Potential to reduce climate impact with digitalisation in agriculture

– literature review and a case study of milk

Frida Edman, Fereshteh Pourazari, Serina Ahlgren, Danira Behaderovic, Per Peetz Nielsen
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Authors: Frida Edman[1], Fereshteh Pourazari[1], Serina Ahlgren[1], Danira Behaderovic[1], Per Peetz Nielsen[1], Victor Kardeby[2]

1) RISE, Department of Agriculture and Food
2) RISE, Department of Industrial Systems

The overarching vision of the programme Mistra Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one that is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets. By taking a holistic perspective and addressing issues related to agriculture and food production, as well as processing, consumption and retail, Mistra Food Futures aims to play a key role in initiating an evidence based sustainability (including environmental, economic and social dimensions) and resilience transformation of the Swedish food system. This report is a part of Mistra Food Future's work to identify agricultural systems with potential to make agriculture net-zero, one of the central issues within Mistra Food Futures.

Mistra Food Futures is a transdisciplinary consortium where key scientific perspectives are combined and integrated, and where the scientific process is developed in close collaboration with non-academic partners from all parts of the food system. Core consortium partners are Swedish University of Agricultural Sciences (SLU), Stockholm Resilience Centre at Stockholm University and RISE Research Institutes of Sweden.

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Abstract

The agricultural sector in Sweden needs to reduce greenhouse gas (GHG) emissions. Digitalisation has the potential to contribute to this reduction. The term digitalisation is used to describe a process for digital transformation of products and processes. The purpose is to enable better decisions by using an increased insight through collecting data, and to process the collected data using different smart algorithms.

In this report, we present a literature review on research of the potential to reduce climate impact with digitalisation in agriculture. The result of the literature review was applied on a case study, where different scenarios with varying degrees of digitalisation were tested to quantify possible reductions in GHG emissions when introducing digitalisation techniques at a Swedish dairy farm.

The results shows that implementation of various digitalisation technologies at a Swedish dairy farm has a potential to reduce the carbon footprint of Swedish milk by 16 %. Precision livestock farming shows the largest potential with an estimated reduction of 14 %, primarily due to feed efficiency and improved animal health and longevity, reducing the total number of animals while maintaining high milk output. It is however important to evaluate the whole system, as changes in the dairy system might impact other farms and food producing systems. This indicates a need for research to further investigate the potential GHG reduction when introducing digitalisation in agriculture.

Keywords: Digitalisation, agriculture, sustainability, greenhouse gas (GHG) emissions, precision agriculture, dairy production

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1. Introduction

1.1. Background

This report forms part of the research program MISTRA Food Futures, and more precisely part of work package (WP) 5.

The overall aim of MISTRA Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one which is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets.

In WP5, the aim is to identify agricultural systems with potential to make agriculture net-zero regarding greenhouse gases (GHG) in year 2045. For this purpose, a large simulation model is constructed taking into account several measures which can help achieve the target. This report is one of the approximate 17 different background reports which will feed into MISTRA Food Futures WP5 simulation modelling work.

1.2. Aim

The aim of this report was to give input to MISTRA Food Futures WP5 on the potential to make agriculture net-zero regarding GHG emissions in year 2045, with aid of digitalisation. More specifically the aim was to:

- Perform a very broad literature review on the potential GHG reduction when introducing digitalisation in agriculture.
- Perform a more in-depth literature review on the potential GHG reduction when introducing digitalisation in Swedish milk production.
- Perform a case study on Swedish milk production where digitalisation is introduced.

Automation will not be considered in this report more than briefly in the context of digitalisation.

1.3. What is digitalisation?

The terms digitalisation and digitisation are interchangeably used to describe a process for digital transformation of products and processes. The purpose is to enable better decisions by using an increased insight through collecting data, and to process the collected data using different smart algorithms. In the literature, Brennen and Kreiss (2016) differentiate these two words where digitisation is the act of converting analogue methods of collecting data into digital equivalents whereas digitalisation is used to describe a process where digital technology is used to change working methods, remove time consuming or error prone activities, or restructure entire processes. This distinction is seldom used in everyday discussions where a general understanding is that digitalisation uses different methods and technologies to identify and implement changes in business policies, working processes and technology.

2. Method

A literature review was conducted to get a comprehensive picture of the current research on the potential to reduce climate impact with digitalisation in agriculture. The literature was searched through Google Scholar and Scopus using the following keywords:

- Digital/digitalization/digitalisation
- Monitoring
- Automatic/autonomous
- Precision
- AI
- GHG/carbon footprint/life cycle assessment/climate impact
- Smart farming
- Variable rate application
- Controlled traffic farming

The literature search resulted in three main types of papers:

- Papers that assess technologies
- Papers that model the future/scenario studies
- Reviews of current research

Most of the retrieved papers did not quantify the potential reduction of GHG emissions.

Secondly, a case study on a Swedish dairy farm was conducted. The purpose of the case study was to quantify possible reductions in GHG emissions when introducing digitalisation techniques at a Swedish dairy farm. A general Swedish dairy farm was used as baseline, assuming low degree of digitalisation. Using the climate simulation modelling tool Vera – Klimatkollen, the GHG emissions, expressed per kg of energy corrected milk at farm gate was calculated. A number of scenarios, including varying degrees of digitalisation, were narrated (based on the outcome of the literature review) and modelled.

3. Digitalisation in crop cultivation

The application of precision agriculture (PA) practices, referring to a large reservoir of precision agriculture technologies, in agricultural field operations could positively contribute to GHG emission reduction through:

(i) The enhancement of the ability of soils to operate as carbon stock reserve by less tillage (Angers and Eriksen-Hamel, 2008),
(ii) The reduction of fuel consumption through less field operations with agricultural machinery (direct GHG decrease)
(iii) Reduction of inputs for the agricultural field operations e.g. reduced nitrogen fertilisation (Khan *et al.*, 2007; Waldrop *et al.*, 2004) and precision irrigation (McCarthy *et al.*, 2020).

Therefore, GHG mitigation measures which refer to new technologies and techniques on all agricultural practices (precision/variable rate sowing/planting, fertilising, spraying and irrigation) can significantly reduce the amount of inputs that are responsible for GHG contribution and thus reduce climate change impact of agriculture; while at the same time taking into account that crop production should be maintained or even increased in the challenge of ensuring food security and safety for human food consumption.

A study by Lantmännen (2019) on future agriculture estimates that only in 2015, over 4.5 million tonnes of CO_2 is emitted from Swedish arable lands (about 2.5 million hectares) producing 14.5 million tonnes of dry matter per year. This report, however, concluded that there is a great potential to increase harvests with digitalisation in crop production. Based on full implementation of precision cultivation and digitisation, optimal management, optimised crop rotations and continued plant breeding, harvests can increase by about 38 % compared to 2015 and climate impact can be reduced by about 69 % by 2030. A yield increase of 48 % is expected until 2050. This requires a full implementation in terms of technology and that all conditions are in place, e.g. optimal supply of nitrogen, secured water supply and plant protection methods that keep pace with the pests (Lantmännen, 2019).

Precision agriculture technologies can be divided into these main categories (Radoglou-Grammatikis *et al.*, 2020; Schwarz *et al.*, 2011): (1) the guidance systems (i.e. driver assistance, machine guidance and controlled traffic farming), (2) the recording technologies (i.e. soil mapping, soil moisture mapping and canopy mapping) and (3) the reacting technologies (variable application of resources, pesticides, seeding and weeding). As recording technologies remain supportive and are often incorporated into the other two precision agriculture practices, it is not further discussed here.

Assessing the impacts of precision agriculture on GHG emissions and farm economics across EU, Soto *et al*. (2019) scaled the importance of Precision Agricultural Technologies (PATs) on GHG reduction potential with the variable rate nutrient application having the highest reduction potential (Table 1).

Table 1. Ranking of Precision Agricultural Technologies (PATs) on GHG reduction potential.

RANKING OF PATS	PAT TYPE	GHG REDUCTION POTENTIAL
1	Variable rate nutrient application	5
2	Variable rate irrigation	3
3	Controlled traffic farming	2
4	Machine guidance	2
5	Variable rate pesticide application	2
6	Variable rate planting/seeding	1
7	Precision physical weeding	1

3.1. Guidance systems

Guidance systems are hard- and software which guide tractors and implements over a field, which include all forms of automatic steering/guidance for tractors and self-propelled agricultural machinery, such as driver assistance and machine guidance.

