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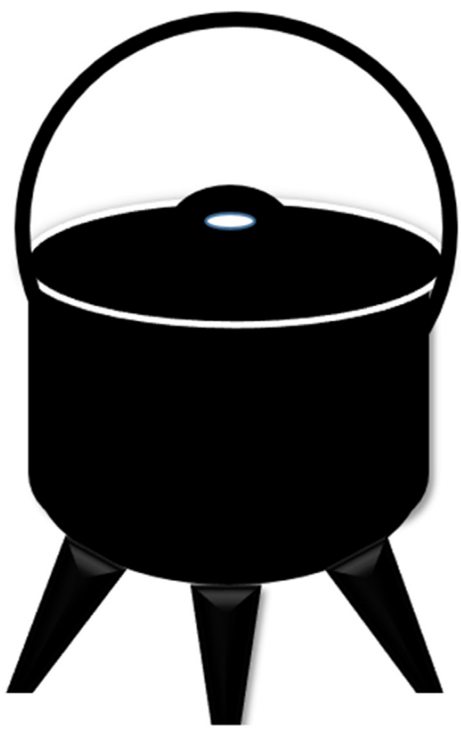
Towards sustainable livestock systems: Developing and applying methods for broad sustainability assessment of pig and cattle systems

Stanley Zira



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Towards sustainable livestock systems: Developing and applying methods for broad sustainability assessment of pig and cattle systems

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Abstract

Meat and milk are valuable foods from livestock that contribute to quality of life for humans but have negative environmental, social and economic impacts. Measuring such impacts in sustainability assessments requires methods with a broad and deep focus. The overall aim of this thesis was to further develop sustainability assessment methods to broadly evaluate livestock systems and to use these methods to increase knowledge on how future sustainable pig and cattle production systems can be developed. Social life cycle assessment (S-LCA), Life cycle sustainability assessment (LCSA) and the One Health framework were developed further and used to assess the impacts of the different livestock systems i.e. organic and conventional Swedish pig production, future pig production scenarios and three cattle systems (cropland based dairy, grassland based dairy and grassland based suckler beef production) in southern Europe.

S-LCA, LCSA and the One Health framework sustainability methods can assess important sustainability aspects for pig and cattle production systems and identify important trade-offs. Organic pig production had lower social risk for negative social impacts for pigs and consumers than conventional pig production but higher environmental impacts per kg for eutrophication, acidification and fossil depletion. Grassland based suckler beef production was more resilient to economic losses due to changes in interest rates, input prices and output prices, produced more protein (in meat) than found in the feed and had higher profitability compared to the other cattle systems. However, grassland based beef production had higher eutrophication, acidification and fossil depletion compared to the dairy systems. Changing the breeding goal of pigs, changing the diet composition by including silage and having other protein sources than soybean, and using renewable energy sources in future pig production can further reduce negative impacts.

Keywords: Social life cycle assessment, Life cycle sustainability assessment, One Health, pork, milk, beef, breeding, feeding

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Hållbara djurproduktionssystem: Utveckling och tillämpning av metoder för bred hållbarhetsutvärdering av produktionssystem för gris och nötkreatur

Sammanfattning

Kött och mjölk är värdefulla livsmedel som bidrar till människors livskvalitet men har negativa miljömässiga, sociala och ekonomiska effekter. Att utvärdera sådana effekter i hållbarhetsbedömningar kräver metoder med både brett och djupt fokus. Det övergripande syftet med denna avhandling var att vidareutveckla metoder för hållbarhetsutvärdering av djurproduktionssystem och att använda dessa metoder för att öka kunskapen om hur framtida, hållbara produktionssystem med grisar och nötkreatur kan utvecklas. Social livscykelanalys (S-LCA), livscykel-hållbarhetsutvärdering (LCSA) och One Health-ramverket vidareutvecklades och användes för att studera effekterna av olika djurproduktionssystem: ekologisk och konventionell grisproduktion, framtida grisproduktionsscenarier, och tre olika produktionssystem med nötkreatur i södra Europa (mjölkproduktion baserad på åkermark, mjölkproduktion delvis baserad på bete och nötköttsproduktion med dikor baserad på bete och grovfoder).

S-LCA, LCSA och One Health-ramverket kan användas för att utvärdera viktiga hållbarhetsaspekter för djurproduktionssystem. Ekologisk grisproduktion hade lägre risk för negativa sociala effekter för grisar och konsumenter än konventionell grisproduktion men högre miljöpåverkan per kg för övergödning, försurning och utarmning av fossila resurser. Produktionssystemet med dikor var mer motståndskraftigt mot ekonomiska förluster på grund av förändringar i ränta, priser på insatsvaror och avräkningspriser. I detta system producerades mer protein (i kött) än mängden protein som gick åt i fodret och lönsamheten var högre jämfört med de andra produktionssystemen. Däremot hade produktionssystemet med dikor högre övergödning, försurning och utarmning av fossila resurser jämfört med mjölksystemen. Att ändra avelsmålet för grisar, ändra fodersammansättningen genom att inkludera ensilage och ha andra proteinkällor än sojabönor, och använda förnybara energikällor i framtida grisproduktion kan minska de negativa effekterna.

Nyckelord: Social livscykelanalys, livscykel-hållbarhetsanalys, One Health, griskött, mjölk, nötkött, avel, utfodring

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Preface

Prosperity in a society is not about the greatest number of the powerful, rich and vocal individuals within that society or the inventions made but rather on the health of the environment, people and organisms within that society.

Dedication

I dedicate this work to my family and all sustainability change agents working flat out to make the world a better place tomorrow.

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List of publications

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I. Zira, S., Röös, E., Ivarsson, E., Hoffmann, R., Rydhmer, L. (2020). Social life cycle assessment of pig production. International Journal Life Cycle Assessment 25, 1957–1975.

II. Zira, S., Rydhmer, L., Ivarsson, E., Hoffmann, R., Röös, E. (2021). A life cycle sustainability assessment of organic and conventional pork supply chains in Sweden. Sustainable Production and Consumption 28, 21-38.

III. Zira, S., Röös, E., Rydhmer, L., Hoffmann, R. Sustainability: Assessment of economic, environmental and social impacts, feed-food competition and economic robustness of dairy and beef farming systems in Southern Europe. (submitted)

IV. Zira, S., Röös, E., Ivarsson, E., Friman, J., Møller, H., Samsonstuen, S., Olsen, H.F., Rydhmer, L. (2022). An assessment of scenarios for future pig production using a One Health approach. Livestock Science, 104929.

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Abbreviations

AsUsual	future pig production scenario with same trends as current pig production
ATF	animal task force
BLUP	best linear unbiased prediction
CO_2 eq	carbon dioxide equivalents
COVID-19	coronavirus disease 2019
DCB eq	dichlorobenzene equivalents
E-LCA	environmental life cycle assessment
FAO	food and agriculture organization
FCR	feed conversion ratio
FDP	fossil depletion
FEP	freshwater eutrophication potential
FET	freshwater ecotoxicity
GenTORE	genomic management tools to optimize resilience and efficiency (H2020 project)
GWP100	global warming potential over 100 years
HolSy	cropland based system in lowland France with Holstein cattle
IND	indicator values for livestock systems other than the reference system
IRR	internal rate of return
ISO	international standard organization
KRAV	this is a Swedish organization that develops and maintains regulations for organic agriculture
LA-MRSA	livestock associated methicillin resistant staphylococcus aureus
LCC	life cycle costs
LCSA	life cycle sustainability assessment

MEP	marine eutrophication potential
MET	marine ecotoxicity
MonSy	grassland based cattle system in highland France with Montbeliarde breed
NPV	net present value
N eq	nitrogen equivalents
OIE	World organization for animal health
P eq	phosphorous equivalents
ParSy	grassland based cattle system in highland Spain with Parda de Montana breed
REF	indicator values for reference livestock system
RSP	relative sustainability points (paper II high=poor, paper IV high=good)
RUsP	relative unsustainability points (high=poor)
SETAC	society for environmental toxicology and chemistry
SHI	social hotspot index
S-LCA	social life cycle assessment
SO_2 eq	sulphur dioxide equivalents
SR	social risk
SRT	social risk time
SusFeed-new	future pig production scenario with sustainable feed and pigs selected with new breeding goal
SusFeed-old	future pig production scenario with sustainable feed and pigs selected with old breeding goal
SusFeedPig	future pig production scenario with sustainable feed and pigs selected with new breeding goal and with access to pasture
T	activity variable
TAP100	terrestrial acidification potential over 100 years
TET	terrestrial ecotoxicity
UNEP	United Nations' environment programme
VA	value added
W	weight
WHO	World health organization

1. Introduction

Livestock production systems have positive impacts on the environment, people and animals. Positive impacts of livestock production systems include ruminants grazing species-rich semi-natural pastures thus contributing to biodiversity conservation (Dumont et al., 2019). Livestock production systems also provide benefits from an economic perspective, with approximately 40% of the value of total EU agricultural production coming from livestock products (Peyraud and MacLeod, 2020). However, livestock production systems also have negative impacts. Improved breeding, feeding and housing can help to reduce these negative impacts. Multidisciplinary analyses of environmental, economic and social sustainability issues are required to guide such development work.

Life cycle assessment (LCA) has been used in the past to assess the sustainability impacts of various livestock products with much focus on environmental impacts using environmental LCA (E-LCA). Few studies assessing environmental, economic and social sustainability issues such as life cycle sustainability assessment (LCSA) have been performed for livestock. Therefore, the development of multidisciplinary assessment methods that can evaluate environmental, economic and social sustainability issues are required to identify opportunities for improvement and avoid burden shifting in livestock production chains.

The aim of this thesis was to further develop methods to assess sustainability and to use the methods to increase knowledge on how future sustainable pig and cattle production systems can be developed.

2. Background

2.1 What is sustainability?

The Brundtland commission defined sustainability as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs (WCED, 1987). The report noted trade-offs between economic development and ecological degradation. Sustainability was interpreted as encompassing three pillars, namely social, economic and environmental (Allen et al., 1991). This interpretation of three pillars has been contested, arguments have been raised against the use of pillars (Ekardt, 2019; Kiss et al., 2011; Gibson, 2001). However, the three pillars of social, economic and environmental sustainability are a useful categorisation of sustainability issues to ensure a broad coverage of important aspects (Garren and Brinkmann, 2018).

2.2 Meat and milk production

The global production of meat has more than tripled over the past 50 years and milk production has doubled over the same period (Ritchie and Roser, 2017). Trends indicate that meat and milk production will continue to increase globally due to increases in incomes in low income countries (FAO, 2018). In high income countries, the production may not decline due to a low reduction in consumption because of existence of personal, socio-economic and political barriers to reduction of consumption (Kwasny et al., 2022) and foreign demand (European Commission, 2019).

2.2.1 Production systems

The two main pig production systems in Sweden are organic and conventional. The organic system can be EU or KRAV certified and in total 2% of the Swedish pig production is organic (Jordbruksverket, 2017). Many pig farms (organic and conventional) are integrated, i.e. they have sows producing piglets and these piglets are raised until slaughter (so called slaughter pigs) on the farm. The same pig breeds are used in both conventional and organic systems and almost all slaughter pigs are three-breed crosses.

Cattle production systems vary in Europe, some are dairy farming systems producing milk and meat, while others are suckler beef farming systems producing only meat. In dairy farming systems, the calf is separated from the cow after birth and in suckler beef farming systems the calf suckles the cow. Cattle systems also vary in terms of land used for feed and pasture, i.e. cropland vs grassland based systems. Different breeds are used in different cattle production systems e.g. Holstein and Montbeliarde for dairy and Parda de Montana for suckler beef.

2.2.2 Breeding

Breeding is the selection of animals to be parents based on their genetic capacity for traits of interests. The specific traits and the emphasis on each trait is indicated in a breeding goal. The first step in breeding is the identification of the most relevant goal traits. The next step is to give all traits appropriate weights, so that the breeding results in an optimal overall genetic improvement, i.e. an improvement of offspring of selected animals when compared to the previous generation. Soleimani and Gilbert (2020) and Ottosen et al. (2020) indicate that breeding can reduce negative impacts on the environment. Traits such as feed efficiency can be improved over generations and this results in lower impacts of production of livestock products. Due to genetic improvements milk yield increased by 30% per cow between 1960 – 2000 and pig meat yield increased by 20% per pig under the same period (Thornton et al., 2010). Dairy breeds like Holstein are specialised on high milk yield and currently, less than 20% of the dairy cows produce 50% of the global milk production (Simões et al., 2021). The annual increase in pig growth rate is 5 g/pig/day (Hermesch et al., 2015) due to genetic improvement and adequate nutrition. The breeding goal has changed over time from focus on higher yield to a broader goal. In pig breeding in

1975, most emphasis was on lean growth and now more emphasis is on lifetime reproduction (Knap and Knol, 2022).

2.2.3 Feeding

In the EU, the average pig diet has large amounts of cereals produced in Europe but a large part of the protein in the diets is derived from soybean and its by-products from outside Europe. Soybean is imported mainly from south American countries with higher resource use intensities than the EU of e.g. fertilizer (Sporchia et al., 2021) and pesticides (Mall et al., 2018). Soybean is also used in cattle feed, although to less degree than in pig feed. The heavy reliance on cross-continental soybean imports in the EU has led to calls for a transition, for environmental and social reasons, to more locally produced protein sources such as faba beans, peas, rapeseed meal and cake, and potato protein, and even led to increased cultivation of soybean in Southern Europe (Chancellor, 2018). Promising results of alternative local protein sources have been revealed, such as yeast produced from forest waste (Cruz et al., 2020, 2019) and silage (Friman et al., 2021).

2.2.4 Sustainability issues associated with livestock

Since the 'Livestock's Long Shadow' report by Steinfield et al. (2006), livestock systems are increasingly recognized for emissions to air, water and soil. Livestock systems produce greenhouse gases, e.g. methane from cattle, and this contributes to the increase in temperature known as global warming. Livestock systems release nitrogen and phosphorous into the environment especially through manure. This causes increased biomass growth in water as a result of nutrient leakage and is known as eutrophication. Manure emits ammonia and use of diesel in crop production emits sulphur and these emissions can result in acid rain. The acid rain contributes to the decrease in pH values in the natural environment known as acidification. The production of feed for livestock systems uses fossil fuels, and fossil resources are finite and may get exhausted in the future. The use of land to produce cereals, oil seeds and pulses used for feed causes loss of species diversity and richness (Guyomard et al., 2021) and different land use systems result in a difference in species richness (Knudsen et al., 2017). The production of feed in the conventional way in livestock systems uses chemicals or pesticides and these may drift into the natural environments and cause toxicity problems for organisms and humans. Deforestation and the management of soil in the production of crops in livestock systems for feed can cause losses of soil carbon.

Risk of poor health and safety for workers and local communities (Chen and Holden, 2017), consumers (Grunert et al., 2018) and animals (Boogaard et al., 2011) have been reported in livestock production systems. The negative impacts of livestock production pose a threat to the future existence of fair, animal friendly, healthy and environment-friendly livestock production.

Mitigation of impacts is required and in this task a deeper understanding of the current livestock systems including impacts from upstream industries is needed. Different assessment methods have been developed for different impacts. For environmental impacts, several methods have been developed, e.g. environmental life cycle assessment (E-LCA), strategic environmental assessment, environmental impact assessment, environmental risk assessment, and ecological footprint (Finnveden et al., 2009). For social impacts, methods such as social impact assessment (Vanclay et al., 2003), and social life cycle assessment (S-LCA) (Benoit et al., 2012) have been developed and for economic impacts, methods such as economic impact analysis (Weisbrod and Duncan, 2016), and life cycle costing has been developed (Woodward, 1997). For combined assessment of environmental, economic, and social impacts, life cycle sustainability assessment (LCSA) has been developed (Finkbeiner et al., 2010). The dominant method for sustainability assessment of food, including livestock products, is E-LCA (Poore and Nemecek, 2018). S-LCA has been used for some livestock products, e.g. for milk (Reveret et al., 2015; Chen and Holden, 2017), honey (D'Eusanio et al., 2018), eggs (Pelletier, 2018) and chicken (Tallentire et al., 2019). Life cycle costing has been performed for ham (Lotti and Bonazzi, 2014), milk (Florindo et al., 2017) and beef (Ruviaro et al., 2020). LCSA has also been used e.g. for milk (Chen and Holden, 2018) and pork (Valente et al., 2020).

No S-LCA study has included animals as stakeholders, yet animal welfare is an important sustainability issue (Tallentire et al. 2019; Neugebauer et al., 2014) and animals are sentient beings. No S-LCA for pigs has been published, yet pork is one of the most consumed meat in the world. No life cycle costing study has focused on profitability indicators for pig production, yet the profitability of a farm does not depend on costs alone. Most of the E-

LCA studies have focused on only one to three impact categories (so called simplified LCA, McClelland et al., 2018). Very few LCSA studies have been performed for the common livestock species used for food products.

