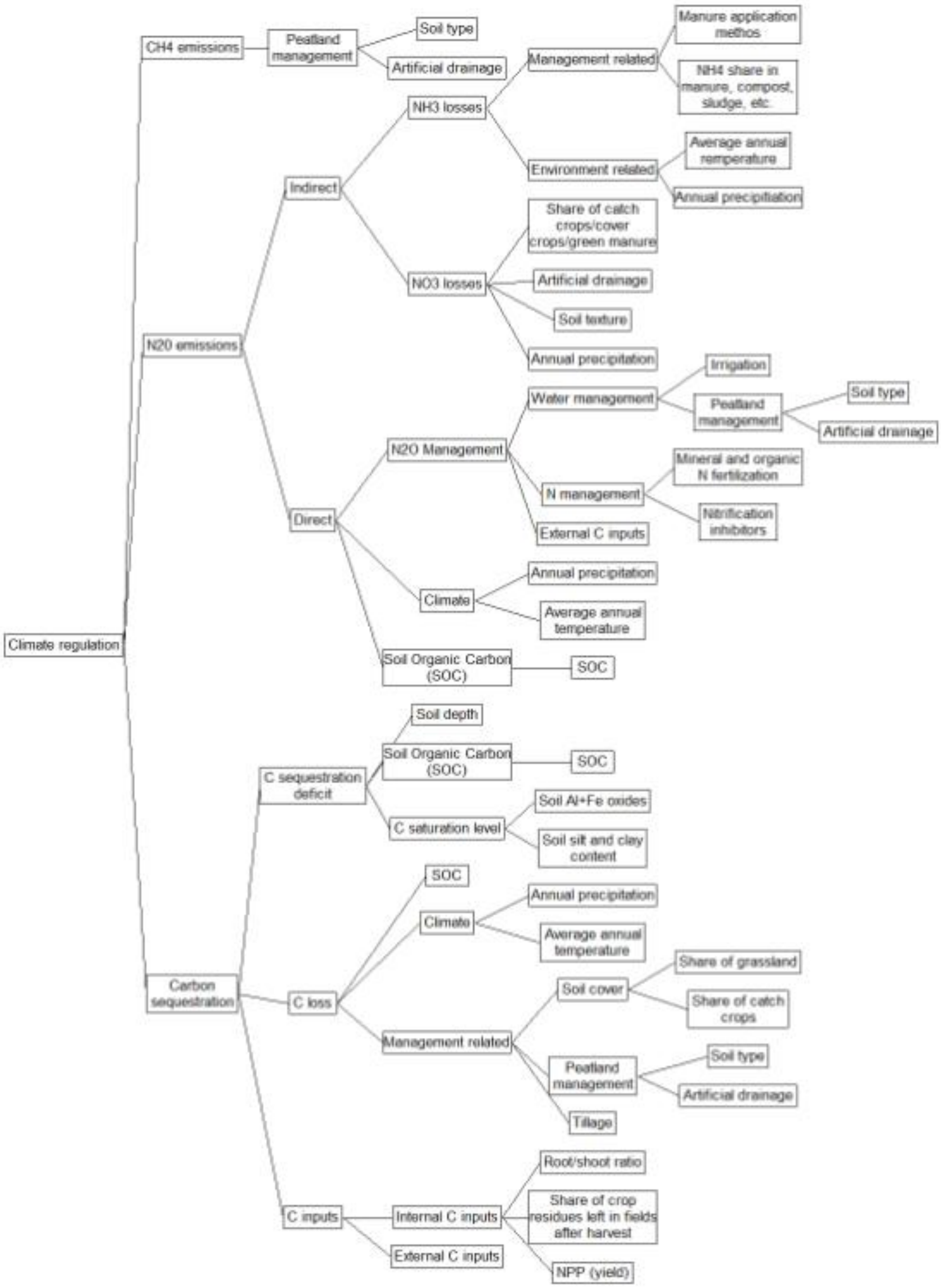
Section	Sub-section	Data field	Data source	Value from case-study	Attribute value as entered in Soil Navigator
Management	Water management	Artificial drainage	Farmer	No	No
Management	Water management	Irrigation	Farmer	No	No
Management	Pest management	Chemical	Farmer	No	No
Management	Pest management	Biological	Farmer	No	No
Management	Pest management	Mechanical	Farmer	No	Yes
Management	Harvest	Expected yield	Farmer	Medium	Medium
Management	Harvest	Net primary Productivity (Total biomass yield)	Farmer	4-10 t DM/ha	4-10 t DM/ha
Management	Harvest	Annual Yield harvested via grazing	Farmer	None	<20%
Management	Harvest	Crop failure (per 20 years)	Farmer	None	<1 years
Environment	Climate	Annual precipitation	SMHI, average annual precipitations 2004-2023, local weather station	665mm	550-750 mm
Environment	Climate	Precipitation in first growing month	SMHI, average precipitations for May 2004-2023, local weather station	39mm	>30 mm
Environment	Climate	Precipitation October to February	SMHI, average precipitations for Oct-Feb 2004-2023, local weather station	301mm	300-500mm
Environment	Climate	Precipitation March to August	SMHI, average precipitations for Mar-Aug 2004-2023, local weather station	322mm	300-500mm
Environment	Climate	Average annual temperature	SMHI, average temperatures 2004-2023, local weather station	8.4C	6-9 C
Environment	Climate	Average temperature in first growing month	SMHI, average temperatures for May 2004-2023, local weather station	11.3C	>5 C
Environment	Climate	Number of days with temperature more than 5C	SMHI, average number of days above 5C 2004-2023 , local weather station	238	230-240 days
Environment	Topography	Altitude	Lantmäteriet 2025	28 masl	<200 masl
Environment	Topography	Slope degree	ESRI, Farmer	Flat	Flat (<2 deg)