3.1.1. Machine guidance

Active machine guidance refers to the applications of Global Navigation Satellite System (GNSS) for steering and guidance through driver assistance and/or machine auto-guidance. Driver assistance helps the driver keep the line in the field through add-ons which are not usually integrated in the tractor’s systems and can be added with extra cost. Machine auto-guidance systems are integrated in the tractor’s hydraulics and can directly take over steering operations; helping to avoid gaps and overlaps in multiple passes with the tractor. These advanced systems are coupled with on-board computers which allow for headland steering, section control and that accept drive-maps (routing) and task maps to operate implements. Passive machine guidance does not apply satellite navigation systems but merely guides the tractor, potentially resulting in drifts from lines. Machine auto-guidance systems are one of the most adopted precision agriculture technologies because the impact on the farm is measurable and accurate. However, farm size matters for the technology to provide substantial results, especially in terms of environmental impact.

Shockley *et al*. (2011) modelled a commercial Kentucky corn and soybean farm under no-till conditions where machine guidance during planting and fertiliser application led to cost savings of approximately 2.4 %, 2.2 % and 10.4 % for seed, fertiliser and tractor fuel, respectively, which can be translated to GHG emission mitigation. In Sweden, utilising GPS is shown to save up to 18 hours per hectare operation times for cultivation, sowing, rolling and harvesting (Anderson, 2004). Guidance systems such as lightbar and auto-steering can reduce fuel consumption by 6–10 % (Bora *et al*., 2012).

3.1.2. Controlled traffic farming

Controlled traffic farming is a management strategy that built on permanent wheel tracks where the crop zone and traffic lanes are permanently separated. To keep machinery in the same lanes, navigation technologies are applied. By always driving on the same lane in the fields, a better soil structure in the cropping areas can be achieved, leading to increased yields.

In Sweden however, a six-year study did not show a significant crop (maize, wheat and rape) yield increase in plots with controlled traffic farming compared to traditional random traffic farming (Holm *et al*., 2017). In Denmark, the impact of widespread adaptation of controlled traffic farming coupled with auto-guidance was assessed by Jensen *et al*. (2012), looking at wheat, rape seeds, maize and sugar beets. They estimated a fuel use reduction of 25–27 % in cereals due to less overlap and reported 3–5 % savings on pesticides and fertilisers.

Vermeulen *et al*. (2010) has analysed the impact of controlled traffic farming in GHG emissions directly and indirectly, by reducing energy inputs, facilitating zero tillage and increasing fertiliser efficiency. The authors reported an approximate reduction of tractor fuel requirements of 40 % and 70 % while using uncontrolled traffic zero tillage and controlled traffic zero tillage farming, respectively, in comparison to conventional tillage.

Tullberg *et al*. (2018) determined the emissions of N_2O and CH_4 in 15 different cultivated grain crops in Australia and reported that controlled traffic farming can reduce the soil emissions of N_2O and CH_4 by 30–50 %. Those authors also estimated that the converting 50 % of the 22 M ha of dryland grains in Australia to controlled traffic farming could reduce annual emissions from Australian cropping (currently 5.0 Mt CO_2e) by 0.6–1.7 Mt CO_2e. In a review, Gasso *et al*. (2013) concluded that controlled traffic farming, when compared with random traffic farming, is able to reduce soil emissions of N_2O (21–45 %) and CH_4 (372–2100 %), in-field operations direct emissions (23 %), and indirect impacts associated with fertilisers (1–26 %), pesticides (1–26 %), seeds (11–36 %), and fuels (23 %). Controlled traffic farming in addition, is likely to cause reductions on environmental issues, such as ammonia emissions, and run-off of soil, nutrients, and agrochemicals.

3.2. Reacting technologies

Reacting technologies are implements, hard- and software that together can vary the placement of agricultural inputs in the field, which include technologies such as variable rate irrigation and weeding and variable rate application of seeds, fertiliser and pesticides.

3.2.1. Variable rate nutrient application

According to Eurostat (Dace and Blumberga, 2016), there is a nitrogen surplus in the EU-28 member states. Therefore, variable rate application of inorganic fertilisers and manure allows for the optimum application of nutrient according to the crop needs, reducing the final fertiliser (or manure) quantity and its associated GHG emissions from reduced fuel use and from reduced N fertiliser production and use. GHG emissions can be further reduced when N fertilisation is combined with precipitation prediction or appropriate irrigation scheduling.

Programs such as DataVäxt and markdata.se provide Yara N-sensor scanning crops' N status and utilising GPS to create a N map of the field in real time. Created maps are further linked to CropSat and satellite images for continuous monitoring of the N status of the field, suggesting site specific N requirements throughout the growing season.

Kazlauskas *et al.* (2021) compared the effect of fixed and variable rate fertilisation in spring barley, winter oilseed rape, winter wheat and faba beans in Lithuania and showed that an application of a variable fertilisation rate can reduce the total amount of nitrogen, phosphorus, and potassium fertilisers by approx. 25 %, energy consumption for fertilization by 3463 MJ/ha, and emissions of GHG by 340 kg CO_2e/ha compared to fixed fertilisation rate. The European project SERPEC-CC mapped the potentials of 650 relevant technologies for reducing the emission of GHG in European Union across ten major sectors (Wesselink and Deng, 2009). This project identified that variable rate nutrient application has the potential to reduce the baseline GHG emission rate by 5 % (i.e. this impact is only assigned to mineral fertiliser application without considerations for yield impact). The authors also pointed out that by making effective allowance for manure and residual N with variable rate technology the GHG emission reduction can reduce by another 5 %. In Munich, Germany, Sehy *et al.* (2003) examined the use of variable rate N application and GPS in maize crop and found that N_2O emissions decreased by up to 34 % in low-yielding areas.

3.2.2. Variable Rate Irrigation

Variable rate irrigation can either be executed using a retrofitted self-propelled irrigation system or micro-irrigation. The common types of self-propelled irrigation systems are centre pivot and linear move sprinkler systems that apply water above the canopy of the irrigated crop (Rogers *et al.*, 2019), having irrigation efficiency (ratio of water amount consumed by crop to the amount supplied through irrigation) of up to 85 %. New developments in pivot systems are the "Low Energy Precision Application" and "Low Energy Spray Application" with irrigation efficiency around 97 % (Adeyemi *et al.*, 2017).

Micro-irrigation, a high-tech type of variable rate irrigation system (drip or trickle emitters, micro-sprinkling and micro-spray, and subsurface irrigation), is used in high value crops, as they increase crop yield, use water more efficiently, maintain warmer soil temperature and might result in less pesticide use (Chantre *et al.*, 2018). Lower quantities of water irrigation require lower pumping energy which, when powered by either fossil fuel motors or electricity, influence GHG emissions.

Increased soil water content accelerates microbial respiration of soil organic matter, which enhances CO_2 and N_2O emissions (Trost *et al*., 2013). A review by Trost *et al*. (2013) compared N_2O emissions from irrigated and non-irrigated fields showing an increase of N_2O emissions (about 50 % to 140 %) under irrigation, in most cases studies. This shows that when variable rate irrigation is applied N_2O emission from irrigated soils will be significantly influenced. Variable rate irrigation systems can also assist irrigation scheduling combined with meteorological prediction models and fertilisation schedules in order to keep soil water availability in such levels to avoid provoking more GHG emission production through N_2O.

Reduction in N_2O emissions of up to 68 % was reported by Maris *et al*. (2015) when two water-saving irrigation strategies including surface drip irrigation (average irrigation water applied 449 mm) and subsurface drip irrigation (average irrigation water applied 241.50 mm) were compared. A cotton study in China showed that drip irrigation and a plastic film mulching decreases N_2O emissions by 36 % compared to the furrow irrigation, which is mulch-free (Wu *et al*., 2014). CH_4 emissions was reduced by up to 350 kg CH_4/ha (about 40% reduction) in a loam soil in Spain when sprinkler irrigation was applied to the paddy field instead of flood irrigation (Fangueiro *et al*., 2017).

Irrigation systems use a tremendous amount of energy which results in substantial GHG emissions depending on the energy source (Rothausen and Conway, 2011). McCarthy *et al*. (2020) examined the energy consumption and GHG emissions when Low Energy Precision Application is adopted. The study showed a reduction of energy use by 19 % and GHG emission by 15 % in fields treated with Low Energy Precision Application.