Recently, the One Health framework, a method for evaluation of sustainability of livestock systems through assessments of the health and well-being of humans and animals and environmental impacts, was developed by Stentiford et al. (2020). The One Health concept highlights the importance of achieving optimal health and well-being outcomes recognizing the interconnections between people, farmed organisms (animals and plants) and their shared environment (One Health Commission, 2021). Focus is on zoonotic and non-zoonotic diseases, occupational health, food safety and security, antimicrobial resistance, and environmental contamination (CDC, 2018). As a result of the health implications of changes in the interactions between people, animals and the environment – e.g. as a result of increased global trade and intensification of farming – the One Health concept has become more important in recent times. The One Health approach has to date been applied mainly in studies of zoonotic diseases, including Tuberculosis B (Good et al., 2018), Q-fever (Conan et al., 2020), and COVID-19 (Mushi, 2020). However, Stentiford et al. (2020) designed a novel framework to capture a wide range of aspects relevant to the sustainability of aquaculture production. This sustainability assessment method (Figure 3) had 13 success metrics scored for the environment, organisms and people. Considering health aspects of livestock products judging from, for example the impacts of COVID-19, believed to have originated from meat from wild animals (Platto et al., 2021) and the effects of business viability on the farmers' mental health (Daghagh Yazd et al., 2019), the One Health framework is useful to develop for the livestock industry. No One Health framework assessment for pigs or cattle have been published.

In general, sustainability studies have indicated differences in sustainability performance of compared systems especially due to differences in feeding. Feed production, including the soybean production, is a hotspot especially for pigs (Sporchia et al., 2021; Gunnarsson et al., 2020), and methane production from direct enteric fermentation in cattle is another hotspot (Arvidsson Segerkvist 2021, 2020). Extensive cattle systems are more sustainable than intensive cattle systems when the functional unit is per unit area and intensive systems are more sustainable than extensive systems when the functional unit is per kg product (e.g Salou et al., 2017), but few studies include more than one functional unit. Trade-offs between sustainability pillars are not well understood for cattle (Arvidsson Segerkvist 2021, 2020) and pig production (Gunnarsson et al., 2020), and this requires that sustainability assessments of livestock production systems include more indicators. Areas of improvement of livestock systems need to be identified considering that the global demand for livestock products is anticipated to rise by 70% in 2050 (Alexandratos and Bruinsma, 2012).

2.2.5 Feed-food competition

Feed-food competition, i.e. how efficiently crops are used to produce food for humans, has been described as important for sustainability of livestock production systems and systems that use less human edible feed are better than the ones that use more (Salami et al., 2019; Mottet et al., 2017). Direct feed-food competition occurs when feed that can be used for humans is used for animals and indirect competition occurs when cropland is used for animal feed rather than human food (van Zanten et al., 2022). Feed conversion efficiency for protein has been used by Mottet et al. (2017) and Wilkinson et al. (2011). van Zanten et al. (2016) has used land use ratio to assess feed-food competition. In LCA, van Hal et al. (2019) recently developed a food allocation factor for use to account for feed-food competition. A food system approach, i.e. measuring the impacts of the whole food system, is another method proposed by van Zanten et al. (2019) to account for feed-food competition. Most studies on feed-food competition are for protein production and in general dairy systems produce more protein than they use in feed (i.e. lower feed-food competition) compared to suckler beef systems (Hennessy et al., 2021; Wilkinson et al., 2011).

Without development of livestock production systems which decrease the ongoing feed-food competition, global crises such as the current food crisis caused by the war in Ukraine (a major food producing country), may create shocks on the commodity prices leading to high costs of livestock feeds for farmers especially for farmers relying on off-farm feeds.

2.2.6 Robustness

Robustness of a farming system refers to the ability of the system to maintain its functions over time despite disturbances and shocks (Urruty et al., 2016). Different agricultural outputs have been used as indicators of robustness e.g.

yield as an indicator of robustness to drought and farm income to price volatility. Mosnier et al. (2009) used the latter to assess the sensitivity of farmers' incomes to climatic and economic perturbations in France. They found that variation in beef price and weather had a profound effect on farm profitability. Robustness is an important aspect of sustainability (Goede, 2014) but only few studies have assessed farm robustness using economic output. Sustainability methods such as LCSA fails to capture the robustness of a farm as it is mainly a method for measuring efficiency (Röös et al., 2021). The lack of development of robust livestock production systems may make livestock production more vulnerable to shocks caused by global crises such as the high fuel costs caused by the current embargo on Russian oil by the EU and US.

2.3 The history of life cycle assessment

Life cycle assessment (LCA) is a method to evaluate environmental impacts of a product or service throughout its lifecycle from the extraction of raw materials, production, distribution, use and end of life of the product. Social LCA involves assessing the risk of social impacts (UNEP, 2009), environmental LCA involves the assessment of environmental impacts (ISO, 2006) and life cycle costing involves costs (Woodward, 1997) along the entire chain. To assess the impacts of a product, the product utility is important as impacts are assessed per given unit of function known as the functional unit. The functional unit ensures that different products are compared on an equivalent basis. The most common functional unit for agricultural studies is kg product (e.g. milk or meat) but assessing per unit land area is also done.

After the Second world war, countries in the now so called 'developed world' started focusing on increasing production efficiency in agriculture. The productivity of crops and animals per hectare of land became the primary concern, with breeders selecting animals and crops for faster growth and higher yields. Crop and animal nutrition specialists also complemented plants' and animals' higher genetic capacity for yield by providing adequate nutrients in fertilizers and feeds respectively. The farmers mechanized and shifted from mixed farming to specialized crop and livestock production. Crops were produced under controlled environments using pesticides and animals were reared indoors under controlled environments using antibiotics.

As a result of high productivity at the farms, food became abundant and affordable for the consumers. However, little attention was given to the potential negative impacts, e.g. the threat of pesticides to biodiversity including species which are useful for pollination of agricultural crops.

Monitoring or measuring the negative impacts of agriculture can be complex but sustainability assessment methods have been developed and used. The interest on which impacts to measure started as early as 1960s and has also evolved over time. A description of impacts, interest and sustainability assessments methods can be distinguished into three periods described below.

2.3.1 Period 1960 – 1989: The genesis of different sustainability assessment methods

The concern about environmental degradation and resource use increased in the 1960s, leading to interest in environmental impacts. Many sustainability assessment methods were developed in the 1960s, e.g. environmental impact assessment (EIA) (Burdge, 1991), strategic environmental assessment (SEA) (Fundingsland-Tetlow and Hanusch, 2012), environmental risk assessment (ERA) (Ragas, 2011) and E-LCA (Bjørn et al., 2018) but E-LCA became dominant over the other methods for food products (Roy et al., 2009).

E-LCA initially focused on energy use but later broadened to include emissions and waste (Guinee et al., 2011). Coca Cola was the first company to use E-LCA in the food industry, for packaging, in the 1960s (Hunt & Franklin, 1996). There was a general lack of interest in discussing E-LCA in the 1980s (Finnveden et al., 2009), but when interest started growing again in the 1990s, most E-LCAs on food focused on the packaging of the food. These did not consider the food in the package; governments and consumers were concerned about packaging primarily (Verghese et al., 2012). The first E-LCA on an agricultural product was in 1990 on tomatoes (Gysi and Reist, 1990) and later studies included animal products (Weidema, 1993).

Concerns about economic costs of projects in the 1960s led to the first use of life cycle costing by the US department of defense (Hoogmartens et al., 2014). Later in the mid-1980s the construction industry started using life cycle costing (Gluch and Baumann, 2004) as a way to analyse costs incurred over the course of life of infrastructure, such as roads.

2.3.2 Period 1990 – 2009: Guidelines and standardization of sustainability assessment methods

The period between 1990-2009 saw the concern about social, environmental and economic impacts rising. The United Nations' environment programme (UNEP) and the Society for environmental toxicology and chemistry (SETAC) in 2002 formed the life cycle initiative which is meant to enable global understanding of life cycle thinking (Huertas-Valdivia et al., 2020). S-LCA was developed as a counterpart of E-LCA (Klöpffer and Ciroth, 2011). The life cycle initiative published S-LCA guidelines in 2008 (UNEP, 2009) and presented, two types of S-LCA; type I - performance reference point and type II - impact pathways.

Within this period the E-LCA methodology developed and became standardized within the ISO 14040-14044 environmental standards (ISO, 2006) such that industries and researchers started using E-LCA following the same four stages. The first stage of E-LCA is the goal and scope. This aims to define the boundary of the E-LCA. The second stage is an inventory analysis, in which data on inputs and outputs, i.e. raw materials and emissions to the environment respectively, is collected. The third stage is the impact assessment and is meant to characterize the impacts, i.e. giving units to the impacts. The last stage is the interpretation stage in which results and a sensitivity analysis are presented and critically reviewed. The stages and process flows are shown in Figure 1.

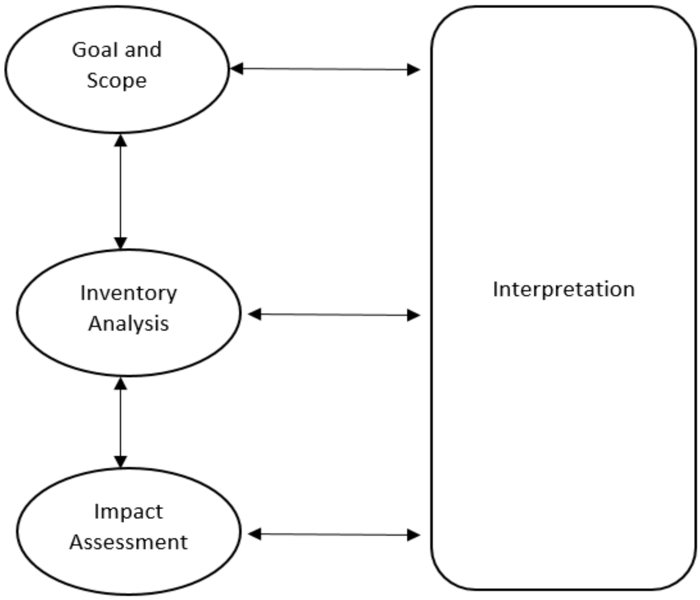

Figure 1. Life cycle assessment framework

Life cycle costing became standardized for buildings in ISO 15686-5:2008 (ISO, 2021). For food products, life cycle costing was performed on the production assets and on the product itself (Settanni et al., 2008), i.e. costs associated with the production of the product from its raw material to finished product. Three types of life cycle costing were defined based on scope: conventional life cycle costing which includes the evaluation of the costs of production and maintenance of a product during its life time, environmental life cycle costing which includes conventional life cycle costing plus costs on the environment, and societal life cycle costing which includes evaluation of all the present and future costs borne by the society (Hunkeler et al., 2008).

2.3.3 Period 2010 – 2020: Revision of sustainability assessment methods and joint assessment

The period starting 2010 saw an increased interest in environmental impacts and use of E-LCA (McClleland et al., 2018; McAullife et al., 2016; Jacquemin et al., 2012) but interest in development of the assessment of social and economic impacts was also noticeable. The life cycle initiative published a code of practice on environmental life cycle costing in 2011 (Swarr et al., 2011). ISO (2021) indicates that guidelines for life cycle costing for buildings and constructed assets were revised in 2017. Life cycle costing was applied to different sectors such as energy sector, e.g. solar (Fan, 2014) and construction, e.g. bridges (Safi, 2013). A few life cycle costing studies were performed in the agri-food sector for livestock, e.g. beef (Florindo et al., 2017), milk (Ruviaro et al., 2020), and ham (Lotti and Bonazzi, 2014). S-LCA was applied to different sectors such as technology e.g. media and communication (Moberg, 2010), and a laptop computer (Ekener, 2013). A few S-LCA were performed for the agri-food sector for livestock e.g dairy cattle (Reveret et al., 2015; Chen and Holden, 2017). In this period, the life cycle initiative revised the S-LCA guidelines and animal welfare is now considered as a subcategory under society (UNEP, 2020) but animals are not regarded as stakeholders.

This period also saw a new interest in analysing the three pillars together using life cycle sustainability assessment (LCSA) as described in Figure 2 (Finkbeiner et al., 2010) and the life cycle initiative developed an LCSA framework in 2011 (UNEP, 2011). The challenge of connecting social impacts to the functional unit in S-LCA was a barrier to LCSA development (Lin et al., 2020). Even if E-LCA is the most advanced method, with 18 impact indicators for Recipe 2016 (Huijbregts et al., 2016), most E-LCA in LCSA studies still focus on one to three impacts indicators for livestock production.

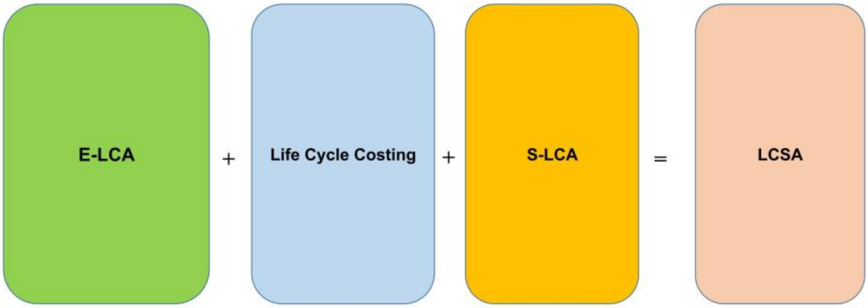

Figure 2. Life cycle sustainability assessment

Another method developed to analyse economic, environmental and social impacts is the One Health framework shown in Figure 3 (Stentiford et al., 2020). The One Health framework originated from the One Health approach which was derived from the phrase “One World – One Health”. This phrase was first used in the US in 2004 in a workshop on the spread of diseases among people, domestic animals and wildlife populations in a globalized world (Calistri et al., 2013). Later, in 2010, the One Health approach gained currency when the Food and Agricultural Organization (FAO), the World Organization for Animal Health (OIE) and the World Health Organization (WHO) agreed to share a common goal of reduced health risks at the animal-human-ecosystems interfaces (FAO-OIE-WHO Collaboration, 2010).

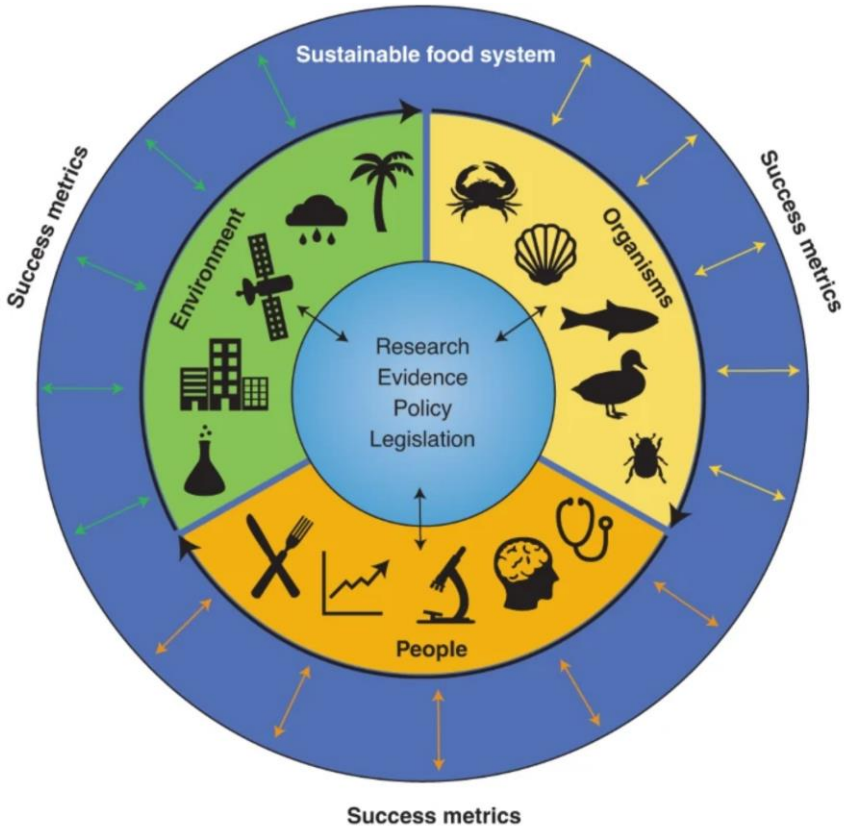

Figure 3. One Health framework for aquaculture developed by Stentiford et al. (2020 p 469)

3. Aim, objectives and structure

3.1 Aims and objectives

The overall aim of this thesis was to further develop sustainability assessment methods to broadly evaluate livestock systems and to use these methods to increase knowledge on how future sustainable pig and cattle production systems can be developed.

Specific objectives were:

- To further develop S-LCA, LCSA and the One Health framework for pig and cattle production systems;
- To assess the economic, environmental and social sustainability of contrasting pig and cattle production systems using LCSA;
- To assess the sustainability of improved future pig production systems using a One Health framework;
- To identify improvement areas for sustainable pig and cattle production systems.

3.2 Structure of work

The work started with the development of a new approach to S-LCA (paper I, see Figure 4), which involved gathering topical social sustainability issues from literature and experts for the creation of indicators used in S-LCA, using activity time to connect to a functional unit and also including animals as a stakeholder. Social sustainability issues from a 'predesigned' database describing risk of negative social impact were used for the LCSA for pig production systems in paper II. In paper III, the S-LCA methodology in paper I was used in a LCSA for cattle production systems and the sustainability assessment also included feed-food competition and robustness. Paper IV assessed future pig production systems using a performance based approach for the One Health framework.