Table A2: Soil Navigator data field list as displayed for an organic crop farm field, with associated data source and attribute value – (3/3)

Section	Sub-section	Data field	Data source	Value from case-study	Attribute value as entered in Soil Navigator
Soil	Soil physical properties	Soil type	Farmer	Organic	Organic
Soil	Soil physical properties	Soil texture	Farmer	Sand	Sand
Soil	Soil physical properties	Clay content	Soil analysis February 2025	2%	<10 %
Soil	Soil physical properties	Soil crusting/capping	Farmer	No	No
Soil	Soil physical properties	Thickness of organic layer	Farmer	15cm	10-20 cm
Soil	Soil physical properties	Potential rooting depth	Farmer	Possibly more than 1m due to hemp roots.	>100cm
Soil	Soil physical properties	Groundwater table depth	Farmer	At least 1m	0.4-1.0 m
Soil	Soil physical properties	Soil organic carbon	Soil Navigator	0.99%	<1 %
Soil	Soil physical properties	Soil organic matter	Soil analysis February 2025	1.97%	<2.0 %
Soil	Soil physical properties	Soil bulk density	Soil analysis	1.36	1.35-1.50 kg/dm3
Soil	Soil physical properties	Drainage class	Farmer	Well drained	Well drained
Soil	Soil chemical properties and stoichiometry	Soil pH	Soil analysis August 2016	6.725	6.5-7.1
Soil	Soil chemical properties and stoichiometry	Cation exchange capacity	Literature	<6 meq/100g	<10 cmol IE/kg
Soil	Soil chemical properties and stoichiometry	Soil C:N ratio	Soil analysis February 2025	18.57	12-30
Soil	Soil chemical properties and stoichiometry	Soil N:P ratio	Soil analysis February 2025; Soil analysis August 2016	5.95	<10
Soil	Soil chemical properties and stoichiometry	Plant available P	Soil analysis August 2016	13.34	>4.0 mg P/100g
Soil	Soil chemical properties and stoichiometry	Plant available K	Soil analysis August 2016	6.5	5.1-10.0 mg K/100g
Soil	Soil chemical properties and stoichiometry	Plant available Mg	Soil analysis August 2016	5.56	4.1-8.0 mg Mg/100g
Soil	Soil chemical properties and stoichiometry	Salinity	Soil analysis February 2025	0.136	<2 Ece dS/m
Soil	Soil biology	Bacterial biomass	Soil analysis February 2025	*Value not used*	*Left blank*
Soil	Soil biology	Fungal biomass	Soil analysis February 2025	*Value not used*	*Left blank*
Soil	*Soil biology*	*Earthworm richness*	*Not collected*		
Soil	*Soil biology*	*Earthworm abundance*	*Not collected*		
Soil	*Soil biology*	*Nematode richness*	*Not collected*		
Soil	*Soil biology*	*Nematode abundance*	*Not collected*		
Soil	*Soil biology*	*Microarthropod richness*	*Not collected*		
Soil	*Soil biology*	*Microarthropod abundance*	*Not collected*		
Soil	*Soil biology*	*Enchytraeid richness*	*Not collected*		
Soil	*Soil biology*	*Enchytraeid abundance*	*Not collected*		