3.2.3. Variable rate pesticide application

Variable rate pesticide application technologies enable changes in the application rate to match actual or potential pest stress in the field and avoid application to undesired areas of the field or plant canopies. Moreover, by performing variable rate pesticide application in the same operation as variable rate nutrient application the number of operational activities can be further reduced. There are two types of variable rate pesticide application technology:

i) The map-based variable rate pesticide application: which adjusts the application rate based on a prescription map, using a satellite navigation system to identify the field position. The input rate is changed as the applicator moves through the field (Grisso *et al*., 2011).

ii) The real-time sensor-based variable rate pesticide application: which uses the current situation of pest stress or canopy characteristics which is identified by the differences in colour, shape, size, texture, reflectance, and temperatures of pests detected by different sensor types (colour cameras, photodetectors, laser scanners, multispectral and hyperspectral cameras, thermal cameras, and ultrasonic sensors). The sensor input can also be used to control the direction and rate of chemical application (Karkee *et al*., 2013).

There are also technologies of variable rate pesticide application that combine sensor-based and map-based applicators to achieve higher precision; e.g. Greenseeker (Păcurar *et al*., 2019) and Isaria (Baillie *et al*., 2018).

The environmental benefits from pesticide application reduction are e.g. less soil and water contamination, less biodiversity loss (Timmermann *et al*., 2003). There is significant work on the saved pesticide quantity that ranges from 11 to 90 % for herbicide use in different arable crop types (Dammer and Wartenberg, 2007; Gerhards *et al*., 1999; Timmermann *et al*., 2003). Variable rate pesticide use can also cause reductions in insecticide use by 13 % in winter wheat (Dammer and Adamek, 2012), while spray overlap can be significantly decreased with impact on the total pesticide use (Batte and Ehsani, 2006).

The impact of the high pesticide reduction shown from the literature is environmentally significant, but, in terms of GHG emission reduction, the contribution of this technology to the total agricultural effect is slight. The reason is that in this case GHG emissions are mitigated only during the industrial production of the pesticide. Even if the index of GHG emission production for every kg of pesticide is very high in comparison to other agricultural inputs (seed, fertilisers, and fuel), the total applied quantity is very low, mirroring a low total impact on GHGs (IPCC, 2007).

3.2.4. Variable Rate Planting/seeding

Variable rate planting/seeding is the method of varying the rate of plants or seeds according to local soil conditions (Grisso *et al*., 2011). More advanced systems have independent planting/seeding elements which can also differentiate the application rate on-the-go per row using a field map (e.g. Trimble). Variable rate planting/seeding eliminate double planting and in very heterogeneous fields redistribute within field seeds in the optimum quantity. Thus, this system can perform better in heterogeneous fields because seed rate differentiation will affect the yield in low crop performance zones and the final output will be in favour of the farmer.

Multi-hybrid planting/seeding technology has been developed in recent years. Seeding machines are able to seed two or more different hybrids (or different crop varieties) at the same time: one high-demanding and high-yielding hybrid which is sown on the high-performance zones of a field, while the other hybrid is a more resilient, but less yielding hybrid, which is sown on the low performance zones of the same field.

When applying variable rate planting/seeding it is possible that the total plant/seed quantity used in the field will be lower (less GHG emissions coming from the production of the plant or the seed) or the same as in conventional seeding. Nevertheless, an effect of this technique on GHG emissions can be expected through the increased yield (Hörbe *et al*., 2013). Hörbe *et al*. (2013) performed two experiments which tested the economic returns of variable rate seeding maize and reported yield increase of 1.9 and 0.9 tonnes/ha in low crop performance and high crop performance zones of the field, respectively; suggesting an environmental benefit of variable rate seeding/planting.

3.2.5. Precision physical weeding technology

A promising approach for weed detection is a continuous ground-based image analysis system which locate crop rows in the field (Martelloni, 2014). Another detection system is ultrasonic sensors which detect plant density; when the plant density is increased the harrow treats this part more aggressively (Peteinatos *et al*., 2015). In this system, a system for online weed control was developed and the system automatically adjusts the tine angle of a harrow and creates different levels of intensity.

No data was found on the direct impacts of precision physical weeding on GHG emissions. Potentially, precision physical weeding technology can reduce GHG emissions through reducing the pesticides production and use. Fuel consumption can also be reduced. As in the case of variable pesticide application, the impact on the avoided GHG emissions of the total agricultural system is expected to be low, however if yield increases can be achieved larger GHG emission savings can be expected.

4. Digitalisation in animal production

4.1. Precision Livestock Farming

Digitalisation and digitisation describe the process of digital transformation in production with the purpose to make better informed decisions by collecting data and process the collected data using different smart algorithms. When applied on livestock production, this is usually called precision livestock farming (PLF). It aims to monitor and analyse the production based on continuous real-time data from animals and environment (Berckmans, 2017). Precision livestock farming has in several studies showed the potential to improve production (Gómez *et al.*, 2021; Lovarelli *et al.*, 2020; Monteiro *et al.*, 2021).

Precision livestock farming could positively contribute to a reduction of GHG emissions by production optimisation, rather than reducing the GHG emissions directly. This could be achieved by increasing animal health and welfare and optimising the management, such as early detection of oestrus, optimising feed management, and analysing the production such as milk analyses, carcass composition prediction, etc. Additional technologies, such as building simulation models of the production, could be an important support in decision-making and provide valuable information on the efficacy of possible mitigation strategies to reduce GHG emissions.

Some GHG emissions, for example from enteric fermentation, originate from complex, biological processes, for which digital technologies enable a certain improvement but not a reduction to zero. The GHG emissions from such biological processes could however be reduced by other measures, such as feed supplements (Honan *et al.*, 2021) and other improvements of feeding strategies (Lantmännen, 2019). These measures are not directly connected to digitalisation, but the digitalised technologies could contribute to development, improvements, and progress in research by enabling detailed monitoring, such as ingestible pills, and by analysing the collected data. Jose *et al.* (2016) also underlines the urgent need of cost-effective tools and technologies to quantify GHG emissions and especially in complex processes of the livestock production, such as the production of methane through enteric fermentation, where the quantification is time consuming and often requires complex and expensive equipment.

4.2. Technologies

There is a great range of technological systems (see Table 2), digitalised tools, sensors and software and a range of national and international companies implementing these technologies to their portfolio of tools for farmers to use. These tools use advanced AI and machine learning, e.g. for detecting deviances which could be used for identifying animals in need of extra attention.

Table 2. Precision livestock farming technologies.

TECHNOLOGY	MAIN OBJECTIVE/FUNCTION	INDIRECT EFFECT ON GHG EMISSION
ACTIVITY METERS AND ACCELEROMETERS (E.G. NECK COLLARS)	Record animal activity and behaviours.	Detection of oestrus, poor health, diseases, etc.
AI, ALGORITHMS, SIMULATION MODELS AND ANALYSIS SOFTWARE	Analysing production based on collected data and modelling production.	To predict, improve and optimise the production, such as detection of abnormalities, detection of oestrus, etc.
AIR SENSORS	Register air quality.	Detect poor air quality.
AUTOMATED AND DIGITALISED FEEDING SYSTEMS	Control and register the amount of feed provided and consumed.	Optimised feed management, animal growth and reducing ammonia emissions.
AUTOMATIC DRAFTER (AD)	Sort animals based on their weight.	Optimised time of slaughter.
DIGITAL REPORTS	Communication of production data to farmer, to act as decision-support.	Increased knowledge of the production and improved production by better decisions.
DRONES	Tracking location and daily inspection of animals.	Reduced need to look for animals on pasture, i.e. shorter transportation.
GPS	Tracking location.	Reduced need to look for animals on pasture, i.e. shorter transportation.
HEAT CAMERAS	Register animal temperature or housing environment temperature.	Detection of diseases and issues with housing environment temperature.
INGESTIBLE PILLS	Registration of digestion and detection of nutritional needs and digestive disorders.	Optimised feed management, animal growth, reduced ammonia emissions and detection of digestive disorders.
MICROPHONES	Register sounds.	Detection of respiratory diseases, farrowing, oestrus, etc.
MILKING PARLOUR-RELATED TECHNOLOGIES	Register milk characteristics, detecting abnormalities of udder and teats, etc.	Detection of abnormalities and diseases, such as abnormalities of milk, milk yield, milk quality, etc. Additional potential to improve feed ratios to animals, based on fat and protein content of milk.
NEXT GENERATION FEEDING SYSTEM	Provide feed with a tailored composition of nutrients.	Optimised feed management, animal growth and reduced ammonia emissions.
REAL TIME LOCATION SYSTEM (RTLS)	24/7 tracking of animals housed indoor. Mainly used for dairy cows.	Optimised health surveillance, heat detection and to track animals.
RUMINAL PH-SENSORS	Register ruminal pH.	Optimised ruminal function.
VIDEO CAMERAS	Register behaviours, location, body condition, weight, carcass composition prediction, face recognition, cleanliness, etc.	Optimised body condition and optimised time of slaughter, and to detect and avoid undesirable behaviours, such as aggressive behaviours, resulting in increased animal health and welfare. It could additionally recognise individuals, for an individualised production.
VIRTUAL FENCES	To fence in the animals without disturbing the surroundings by a fence.	No effect except the reduction of material cost for the physical fences. It could however increase the use of natural grassland and increase grazing, resulting in improved biodiversity.
WEIGHING SYSTEMS BASED ON IMAGE ANALYSIS	Determine the weight of individuals or groups.	Optimised time of slaughter.