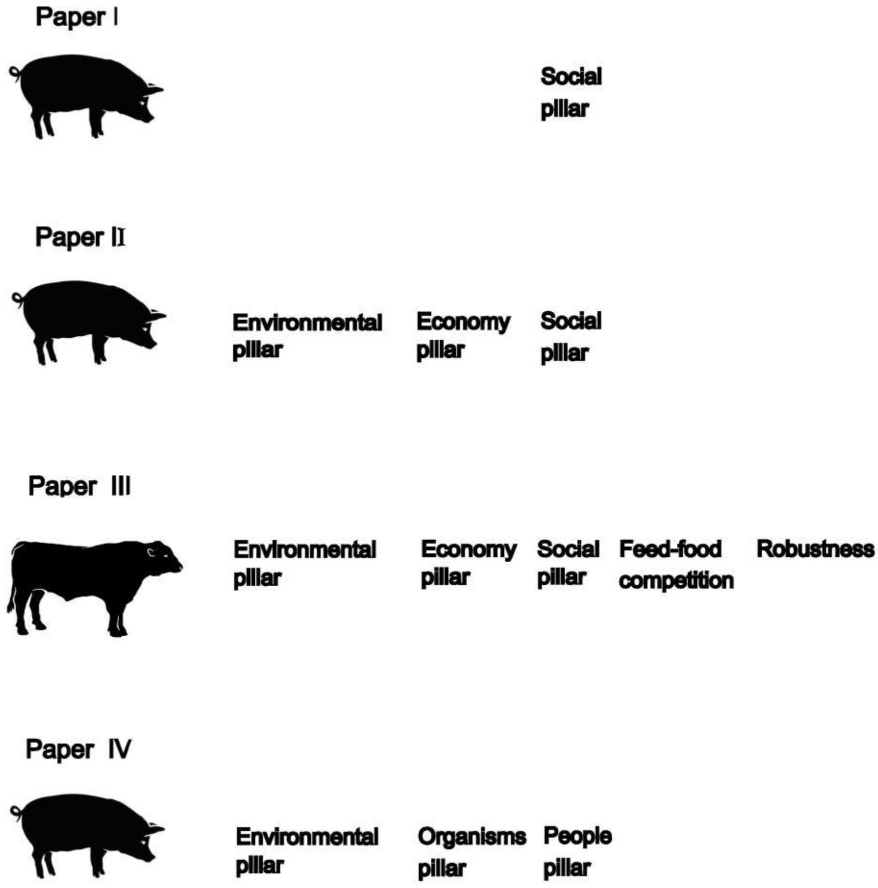

Figure 4. Structure of work

Pig and cattle illustrations from Fredrik Saarkoppel, SLU library

4. Materials and Methods

4.1 Social life cycle assessment

Social life cycle assessment (S-LCA) was developed and used to assess the risk of negative social impacts of pig production. We used negative issues and a few positive issues but not in the same way both positive and negative were used by Ekener et al. (2018). We used favourable issues such as farmers' support to neighbours on the country side and presence of farm stores but it was the 'risk of missing' these valuable aspects that we assessed.

4.1.1 Description of the studied pork production systems

We assessed conventional and organic pork production because these were the two main systems in Sweden. In short, organic pig production has the following requirements: pigs must have outdoor access all year and grazing during summer, inorganic chemicals in fertilizers and pesticides must not be used in crop production, at least 50% of the feed shall come from the own farm, roughage shall be given to all pigs, slaughter pigs shall not stay overnight at the slaughterhouse, drivers shall use fuel-efficient driving techniques, and electrical energy from renewable sources like wind, solar and hydro shall be used (KRAV, 2019). There are also some requirements on housing and management aiming for high animal welfare. In the conventional pig production there are no corresponding requirements.

4.1.2 Scope

Social impacts were studied in all four papers and in paper I the assessment of risk of negative social impacts was the main focus. The system boundary for the S-LCA of pork production in paper I included the following processes: feed production, pig production, slaughter of pigs and consumption of pork. On-farm feed included the following activities: production of wheat and barley. Off-farm feed included rapeseed from Denmark, soybean meal and cake with soybean produced in Brazil and China for conventional and organic pork production systems respectively. We assessed social risks on workers, farmers, consumers, local community, society and pigs within the system boundary. The functional unit was 1 000 kg pork. Subcategories were identified from social sustainability issues obtained from a literature search and an expert workshop.

4.1.3 Method development

The analysed indicators were derived from social issues gathered from literature and experts using the process flow in Figure 5. Data for inventory indicators for social sustainability issues were collected from case-specific sources, e.g. survey data, interviews, published articles, reports and websites, and generic sources, e.g. databases from international organizations such as ILO (International labour organization), the World Bank, United nations agencies and third party certification agencies.

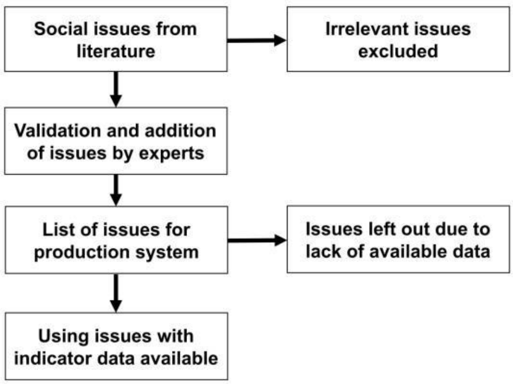

Figure 5. Summary of the S-LCA method in Paper I

4.1.4 Indicators evaluated

Social Risk Time

To connect risk of negative social impacts to the functional unit, we used different so called activity variables, i.e. time based variables for processes activities required to produce the functional unit. Social Risk Time (SRT), i.e. the social risk of negative impacts corrected for time or exposure, was computed according to Tallentire et al. (2019). SRT for each subsystem were summed up for each stakeholder and this was done using the formula:

$$SRT_{ij} = \sum_{k=1}^{K}(T_{ij} * SR_{ijk} * W_{ijk})$$

where SRT_{ij} denotes social risk time for stakeholder i (e.g. farmers) in subsystem j (e.g. wheat production), T_{ij} denotes the activity variable (e.g. workhours) in subsystem j for stakeholder i, SR_{ijk} denotes the social risk for inventory indicator k (e.g. low wages) in subsystem j for stakeholder i, and W_{ijk} is the weight of inventory indicator k in subsystem j for stakeholder i. An example for the calculation of SRT and SHI is shown in chapter 8 (Appendix).

Different activity variables (T) were used to relate the negative risk of social impacts from the different stakeholders to the functional unit. For workers and farmers, the work hours required to produce the functional unit were used as an activity variable. Pig life days (the number of pigs multiplied by days needed to produce the functional unit) were used as an activity variable for pigs. For local community and society, we used people hectare days i.e. the number of people in an area (per hectare) multiplied by the number of hectares and the number of days needed to produce the functional unit.

Social risk (SR) measures the risk of negative social impacts for an inventory indicator and was calculated for all indicators depending on data availability. SR corresponds to Ri used by Tallentire et al. (2019) and Benoit et al. (2012). SR was normalized following Chen and Holden (2018). We used the European average performance as a reference point with values greater than 0.5 indicating higher risk and less than 0.5 indicating lower risk than European average. However, for the inventory indicators describing wage and income, we used the national minimum wages in each country as the reference point instead of European average because the social risk associated with wage depends on the living costs in a specific country. The formulas used to calculate SR were:

$$SR = 1 - EXP(LN(0.5) * IND/REF)$$

when a *higher* value than the reference point reflects a more negative impact, and

$$SR = EXP(LN(0.5) * IND/REF)$$

when a *lower* value than the reference point reflects a more negative impact, where IND is the inventory indicator for the subsystem and REF is the reference point.

We used a web questionnaire for expert weighting of subcategories in paper I and the weighting was performed using the Analytical Hierarchical Processing (AHP) (Saaty, 1990) which involves pairwise comparisons. The geometric mean vectors were obtained using the AHP package (Glur, 2018) in the R programme.

Social Hotspot Index

In addition to SRT, we also computed the social hotspot index (SHI), which is the risk of negative social impacts relative to the worst possible case for each stakeholder (Benoit et al., 2012). SHI values range between 0 and 1, and a high value of SHI indicates a high potential of negative social impact. SHI for a stakeholder in a specific subsystem was calculated according to Tallentire et al. (2019) and Benoit et al. (2012) using the formula:

$$SHI_{ij} = SRT_{ij} \,/\, \widehat{SRT}_{ij}$$

where SRT_{ij} denotes social risk time for stakeholder i in subsystem j, and $\widehat{SRT}_{ij}$ denotes the worst possible SRT for stakeholder i in subsystem j. The SHI for each stakeholder was then calculated by summing subsystems considering the proportion of time for each subsystem as shown in the formula:

$$SHI_i = \frac{\sum_{j=1}^{J} SHI_{ij} * T_{ij}}{\sum_{j=1}^{J} T_{ij}}.$$

4.2 Life cycle sustainability assessment

Life cycle sustainability assessment (LCSA) included E-LCA, life cycle costing and S-LCA (Finkbeiner et al., 2010). Conventional and organic pork production were assessed in paper II and three cattle production systems in paper III. In this chapter (4.2) focus is on paper II, and the following chapter (4.3) focuses on paper III. The LCSA in paper II was performed on the same systems as the ones studied in paper I.

4.2.1 Scope

The S-LCA for pig production in Paper II was performed using a risk of negative social impact assessing database for S-LCA called Soca. Soca was used for all stakeholders except pigs and consumers which were not included in the database. The system boundary for the LCSA included: 1) farm and feed production (crop cultivation, feed production and pig production), 2) slaughter, 3) wholesaling and retailing, and 4) consumption. On-farm feed included: production of wheat, barley, oats and faba beans and off-farm feed included soybean meal and cake with soybean produced in Brazil and China as in Paper I. The functional unit was 1 000 kg pork and 1 000 ha. The S-LCA included social risks of negative impacts on: workers, local community, society, value chain actors, consumers and pigs. The environmental impacts were computed using OpenLCA 1.10.2 (Greendelta, 2019) with Ecoinvent 3.3 (APOS) (Ecoinvent, 2016) as a database for E-LCA and the negative risk of social impacts were computed using Soca v.1 (Greendelta, 2017) as a database for S-LCA. For pigs and consumers (not in Soca) we used the same subcategories as in the S-LCA in Paper I. Life cycle costing was performed using Microsoft Excel®.

4.2.2 Indicators evaluated

In LCSA, the environmental, economic and social indicators of different systems need to be compared using the same unit. In paper II, we used relative sustainability points (RSP). Since a higher RSP value in paper II means more unsustainable, we later realised it would be better to call these points relative *un*sustainability points (RUsP). Thus RUsP is used in paper III. RSP (as well as RUsP) measures a system with respect to a reference and the score is between 0 and 1. In paper II, we used the conventional pork supply chain as the reference and calculated RSP for environmental, economic and social indicators. An RSP[1] score below 0.5 indicated that the

[1] Note that RSP in paper II has the same meaning as RUsP in paper III and higher points indicates more unsustainable, whereas higher RSP in paper IV indicates more sustainable

organic pork supply chain is better than the conventional pork and above 0.5 indicated the opposite. RSP was calculated using the formulas:

$$RSP = 1 - EXP(LN(0.5) * IND/REF)$$

when a *higher* value for an indicator reflects a more negative impact,

$$RSP = EXP(LN(0.5) * IND/REF)$$

when a *lower* value for an indicator reflects a more negative impact of an indicator, where IND and REF are the environmental, economic or social indicator values for organic and conventional pork production, respectively.

Environmental indicators

We analysed global warming potential (100 years), freshwater eutrophication, marine eutrophication, terrestrial acidification, fossil depletion, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity and human toxicity potential using Recipe H (V1) (Goedkoop et al., 2013). We analysed biodiversity damage potential, i.e. the differences in species richness between a pristine or undisturbed ecosystem over time and an area used for pig production purposes (Knudsen et al., 2017). We also analysed soil carbon loss, i.e. the difference between the steady state of soil carbon after 100 years with initial soil carbon as 100 tonnes carbon per ha at time (t_0) using the introductory carbon balance model following Moberg et al. (2019) for the different crops.

Economic indicators

Conventional and organic pork production use different inputs and therefore we calculated the value added (VA) over life cycle costs (LCC) and labour costs. LCC were calculated as operational costs excluding wages, interest, depreciation, rent, and taxes, and VA was the difference between the product price and the LCC (Konstantas et al., 2020; 2019) for each supply chain stage i.e. farm, slaughterhouse, and wholesaler and retailer. The VA/(LCC + labour costs) ratio gave an indication of the value created at each stage.

Social indicators

The social risk of negative impacts corrected for time, social risk time (SRT), was computed for each stakeholder with equal weighting (a difference from paper I) and this was done using the formula:

$$SRT_{ik} = \sum_{j=1}^{J} (T_{ijk} * SR_{ijk})$$

where i denotes the stakeholder (e.g. workers), j denotes the inventory indicator (e.g. fair salary for workers), k denotes the subsystem (e.g. slaughterhouse) and *SRT* denotes social risk time for stakeholder i, T_{ijk} denotes the activity variable for stakeholder i for indicator j and subsystem k and SR_{ijk} denotes the social risk for stakeholder i for indicator j and subsystem k.

Social risk (SR), a measure of the risk of negative social impacts for an inventory indicator, was based on performance reference levels or thresholds on a reference scale: no risk (0), very low risk (0.01), low risk (0.1), medium risk (1), high risk (10) and very high risk (100). No social hotspot index was used in Paper II (although T varied between the organic and the conventional system) because the exponential increase in social risk (SR) decreased the importance of T in the calculation of SRT at high social risk values. A system with a lower SRT is better when comparing two supply chains. Risk work hours was used as time unit for workers, local community, society and value chain actors in Soca (Greendelta, 2017). As in Paper I, pig life days was used for pigs and people consumption days was used for consumers.

4.3 Life cycle sustainability assessment complemented with feed-food competition and robustness

The sustainability assessment in paper III included LCSA, feed-food competition and economic robustness. We assessed two dairy production systems and one beef production system with suckler cows in southern Europe.

4.3.1 Description of the studied cattle production systems

HolSy is a conventional dairy system located in the lowlands of France in the West Atlantic region - Pays de Loire, based on Holstein cows. Ninety-six percent of the total land used is cropland and semi-natural pastures only make 4% of the total land. MonSy is also a conventional dairy system. It is located in the highlands of France in Central Mountain region – Auvergne, and based on Montbeliarde cows. Seventy-five percent of the total used is cropland and 25% is semi-natural pasture. HolSy and MonSy, as all other dairy systems, produce both milk and meat. ParSy is an organic beef system located in the highlands of the Spanish Pyrenees, based on Parda de Montana cows and calves. Twelve percent of the total land used is cropland and 88% is semi-natural pastures. The animals are kept indoors during the cold season, i.e. from November to February and have access to grazing during the warm seasons in all the systems. HolSy has all year round calving and MonSy and ParSy have seasonal calving.

4.3.2 Scope

In paper III, the LCSA was performed with indicators from literature and experts for S-LCA. The LCSA was complemented with the assessment of human edible feed conversion ratio and economic robustness, because LCSA neither captures feed-food competition nor profitability and economic performance of farms over time. Our system boundary for the LCSA included: 1) pasture management, 2) the production of feed, 3) animal housing and 4) manure management. On-farm feed included the activities production of wheat, barley, maize silage, grass and alfalfa. Off-farm feed included production of powdered milk, protein concentrate, vitamin and mineral premix, and soybean meal and cake with soybean produced in Brazil and processed in France. HolSy did not have barley and alfalfa. MonSy did not have barley and powdered milk. ParSy system did not have protein concentrate, soybean and wheat. We assessed social sustainability through social risks of negative impacts on workers, farmers and cattle. In general, the S-LCA was performed with the method developed in paper I. The weighting of subcategories within stakeholder was, however, done in a simpler way in paper III. Experts were asked to distribute 100 points over the different subcategories to indicate their relative importance and the average points were used as weights.

The functional unit was 1 000 kg protein. We used kg pork when we analysed pork production, but here we used protein instead of milk and beef because protein is a common functional unit for dairy and beef production systems. The environmental indicators were computed using OpenLCA 1.10.2 (Greendelta, 2019) with Agribalyse (2020) as a database for E-LCA. Social and economic impacts were computed using Microsoft Excel®.

4.3.3 Indicators evaluated

Life cycle sustainability assessment

In LCSA in paper III, the environmental, economic and social indicators of the three cattle systems needed to be compared using the same unit (as we did for the pork production systems in paper II). As described above, we used relative unsustainability points (RUsP) in paper III, and HolSy was the reference. Note that RSP in paper II and RUsP in paper III is the same measurement and in these articles higher points indicate increased unsustainability. In paper IV, higher RSP indicates increased sustainability.

Feed-food competition

We complemented LCSA with RUsP indicators for feed-food competition for the three cattle systems. Protein and fat intake in feed and protein and fat output in meat and milk was used to compute two feed-food competition indicators, i.e. human edible feed conversion ratio protein and human edible feed conversion ratio fat. The human edible feed conversion ratio protein was the amount of human edible protein in feed per kg protein in milk and meat or meat and human edible feed conversion ratio for fat production was the amount of human edible fat in feed per kg fat in milk and or meat.

Robustness

We complemented LCSA with an analysis of the economic robustness of different systems describing how sensitive the farms were to changes in interest rates, input prices and output prices. We used the net present value (NPV), i.e. the difference between the present value of cash inflows and the present value of cash outflows over a period of time, and the internal rate of return (IRR), i.e. the discount rate that results in an NPV value equal to zero, to evaluate robustness. A high NPV reflects a high rate of return on investment, i.e. a high IRR. We calculated NPV and the expected changes in NPV due to changes in interest rates, producer prices of meat and milk, support payments and feed, energy and rental costs (one at a time) and the IRR for the farm.