Appendix 3 – Climate Regulation decision model

Figure A3: Structure of the decision model for Climate Regulation (Henriksen et al 2018:12)



Appendix 4 – Interview guide stakeholders

Interview guide stakeholders

1) Consent form

2) Thesis outline presentation

3) Current situation, way of working

1) What is your current role?
2) What are your main activities?
3) How often do you work with farmers?
4) What type of farmers are you working with?

4) Perception of Digital technologies

1. Do you use Digital Technologies (electronic tools used for data collection, storage, processes or communication) (DT) in your line of work?
   a. If yes, which ones and what is their purpose? DDS?
   b. How often do you use them?
2. As far as you know, which digital tools are available to farmers to manage farm operations and soil health in Sweden?
3. How would you rate the level of knowledge/usage of the farmers you are working with regarding DT? Is it the same across all farm types?
4. From your experience, what do you think is the current level of uptake in the use of DT and DDS by farmers? Why? What is the current level of trust in these tools?
5. How adapted are they depending on the farm type? Would you say that these are adapted to organic or small scales farms as well?
6. What do you think are the main benefits from using DT when working with farmer?
7. What opportunities does it bring? In which area of the farm management would it bring the most benefits?

   <u>Propose following if no suggestions:</u> to help in transition, communication, farm design, management of resources, application of agroecological principles, income, optimisation of inputs and resources use? Gain of time?
8. What do you think are the main barriers?

   Use PESTEL themes as suggestions (Political, Economic, Social, Technological, Environmental, Legal/regulatory).
9. What do you think are the main risks when using DT in farming?

   <u>Propose following if no suggestions</u>: adaptability of tool to organic farm, lack of collaboration to develop these tools, practices could seem not adapted, dependence on companies supplying the tool, privacy of data, appropriation of data, loss of management power, time, loss of local knowledge and connection to the land.

1

10. Would you see a benefit in using more DT and Decision Support Systems with farmers? If yes, what do you think might help farmers using more DT on their farm? What are the main drivers/enablers?

    <u>Propose following if no suggestions:</u> training, subsidies, sharing of experience, tool access, user experience, participatory approach, adapted policies, etc.

5) Soil Navigator presentation, assessment results and management recommendations

6) Feedback/comments on the tool

11. What is your current level of knowledge of the tool? Have you heard about the tool before?
12. Have you used or are you using similar tools (DSS for example)?

13. Based on the previous presentation, what do you think are the benefits from using this tool (for farmers and advisers)?

(<u>Propose following if no suggestions:</u> help in communication? education in soil functions? improvement suggestions? Etc.)

    a. How would you use the tool with a farmer?
    b. If you would rather not use it, why? What do you see are its limitations?

14. Based on the previous presentation of the tool, would you trust the evaluation of the soil characteristics and suggestions proposed?

    a. What do you think would be required to increase the level of trust in the tool results and suggestions? what could be the enablers?

(<u>Propose following if no suggestions:</u> Training, more knowledge on how the tool works at the back end?)