4.3. Digitalisation impacts in dairy production

The mentioned technologies (Table 2) are examples of technologies which could be suitable for implementation in animal production. They contribute to several digitalisation impacts in dairy production, explained below. Further, there are measures which potentially could reduce emissions, but which are not directly connected to digitalisation. These measures are for example breeding, and feed additives with a reducing effect on methane emissions from enteric fermentation; these measures are not included in this study.

4.3.1. Detection of oestrus

Early detection of oestrus among dairy cows could positively contribute to GHG emissions reduction. An undetected oestrus results in a delay of 21 days before insemination, during which time the animal will eat and generate emissions. Technologies supporting early detection of oestrus are e.g. different kind of sensors, detecting behavioural and physiological changes or in-line systems analysing milk samplings for progesterone such as Herd Navigator (DeLaval).

4.3.2. Diseases

A decreased prevalence of diseases could result in an increased milk yield, resulting in a reduction of GHG emissions per unit. Diseases also affect the longevity of the cow, resulting in additional negative effects of the production. Furthermore, a decreased prevalence of diseases would reduce the use of veterinary medicinal products. A recent study analysing environmental impact of Swedish pork did however find that there are no available lifecycle assessment methodologies applicable for assessing the environmental impact of veterinary medicinal products (Landquist *et al*., 2020).

In Swedish dairy farms connected to Kokontrollen, there is an average disease incidence of 21 % per lactation year (Växa, 2021). The three most common diseases are clinical mastitis, digital diseases and calving paralysis, corresponding for 64 % of the total disease incidence, i.e. a disease incidence of 13.5 %.

Technologies supporting early detection of diseases, resulting in reduced disease incidence, are e.g. activity meters and Real Time Location System which uses changes in behaviour patterns to detect deviations, or in-line monitoring systems analysing milk samples such as Herd Navigator (DeLaval). Mastitis is best detected by analysing the cell content of the milk, while other diseases are best detected using different kind of sensors such as neck collars, cameras, vocalisation sensors and related AI and algorithms, to register behavioural changes and abnormalities.

Clinical mastitis and subclinical mastitis

Mastitis is an intramammary infection usually caused by a pathogen (Ashraf and Imran, 2018; Växa, 2020), but could also be caused by allergy or physical trauma (Ashraf and Imran, 2018). There are two stages of mastitis, clinical and subclinical, depending on the severity of infection (Ashraf and Imran, 2018). Clinical mastitis often results in physiological symptoms and changes occur in the milk appearance and udder, while there are no visible symptoms in subclinical mastitis (Ashraf and Imran, 2018). In dairy herds connected to Kokontrollen, the disease incidence for clinical mastitis is 8.8 % per lactation year (Växa, 2021).

The GHG emissions from clinical mastitis origin from culling and mortality, discarded milk, reduced milk production and prolonged calving intervals (Gülzari *et al*., 2018; Mostert *et al*., 2019). Clinical mastitis is affecting the milk production throughout the lactation, including after recovery (Hagnestam *et al*., 2007).

Studies have found that a reduction of clinical mastitis could positively contribute to GHG emissions reduction. The potential reduction is however complex to estimate since it is affected by several factors, such as age, in what week in lactation clinical mastitis occurs and different origin of GHG emissions. Mostert *et al*. (2019) found that clinical mastitis increases the GHG emissions by approx. 6 % per lactation year. If only considering milk losses (i.e. not including an increased longevity), clinical mastitis reduced milk yield on average by 5 %. Gülzari *et al*. (2018) found a potential reduction of farm GHG emissions by 4 % if the level of somatic cell count was reduced from 800,000 cells/ml to 50 000 cells/ml. Hagnestam-Nielsen *et al*. (2009) found that milk with somatic cell count of 500 000 cells/ml could result in a daily milk loss of 3–18 %. The regulated maximum level of somatic cell count in milk for consumption is 400 000 cells/ml (Regulation (EC) 853/2004 of the European Parliament and of the Council of 29 april 2004 laying down specific hygiene rules for on the hygiene of foodstuffs, Annex III, Section IX, Ch I, III 3a[i]).

Subclinical and clinical mastitis are best detected by analysing the cell content of the milk. Additionally, technologies recording udder temperature and analysing behaviours could be used to detect clinical mastitis. Since there are no visible symptoms of sub-clinical mastitis (Ashraf and Imran, 2018), technologies would not support an early detection of subclinical mastitis based on physical appearance. Technologies could however be used to detect risk factors in the environment, such as poor environmental hygiene.

Hoof and limb disorders

Hoof and limb disorders cover several diagnoses. The disease incidence in Swedish dairy herds connected to Kokontrollen is 2.4 % per lactation year, where the animal has been treated by a veterinarian (Växa, 2021). The most common disease is digital dermatitis (DD), a contagious eczema resulting in lameness, frequently occurring in intensive, loose housing systems (SVA, 2021). Half of the Swedish herds in loose housing systems are estimated to have one or more disease incidences per year (SVA, 2021). In an infected herd, about 20 % of the animals show acute symptoms (SVA, 2021).

Digital dermatitis can decrease milk yields and increase GHG emissions by 0.4 % per case of digital dermatitis (Mostert, 2018). The contribution to GHG emissions by sole ulcer and white line-disease were also investigated, where the result showed a contribution of 3.6 % and 4.3 % per lactation year, respectively (Mostert, 2018).

Digital diseases could be detected by behavioural and locomotion observations, indicating that cameras, neck collars and other sensors which register behaviours and locomotion could be used.

4.3.3. Longevity

The longevity of the cow is affected by several factors, such as diseases, high somatic cell count and extended calving intervals (Jordbruksverket, 2014; Växa, 2021). In Swedish dairy production, the average longevity is 2.5 lactations (SLU, 2022). An ongoing study is investigating how an increased longevity could affect the GHG emissions (SLU, 2022).

There are no technologies specifically supporting an increased longevity. However, an increased longevity is achieved by an increased animal health and welfare, together with better decisions on what animals to replace and when. Technologies supporting this are sensors such as activity meters, cameras and vocalisation sensors, related algorithms and simulation models and digital reports.

4.3.4. Digitalised feeding strategies

Precision/optimal feeding to avoid overfeeding/underfeeding the animals and reduce waste can reduce GHG emissions. Technologies supporting an improved feeding strategy are weighing systems, automated and digitalised feeding systems and sensors such as cameras and ingestible pills, together with supporting software.

4.3.5. Reduction of fossil fuels

Technologies, such as GPS, drones and digital fences, could positively contribute to GHG emissions reduction by decreasing the need of transports based on fossil fuels during daily inspections of animals on pasture. Monitoring of continuous real-time data of the production could also reduce the need for on-farm visits by veterinarians and others, potentially resulting in a decreased need of fossil fuels. There is however no research quantifying the possible reduction. Further, smart buildings (ventilation, heating etc) and milk cooling systems can decrease energy.

4.3.6. Software for analysing data

Software, such as simulation models, algorithms and AI, are used in addition to the previously mentioned technologies. It is used to predict, detect, and communicate anomalies in the production (Cockburn, 2021). There are however only a few algorithms ready for application. To develop better and more useful algorithms, an increased number of datasets are required (Cockburn, 2021).

Simulation models of on-farm GHG emissions are useful tools to predict GHG emissions and to understand the system behaviour (Gómez *et al*., 2021). The simulation models require accurate estimates of the production as input variables, such as digestion kinetic parameters, animal health and behaviours. Simulation models could also be used in developing mitigation strategies of GHG emissions (Gómez *et al*., 2021).

5. Case study on Swedish dairy production

As the previous chapters have shown, there are several digitalisation measures which can be applied in agriculture to increase productivity, and to reduce costs and GHG emissions. In this section, we want to illustrate what effect digitalisation can have on the GHG emissions from milk produced in Sweden. We do not have the possibility to include all of these measures in a case study, but a few will be highlighted in the following chapter.