4.4 One Health framework

The One Health framework developed by Stentiford et al. (2020) includes assessment of impacts on people, organisms and the environment. In their case, the organisms were fish or shellfish in aquaculture. We adapted the indicators to pigs and pork, and used the framework to study future scenarios of conventional pig production in paper IV.

4.4.1 Description of the reference case and future scenarios in pork production

The One Health framework by Stentiford et al. (2020) was used to compare future (year 2040) pig production scenarios: AsUsual, SusFeed-old, SusFeed-new, SusFeedPig to a reference case and determine how they performed. The reference case was based on today's production system in Sweden (2019/20) and the purpose of having this case in the study was to use this as a benchmark. The AsUsual scenario was based on the assumption that the current trends will continue, i.e. certified soybean from Brazil will be used in feed, renewable electricity and third generation biodiesel from forest waste products will be used as an energy source, and that the pigs will be selected according to the breeding goal used in today's pig production. In the SusFeed-old scenario, it was assumed that soybean will be replaced by local protein sources such as yeast protein produced from forest waste, that silage will be used to improve pig welfare and that the same breeding goal as in the AsUsual scenario will be used. Assuming that the same feed as in the SusFeed scenario will be used and that the breeding goal will change to further improve traits important for feed efficiency and animal welfare, the SusFeed-new scenario was created. Assuming that pigs in the SusFeed-new scenario will have outdoor access, we also created the SusFeedPig scenario. All four future scenarios assumed a genetic trend due to selection from now to year 2040. Note that the scenario here called SusFeed-old refers to the scenario called SusFeed in paper IV, and the scenario here called SusFeed-new refers to a scenario described in the sensitivity analysis in paper IV. The scenarios are described in more detail in Table 1.

Table 1. Description of reference case and future scenarios in pork production (Zira et al., 2022)

		Reference case	**AsUsual**	**SusFeed-old SusFeed-new**	**SusFeedPig**
Feed	Soybean meal	yes	yes	no	no
	Yeast meal	no	no	yes	yes
	Maize meal	yes	yes	no	no
	Wheat bran	yes	yes	yes	yes
	Other by-products	yes	yes	no	no
	Silage mixed in feed	no	no	yes	yes
	Sows get silage as enrichment	no	no	yes	yes
Rearing and breeding	Pigs have access to veranda	no	no	yes	yes
	Pigs on summer pasture	no	no	no	yes
	Pigs receive large amounts of straw	no	no	yes	yes
	Breeding goal	current	current	old: current new: new	new
Energy	Electricity from renewable sources	partly	100%	100%	100%
	Biodiesel	no	yes	yes	yes
	Ammonia as marine fuel	no	yes	yes	yes

We compared pigs bred using the current breeding goal and a new breeding goal aiming for increased over-all feed efficiency and improved animal welfare. Table 2 presents the economic weights used for the genetic evaluation according to the two breeding goals.

Table 2. Selection traits and their relative economic weights used to estimate genetic change for pigs (Zira et al., 2022)

	Economic weights	
Selection traits	**Current breeding goal**	**New breeding goal**
Litter size, number of live born piglets	32.0	12.0
Piglet survival, % of live born	-	8.0
Interval weaning-service ≤7 days, %	-	7.0
Sows free from shoulder ulcers, %	-	4.0
Productive life length (sow longevity), d	-	1.0
Weaners mean growth rate, weaning to 35 kg, g/d	-	1.0
Growers-finishers mean growth rate, 35 to 60 kg, g/d	18.0	14.0
Growers-finishers feed efficiency, g growth/MJ ME	18.0	15.0
Leg strength, points from 1 to 5	20.0	15.0
Slaughter pigs treated from disease, %	-	7.0
Leanness, meat percent in carcass, %	12.0	5.5
Meat quality, juicy meat, % liquid remaining in meat	-	10.5

The selection was based on Best Liner Unbiased Prediction (BLUP) breeding values which were simulated with the SelAction program (Rutten et al., 2002). Genetic parameters were collected from the literature. The simulated breeding program included only one synthetic breed representing all three breeds involved in a standard cross breeding program. In the simulation, 70 boars and 1 000 sows were mated in each generation. The response to selection (i.e. the genetic trend) presented in Table 3 was used as an input in the One Health framework.

Table 3. The mean phenotype values for sow and slaughter pig traits in the reference case 2019/20, and after selection until 2040 with a current and a new breeding goal (Zira et al., 2022)

	2019/20	**2040**	**2040**
	Reference	**Current**	**New**
Interval weaning-service ≤7 days, % of sows	90.0	88.8	90.4
Litter size, number of live born piglets	14.6	16.7	15.1
Piglet mortality, % of live born	18.0	20.2	16.7
Productive life length (sow longevity), days	570	615	669
Sows with shoulder ulcers, % of sows	20	20	18
Replacement rate, %	47	44	41
Weaner's mean growth rate, weaning-35kg, g/d	600	636	667
Weaner's energy requirement, MJ ME/d	15.7	15.7	16.4
Grower's mean growth rate, 35-60 kg, g/d	680	870	880
Grower's energy requirements, MJ ME/d	19.0	21.7	21.7
Finisher's mean growth rate, 60-120 kg, g/d	834	1070	1090
Finisher's energy requirements, MJ ME/d	36.2	39.7	39.4
Overall feed conversion, MJ/kg growth	33.5	29.9	29.4
Leg strength at performance test, 1-5 points, 5 best	3.5	4.2	4.3
Slaughter pigs treated for disease, % of pigs	20	20	18
Leanness, meat in carcass, %	58.6	62.8	59.3
Meat quality, drip loss, % (lower drip loss = better quality)	5	7	5

4.4.2 Indicators evaluated

We used the One Health framework by Stentiford et al. (2020) for the evaluation of future scenarios in comparison to the reference case. This One Health framework had 13 success metrics (Table 4) scored on a scale of 1–5 for people, organisms and the environment using presence of research, legislation and policy. We adapted it, using a different set of indicators and a scoring method, because we considered the challenges of forecasting research, legislation and policy on future pig production, and also that use of quantitative indicators brought additional value to the analysis.

Relative sustainability points (RSP[1]) for success metrics were used to compare the performance of the scenarios. The reference case had an RSP equal to 0.5 and higher RSP values indicated higher sustainability in paper IV.

[1] Note that RSP in paper II has the same meaning as RUsP in paper III and higher points indicates more unsustainable, whereas higher RSP in paper IV indicates more sustainable

Table 4. One Health framework for sustainable pig production (Zira et al., 2022), with success metrics from Stentiford et al. (2020)

Pillar	Success metrics	Indicators for the success metrics
People	Nutritious and safe food	Microbe prevalence, Meat quality
	Quality employment	Working hours, Social recognition, Health, Working conditions, Sabotage
	(Gender equalization)	Left out because future gender equalization mainly depends on factors outside the pig production system
	(Equitable income generation)	Left out given the difficulty of forecasting profitability in a future market
	Knowledge and skills generation	Technical knowledge and management skills development, Co-ownership of sustainability narrative
Organisms	Healthy stock	Cleanliness, Enrichment material, Silage, Injuries, Diseases, Longevity, Space, Deep litter, Grazing, Veranda, Weaning age
	Biosecure farms	Injuries from predators, African swine fever, Salmonella
	Safe farms	Antibiotic resistant Staphylococcus, Salmonella
	Minimal chemical hazards	Antibiotic usage (disease resistance in the breeding goal)
	Optimized farm systems	Breeding goal improving animal welfare
Environ-ment	Optimal water quality	Ecotoxicity, Eutrophication
	Optimal water usage	Water use for feed production
	Protected biodiversity and natural capital	Biodiversity damage potential, Soil carbon loss
	Low energy use[1]	Climate impact, Fossil depletion
	Low spatial footprint	Land use

[1] This metric is called "Low-energy production" in Stentiford et al. (2020)

Social points are a score based on literature and expert advice with three levels: 5 (very good), 3 (fair) and 1 (very poor). The levels are based on the thresholds. Social points were used to standardize the scoring of indicators for people and organisms.

Environmental indicators were used to assess impacts in the same way as in E-LCA but the impacts were expressed as RSP under the respective success metric. In addition to climate impact, eutrophication, fossil depletion, biodiversity loss, ecotoxicity and soil carbon loss described and used in paper II, we included blue water footprint (consumption of water from rivers, lakes and underground) and green water footprint (consumption of water from precipitation that evaporated, transpired by plants with data from Mekonnen and Hoekstra, 2012; 2011) and land use (occupation of land for a year's period for human purposes).

The system boundary for the success metrics under the environment pillar included: the cultivation of soybean meal in Brazil, rapeseed meal and cake in Sweden, yeast meal in Sweden, maize grain in Denmark, monocalcium phosphate in Germany, synthetic crystalline amino acids in Denmark, potato protein in Sweden and fish meal processing in Sweden. At the pig farm the following activities were included, production of: wheat, triticale, oats, barley, faba beans, peas, rapeseed, grass-clover and slaughter pigs including manure management. Energy and transport were also included.

5. Results

5.1 Social life cycle assessment for pork production

5.1.1 Indicators

We used a total of 93 indicators with 32 for workers, 12 for local community, 16 for consumers, 21 for pigs and 12 for society in paper I. In addition, we identified 63 indicators that could not be used due to lack of data. In paper II, we used a total of 63 indicators with 15 for workers, 13 for local community, 8 for consumers, 21 for pigs, 4 for society and 2 for value chain actors.

5.1.2 Social hotspot index and social risk time

The results from the S-LCA of Swedish organic and conventional pork production (paper I) showed that the organic system had lower social risk of negative impacts than the conventional system for all stakeholders when social sustainability was measured using SHI (Table 5) as the organic system did not use pesticides, had farm stores, pigs were seen outdoors, pork had better extrinsic attributes for consumers (e.g. access to information about the origin of the meat) and pigs had better welfare (e.g. access to roughage and pasture).

Farmers and society had the highest values in both systems, indicating that they had higher risks of negative social impacts than other stakeholders. This was mainly due to low farmer incomes and for society, the reduction of work opportunities due to mechanization and loss of pig genetic diversity due to use of specialized breeds. When social sustainability was measured using SRT, i.e. the social risk of negative impacts corrected for time or exposure, the conventional system had lower impacts for workers, farmers, local community and society than the organic system as the conventional system required longer production time per unit volume when compared to the organic system. For consumers and pigs the organic system had lower impacts for both SHI and SRT as pork had better extrinsic attributes for consumers, and pigs had better welfare at the farm than in the conventional system such that these compensated for the longer production time for organic.

For workers, soybean had the highest SRT in the organic system because most of the workers' time was spent at the soybean farm in the organic pork production chain, whereas in the conventional system it was pig production that consumed the most time. Organic soybean production in China was labour intensive because it was done by small scale farmers using manual labour. For the pigs as stakeholders, the pig farm had the highest SRT in both systems because pigs spent considerably more of their lifetime at the farm compared to the slaughtering facility. For local community in both systems, the pig farm had the highest value of SRT because more land was required to produce wheat and barley than for soybean and rapeseed. Organic pork had lower negative impacts on the local community at the pig farm because of presence of farm stores and presence of pigs outdoors which is an attractive feature for landscapes' aesthetics.

At the subsystem level, workers and society at soybean farm had a higher risk of negative social impacts in the organic chain than in the conventional one. This was because Chinese soybean had longer production time than Brazilian soybean and also that larger quantities of soybeans were required in the organic chain than in the conventional one.

SHI alone can be used to assess systems with similar activity variables, but when there is a large difference between activity variables of two systems both SHI and SRT could be used in parallel. SRT can be used for risk comparisons within and across systems, but only for stakeholders with similar units, e.g. workers and farmers and not for stakeholders with different units, e.g. workers and consumers. SHI has no unit and can be used for comparisons between different stakeholders within and across systems.

Table 5. Social Risk Time (SRT) and Social Hotspot Index (SHI) for stakeholders for 1 000 kg of consumed pork with values with a green background indicating the overall results for stakeholders. The poorer of the two is marked in bold; Zira et al., 2020).

Stakeholder category and Subsystem	Social Risk Time (SRT)		Social Hotspot Index (SHI)	
	Conventional	**Organic**	**Conventional**	**Organic**
Workers	5.7	**29**	**0.40**	0.31
Soybean farm	0.64	**20**	0.24	**0.27**
Rapeseed farm	**0.07**	0.05	**0.11**	0.10
Pig farm	3.7	**7.9**	0.42	0.42
Slaughterhouse	1.3	1.3	0.48	0.48
Farmers	15	**29**	**0.52**	0.48
Local commun.	2 200	**5 000**	**0.42**	0.20
Soybean farm	120	**360**	**0.27**	0.14
Rapeseed farm	**160**	57	**0.13**	0.09
Pig farm	1 900	**4 600**	**0.45**	0.21
Slaughterhouse	15	15	0.32	0.32
Consumers	**9 000**	7 500	**0.36**	0.30
Pigs	**1 700**	1 200	**0.34**	0.22
Pig farm	**1 700**	1 200	**0.34**	0.22
Slaughterhouse	**0.25**	0.15	**0.48**	0.30
Society	1 700 000	**7 600 000**	**0.48**	0.46
Soybean farm	59 000	**380 000**	0.21	**0.23**
Rapeseed farm	**130 000**	68 000	**0.17**	0.15
Pig farm	1 500 000	**7 200 000**	**0.53**	0.49

Social risk time units: Workers and farmers - hours, Local community and society – people hectare days, Consumers – people consumption days, Pigs – pig life days

5.2 Life cycle sustainability assessment for pigs

The organic pork supply chain performed better than the conventional one for 11 out of 20 indicators when the systems were compared based on 1 000 kg of pork as shown in Figure 6 (from paper II). However, per 1 000 ha farmland, the organic pork supply chain had lower RSP[1] in 18 of the 20

[1] Note that RSP in paper II has the same meaning as RUsP in paper III and higher points indicates more unsustainable, whereas higher RSP in paper IV indicates more sustainable

indicators and thus outperformed the conventional system. This was because the organic chain used less inputs per hectare except for fuel.

The conventional pork supply chain performed poorer for toxicity indicators, pig welfare and perception of value indicators for consumers, as conventional chain used pesticides, pigs did not have access to silage and outdoor environment and the origin of conventional pork was less known compared to organic pork.

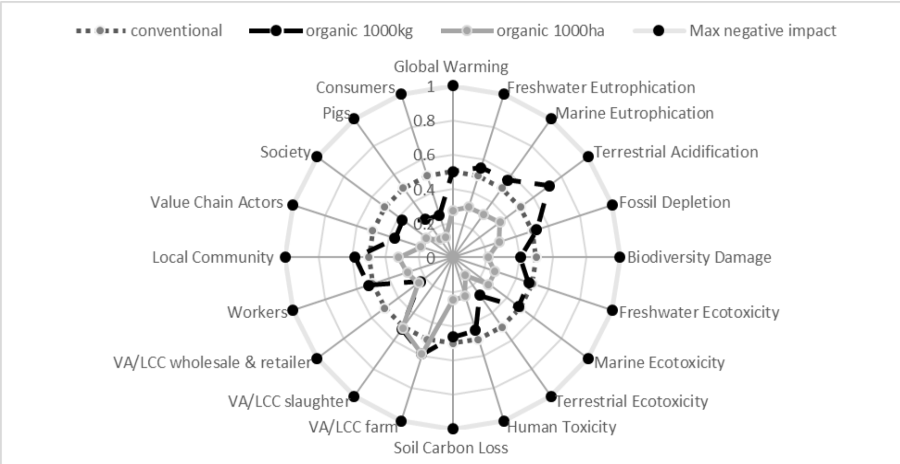

Figure 6. Life cycle sustainability assessment in relative sustainability points (RSP[1]) for the organic pork supply chain for 1 000 kg pork fork weight and 1 000 ha farmland with the conventional pork supply chain as the reference (RSP[1]=0.5). VA/LCC means value added over life cycle cost + labour costs (Zira et al., 2021).

5.2.1 Environmental assessment

The organic pork supply chain per 1 000 ha of farmland had lower environmental impacts than the conventional pork supply chain in all impacts (Table 6) due to that organic agriculture used less inputs per hectare apart from fuel. Global warming potential was the same for both supply chains when assessed per 1 000 kg of pork but the conventional pork supply chain had lower environmental impacts than the organic pork supply chain for freshwater eutrophication, marine eutrophication, terrestrial acidification and fossil depletion since the conventional pork chain required less inputs per kg pork. The organic pork supply chain had lower environmental impacts

[1] Note that RSP in paper II has the same meaning as RUsP in paper III and higher points indicates more unsustainable, whereas higher RSP in paper IV indicates more sustainable

than the conventional pork supply chain for biodiversity damage potential, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, human toxicity potential and soil carbon loss. That pesticides are not used in the organic pork supply chain resulted in slightly lower impacts for freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity and human toxicity potential, but copper, nickel, chrome and zinc emissions from mining contributed the most to these impact categories. Copper contributed the most impact amongst these metals and it was used in generation and transmission of electricity. The assessment of ecotoxicity impacts from metals are associated with large uncertainties depending on the method used (Pizzol et al., 2011) and the results should be interpreted with caution.