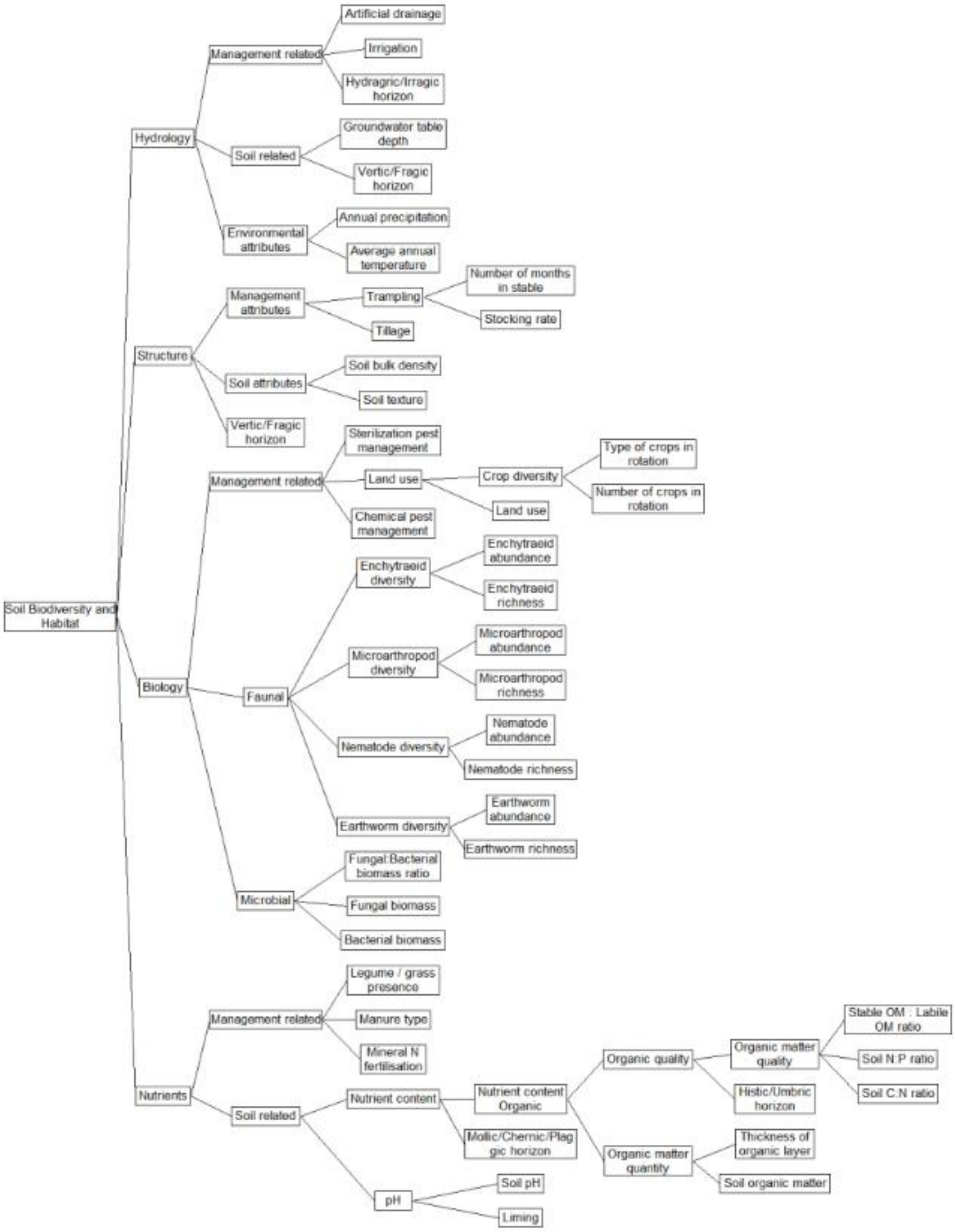
15. This tool has been developed to be easy to use. How would you rate its user friendliness?

16. What do you think would be the main barriers to the use of Soil Navigator?

Use PESTEL themes as suggestion (Political, Economic, Social, Technological, Environmental, Legal/regulatory).

Appendix 5 – Biodiversity and habitat decision model

Figure A5: Structure of the decision model for biodiversity and habitat provisioning (Rutgers et al 2018:13)



Appendix 6 – CAET scoring of case-study farm

Table A6: Scoring of the case-study farm Characterisation of Agroecological Transition (CAET) indices – (1/2)

Diversity	**Score**	**Notes**
CROPS	3	More than three crops but not practicing mixed or inter-cropping
ANIMALS	2	2 horses and 15 goats raised at the farm kept as pets.
TREES	3	Several species of trees surrounding fields observed.
ACTIVITIES, PRODUCTS, SERVICES	3	Production of variety of products, processing of hemp seeds, local shop and cafe.
Total (%)	**69**	