5.1. Methodology of the case study

For the case study an LCA-based calculation tool developed by the Swedish Board of Agriculture was used: Vera – Klimatkollen[1]. The methodology is further described in Berglund (2015). The tool was used to model and calculate the GHG emissions from a typical Swedish dairy farm (Table 3), which represents a baseline scenario to which improvements of digitalisation measures are compared to. Assumptions of digitalisation measures are described in Table 4. Raw data used in the simulation modelling of the scenarios is found in the Appendix. Geographic location of the farm and soil type has been taken into consideration to model potential leakage of nitrogen correctly. It is influenced by precipitation and soil type.

Vera – Klimatkollen model the emissions from the whole farm and allocates the emissions to the products leaving the farm. The simulation model generates results expressed both as total GHG emissions from the farm and GHG emissions per kg of output. In the case study, the reduction in GHG emissions were calculated per kg of energy corrected milk (ECM) (kg CO2e/kg ECM) at farm gate.

All inputs to the farm were compiled, such as feed, fertilisers, seed, fuel, electricity, etc. The emissions generated by these inputs were divided between crop and animal production, according to choices made in the simulation model. Additionally, different use of the crops is important to distinguish. In the simulation model, it is possible to distinguish crops used for on-farm feed and crops being sold, and the quantities of such. The calculated emissions for crops used as on-farm feed were allocated to animal emissions, while emissions coupled to crops being sold are allocated to the crop production.

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[1] https://greppa.nu/vara-tjanster/rakna-sjalv/vera

Emissions originated from animal husbandry, such as enteric fermentation, production of feed, storage of manure, etc., were allocated to animal production and were accounted for in the carbon footprint of milk and meat.

Different inputs related to different crops are important in the simulation modelling. For each crop cultivated at the farm, levels of fertilisation, yield, fuel use, straw removal and timing and technique of spreading manure were documented. This enables allocation of inputs (fertiliser, fuel, etc.) between different crops, and to calculate crop specific emissions (carbon footprint per kg crop).

The emissions covered were:

- Emissions from production of farm inputs
- Emission from on-farm fuel use
- Direct and indirect N_2O emissions from soil
- CH_4 from enteric fermentation
- CH_4 and N_2O from manure (storage and stable)

Vera – Klimatkollen allocates the total GHG emissions of the farm between the sold products. The principles of allocation were the following (Greppa Näringen, 2020):

- Energy and fuel: the total purchased amount of energy and fuel was required as an input in the tool and is divided between crop and animal production based on amount of fuel used for each production category. The tool provides general values for fuel consumption expressed in l/ha for each crop, which enables an estimate of fuel use in the crop production. The remaining fuel was considered used in animal production.
- Mineral fertilisers and manure were allocated to each crop based on the nitrogen inputs obtained by the activity data. Phosphorus and potassium were applied based on hectares of each crop rather than plant specific requirements.
- Emissions from storage of manure were seen as a part of the animal production emissions, whereas emissions from application of manure to soil were allocated to crop production.
- Other inputs and emissions which were divided based on hectares are seeds, indirect emissions from nitrogen leaching and ammonia losses when spreading nitrogen fertilisers.
- Allocation between milk and meat was based on physical allocation, as recommended by the International Dairy Federation (IDF) factors: Allocation to milk = 1–6,04*mass of meat/mass of milk. For allocation between other animal products, economic allocation was applied.

The global warming potential (GWP) factors currently used in Vera – Klimatkollen are 1 kg CO_2e/kg CO_2, 28 kg CO_2e/kg CH_4 and 265 kg CO_2e/kg N_2O (Berglund, 2015).

5.2. Baseline

Activity data for the baseline farm was obtained from Greppa Näringen (Greppa Näringen, 2020). The farm is a fictive farm but is considered representative for Swedish conditions.

The farm is a conventional milk farm located in Västra Götaland county. The farm has 138 ha of cropland and 15 ha of permanent pasture. Ley and fodder crops are used as feed for the cows, some cereal crops and straw are sold from the farm. The farm has 80 dairy cows which produce 10 000 kg energy corrected milk per cow and year, and 65 heifers (30 pregnant and 35 young heifers). Bull calves are sold, and heifers are kept for replacement. Calving age is 24 months old, and the cows have free access to grazing 4 months a year.

The crop rotation consists of oats (under sown with grass), three years of ley (grass and red clover), triticale and field beans. Straw is removed from oat and triticale. Most of the farmyard manure is separated as liquid manure, and some is stored as deep litter. The cereal crops receive both liquid manure and some mineral fertiliser, except for triticale which receives mineral fertiliser and deep litter manure. The ley is fertilised three times during growing season; twice with mineral fertiliser and once with liquid manure.

The products sold annually are 780 000 kg of energy corrected milk, 4100 kg of live weight calves, 20 800 kg of live weight cows, 126 500 kg of oats and 79 260 kg of straw.

5.3. Results

The results show that the total farm GHG emissions are 789 tonnes of CO_2e. The carbon footprint of milk is 0.78 kg CO_2e/kg ECM. The carbon footprint for the other products produced at the farm are presented in Table 3. Observe that the product of multiplying the quantity of each product in Table 3 with respective carbon footprint will give an over-estimation of the total farm emissions, as several of the crop outputs are used as on-farm feed and will thus be double counted.

Table 3. Quantities of products produced at the farm for one year and their respective carbon footprint.

PRODUCT	QUANTITY PRODUCED FOR ONE YEAR	UNIT	KG CO_2E / UNIT
CROPS			
OATS	126 500	kg	0.22
SILAGE (GRASS-CLOVER)	413 270	kg dm	0.31
TRITICALE	153 828	kg	0.22
FIELD BEANS	80 500	kg	0.17
STRAW FROM CEREAL CROPS	140 300	kg	0.03
ANIMAL PRODUCTS			
MILK, IN ECM	780 000	kg	0.78
CALVES, LIVE WEIGHT	4 100	kg	7.30
DAIRY COWS, LIVE WEIGHT	20 800	kg	5.59

As presented in Figure 1, the main contributor to the total farm GHG emissions is methane from feed digestions, corresponding for 53 % of total farm GHG emissions. The second largest emission source is direct and indirect N_2O emissions from soil, corresponding for 20 % of total emissions (indirect N_2O emissions 2 % and direct N_2O emissions 18 %). Emissions from manure (stable and storage) results in 12 % of total emissions, while purchase of inputs such as energy, fertilisers and feed correspond for 16 % of total emissions, including emissions from combustion of fuel.