The organic pork supply chain had lower biodiversity losses than the conventional because of differences in the characterization factors between conventional and organic systems in the model by Knudsen et al. (2017) for 1 000 kg pork. Organic farming systems have lower values for characterization factors indicating higher species richness compared to conventional farming systems (Knudsen et al., 2017). The results conflict with those from another model by Chaudhary and Brook (2018) because the model by Chaudhary and Brook (2018) has a lower resolution than that by Knudsen et al. (2017) and does not capture the difference between organic and conventional land use. More research is still required on biodiversity assessments. The organic farming system sequestrated more carbon because of grass-clover leys but without the grass-clover leys the organic pork supply chain had higher soil carbon losses than the conventional one due to lower yields compared to the conventional farming system.

Table 6. Environmental impacts for production of 1 000 kg pork fork weight and 1 000 ha of farmland in the pork supply chains (poorer of the two marked in bold; Zira et al., 2021).

Impact category	Units	Impacts per 1 000 kg pork		Impacts per 1 000 ha farmland	
		Convent.	**Organic**	**Convent.**	**Organic**
Global warming potential 100[1]	kg CO_2 eq	7 100	7 100	**3 900 000**	1 800 000
Freshwater eutrophication	kg P eq	2.7	**3.1**	**1 500**	800
Marine eutrophication	kg N eq	110	**130**	**61 000**	33 000
Terrestrial acidification100	kg SO_2 eq	200	**260**	**110 000**	68 000
Fossil depletion	kg oil eq	1 300	**1 400**	**720 000**	360 000
Biodiversity damage potential	Potential disappeared fraction	**12 000**	9 000	**6 700 000**	2 300 000
Freshwater ecotoxicity	kg 1.4 DCB eq	**85**	80	**47 000**	21 000
Marine ecotoxicity	kg 1.4 DCB eq	**77**	74	**43 000**	19 000
Terrestrial ecotoxicity	kg 1.4 DCB eq	**10**	4.6	**5 500**	1 100
Human toxicity potential	kg 1.4 DCB eq	**2 000**	1 700	**1 100 000**	430 000
Soil carbon loss 100	tonne carbon	**0.29**	0.26	**160**	66

[1] Global warming potential 100 does not include emissions associated with soil carbon losses

5.2.2 Economic assessment

The farm in the conventional pork supply chain had a higher VA/(LCC + labour costs) ratio than in the organic pork supply chain as shown in Table 7. Impacts per 1 000 ha farmland are not shown since they were almost the same as impacts per 1 000 kg pork. Organic pork supply chain had higher input prices and lower production volumes. More value was generated at the wholesale retailer than at the farm in both chains. More value was generated at the conventional farm per SEK invested in LCC + labour costs. Organic farmers created less value because ecosystem services provided by the farm were not considered in this study and that the inputs used by organic farmers were more expensive than those used by conventional farmers.

Table 7. Value added (VA) over life cycle costs (LCC) plus labour costs ratio (expressed in Swedish krona) for 1 000 kg pork fork weight (poorer of the two marked in bold; Zira et al., 2021).

	Impacts per 1 000 kg pork	
Indicator	**Conventional**	**Organic**
VA/(LCC + labour costs), farm	1.1	**0.83**
VA/(LCC + labour costs), slaughterhouse	5.1	**4.9**
VA/(LCC + labour costs), wholesaler and retailer	**13**	27

5.2.3 Social assessment

The organic pork supply chain had lower SRT for all stakeholders except workers and the local community per 1 000 kg (Table 8). The organic pork supply chain per 1 000 ha farmland performed better than the conventional for all the stakeholders and this was due to less economic activity per hectare, i.e. lower inputs except for fuel and lower outputs per hectare than the conventional one.

Table 8. The social risk time for 1 000 kg pork fork weight and 1 000 ha of farmland in the pork supply chains (poorer of the two marked in bold; Zira et al., 2021)

		Impacts per 1 000 kg pork		Impacts per 1 000 ha farmland	
Stake-holder	**Units**	**Conventional**	**Organic**	**Conventional**	**Organic**
Workers	hours	52 000	**56 000**	**29 000 000**	14 000 000
Local community	hours	74 000	**93 000**	**43 000 000**	24 000 000
Value chain actors	hours	**48 000**	31 000	**27 000 000**	8 600 000
Society	hours	**69 000**	46 000	**39 000 000**	12 000 000
Consumer	people days	**44 000**	19 000	**25 000 000**	4 900 000
Pigs	pig life days	**280 000**	130 000	**160 000 000**	32 000 000

By definition, SR in this study increases exponentially as SR can take any value from the listed values 0, 0.01, 0.1, 1, 10 or 100, whereas in paper I, SR increases linearly (scored between 0 and 1). Because of this SRT alone (without SHI) can be used in the assessment of a system in paper II due to that differences in SR make a notable difference in SRT.

5.3 Sustainability assessment for cattle

MonSy performed better than the reference system HolSy for 13 out of 26 indicators and better than ParSy for 12 out of 26 indicators as shown in Figure 7 (from paper III).

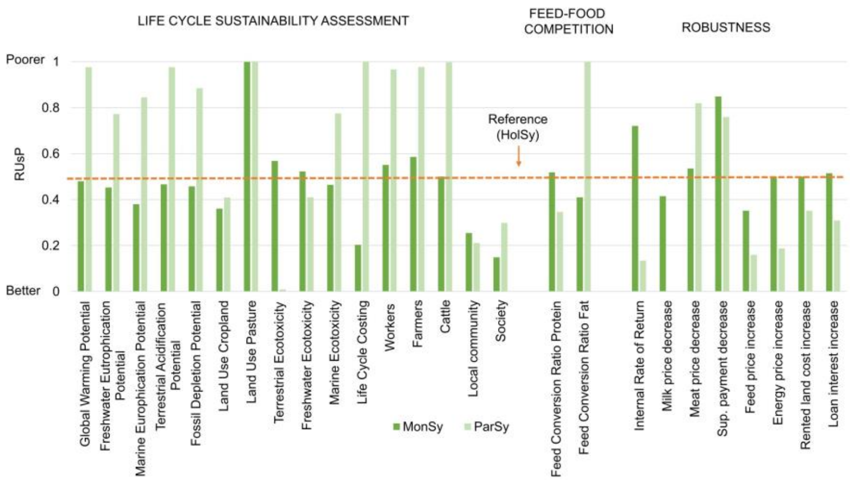

Figure 7. Life cycle sustainability assessment, feed-food competition and robustness in relative unsustainability points with HolSy as the reference (RUsP=0.5, dotted line) using social risk time for risk of negative social impacts (Zira et al., submitted).

5.3.1 Life cycle sustainability assessment

MonSy, the semi-natural pasture based dairy system performed better for most environmental impact indicators and life cycle costs compared to the other cattle systems (see Figure 7 and respective values in Table 9). This was because MonSy produced both milk and beef hence the amount of protein was larger than ParSy, the suckler beef system and also that MonSy used semi-natural pastures for feed hence reducing the amount of fertilizers and pesticides compared to HolSy, the cropland based dairy system. ParSy performed better than other systems for cropland use and terrestrial and freshwater ecotoxicity because it used more feed from semi-natural pastures, used alfalfa in place of soybean and did not use pesticides due to that it was organic. MonSy performed slightly better for cattle compared to HolSy because of good animal welfare, i.e. better thermal comfort due to that the farm was located in highlands and less ketosis, calf mortality and mastitis due to breed characteristics. The smaller size of the farms in the lowlands in Pays de Loire (HolSy) and closeness to each other can make farmers feel less isolated. Less isolation and less dependence on support payments contributed to the better performance for farmers by HolSy compared to the other systems. ParSy performed better for the local community because of the same reasons as ecotoxicity.

Table 9. Life cycle sustainability assessment for 1 000 kg protein at farm gate for the different cattle systems (poorest of the three marked in bold; Zira et al., submitted).

Indicator	Units[1]	HolSy	MonSy	ParSy
Global warming potential 100	kg CO_2 eq	52 000	49 000	**280 000**
Freshwater eutrophication	kg P eq	3.8	3.3	**8.1**
Marine eutrophication	kg N eq	290	200	**780**
Terrestrial acidification 100	kg SO_2 eq	950	860	**5 100**
Fossil depletion	kg oil eq	1 700	1 500	**5 300**
Land use (cropland)	m^2	**79 000**	51 000	60 000
Land use (semi-natural pasture)	m^2	1 600	18 000	**420 000**
Terrestrial ecotoxicity	kg 1.4 DCB eq	190	**230**	2.4
Freshwater ecotoxicity	kg 1.4 DCB eq	46	**49**	35
Marine ecotoxicity	kg 1.4 DCB eq	20	18	**43**
LCC	€/1 000 kg protein	490	160	**6 300**
Workers	SRT, hours (SHI)	45 (0.50)	52 (0.52)	**220** (**0.61**)
Farmers	SRT, hours (SHI)	48 (0.36)	61 (0.39)	**260** (**0.41**)
Cattle	SRT, cattle life days (SHI)	1 500 (**0.52**)	1 500 (0.50)	**13 000** (0.40)
Local community	SRT, people hectare days (SHI)	**260 000** (0.44)	110 000 (**0.50**)	89 000 (0.31)
Society	SRT, people hectare days (SHI)	**4 300 000** (0.34)	1 000 000 (0.32)	2 200 000 (**0.44**)

[1] SRT = social risk time and SHI = social hotspot index (SHI within parenthesis)

5.3.2 Feed-food competition

ParSy performed better for feed-food competition for protein and MonSy performed better for feed-food competition for fat (Figure 7). All systems had human edible protein FCR larger than 1 (Table 10) which indicates that they used more protein in the feed than they produced in the food product (milk and or meat). Dairy systems had human edible fat FCR below 1 indicating that they were net producers of human edible fat because of higher total amount of fat in milk and meat. Even a high use of semi-natural pastures resulted in feed-food competition for protein (but not for fat production in the dairy systems).

Table 10. Feed-food competition for the different systems (poorest of the three marked in bold; Zira et al., submitted).

Indicator	Units	HolSy	MonSy	ParSy
Food conversion ratio protein	kg human edible protein in feed/kg human edible protein in milk and or meat	1.8	**1.9**	1.1
Food conversion ratio fat	kg human edible fat in feed/kg human edible fat in milk and or meat	0.25	0.19	**2.1**

5.3.3 Robustness

ParSy performed better when compared to the other systems for most of the robustness indicators (Figure 7 and Table 11 for the NPV changes and IRR). The low initial investment costs and large support payments because of nature conservation, resulted in ParSy having the highest internal rate of return. This indicates that the ParSy farm had higher returns on invested capital and was more economically viable than HolSy and MonSy farms. The increase in interest rate has a higher effect on farm robustness than other costs increases.

Table 11. Robustness to economic shocks for the cattle systems, internal rate of return per farm and net present value in thousand euros per farm (poorest of the three marked in bold; Zira et al., submitted).

	HolSy	MonSy	ParSy
IRR	3.3%	**1.7%**	9.0%
NPV without changes	201	**51**	266
Change with interest on loans increasing by…			
… 1%	-45	**-47**	-24
… 3%	-125	**-129**	-67
… 5%	-193	**-200**	-104
Change with a 5% decrease …			
… in producer price of milk	**-190**	-147	
… in producer price of meat and cattle	-19	-21	**-47**
…in support (incl. coupled animal) payments	-18	**-49**	-37
Change with a 5% increase …			
… in feed prices (incl. concentrates)	**-32**	-20	-8
… in energy prices (fuel & electricity)	**-10**	**-10**	-3
… in rent of leased land	**-8**	**-8**	-5

5.4 One Health framework

The future pig production scenario with sustainable feed and pigs selected with the old breeding goal (SusFeed-old) performed better than the reference case on nine out of 13 success metrics, while the scenario with sustainable feed and pigs selected with the new breeding goal (SusFeed-new) performed better on 11 (Figure 8 from paper IV). The scenario where pigs were also allowed access to pasture, i.e. with sustainable feed and pigs selected with the new breeding goal and with access to pasture (SusFeedPig), performed less well, with eight out of 13 success metrics with a better score than the reference case.

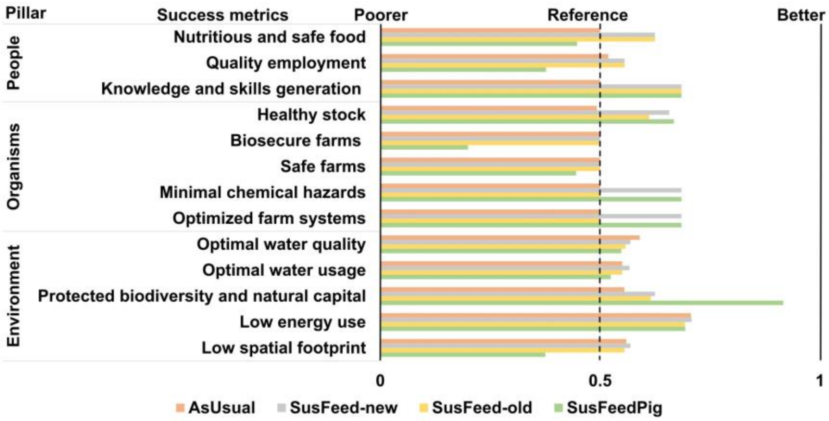

Figure 8. The One Health framework results for future scenarios (2040), presented in relative sustainability points (RSP[1]). The reference is the current production system (2019/20).

5.4.1 People

SusFeedPig performed poorly compared to the reference case and other scenarios for nutritious and safe food because outdoor pigs had higher risks of becoming infected by food-borne pathogens such as *Salmonella* species. SusFeedPig also performed poorly for quality employment compared to the reference case and other scenarios because more labour was required for outdoor work e.g. shifting fences on pasture and more time was spent outdoors which is problematic in extreme weather, e.g. high sun exposure or heavy rainfall. Working outdoors can also be pleasant, but here the experts that we consulted made the judgement that overall the negative sides of outdoor work dominates for workers. SusFeedPig also had challenges for people related to monitoring animals in the outdoor environment, higher risk of musculoskeletal disorders due to heavy work and higher risk of attack by aggressive sows when compared to the reference case and the other scenarios.

[1] Note that RSP in paper II has the same meaning as RUsP in paper III and higher points indicates more unsustainable, whereas higher RSP in paper IV indicates more sustainable

5.4.2 Organisms

SusFeed-new and SusFeedPig performed better for healthy stock, minimal chemical hazards and optimized farms because there was lesser antibiotic usage and improvement in animal welfare when compared to the reference case and other scenarios with the old breeding goal. For healthy stock, both SusFeed scenarios and SusFeedPig performed better than AsUsual and the reference case because of enrichment material and a veranda. SusFeedPig had better welfare for pigs than the reference case and other scenarios as pigs were kept on pasture during summer. Having pigs outdoor lowered the risk of LA-MRSA in SusFeedPig, because LA-MRSA proliferates inside the pig houses. However, outdoor access to pigs had a downside in that pigs in SusFeedPig had higher risk of African swine fever than the reference case and other scenarios because of possible contact with wild animals such as wild boars which could host the African swine fever virus.

5.4.3 Environment

SusFeedPig performed poorly for optimal water quality because it had high marine eutrophication which was created by ammonia production from manure from pigs on pasture. Leaching from the production of on-farm protein feeds also contributed because the quantities of faba beans and peas required in SusFeedPig were greater than those in AsUsual and Reference case due to the absence of by-products from the agri-food industry in SusFeedPig. We assumed that the availability of by-products was limited by competing demand for such resources in the future scenarios except for the AsUsual scenario and the reference case. By-products were assumed to have no environmental impacts, i.e. all impacts were allocated to the main product. The non-use of by-products in SusFeedPig also resulted in the poor performance for optimal water quality as well as optimal water usage. SusFeed performed better for protected biodiversity because of higher species richness due to less use of annual crops in feed than the reference case and other scenarios. SusFeedPig performed better than the reference case and other scenarios for natural capital because of low soil carbon loss created by carbon sequestration associated with grass-clover cultivation. SusFeedPig performed poorly for spatial footprint because on top of land for feed crops, land was also used for pastures.

The benefits of the breeding goal were seen by comparing SusFeed-old and SusFeed-new. The new breeding goal improved healthy stock, minimum chemical hazards, optimum water usage, optimum farm systems, optimum water quality, and low spatial footprint as feed efficiency, disease resistance and mortality of the pigs were genetically improved. The benefits of the sustainable feed sources and outdoor access in the form of a veranda were seen by comparing AsUsual and SusFeed-old. The sustainable feed sources and veranda improved nutritious and safe food, knowledge skills and generation, healthy stock, and protected biodiversity and natural capital as silage improved pig welfare without having to expose the pigs to diseases on pasture. The benefits of pigs on pasture were seen by comparing SusFeed-new and SusFeedPig. Pasture improved protected biodiversity and natural capital as more carbon was sequestrated by having the grass-clover cultivation.

6. Discussion

6.1 Indicators

The inclusion of many indicators in the sustainability assessment methods is important because it makes it possible to identify trade-offs, but indicator selection, number and type of indicators, combining the indicators and scoring presents a set of challenges and needs to be carefully considered.