Synergies	**Score**	**Notes**
CROP-LIVESTOCK-AQUACULTURE INTEGRATION	2	The animals kept on the farm are not fully integrated in the agroecosystem but are fed with fodder from farm production.
SOIL-PLANTS SYSTEM MANAGEMENT	3	Practices no till on totality of farming area, the soil is mostly covered with cover crops or crop residues.
INTEGRATION WITH TREES	1	A few apple trees provide apples for CSA boxes
CONNECTIVITY BETWEEN ELEMENTS	3	Trees and natural water areas surround the farm fields
Total (%)	**56**	

Efficiency	**Score**	**Notes**
USE OF EXTERNAL INPUTS	1	Some inputs such as green manure are produced on farm but the totallity of seeds have to be purchased.
MANAGEMENT OF SOIL FERTILITY	4	No synthetic fertilisers are used on the farm, only compost and cow manure.
MANAGEMENT OF PESTS & DISEASES	4	Pest and diseases are managed via biological or mechanical means.
PRODUCTIVITY AND HOUSEHOLD's NEEDS	4	All household's needs are met.
Total (%)	**81**	

Recycling	**Score**	**Notes**
RECYCLING OF BIOMASS AND NUTRIENTS	4	All residues or by-products are recycled on the farm.
WATER SAVING	0	No water saving equipment, the crop system is mainly rainfed.
MANAGEMENT OF SEEDS AND BREEDS	0	All seeds are purchased.
RENEWABLE ENERGY USE AND PRODUCTION	2	Use electricity from renewable sources as part of KRAV certification requirements. Diesel is still used for farming equipments and machinery.
Total (%)	**38**	

Resilience	**Score**	**Notes**
STABILITY OF INCOME/PRODUCTION	4	Farmer's perception that income and production are stable and increasing over time.
MECHANISMS TO REDUCE VULNERABILITY	3	Farmer's perception that they have overall good access to assurances and credits.
INDEBTEDNESS	3	The level of debt is limited and capacity to reimburse is total.
DIVERSITY OF ACTIVITIES, PRODUCTS AND SERVICES	3	Production of variety of products, processing of hemp seeds, local shop and cafe.
Total (%)	**81**	

Culture & Food Tradition	**Score**	**Notes**
APPROPRIATE DIET AND NUTRITION AWARENESS	4	The farmer has a healthy, nutrious and diversified diet.
LOCAL OR TRADITIONAL IDENTITY	3	The farmer promotes locally sourced food via the organisation of cultural and social events.
USE OF LOCAL VARIETIES/BREEDS	3	The farmer promotes locally sourced and traditional products.
Total (%)	**83**	

Co-creation and knowledge sharing	**Score**	**Notes**
PLATFORMS FOR THE HORIZONTAL CREATION	4	The farmer is part of several farmer and industry groups, in addition to having ongoing collaboration with local educational organisations.
ACCESS TO AGROECOLOGICAL KNOWLEDGE	4	The farmer is part of a networking group working on promoting regenerative farming practices.
PARTICIPATION OF PRODUCERS IN NETWORKS	4	Farmer's perceptions that there is a good level of support within the local community.
Total (%)	**100**	

Table A6: Scoring of the case-study farm Characterisation of Agroecological Transition (CAET) indices – (2/2)

Human and Social values	Score	Notes
WOMEN'S EMPOWERMENT	4	The farmer is a women, in charge of making the majority of the decisions on the farm.
LABOUR (PRODUCTIVE CONDITIONS, SOCIAL INEQUALITIES)	4	The farmer has full access to capital and decision making. No social inequalities observed with employees.
YOUTH EMPOWERMENT AND EMIGRATION	2	Farmer's perceptions that young people are interested but experiences difficulties to connect with them.
ANIMAL WELFARE	4	No animal welfare issues reported on the farm.
Total (%)	**88**	

Circular and solidarity economy	Score	Notes
PRODUCTS AND SERVICES MARKETED LOCALLY	4	All products are marketed locally.
NETWORKS OF PRODUCERS, RELATIONSHIP WITH CONSUMERS AND PRESENCE OF INTERMEDIARIES	3	Networks are well established, with the involvement of distributors for the sale of bulk products such as rye or emmer wheat grains.
LOCAL FOOD SYSTEM	2	A part of the inputs comes from outside the local market, mainly seeds. Some products are also marketed outside the region or the country.
Total (%)	**75**	