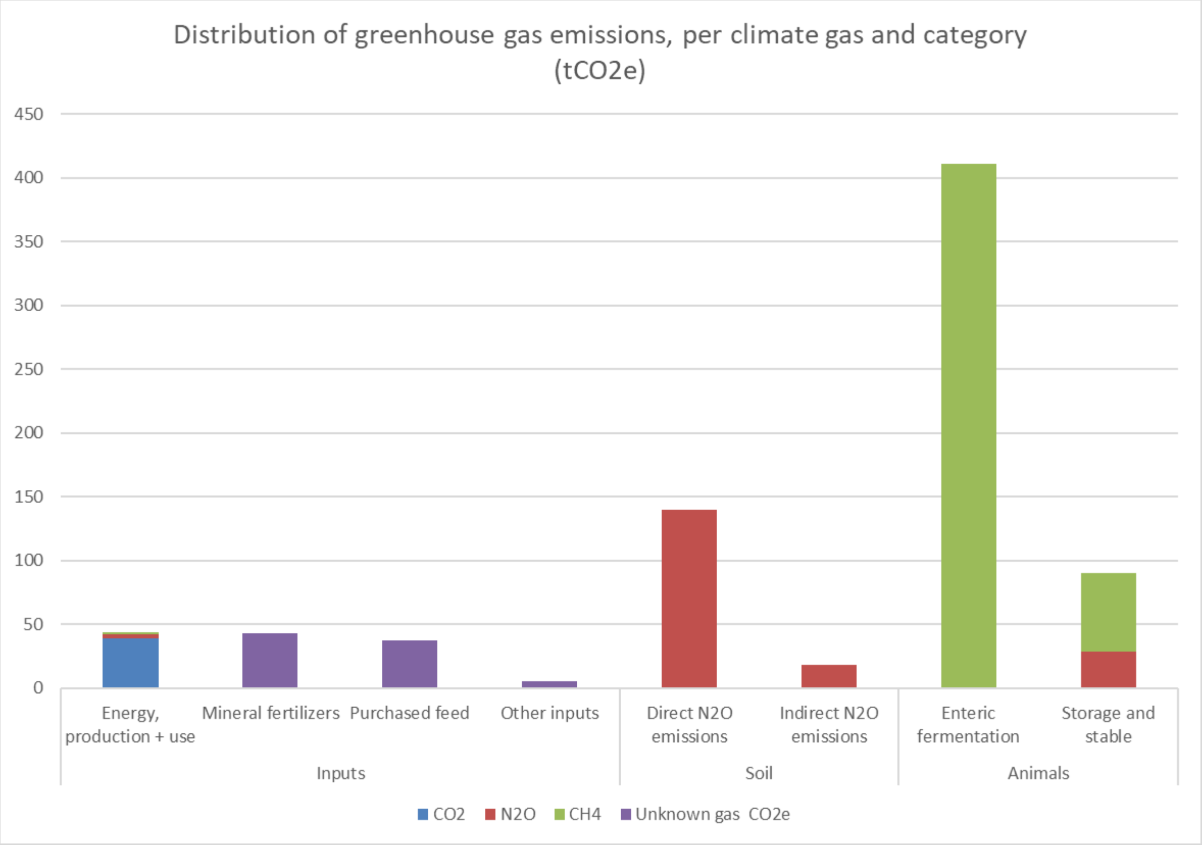

Figure 1. Distribution of greenhouse gas emissions for the baseline dairy farm, presented per climate gas and emission category.

5.4. Digitalisation scenarios

Scenarios describing possible improvements by implementing digitalised technologies in milk production are presented in Table 4. The digitalisation scenarios are compared to the baseline scenario (Scenario 0), and the possible reduction of GHG emissions (here expressed as reduction in the carbon footprint of milk) compared to the baseline is presented in Figure 2. All the results are expressed in percentage points.

The results show that application of digitalised technologies could reduce the carbon footprint of Swedish milk by 16 %. Improvements in livestock production contributes to most of the total reduction potential and have potential to reduce the carbon footprint by 14 % whereas improvements in crop production have a potential to reduce the carbon footprint by 2 %, see details in Figure 2. The expected improvements for each scenario are described in Table 4. For the whole farm the reduction in GHG emissions would be even larger (23 %) as some crops are sold from the farm and not used in the milk production, this reduction is not included in the milk results.

Table 4. Description of the studied scenarios and included improvements for each scenario. Scenario 1a-d describe scenarios where precision livestock farming (PLF) is practised. Scenario 2a–c represents cases where precision agriculture technologies (PAT) for crop production are practised. The Scenarios 1a–1d and 2a–c build on each other, i.e. each scenario includes improvements made in the previous scenario.

SCENARIO	DESCRIPTION
0 – LOW DIGITALISATION	Implementation of digitalisation technologies in milk production is low.
1A – PLF: REDUCED MASTITIS	Increased milk production is achieved due to decreased prevalence of mastitis. Supporting technologies are milking parlour-related technologies, sensors such as cameras, and systems, algorithms and simulation models analysing collected data.
1B – PLF: INCREASED LONGEVITY	Longevity of the dairy cows is increased from 4.5 to 8 years, resulting in a reduction of replacement heifers. This results in reduction of GHG emissions from replacement heifers (from enteric fermentation) and from reduced feed requirements and production (and in extent requirement for land is reduced which has an impact on use of fuel and mineral fertilisers). Manure is reduced as a consequence of a reduced number of animals, but as land requirements are also reduced this does not increase mineral N requirements significantly. Supporting technologies are sensors such as cameras, systems, algorithms and simulation models analysing collected data and digital reports.
1C – PLF: INCREASED FEED EFFICIENCY	Feed efficiency (kg dm feed/kg milk) is increased by 25 %. Fodder spill is also reduced from 10 to 2 %. The same assumption as in Scenario 1b is applied (i.e. less land is needed for feed production and less feed is purchased). Supporting technologies are sensors such as cameras, microphones and ingestible pills, milking parlour-related technologies, systems, algorithms and simulation models analysing collected data and digital reports.
1D – PLF: REDUCED CALVING AGE	Age of first calving is reduced from 24 to 22 months, resulting in a reduction of replacement heifers (for details, see Scenario 1b). Supporting technologies are sensors such as cameras and microphones, systems, algorithms and simulation models analysing collected data and digital reports.
2A – PAT: REDUCED FUEL CONSUMPTION	Reduced fuel consumption by 25 %. Supporting technologies are controlled traffic farming in crop cultivation.
2B – PAT: INCREASED NITROGEN EFFICIENCY	Mineral nitrogen N need is reduced by 4 % for all crops while maintaining the same yield levels. Supporting technologies are N-sensors.
2C – PAT: OPTIMISED CROP MANAGEMENT	Optimised crop management and full implementation of N-sensors, resulting in potentially increased yields by 15 % for cereal crops and 4.5 % for grass crops.
3 – PLF + PAT: ALL TECHNOLOGIES COMBINED	Optimised production where all supporting technologies are applied.

The impact on GHG emissions (expressed as CO_2e per kg milk) when implementing the digitalisation technologies in Table 4 is presented in Figure 2. The results are presented as improvements in animal production technologies (1a–d) and improvements in crop production technologies (2a–c). Scenario 1a–d build on each other, i.e. Scenario 1b includes improvements in 1a. Scenario 2a–c likewise build on each other, and when all scenarios are added they result in Scenario 3.

The largest GHG emission reductions are obtained by increased longevity of the cows and increased feed efficiency, both corresponding for a potential reduction of GHG emissions by 7 % (Scenario 1b and 1c respectively, Figure 2). The reduction from an increased longevity is mainly caused by a reduced number of replacement heifers, from which methane emissions from enteric fermentation and feed requirements are derived. Potential reductions in GHG emissions when implementing precision agriculture technologies in crop production are about 1 % from reduced fuel consumption and 1 % from optimised crop management. The combined effect of all technologies has a potential reduction by 16 % of the GHG emissions per kg energy corrected milk.

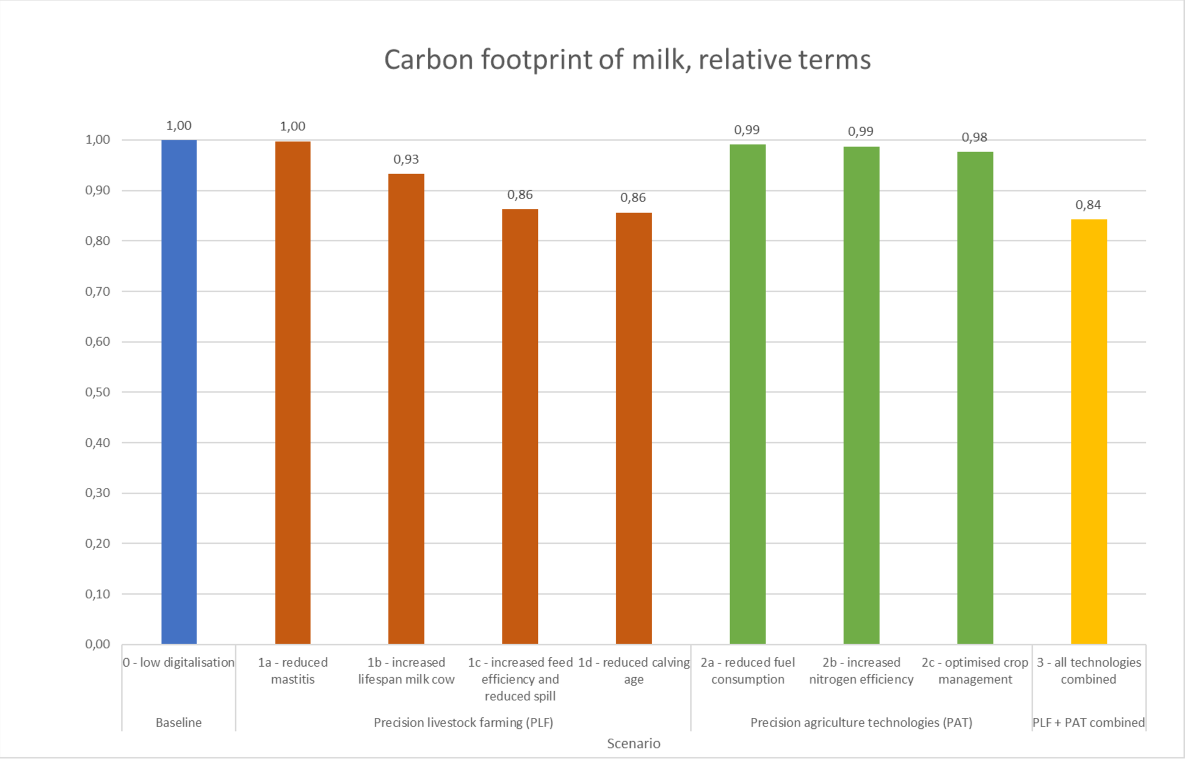

Figure 2. Modelled GHG reduction possibilities in milk production. The animal production improvement scenarios (1a–d) build on each other, i.e. the improvements in 1b include the improvements in 1a. In other words, the scenarios 1a–d are not additive. In Scenario 2, the counting starts over, i.e. Scenario 2a is the reduction compared to Scenario 0. The scenarios 2a–c are not additive as they build on each other. Scenario 3 combines Scenario 1d and 2c, which results in the scenario with the largest reduction potential.