6.1.1 Indicator selection

The gathering of social sustainability issues from both literature and experts for a livestock production system can improve assessment because it leads to the selection of relevant sustainability indicators affecting the studied production system. Even if all identified indicators cannot be used due to lack of data, all of them can be presented in order to increase transparency. Hopefully researchers will find the data needed for these indicators when performing future assessments. The use of Soca (Greendelta, 2017), a predesigned database assessing risk of negative social impacts in paper II, was quicker and simpler but indicators were fewer than in paper I, indicators were at a high level and indicators for specific pig systems were missing. The choice of indicators influences the result of the evaluation and even when using a predesigned database, relevant indicators must be chosen by the researchers. It is more difficult to evaluate the indicators in a predesigned database than in your own literature search or your workshop with experts. This could make results from social impact assessing databases i.e. those assessing risk of negative social impact less accurate. The new S-LCA guidelines (UNEP, 2020) now encourage selection of indicators based on materiality assessment i.e. an engagement with stakeholders to find out how important are specific issues to them, as we did for paper I. Several indicators were added and deleted from the ones identified in the literature search as a result of our workshop. Since it is not feasible to work with all stakeholders, it should be kept in mind that the selection of individual stakeholders (and experts) may matter for the final list of issues. Accordingly, the background of participators should be presented. The S-LCA that we performed in paper I (using indicators from literature and experts) and in paper II (using indicators from the predesigned database Soca) can be compared for workers, local community and society since these stakeholders were included in Soca and the two S-LCA were performed on the same production systems. Using 1 000 kg pork as the functional unit, the results for the two sources of indicators were similar for pigs and consumers (for which Soca was not used), but not for workers, local community and society. The results differed because of that in paper I, the indicators were specific to pork production whereas in paper II they were at a higher level, i.e. agricultural level. The indicators in paper II omitted work-related health indicators specific to pork production (e.g. musculoskeletal disorders), direct pesticide toxicity in soybean production and access to the pork through on-farm stores for people in the local community. In addition, the activity variables differed for local community and society. In paper II, the activity variable was work hours for all stakeholders, but in paper I it was people hectare days for local community and society. The use of people hectare days caused a high SRT in the organic pork supply chain in paper I. In other words, there was a change from a smaller activity variable based on work hours in paper II to a larger activity variable based on area of land in paper I. It seems more relevant to use people hectare days because the risk of negative social impact for local community and society is more influenced by the hectares of land used than the work hours used for crop production or animal production for example.

The production systems being studied also matters for the choice of relevant indicators. For example, when comparing conventional to organic systems, there is a need to include indicators such as terrestrial and freshwater ecotoxicity and soil carbon for a fair comparison (van der Werf et al., 2020). We did include ecotoxicity in paper II and III, but soil carbon was only included in paper II. Soil carbon would have been interesting also in paper III, but it was difficult to find data for the studied systems. However, paper III compares systems with different land use rather than conventional and organic systems.

6.1.2 Number and type of indicators, and trade-offs

E-LCA in LCSA for livestock production system can include a wide range of impact categories (paper II) even though the European platform on life cycle assessment recommends the inclusion of as few as at least three impact categories (Mcclelland et al., 2018). Noya et al. (2017) and Reckmann et al. (2012) recommend at least six impact categories for pigs, i.e. GWP100, TAP, FEP, MEP, water depletion and FDP on the basis that these are the most important. Additional inclusion of FET, MET, HTP and TET helps to assess the impacts of pesticide use, the use of BDP helps to assess the impact on biodiversity and use of SCL helps to assess the impact on soil carbon. By only using the six indicators recommended by Noya et al. (2017) and Reckmann et al. (2012) in paper II we would have missed important trade-offs of intensification, i.e. between reactive nitrogen associated impacts (eutrophication and acidification) and biodiversity loss and between toxicity impacts (ecotoxicity and human toxicity) and biodiversity loss. The trade-off between fossil depletion and ecotoxicity impacts, i.e. mechanical versus chemical weed control, would also be missed.

Trade-offs also exist between the pillars as shown by the following examples. Access to outdoor environment improves the pig's freedom of movement and people in local communities can see pigs on pasture, but it increases risk of diseases such as toxoplasmosis (Kijlstra et al., 2004) and economic costs for fencing as well as environmental impacts such as MEP per kg of pork. In general, solid manure has more ammonia emission but less methane emissions due to better aerobic conditions (Berglund et al., 2013). Deep straw beds improve welfare for sows, but solid manure from deep straw has a high methane conversion factor (17%) compared with 3.5% for liquid manure (Swedish Environmental Agency, 2021). Improving animal welfare can increase environmental and economic costs of meat and this is in line with Rossi and Garner (2014) and Appleby (2005). In paper III, using semi-natural pastures lowers feed costs and environmental impacts of concentrate feed production in dairy cattle systems but increases the dependence of farm profitability on support payments. Producing both meat and milk in the same system has lower environmental effects on most indicators, but farmers are more economically vulnerable to economic losses due to changes in interest rates, input prices and output prices, compared to producing beef only. Having few indicators may make it hard to see such trade-offs between indicators, trade-offs from new inventions in livestock systems and what the real problem is, in the big picture.

Economic sustainability assessments for livestock production systems using life cycle costing can have profitability indicators e.g. value added over life cycle costs plus labour costs as in paper II and net present value, internal rate of return as in paper III rather than focusing on life cycle costs alone. Profitability indicators and life cycle costs complement one another. The performance of a livestock farm does not depend on costs alone but on profits as well.

6.1.3 Combining life cycle assessments with other indicators

Sustainability assessments can combine LCSA with other indicators connected to sustainability such as robustness and feed-food competition. Resilience frameworks for farming systems that can assess robustness have been proposed, but few have been used to assess robustness (Röös et al., 2021). Agricultural output indicators that have a link with shocks can be used to assess robustness. Economic robustness of European farming systems is an important issue especially looking at the impact of the COVID-19 pandemic and the invasion of Ukraine by Russia that has taught the world that sharp increases in oil, gas and grain prices can occur and even increases in interest rates.

LCA measures efficiency and fails to capture feed-food competition. Feed-food competition is a cross cutting issue for all the sustainability pillars i.e. it is an economic issue, an environmental issue and a social issue. For example, is having cattle production systems in Europe such as HolSy (paper III) with human edible protein feed conversion ratio approximately equal to 2, the best way to use resources (economically, environmentally and socially) when people usually supplied grain by Ukraine are faced with hunger? Different approaches i.e. food allocation factors in LCA, human edible feed conversion and land use ratio have been used to account for feed-food competition but they all have limitations and a food system approach seems to be the best way forward (van Zanten et al., 2019). Future studies could explore combining LCSA with food system indicators.

6.1.4 Scoring

For S-LCA in paper I, we used the average European social conditions for all humans (or pigs) as the reference, i.e. the benchmark against which we compared the systems under study, but this may not be the best. We chose European production as a reference because of data availability and of Europe's advantages in a global perspective but there are still challenges (ATF, 2019), i.e. animals still die on their way to the slaughterhouse in Europe (Voslarova et al., 2017). Preferably, some more 'absolute' state of social sustainability should be used, however such are difficult to establish for many indicators. The reference could be set depending on the strategic choice of the decision makers. They could for example choose to place more emphasis on animal welfare and use 'no mortality during transport' as a goal and a reference.

Another way of improving the S-LCA can be to use reference values that have been agreed to by the involved stakeholders in advance, e.g. having animal care takers agreeing on the performance reference for work hours per day for workers.

When using a goal as a reference, such as maximum number of work accidents per year, it can be discussed whether any accident is acceptable at all. This is an ethical question, but using zero as a reference in our calculations would make it impossible to calculate with division. Other ways that avoid dividing, such as subtraction from the reference, could be used in future studies.

In paper IV, we used performance scoring for the One Health framework instead of policy and legislation as done by Stentiford et al. (2020). For performance assessments, using a performance scoring system can be recommended in place of policy and legislation scoring but the scoring method depends on the purpose of the research. This means that policy and legislation could be used e.g. if the purpose is for policy development. The One Health framework may need some revisions for the success metrics called optimized farm systems, biosecure farms, safe farms and minimum chemical hazard. Optimized farm systems is now under organisms but could be moved to environment, and biosecure farms, safe farms and minimal chemical hazard are now under organisms but could be moved to people in order to avoid the risk of the animals' situation being overshadowed by indicators that have more to do with the environment and people than the animals.

6.2 The functional unit

The relevance of results based on different functional units (mass or area) depends on the perspective of sustainability. The linking of negative impacts to the functional unit and how results are to be used needs to be considered when selecting the functional unit.

6.2.1 Functional unit and interpretation of results

In LCSA, more than one functional unit can be adopted. The use of more than one functional unit is also proposed by Salou et al. (2017) for agricultural LCA. The organic pork supply chain outperformed the conventional one for 18 of the 20 indicators in paper II when the results were expressed per unit area. Organic systems have lower inputs, for example fertilizers and fuels per area unit and usually have lower impacts per unit area than conventional systems (Meier et al., 2015; Tuomisto et al., 2012). When the units were expressed per unit product in paper II, the organic pork supply chain outperformed the conventional one for 11 out of 20 indicators. For LCSA in paper III, Figure 9 shows the results per 1 000 kg and Figure 10 shows results per 1 000 ha. When changing from 1 000 kg to 1 000 ha, all LCSA results become better for MonSy and ParSy compared to HolSy because of lower land use in HolSy. We presented only Figure 9 in paper III (in order to reduce the length of the article) but that can be questioned.

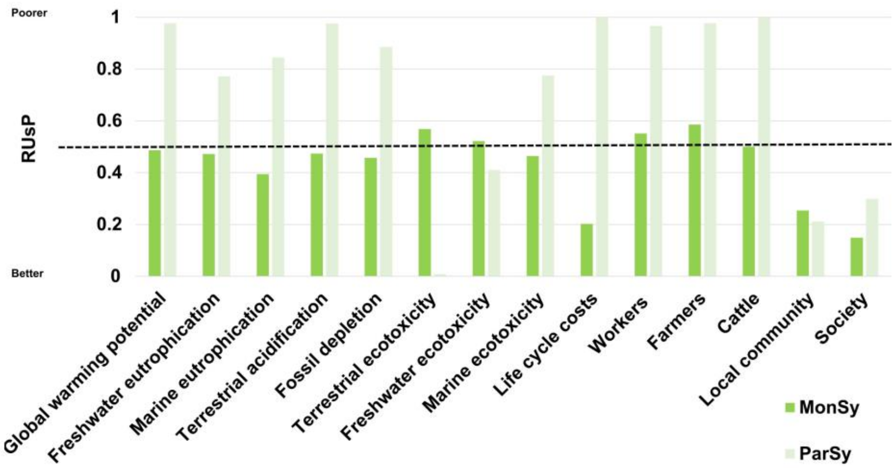

Figure 9. Life cycle sustainability assessment per 1 000 kg protein. RUsP=0.5 (dotted line) is the reference.

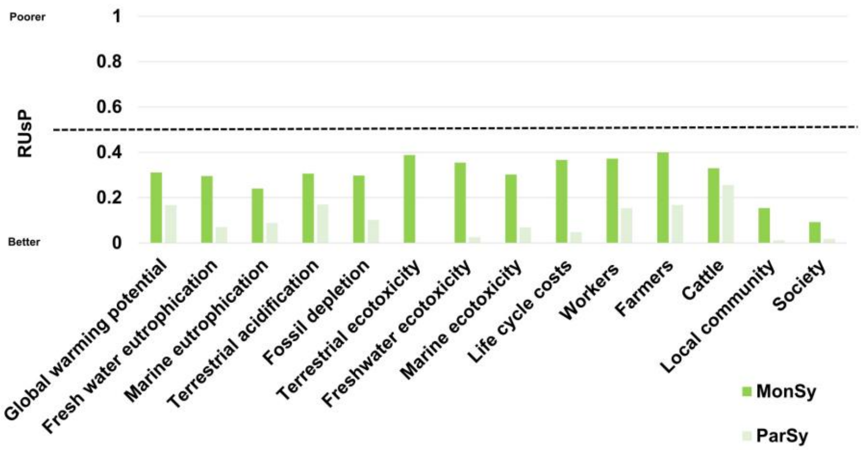

Figure 10. Life cycle sustainability assessment per 1 000 ha. RUsP=0.5 (dotted line) is the reference.

In our LCSA of pig production (paper II) the two functional units (1 000 kg of pork and 1 000 ha of farmland) gave different results; organic chain clearly outperformed conventional chain when impacts were compared based on area while organic chain only slightly outperformed the conventional chain when the impacts were compared based on product based units. The relevance of the results based on different functional units (mass or area) depends on the perspective of food system sustainability. For example, Garnett (2014) differentiate between the efficiency and the demand-restraint (or the sufficiency) perspectives. Using the product (e.g. mass) as a functional unit fits the efficiency perspective where the production of more with less is the focus. For those adhering to the sufficiency perspective, total impacts can (and should be) moderated through lowered consumption which makes reducing impacts per kg less important. Rather use of land in ways that reduces per ha impacts is more central and then consumption volumes will have to adjust (through e.g. consumption side policy) to the amounts that can be produced from that land. For many environmental impact categories, including eutrophication and acidification, emissions per hectare are a better proxy for impacts since these impacts are heavily influenced by the receiving recipient i.e. size of land (Muller and Schader, 2017). Hence, exclusive consideration of per kg impacts in decision making might favour production systems that increase point pollution.

Using mass based functional units have faced criticism because they result in unfair comparisons. For example, 1 kg plant protein is not equivalent to 1 kg animal protein in terms of function in the human body (Lim et al., 2021). The mass based functional unit focusing on a specific product (such as meat) has also faced criticism because livestock systems perform other functions than food production or produce other common goods. For example, grass-based systems preserve and enhance biodiversity when semi-natural pastures are used with low grazing intensity (Bengtsson et al., 2019) and allocation of impacts to common goods such as preservation and enhancement of biodiversity as recommended by Bragaglio et al. (2018) could be done in future studies.

Interpretation of social results

The choice of using SRT or SHI in LCSA when presenting the RSP or RUsP may affect the results in LCSA, when the activity variables differ between systems. We chose to use SRT in paper III, i.e. taking time into consideration, but SHI can be used when there is no need to take time into consideration. Figure 11 shows the results when using SRT and Figure 12 shows the results when using SHI. Changing from SRT to SHI indicates that results for farmers, workers and cattle, were not different but there were differences for the local community and society. The large differences in RUsP (SRT) and RUsP (SHI) results for the local community and society were due to the large differences in SHI values between the reference system and the other two systems for the local community and society compared to other stakeholders.

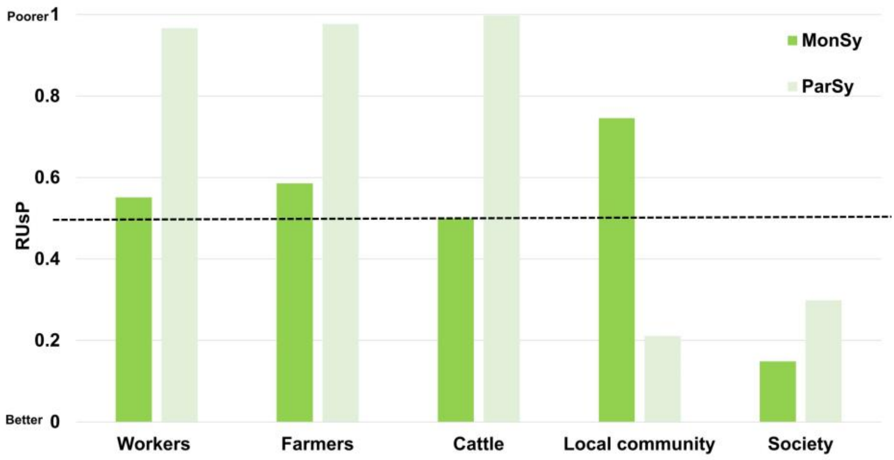

Figure 11. Social life cycle assessment in relative unsustainability points (RUsP) using social risk time (SRT) for describing risk of negative social impacts.

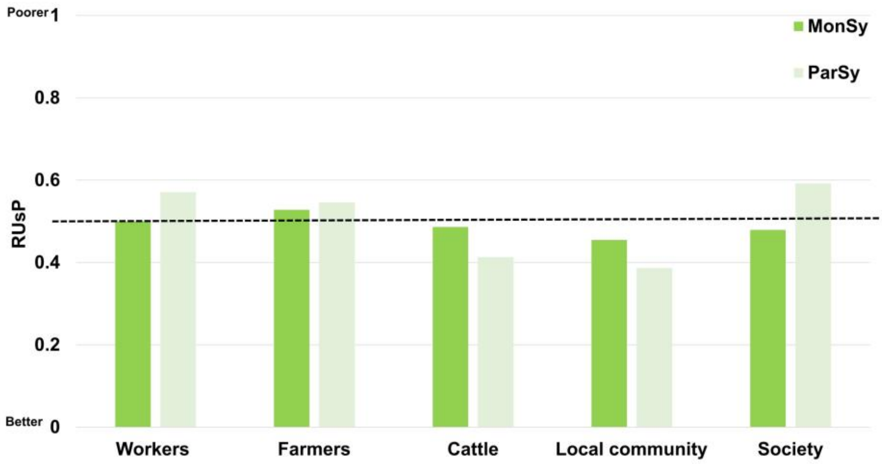

Figure 12. Social life cycle assessment in relative unsustainability points (RUsP) using social hotspot index (SHI) for describing risk of negative social impacts.