Responsible Governance	Score	Notes
PRODUCERS' EMPOWERMENT	4	Farmer's perception thar their rights are respected, with capacity and means to develop their skills.
PRODUCERS' ORGANIZATIONS AND ASSOCIATIONS	4	Several organisations exsist to promote local and organic. The farmer perceives to have easy access to these networks.
PARTICIPATION OF PRODUCERS IN GOVERNANCE OF LAND AND NATURAL RESOURCES	4	The farmer percieves that enough mechanisms are in place to influence decisions made on the use of land and natural resources.
Total (%)	**100**	

Appendix 7 – A-WEAI scoring of case-study farm

Table A7: Scoring of the case-study farm women empowerment index (A-WEAI) obtained from farmer's interview.

Domains	Areas of Assessment	Answer	Score max	Score	Score (%)
Productive decisions	About CROPS PRODUCTION, ANIMAL PRODUCTION, OTHER ECONOMIC ACTIVITIES	Decisions taken by the farmer herself	1	1	100%
	About MAJOR & MINOR HOUSEHOLD EXPENDITURES	Decisions taken by the farmer herself	1	1	
	Perception of decision making about CROPS PRODUCTION, ANIMAL PRODUCTION, OTHER ECONOMIC ACTIVITIES	Decisions taken by the farmer herself	1	1	
	Perception of possibility of decision making about MAJOR & MINOR HOUSEHOLD EXPENDITURES	Decisions taken by the farmer herself	1	1	
Access to and decision-making power about productive resources	Secure land tenure for men and women	Land owned by the farmer	1	1	100%
	Access to credit	Possible for women in secured channels	1	1	
	Ownership of CROPS, SEEDS, ANIMALS, and OTHER PRODUCTIVE ASSETS	Owned by the farmer	1	1	
	Ownership of MAJOR & MINOR HOUSEHOLD ASSETS	Owned by the farmer	1	1	
Control over use of income	Decisions about the use of the revenue generated by CROP PRODUCTION, ANIMAL PRODUCTION and OTHER ECONOMIC ACTIVITIES	Farmer contributed to all decisions taken on the farm operations	1	1	100%
Leadership in the community	If these groups exist in your community, how often do you participate in their activities and meetings? WOMEN'S ASSOCIATIONS AND ORGANIZATIONS	Farmer sometimes participates to women's networking group (Aurora i Lund).	1	0.33	50%
	COOPERATIVES FOR RURAL PRODUCTION Social Movements, Union of Rural Workers, Political Groups, Religious Groups, Training for, Capacity Development, Other	Farmer involved in numerous collaborations with University, Regenerative farmer groups, and active on social medias.	1	0.66	
Time use	More than 10.5 hours spent working per day	Yes, both for women and men employed at the farm.	1	0.5	75%
	Time spent in AGRICULTURAL ACTIVITIES + FOOD PREPARATION & DOMESTIC WORKS + OTHER GAINFUL ACTIVITES	Women's time perceived as similar to men	1	1	
A-WEAI score (average)					**85%**

Appendix 8 – SOCLA scoring of case-study farm

Table A8: Scoring of the case-study farm soil health index (SOCLA) obtained from farmer's interview and observations from soil sampling

Indicators	Characteristics	Score	Notes
Structure	Few aggregates that break with little pressure	3	Due to sandy soil characteristics
Compaction	No compaction, flag can penetrate all the way into the soil	5	Observation from soil sampling
Soil depth	Superficial soil (> 10cm)	5	Observation from soil sampling and farmer's observation
Status of residues	Presence of last year's decomposing residues	3	Observation from soil sampling. (hemp straws and roots present on field and in soil samples).
Color, odor, and organic matter	Dark, brown, fresh odor, and abundant humus	5	Observation from soil sampling
Water retention (moisture level after irrigation or rain)	Limited moisture level available for a short time	3	Farmer's observation of a soil well drained
Soil cover	More than 50% soil covered by residues or live cover	5	Farmer's observation
Erosion	No visible signs of erosion	5	Observation from soil sampling
Presence of invertebrates	A few earthworms and arthropodes present	3	Observation from soil sampling
Microbiological activity	*x*	*x*	*Not assessed*
Final score (average)		**4**	

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