6. Discussion

6.1. When can digitalisation technologies be implemented?

Several of the described digitalization technologies and systems can be implemented today. However, applying digitalised technologies in primary production is considered a relatively large investment (Odintsov Vaintrub *et al*., 2021). You need a large set of different types of digitalised technologies to fit the different needs on the farm. This factor together with the cost for each technology can result in a large total cost for the enterprise. Another issue is the ability to communicate between tools of different brands, and this can potentially constitute an obstacle for reaching the full potential of the digitalisation technologies on farm level.

In a report investigating Swedish farmers attitudes towards precision farming techniques, it was concluded that economy was an important factor for the implementation. However, the individual interest in technology plays a role, the most interested farmers might settle with technique which only breaks even economically, while less interested farmers will require higher economic benefits to adopt new technology. Moreover, it is important that farmers share experiences and have access to information about new technologies (Olsson, 2008). In Sweden, the access to information about new technologies could be considered sufficient. However, information on the economic benefits of implementing digitalisation technologies could result in a higher level of implementation among farmers with a low technological interest, especially considering the increasing costs of inputs.

There are currently several pilot farms in Sweden, funded by private actors to promote and test new technologies, including digitalisation technologies. This is likely to increase implementation rates among farmers, provided that economic conditions allow investments. However, there are raised concerns that full potential of digitalisation will not be reached as farmer advisory services will not be able to provide sufficient support and knowledge. A reason for this could be low economic profitability for advisory services to develop and expand their services. Another concern being raised is access to reliable digital infrastructure (Andersson and Johnsson, 2018).

A German paper examining German farmers attitudes towards smart farming technology provides insight to barriers and hinders for implementation of precision technologies on farms: 1) providers of the new technology are not neutral but have a strong profit agenda. This can lead to fast development of new technique which does not fully consider the actual needs of the farmer. 2) There is a lack of information exchange between farmers, technology providers and advisors. 3) Implementation of new technique is highly dependent on access to information and a forgiving learning environment, as well as information both about the technology and agronomy. Lack of engaged agricultural advisors (which can provide neutral information) and/or education can thus be a barrier. 4) Size of farm might be a hinder as larger farms have the benefit of scale effect and stronger economic capacity to invest in new technology. 5) Technological restraints including lack of standardisation between tools so that they easily communicate, software is developing faster than hardware, there is lack of digital infrastructure to handle the large amount of data required (Knierim *et al*., 2019). Solving and working on the above-mentioned issues will be of great importance to reach broad implementation of digitalisation technologies.

In conclusion, these are some potential measures, among others, which can increase the implementation rate of smart technology on Swedish farms:

- Clearly demonstrate economic and environmental benefits of implementing new techniques, so these can be perceived as an economically feasible tool for reaching and complying with environmental goals/requirements, also for smaller farms.
- Increased dialogue and understanding between farmers and providers of technologies, to fully understand farmers needs and how the tools will be used in practice.
- Continuing education of farm advisors and the use of new technology, so they can act as knowledge carriers between farmers and providers of technologies.
- Investment in digital infrastructure.
- Continuous investment in testing environments and pilot farms for new technical solutions.
- Coupling different systems, products and platforms which are currently used to collect data, and enable communication between the different systems.

If measures are taken to increase implementation of precision farming and digitalised technologies in primary production, it would be possible to reach continuous monitoring of production, well-founded decisions, and a significant reduction of GHG emissions in primary production. According to Lantmännen (2019) implementation of digitalisation technologies in arable farming can be achieved already by 2030 during favourable conditions, meaning that also most of the reduction potential can be reached already by 2030. However, implementing x % of the digitalisation technology does not equal reaching x % in potential reduction in GHG emissions, as it will depend on what techniques are implemented, how different tools communicate and complement each other and several other factors.

Estimating the GHG emissions reduction on short-term and long-term due to implementation of digitalisation techniques is a very uncertain estimation, as there are many factors and conditions affecting the implementation, as described in previous chapters. The result of this report estimated a potential of 16 % reduction of the carbon footprint of milk. Of this reduction potential, 12.5 % is reached by implementing digitalisation in crop production (2 %-units, Figure 2, Scenario 2c) and 87.5 % by implementing digitalisation in livestock production (14 %-units, Figure 2, Scenario 1d). If we assume that a full potential of implementing digitalisation technologies in crop production could be reached by 2030, as suggested by Lantmännen (2019), this indicates that we can expect realising 12.5 % of the total GHG reduction potential until 2030. An additional estimation that half of the digitalisation technologies applied to livestock production are realised by 2030, indicates that we can expect 56 % of the total GHG reduction potential until 2030, i.e. 9 % GHG reduction potential from today (Scenario 0). The full potential of 16 % GHG reduction could be reached until 2045.

6.2. Some thoughts on precision farming and GHG reduction potential

Precision farming has in several ways contributed to increased farm productivity, stability and income increase. It is also expected that precision farming/smart farming technologies will contribute to more sustainable agriculture by increasing precision of inputs based on site specific needs and by directly connecting management practices with farm management systems (Knierim *et al.*, 2019). However, literature is limited regarding quantitative data on the effect of precision farming and digitalisation on GHG emissions.

All categories of precision farming and related digitalisation technologies are highly interconnected, and it is difficult to separate them according to their contribution to the reduction of GHG emissions. Some technologies, such as Global Navigation Satellite System and recording technologies, are supportive in precision farming processes while guidance systems have a visible direct result on the production system.

6.3. Scaling up the dairy case study results

The case study was based on a typical Swedish dairy farm (see Chapter 5 for details). Considering the farm characteristics, there are several parameters which might impact the applicability of our results on other farms, for example size, location, soil type, and animal breeds. The “baseline” GHG emissions of each farm implementing digitalised technologies will also impact the applicability and the potential reduction of GHG emissions, where farms with low GHG emissions are likely to have lower GHG emission reduction potential than farms with higher GHG emissions.

The case study was conducted on a mid-size farm in Västra Götaland county, located in the southwest part of Sweden. The geographic location affects the economic situation in different regions and affect access to digital infrastructure and farmer advisory services, which provide neutral knowledge and practical examples of digitalisation technologies.

These advisory services are important for the implementation of new technology as they can act as driving forces and technical support and provide information knowledge and practical examples of digitalisation technologies.

Further, the geographic location affects the conditions of agriculture. The agricultural areas in Sweden with good agronomic prerequisites, such as soil type, climate and field structure (e.g. the plains in Skåne county, Mälardalen, Östergötland, Västra Götaland, etc.) in general have larger farms, coherent fields and larger economic margins. In these areas benefits of scale will likely accelerate the implementation of digitalisation technologies. Areas with smaller farms, smaller and scattered fields will likely not see the same economic benefits in implementing digitalisation technologies (for e.g. woodland areas and north of Sweden) as the technology is designed today.

6.4. Comparison with other GHG reduction measures

In this report we concluded that the implementation of digitalisation technologies has the potential to reduce the carbon footprint of Swedish milk by 16 %. To put our results in comparison with other measures for reducing the carbon footprint of milk, a review of other measures is presented.

A recently published report investigating the soil carbon sequestration potential on Swedish farms found a significant increase in soil organic carbon in the upper 20 cm of the soil. In the study, sampling points which were taken with on average 10 years intervals were analysed for soil carbon changes. The data included 159 observations on dairy farms and was based on actual soil samples. The annual soil organic carbon increase on Swedish dairy farms corresponded to an uptake of 0.22 kg CO_2/kg ECM, which is 17 % of the average carbon footprint of Swedish milk (1.27 kg CO_2e/kg ECM) (Henryson et al., 2022).