6.2.2 Linking risk of negative social impacts to a functional unit

In S-LCA, the risk of negative social impacts can be linked to a functional unit as in paper I and III and this needs to be considered when selecting a functional unit. One of the barriers to development of LCSA has been linking the environmental, economic and social aspects to the same functional unit (Lin et al., 2020; Klöepffer, 2008). Activity variables such as work hours for workers can be used to connect the production of important inputs (e.g. wheat) to the functional unit. For livestock, the animal life days can be easily connected to the functional unit. We used hours for workers and days for animals because production time for worker is usually expressed in hours/week and production time for animals is usually expressed in days. However, connecting the results to the functional unit is challenging for stakeholders such as the local community and society. Soca uses work hours for all stakeholders including local community and society but we used people hectare days as an activity variable in paper I and III, hence including the number of people per hectare where the farms are located multiplied by the number of hectares used in the livestock production system and the duration of the production process in days. People hectare days may seem abstract, but it shows the people affected, the acreage and time between sowing and harvesting and this varies between systems based on population density where the systems are located, yield and growing period of kind of crops used. However, not everything could be connected to functional units. For example, economic robustness, we had to use farm level indicators so that the result would be understandable.

6.3 Animals in livestock sustainability assessment methods

Animal welfare is increasingly being regarded as an aspect of importance in social life cycle assessment (Tallentire et al., 2019; Llonch et al., 2015; Neugebauer et al., 2014). In S-LCA, animals can be presented as stakeholders as in paper I for studies involving livestock production systems. Animals have a certain intrinsic value even if they are used by humans and they need to be taken care of for their own sake, not just for the sake of humans such as consumers (Singer, 1987). Two previous S-LCA studies have included animal welfare aspects (Pelletier, 2018; Revéret et al., 2015), but their focus was on animal caretakers, not the animals themselves. Concerns about animals and their welfare were the basis of the study by Tallentire et al. (2019). The revised guidelines have “Ethical treatment of animals” as a subcategory under *society* (UNEP, 2020) but the inclusion of animals as a stakeholder enhances sustainability assessment in livestock production systems. The One Health framework recognizes animals’ intrinsic value and highlights, one health for all animals, all people and the environment.

6.4 Farmers in livestock sustainability assessment methods

In S-LCA, farmers can be presented as a separate stakeholder and not as part of the workers because family farms with both the farmers and hired workers are common in Europe. Previous S-LCA studies have used workers but aspects that are relevant can differ between these workers and farmers, e.g. forced labour is usually not an issue for farmers but can be an issue for soybean farm workers, as in paper III. The use of both farmers and workers avoided the shifting of impacts from workers to farmers. Farmers are now considered under “smallholders including farmers” within the “Worker” stakeholder in the revised guidelines (UNEP, 2020) but having them as stakeholders could be encouraged because aggregation could mask results for farmers in LCSA.

6.5 Breeding and sustainability assessments methods

Breeding can reduce impacts by improving feed efficiency as shown in paper IV. For example, global warming potential was reduced by 6% with the new breeding goal as compared to the current breeding goal. At the same time, the new breeding goal improved several traits important for animal welfare. Breeding could, indeed, improve major social issues such as high piglet mortality which cannot be addressed by other methods such as labelling (Sørensen and Schrader, 2019). There are, however, goal conflicts within the breeding goal caused by genetic correlations. The genetic correlation between litter size and piglet mortality is one example of an unfavourable correlation. We estimated the litter size to be 16.7 piglets with the current and 15.1 piglets with the new breeding goal. Considering the number of teats per sow, 15 piglets may be manageable without much use of nursery sows. The current breeding goal increases piglet mortality and in the new breeding goal, small progress was made in reducing piglet mortality, resulting in almost 17% piglet mortality in 2040. The last 20 years have also seen the same challenge in the reduction of piglet mortality (Turner et al., 2018) and more needs to be done to reduce pig mortality.

Although breeding can improve growth rate, improving the animal's environment, e.g. providing large quantities of straw at farrowing, can increase weight gain in piglets and also prevent bruising (Westin et al., 2014). Even though pigs selected with the current breeding goal had a larger litter size than those selected with the new breeding goal, pigs selected with the new breeding goal had lower impacts than those selected with the current breeding goal. This was because of the combination of lower piglet mortality, higher growth rate, higher feed efficiency and higher sow longevity (leading to lower sow replacement rate) with the new breeding goal. This is in agreement with Ali et al. (2018) who states that improved production traits (e.g. growth rate) reduced green-house gases emissions and excretions of N and P more than increase in sow efficiency traits. We calculated a growth rate of 1090 g/day and both the litter size and growth rate were in the same range as the estimates in 2050 used by Lassaletta et al. (2019) in a study on future pig production. Our new breeding goal is rather conventional and in the future additional traits important for animal welfare should be considered, for example reduced tail biting. However, the cost of recording new behavioural traits such as tail biting may be an impediment to improvements through breeding.

LCSA can be used in animal breeding by assessing the environmental, economic and social effects of simulated genetic improvements before a new breeding goal is introduced. This can be done in the same way in which E-LCA has been used in the evaluation of the change of environmental impacts before and after genetic change of traits for oats (McDevitt and Mila i Canals, 2011), dairy cattle (van Middelaar et al., 2014), and pigs (Ottosen et al., 2020; Ali et al., 2018). Another way in which LCSA can be used is deriving weights of changing one trait and keeping the other traits in the breeding goal constant. The weights can be used in breeding goals to maximize the reduction of the impacts as done by Besson et al. (2020) for environmental and economic weights for fish. However, it may be difficult to monetize all traits, i.e. calculating economic costs and incomes for all traits. Shoulder ulcers, for example, decrease animal welfare (and thus high social costs) but has almost no economic costs. Having economic, environmental and social weights for traits means working with three different breeding values, i.e. economic, environmental and social breeding values at the same time. Therefore, using LCSA to assess the effects of genetic improvements could be a better option as in Figure 13. LCSA could be used in the breeding program as indicated by the green boxes. LCSA could also be a useful sustainability assessment method to assess the effects of new technologies before they are introduced, such as gene editing (gene editing has not yet been applied in livestock breeding programs).

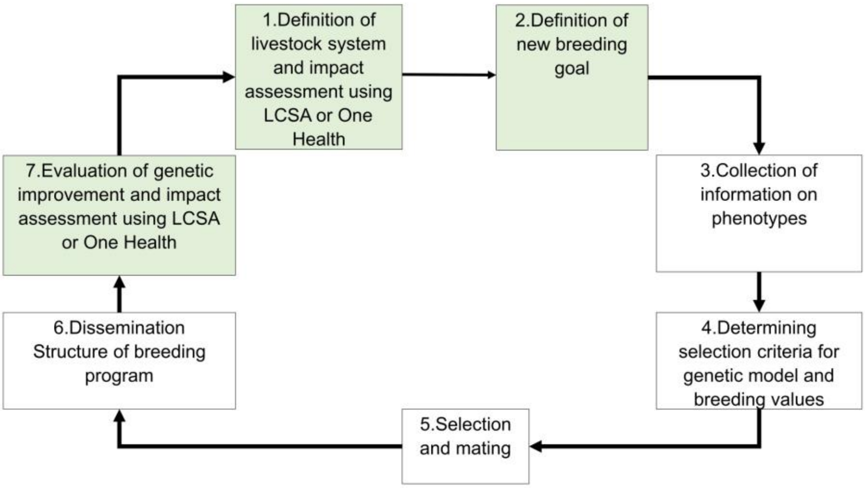

Figure 13. Sustainable future livestock systems: Defining a production system and making initial impact assessment, defining a breeding goal, and the evaluation (based on an illustration by Oldenbroek & van der Waaij, 2014).

6.6 Feeding

Animal feeding can be developed together with animal breeding. The use of by-products can reduce social, environmental and economic impacts. However, competition for by-products for other uses and the influence of the main product on the availability of by-products (van Zanten et al., 2018; Röös et al., 2016) may create challenges. Adjustments of the pig populations so that they commensurate the availability of by-products could be possible (van Zanten et al., 2018), but matching livestock production based on by-products and consumption of livestock products in high income countries may be challenging given the existence of barriers to the reduction in consumption of livestock products (Kwasny et al., 2022).

An increase in crop yields, especially wheat and barley yields, without increase in inputs such as fertilizer may reduce environmental, social and economic impacts in livestock supply chains.

Soybean from South America certified against social and environmental production standards may reduce social and environmental impacts, as well as replacement of soybean by local protein sources.

Yeast protein produced on waste from forestry is a promising local protein source because it does not compete directly with food production in terms of land use (Karlsson et al., 2021). However, the production of yeast depends on the availability of forest biomass waste, forest biomass increment, and the utilization and demand for stem wood, which is the main forest product. The production of yeast will also be affected by competition from alternative uses for lignocellulosic biomass in forest waste in the renewable energy industry e.g. Fisher Tropsch biodiesel. The production of yeast still causes a high climate impact because it requires use of inorganic nitrogen. However, the climate impact can be reduced by 27.5% when organic nitrogen from chicken offal and blood is used in place of inorganic nitrogen (Møller and Modahl, 2020). The positive health effects of yeast (Cruz et al., 2019) could also help facilitate the introduction of this protein source in the future. Silage is another alternative protein source that can be used for pigs because of its positive health benefits to pigs (Presto et al., 2013). The use of silage for pigs can reduce environmental impacts such as global warming potential and land use by reducing grain requirements, as shown in paper IV but particle size of the silage and way of feeding (total mixed ration or as a separate feed) influences the capacity of pigs to consume silage (Friman et al., 2021; Presto et al., 2018).

The use of renewable energy such as Fisher Tropsch and electricity from solar energy in the production of crops can reduce the environmental impacts of feed production.

The use of semi-natural pastures for dairy cattle systems for grazing cattle can preserve biodiversity (Bengtsson et al., 2019), reduce the cost of feed, and reduce most environmental impacts.

In grassland based cattle systems, high quality silage could replace grains and reduce land use for cropland whilst keeping greenhouse gas emissions constant because of lower methane emission from enteric fermentation compared to grass (Åby et al., 2016). This may be more relevant for MonSy and ParSy which have limited areas suitable for crop production.

6.7 Challenges

Data collection for S-LCA is the most time consuming step in LCSA. It is a challenge to find data for reference points as well as performance indicator data. In this thesis, there were many simplifications due to missing data especially indicator data. Obtaining data for life cycle costing is also a challenge because of confidentiality stemming from competition amongst value chain players. This makes LCSA a daunting task if not herculean requiring immense time. Trying to assess future livestock systems based on forecasts using scant current and historic data is also difficult.

LCA is affected by data uncertainty. The use of the S-LCA and LCSA results for decision making can be affected by the uncertainty. Local sensitivity analysis i.e. using one at a time approach as in paper II or having several scenarios as in paper IV are ways to handle uncertainty.

The inclusion of many indicators and aspects in one study may make results difficult to interpret, but can also help us to see what is more or less important.

6.8 Practical recommendations

The application of LCSA and the One Health framework as decision support methods is important for designing and evaluating more sustainable food production in the future. Sustainability assessment methods can be adapted to aid decision making in the development of new livestock production systems and new breeding goals. Understanding the whole system and also all the three pillars of sustainability is the first step in the challenge of creating sustainable livestock systems in the 21st century. Sustainability assessment methods offer a possibility to identify hotspots and therefore determine which parts of the livestock system require re-designing. Sustainability assessment methods also offer a possibility to monitor improvements (and unfavourable trends) over time.

In new breeding goals, sustainability assessment methods can be applied when designing breeding programs. Breeders, nutritionists, farmers' organizations, sustainability analysts, policy makers and consumer organizations need to work together to avoid shifting burdens from one stage of the production chain to another.

6.9 Future research

In this thesis, proxy data at regional level or country level from general databases or secondary studies were used but it would be valuable in future research to collect primary data at farm level, especially for human and animal welfare indicators. It would be also interesting to perform materiality analysis, i.e. identification and prioritization of the issues that are most important, using the stakeholders themselves, e.g. workers, even for weighting of subcategories. We used so called S-LCA Type I, which is an assessment of *risk of* negative impacts but the actual social impacts on humans and animals, i.e. the long term effects equivalent to environmental impacts in E-LCA, also needs to be studied. Di Cesare et al. (2016) did that for exposure of farm workers to pesticides using an impact pathway in a so called S-LCA Type II. Collecting data on long term effects is time consuming and expensive but would be an interesting base for future research. Maybe data collection for S-LCA Type II studies could be affordable if done in cooperation with researchers in e.g. human medicine performing studies on work-related diseases.

Multifunctionality of livestock systems should be taken into account through e.g. economic allocation using willingness to pay to evaluate the economic value of ecosystem services such as plant disease control and soil fertility services provided by leys in pig and cattle systems.

In paper IV, we used SelAction (Rutten et al., 2002), a software program based on the best linear unbiased prediction (BLUP) methodology to predict the multiple traits' response to selection. SelAction is possible to adapt to different breeding programs, but many simplifications are needed to run the program. In the future, outputs from more sophisticated simulation programs built to simulate specific breeding programs for specific animal populations, can be used as input in sustainability assessments. Many breeding programs are now using genomic prediction because it is more accurate than BLUP, and a new software program, ShinySelAction is under development (Dekker et al., 2022) for genomic prediction of multiple traits. The assessment of future livestock systems using genomic prediction could be done with such a simulation program. It would be interesting to have new breeding programs for crops as we did for animals in paper IV, with selection of crops for adaptability to climate change, i.e. drought and disease resistance.

The higher internal rate of return for cropland based dairy compared to grassland based dairy cattle production (paper III) was not anticipated as studies have indicated that grassland based cattle production is more profitable (van den Pol-van Dasselaar et al., 2020; Hanrahan et al., 2018; Florindo et al., 2017). Our result was caused by higher investment costs for the grassland based dairy system than the cropland based dairy system, but more economic data need to be collected and this could be a subject of future research.

Future studies could evaluate the use of these sustainability assessment methods in low input systems in developing countries considering that these countries are more vulnerable to climate change, including robustness against disturbances such as extreme weather is important. In developing countries, animals have multiple functions in addition to food production, such as energy for ploughing and transport, insurance and manure production. To fully reflect the broad role of livestock, there is a need to allocate impacts to all these different functions performed by livestock using allocation factors in the sustainability assessment methods.

7. Conclusions

Sustainability assessment methods can be adapted for pig and cattle production.

S-LCA can be adapted for pig and cattle production systems by gathering relevant social sustainability issues from literature and experts, hence leading to selection of important sustainability indicators rather than using predesigned indicators in social sustainability assessment databases. This increases knowledge on livestock systems impacts.

To be able to make joint assessments of the three pillars of sustainability using a common functional unit is required. S-LCA can be connected to the functional unit using the activity variables for important inputs such as crop production and animal husbandry. To acknowledge the intrinsic value of farm animals, S-LCA can also include animals as stakeholders.

Sustainability assessment can combine LCSA with other indicators that are important for sustainability, e.g. robustness and feed-food competition. E-LCA in LCSA can increase knowledge on livestock systems impacts by including several indicators, including biodiversity and soil carbon loss etc. Life cycle costing in LCSA can increase knowledge about sustainability of livestock systems by using profitability indicators, e.g. net present value and internal rate of return, on top of life cycle costs. Economic viability is central for a sustainable farm and life cycle costing needs to be complemented with internal rate of return since a reasonable return on investment is required for new investments to be made, otherwise farming systems will not be economically sustainable and robust. The One Health framework can be used for assessments of livestock production systems and bring improved health and well-being to people, farmed organisms and the environment.

Trade-offs exists within and between sustainability pillars.

Within the environmental pillar, trade-offs exist between biodiversity and reactive nitrogen associated impacts (eutrophication and acidification), and biodiversity and toxicity impacts. Trade-offs also exist between fossil depletion and ecotoxicity impacts with regards to mechanical versus chemical weed control. Access to the outdoor environment improves the pig's welfare and people in local communities can see pigs on pasture, but outdoor access increases risk of some diseases. Trade-offs also exist between the sustainability pillars. Providing good welfare for pigs can increase costs and environmental impacts. The production of both meat and milk in the same cattle system has lower environmental impacts on most indicators, but dairy farmers are more economically vulnerable to economic losses due to shocks such as changes in interest rates, input prices and output prices, compared to producing beef only. The use of a lot of concentrate in cattle systems make the cattle systems vulnerable to economic shocks.

The choice of indicators and the functional unit influences the results.

The choice of the indicators influences the results and it is important to engage stakeholders in the selection of indicators. Relevant indicators not possible to include in the assessment due to lack of data should be presented for the sake of transparency. The functional unit also influences the results through focus on perspective of sustainability, i.e. efficiency (production with less impact) and sufficiency (changing consumption patterns for less impact). Using the product as a functional unit answers the efficiency perspective and using the farmland answers the sufficiency perspective. Presenting results for more than one functional unit gives a broader base for sustainability discussions.

Challenges and opportunities for sustainability methods exist.

Collection of indicator and reference data for S-LCA is the most time consuming step. Data for some social indicators and economic costs are not available due to confidentiality issues. Data collection makes LCSA challenging to use for future livestock systems because of the complexity of forecasting social indicators and prices in the future, especially when current data on social impacts and prices is not even available. LCSA and One Health framework show the importance of stakeholders working together and sharing data to improve sustainability. LCSA presents opportunities for application in the design of breeding programs to improve sustainability performance.