A report examining the effect of feeding Swedish dairy cows diets where the concentrate was based on by-products showed potential to reduce the carbon footprint of milk compared to concentrates based on cereals and soymeal. When the carbon footprint was compared between the two feeding systems with concentrates based on different ingredients, one only including soymeal and cereals and the other consisting of by-products such as distillers grains, the second diet showed a carbon footprint reduction from 1.19 kg CO_2e/kg ECM to 0.92 kg CO_2e/kg ECM. This is equivalent to a 23 % reduction of the carbon footprint (Henriksson et al., 2019).

In a report from Lantmännen (2021) the theoretical potential for several measures for reduced GHG emissions by 2050 were investigated and expressed per kg of milk. The conclusion was that fossil free agriculture would reduce GHG emissions by 5–8 % per kg milk, methane reducing measures had potential to reduce GHG emissions by 6–7 % per kg milk, treatment of manure and biogas had a potential of 9 % per kg of milk, improvements in animal welfare, life time production and breeding had a potential to reduce GHG emissions by 25 % and improvements in feed production had the potential to reduce emissions by 12–18 % per kg of milk (Lantmännen, 2021).

6.5. System perspective aspects

The system perspective is an important aspect to have in mind when estimating the potential reduction of GHG emissions. In our case study, digitalisation technologies were for example assumed to increase longevity of the dairy cows. As a result, the number of replacement heifers was reduced while the milk output maintained at the same level. This resulted in a reduced carbon footprint of milk as less animals were needed for producing the same quantity of milk. It also resulted in less meat produced from the dairy system, as fewer dairy cows were estimated to be slaughtered each year. Meat from the dairy system (calves and cows) correspond to 60 % of total Swedish beef production, of which meat from dairy cows make up 25 % and calves 35 %. The remaining 40 % origins from beef breed cattle (Cederberg and Henriksson, 2020). The reduction of replacement heifers due to increased longevity did however result in an increased output of sold calves. Considered that these calves are bred for slaughter at farms specialised in meat production, this indicates that the reduced output of meat from dairy cows are counteracted by the increased number of calves, if both dairy and meat production systems in Sweden are considered.

The potential shift from meat from dairy cows to an increased fraction of meat from calves fed for slaughter, and what consequences that might have on total GHG emissions from Swedish beef consumption, should be further investigated. It should also be further investigated how the carbon footprint of Swedish meat might be influenced, as meat from a dairy cow (which both produces milk and meat) has lower carbon footprint per kg meat than meat from a calf which only produces meat. These questions are not covered in this report and should have further attention to understand the changes of GHG emissions in the food supply chain in a system perspective.

Land requirement reduction was another effect which was seen in the results. This was primarily the effect of increased feed efficiency and reduced number of replacements heifers, leading to an overall reduced requirement of agricultural land for feed production. How this spare land will be used would impact the total GHG emissions but was not considered in this report.

Another effect from a reduced number of heifers was reduced amount of manure. This counteracted some of the potential reduction in mineral fertiliser use. However, as N-efficiency was assumed to increase in combination with reduced feed requirements, the total input of mineral fertilisers was lower in the digitalised scenarios compared to the baseline scenario.

7. Conclusions

- Digitalisation in primary production offers a range of different technologies which could be applied to enable better decisions by collecting data, and to process the collected data using different smart algorithms.
- There is limited research which quantifies the effect of digitalisation on GHG emissions from primary production.
- Variable rate nutrient application and irrigation are currently the most effective precision technologies which mitigate GHG emissions from agricultural lands in Europe.
- Implementation of various digitalisation technologies at a Swedish dairy farm has a potential to reduce the carbon footprint of Swedish milk by 16 %.
- Precision livestock farming shows the largest potential with an estimated reduction of 14 %, primarily due to feed efficiency and improved animal health and longevity, reducing the total number of animals while maintaining high milk output.
- Implementation of digitalisation technologies such as controlled traffic farming and N-sensors in the feed production showed a potential to reduce the carbon footprint of milk by 2 %. The relatively low potential is explained by a modest impact from N-sensors in grass production, as well as emissions from feed production having relatively small contribution to the total GHG emissions from dairy production.
- It is important to evaluate the whole system, as changes in the dairy system might impact other farms and food producing systems. For example, how will surplus land be managed, and redundant calves sold from the farm.
- The implementation of digitalisation technologies depends on several factors. Economy, individual farmers' interest, digital infrastructure, access and availability to relevant digitalisation technologies as well as access to agricultural advisors with knowledge in digitalisation technologies. The implementation will most likely occur at larger farms where the investment can pay-off, thus the plain areas of Sweden might have a faster implementation rate than woodland areas.
- Research is needed to further investigate the potential GHG reduction when introducing digitalisation in agriculture.

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Appendix 1

Raw data used in the simulation modelling of the scenarios in the tool VERA – Klimatkollen.

- Scenario descriptions: Scenario 0: low digitalisation
- Scenario 1a–d: Focus on digitalisation in animal production
    - 1a: 90 % reduction of mastitis
    - 1b: 1a + increased longevity due to increased health in dairy cows
    - 1c: 1b + optimised feeding (increased feed efficiency and reduced spill)
    - 1d: 1c + reduced calving age (from 24 months to 22)
- Scenario 2a–c: Focus on digitalisation in crop production
    - 2a: Navigation systems reduce amounts of diesel for field work
    - 2b: 2a + use of N-sensors which reduce total nitrogen input
    - 2c: 2b + overall optimised crop production due to various digitalisation technologies

Table 5. Raw data used when modelling future scenarios with increased digitalisation on a Swedish dairy farm. Blue text indicates sold outputs from the farm. Empty cells indicate no change compared to the base scenario (scenario 0).

SCENARIO	0	1A	1B	1C	1D	2A	2B	2C	3
ANIMAL PRODUCTION									
MILK YIELD (TONNES ECM TOTAL)	780	783	783	783	783				783
DAIRY COWS, NUMBER OF	80								
AVERAGE LIFESPAN PER DAIRY COW, YEARS	4.5		8						8
HEIFERS, NUMBER OF	65		27		25				25
CALVING AGE OF HEIFERS, MONTHS	24				22				22
DAIRY COWS, TONNE LIVE WEIGHT SOLD	20.8		8.7		8.7				8.7
CALVES, TONNE LIVE WEIGHT SOLD	4.1		5.5		6.1				6.1
FEED									
CONCENTRATES, TONNES	52		51	35	35				35
ROUGHAGE (GRASS-CLOVER SILAGE), TONNES	413		327	226	222				222

GRAINSTON	154	145	100	100				100
MINERAL FEED, KG	3 410	2 726	1 881	1 845				1 845
FIELD BEAN, TONNES	81	81	56	56				56
STRAW FOR BEDDING AND FEED, TONNES	61	39	39	37				37
GRAIN, TONNES SOLD	127	127	127	127				127
STRAW FOR BEDDING OR FEED, TONNES SOLD	79	103	103	105				105
FUEL FOR ANIMAL PRODUCTION, 1000 LITRE	2.4							
CROP PRODUCTION								
PURCHASED INPUTS, TONNES TOTAL								
AXAN, N27	43	31	20			41	37	17
DIESEL, 1000 LITRES	12	8.3	6.3		9.6	9.6	9.1	4.4
PK 11-21	5.8	5.8						
FIELD BEAN SEED	6.9		5.2					
OAT SEED	4.7						4.1	2.6
TRITICALE SEED	4.1		2.7				3.6	2.3
LAND USE, HA								
LEY	69	55	38				66	35.4
TRITICALE	23	22	15				20	12.9
FIELD BEAN	23	23	16				23	15.9
OAT	23	23	23				20	20.0
KG MINERAL FERTILISER-N/TONNE YIELD								
LEY, AVERAGE YEAR I–III	19					18.3	16.7	10
OAT	7.3					7.1	6.2	6.2
TRITICALE	17.3					16.6	15.0	14.5
FABA BEAN	0							
FUEL CONSUMPTION (L/HA)								
OAT	75				56	56	56	56
LEY I	80				60	60	60	60
LEY II	60				45	45	45	45
LEY III	60				45	45	45	45
TRITICALE	70				53	53	53	53
FIELD BEAN	70				53	53	53	53
CROP YIELDS (TONNE/HA)								
OAT	5.5						6,3	6,3
TRITICALE	6.7						7.7	7.7
FIELD BEAN	3,5							
LEY, AVERAGE YEAR I–III	6.0						6.3	6.3

MISTRA
FOOD FUTURES