Organic pork production systems are more sustainable when using an area based functional unit.

Assessed with the functional unit being farmland, the results indicate that an organic pork supply chain has lower impacts for all indicators except for life cycle costs at the farm and the slaughterhouse. The organic pork supply chain has higher eutrophication, acidification and fossil resources use than the conventional pork supply chain per kg product. The conventional pork supply chain has higher ecotoxicity, biodiversity loss, poor pig welfare and negative consumer impacts per kg product. The economic assessments results suggest the presence of inequalities in the distribution of profits amongst actors in the organic supply chain. Both the organic and the conventional Swedish pork chain have lower risk of negative social impacts than the average European social conditions for workers, pigs, local community and consumers but the risk of negative social impacts for the farmers and society is the same as the average European social conditions.

Grassland based dairy has lower environmental impacts on most indicators and is a net fat producer and grassland based suckler beef production is more profitable and resilient to economic shocks.

A grassland based dairy system in highlands in southern Europe has lower environmental impacts for most indicators when compared to the other cattle systems. Dairy systems produce more fat (human edible) in milk and meat than found in feed, i.e. they are net suppliers of fat, but they produce less protein in milk and meat than human edible protein found in feed. A grassland based suckler beef system in highlands in southern Europe has lower terrestrial and freshwater ecotoxicity, higher internal rate of return, lower impacts on the local community and is more resilient to economic losses due to changes in interest rates, input prices and output prices than the other cattle systems. A grassland based suckler beef system produces less protein and fat in meat than human edible protein and fat found in feed, even if it uses semi-natural pastures, but feed-food competition for protein is lower than in dairy systems.

Feeding can lead to more sustainable livestock production.

The use of by-products and increase in wheat and barley yields without an increase in inputs, especially fertilizers, can reduce social, environmental and economic impacts in livestock production systems. Use of silage for pigs, yeast protein and other local protein sources to reduce dependence on soybean imports can reduce environmental and social impacts. The use of Fisher Tropsch biodiesel as fuel in crop production can reduce environmental impacts.

Breeding can lead to more sustainable livestock production.

Animal breeding can reduce negative impacts in all three pillars due to genetic gain. A new breeding goal for pigs in future pig production with higher economic weights on traits important for pig welfare and overall feed efficiency than the current breeding goal can improve sustainability in future pig production.

Use of semi-natural pastures and production of milk and meat can lead to more sustainable cattle production systems.

Cattle systems that use semi-natural pastures and produce both milk and meat have low environmental impacts on most indicators and low feed costs. Cattle systems with high support payment to farm income ratio are more economically robust but high dependence on support payments is a social issue for farmers. The increase in interest rates has a higher effect on farm robustness than other costs increases. Grassland and cropland based dairy systems in highland Europe needs more support payments in times of changes in interest rates, input prices and output prices.

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Popular science summary

Livestock systems produce highly appreciated food but they also have negative effects that threaten the future existence of robust, fair, animal friendly, healthy and environment-friendly livestock production. When animals are fed crops and by-products that humans could eat, they compete with humans for food as the human population grows and agricultural land is a limited resource. Livestock systems affect people, animals and the environment and these effects can be classified as social, economic and environmental. Evaluating these effects is easier said than done and requires the development of methods that provide both a broad and deep analysis. The method needs to go in depth to include the entire production chain including e.g. production of fuels and fertilizers used for feed crop cultivation. The method needs to be broad in order to include different types of social, economic and environmental effects and their interaction. The method also needs to describe the sensitivity of production systems to economic changes. Many methods of sustainability assessment have so far focused on negative environmental effects because they are the easiest to measure. More research is required to develop an integrated assessment of the social, economic and environmental impacts of food production from farmed animals. Such an evaluation should also include the farm's sensitivity to economic changes and competition for arable land for feed or food. The goal of this doctoral project was therefore to further develop such methods that can measure negative effects of production systems for pigs and cattle and to use these methods to increase knowledge about how future sustainable production systems can be developed.

We further developed a method for the evaluation of risk of social impacts (social life cycle analysis), a method for the combined evaluation of social, economic and environmental impacts including competition for arable land for feed or food and the farm's vulnerability to economic changes, as well as a method for evaluating the health effects of the production system on people, animals and the environment. We used these methods to study different production systems. We compared organic and conventional pig production in Sweden, and different future scenarios for pig production. For cattle, we compared milk and meat production systems in southern Europe with different cow breeds and more or less use of pasture and forage.

The results showed that the organic system clearly outperformed the conventional system when the basis of comparison was farmland (hectares used), while the organic system was only slightly better than the conventional when the basis of comparison was the product (pork produced) due to that the production in a conventional system is more efficient.

For cattle, suckler beef production was less sensitive to economic changes, the amount of protein in feed used to produce a kg of protein (in meat) was lower, and profitability higher compared to dairy production systems. The system of milk production that was largely based on pasture and forage had lower costs and lower negative effects on the environment compared to the other production systems. The arable land based milk production system had lower economic sensitivity to changes in agricultural subsidies than the other production systems. Using by-products and increasing yields for wheat and barley without an increase in inputs such as fertilizer and use of renewable energy sources in feed production reduces impacts. Changing the breeding goal for pigs, using alternative protein sources and including silage in pig feed can also reduce the negative effects of future pig production, while improving animal welfare. A major challenge in sustainability assessment is the lack of readily available social and economic data, and this limits the possibility of carrying out a comprehensive and broad sustainability evaluation.

Populärvetenskaplig sammanfattning

Lantbrukets djur producerar värdefulla livsmedel, men de har också negativa effekter som hotar den framtida existensen av robusta, rättvisa, djurvänliga, hälsosamma och miljövänliga produktionssystem. När djuren utfodras med spannmål och soja som människor skulle kunna äta konkurrerar djuren med människor om mat vilket är problematiskt i och med att befolkningen växer och jordbruksmarken är en begränsad resurs. Djurproduktionssystem har sociala, ekonomiska och miljömässiga effekter som påverkar människor, djur och miljö. Att utvärdera dessa effekter är lättare sagt än gjort och kräver utveckling av metoder som möjliggör både en bred och djup analys. Metoden behöver gå på djupet för att få med hela produktionskedjan inklusive t. ex. produktion av drivmedel och konstgödsel som används för foderodling. Metoden behöver vara bred för att få med olika typer av sociala, ekonomiska och miljömässiga effekter och deras samspel. Metoden behöver beskriva produktionssystemens känslighet för ekonomiska förändringar. Många metoder för hållbarhetsanalys har hittills fokuserat på negativa miljöeffekter eftersom de är lättast att mäta. Mer forskning krävdes för att utveckla en samlad utvärdering av sociala, ekonomiska och miljömässiga effekter av livsmedelsproduktion från lantbrukets djur. En sådan utvärdering borde dessutom innehålla gårdens känslighet för ekonomiska förändringar och konkurrens om åkermark till foder eller livsmedel. Målet med detta doktorandprojekt var därför att vidareutveckla metoder som kan mäta negativa effekter av produktionssystem för gris och nötkreatur och att använda dessa metoder för att öka kunskapen om hur framtida hållbara produktionssystem kan utvecklas.

Vi utvecklade en metod vidare för utvärdering av sociala effekter (social livscykelanalys), en metod för samlad utvärdering av sociala, ekonomiska och miljömässiga effekter inklusive konkurrens om åkermark till foder eller livsmedel och gårdens sårbarhet vid ekonomiska förändringar, samt en metod för att utvärdera produktionssystemets hälsoeffekter på människor, djur och miljö. Vi använde dessa metoder för att studera olika produktionssystem. Vi jämförde ekologisk och konventionell grisproduktion i Sverige, och olika framtidsscenarier för grisproduktion. För nötkreatur jämförde vi mjölk- och köttproduktionssystem i södra Europa med olika ko-raser och mer eller mindre användning av bete och grovfoder.

Resultaten visade att det ekologiska systemet klart överträffade det konventionella systemet när jämförelsegrunden var jordbruksmark (använda hektar), medan det ekologiska systemet endast var något bättre än det konventionella när jämförelsegrunden var produkten (kött som produceras) pga. produktionen i ett konventionellt system är effektivare. För nötkreatur var produktionen av kött med dikor mindre känslig för ekonomiska förändringar, konkurrensen foder-livsmedel var lägre för protein, och lönsamheten högre jämfört med mjölkproduktionssystemen. Systemet med mjölkproduktion som till stor del var baserad på bete och grovfoder hade lägre kostnader och lägre negativa effekter på miljön jämfört med de andra produktionssystemen. Systemet med mjölkproduktion baserad på åkermark hade lägre ekonomisk känslighet för förändringar i jordbruksstöd än de andra produktionssystemen. Att använda biprodukter och öka avkastningen för vete och korn utan ökade insatsvaror (t. ex. konstgödsel) och användning av förnybara energikällor i foderproduktion minskar de negativa effekterna. Att förändra avelsmålet för grisar, använda alternativa proteinkällor och inkludera ensilage i grisfodret kan minska de negativa effekterna av framtida grisproduktion, samtidigt som djurvälfärden förbättras. En stor utmaning vid hållbarhetsanalyser är bristen på lättillgängliga sociala och ekonomiska data och det begränsar möjligheten att genomföra en samlad och bred hållbarhetsutvärdering.

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8. Appendix

Calculation of Social Risk Time (SRT) and Social Hotspot Index (SHI)

Table A: Example with calculation of Social Risk Time (SRT) and Social Hotspot Index (SHI) for the conventional *pigs* as a stakeholder

Subsystem	*j*	*Subcategory*	*Inventory indicator, k*	*Activity variable* T_{ij}	*Social Risk*, SR_{ijk}	*Weight,* W_{ijk}	*Social Risk Time* $SRT_{ijk} = T_{ij} * SR_{ijk} * W_{ijk}$	*Worst Social Impact Time* $\widehat{SRT}_{ijk} = T_{ij} * \widehat{SR}_{ij} * W_{ijk}$	*Social Hotspot Index* $SHI_{ij} = \frac{\sum_{k=1}^{K} SR_{ijk}}{\sum_{k=1}^{K} \widehat{SR}_{ijk}}$
Farm	1	Animal friendly housing	1	5 000	0	0.025	0	120	
			2		0	0.025	0	120	
			3		0.58	0.025	72.0	120	
			4		0.65	0.025	81	120	
			5		0.37	0.025	46	120	
			6		0	0.025	0	120	

	1	Possibility to express normal behaviour	7	5 000	0.91	0.052	240	259	
			8		0.25	0.052	65	259	
			9		0	0.052	0	259	
	1	Free from fear, pain and injuries	10	5 000	0.50	0.28	710	1410	
	1	Good animal health	11	5 000	0.45	0.04	90	199	
			12		0.48	0.04	96	199	
			13		0.66	0.04	130	199	
			14		0.06	0.04	12	199	
			15		0.08	0.04	16	199	
			16		0.52	0.04	100	199	
			17		0.40	0.04	80	199	
	1	Tail docking	18	5 000	0	0.069	0	344	
			19		0	0.069	0	344	
									0.35
Slaughte r-house	2	Free from fear, pain and injuries	1	0.50	0.50	0.50	0.13	0.26	
	2	Animal friendly management	2	0.50	0.46	0.50	0.12	0.26	
									0.48

i denotes stakeholder where i=1 in this example, j denotes subsystem where j = 1,2 and k denotes inventory indicators where k = 1, 2,…19 and $T_{i1} = 5000$, $T_{i2} = 0.5$, $T_{it} = T_{i1} + T_{i2} = 5000.5$, $SR_{i21} = 0.5$, $SR_{i22} = 0.46$, $W_{i21} = 0.5$, $W_{i22} = 0.5$ and $\widehat{SR}_{i1} = \widehat{SR}_{i2} = 1$

SHI for subsystem j for stakeholder i: $SHI_{ij} = \frac{\sum_{k=1}^{K} SRT_{ijk}}{\sum_{k=1}^{K} \widehat{SRT}_{ijk}} = \frac{\sum_{k=1}^{K} T_{ij} * SR_{ijk} * W_{ijk}}{\sum_{k=1}^{K} T_{ij} * \widehat{SR}_{ij} * W_{ijk}}$

SHI for subsystem 2 for stakeholder i: $SHI_{i2} = \frac{T_{i2} * (SR_{i21} * W_{i21} + SR_{i22} * W_{i22})}{T_{i2} * (1 * W_{i21} + 1 * W_{i22})} = \frac{(SR_{i21} * W_{i21} + SR_{i22} * W_{i22})}{(W_{i21} + W_{i22})} = \frac{(0.5 * 0.5 + 0.46 * 0.5)}{(0.5 + 0.5)} = 0.48$

Same process for calculating SHI_{i1} = 0.35

Stakeholder i: $SHI_i = \left(SHI_{i1} * \frac{T_{i1}}{T_{it}}\right) + \left(SHI_{i2} * \frac{T_{i2}}{T_{it}}\right)$ = (0.35*5000/5000.5) + (0.48*0.5/5000.5) = **0.35**

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LCA FOR AGRICULTURAL PRACTICES AND BIOBASED INDUCTRIAL PRODUCTS

Social life cycle assessment of Swedish organic and conventional pork production

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Abstract

Purpose Sustainable animal food systems are increasingly important to society. Yet for pork, the most consumed meat product in Europe, there is no social life cycle assessment (S-LCA) in the literature. The breath and complexity of social issues and lack of data makes the task challenging. This study examines the risk of negative social impacts in Swedish pork production systems and includes *workers*, *farmers*, *consumers*, *local community*, *society*, and *pigs* as stakeholders.

Methods The objective was to assess the risk of negative social impacts for the production and consumption of 1000-kg pork (fork weight—bone free meat including cooking losses) originating from two different systems: organic and conventional pork production. Relevant social sustainability issues for pork production systems were identified through a literature search and a consultative workshop with experts. A life cycle inventory was conducted to collect data for activity variables and compute Social Risk (SR), a measure of the risk of negative social impacts related to a reference (here the average European social conditions). Analytical Hierarchical Process (AHP) was used to obtain weights for subcategories. The SR scores and the weights were used to calculate Social Risk Time (SRT) that relates the Social Risk to the functional unit by considering the 'exposure' to the risk, and the Social Hotspot Index (SHI), which relates the SRT to the worst possible situation for that system.

Results and discussion The conventional pork system had 42% of inventory indicators with SR > 0.5 and the organic pork system had 32%. For all stakeholders, the *pig farm* had the largest SRT in both production systems except for *workers* in the organic pork system where the s*oybean farm* had the largest SRT. In the conventional pork system, *society* as well as *farmers* at the *pig farm* had SHI > 0.5 slightly, meaning performing the same as European average. In the organic pork system, SHI < 0.5 for all stakeholders and subsystems.

Conclusion Swedish pork production has lower risk of negative social impacts than the average European social conditions for most of the stakeholders: *workers*, *pigs*, *local community*, and *consumers*. *Farmers* and *society* at the subsystem *pig farm* have the same risk of negative social impacts as the average European social conditions. Due to the dependence of the results of the chosen reference level, the reliance on certification, and the indicators included, results should be interpreted and used with care.

Keywords Social life cycle assessment · Pig · Activity variable · Social Hotspot Index · Social Risk Time · Analytical hierarchical processing

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1 Introduction

Pork is the most consumed terrestrial animal meat product in Europe as well as globally. It accounts for 47% of the meat produced in Europe and pork production is growing fast; currently there is a stock of almost a billion pigs worldwide (FAOSTAT 2019). Producing pork requires various resources: the animals themselves, housing facilities, feed, farming machinery, trained farmers and animal caretakers, slaughter facilities, transportation networks, and energy. Several pork production systems (hereafter called pork systems) are operated in Europe. The most common involves rearing pigs indoors in conventional, confined environments (approximately 90% of the slaughter pigs), but there are also alternative

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outdoor or partially outdoor systems including organic pork systems (Bonneau et al. 2011). In Sweden, there are two main pork systems: conventional and organic, with around 2% of production being organic (Jordbruksverket 2017). Both systems use the same high-yielding crossbreds, and the main differences between the systems relate to feed and housing.

The environmental impacts of Swedish pork production, in terms of energy use and potential contribution to global warming, acidification, and/or eutrophication, have previously been examined (Sonesson et al. 2016; Cederberg et al. 2009; Carlsson et al. 2009; Sonesson et al. 2009; Cederberg et al. 2005; Eriksson et al. 2005; Cederberg and Nilsson 2004; Cederberg 2003; Ingvarsson 2002; Cederberg and Darelius 2001). Most studies have focused on environmental hotspot analyses, which indicate that the largest environmental impact comes from feed production and manure management (Sonesson et al. 2016; Cederberg et al. 2005; Eriksson et al. 2005; Cederberg 2003; Cederberg and Darelius 2001). Environmental impacts of organic and conventional pork in Sweden from farm to supermarket (Ingvarsson 2002) and from farm to fork (Carlsson et al. 2009; Sonesson et al. 2009) have also been studied, but the social impacts of different pork systems have not yet been researched.

Sustainable food production is increasingly important to society, practitioners, and academics, partly as a result of the Sustainable Development Goals (SDGs) from the United Nations (UN 2015). The SDGs describe development as a matter not only of economic growth but also of the provision of solutions to social sustainability issues such as poverty, hunger, poor health, low education, gender inequality, access to clean water, access to sanitation, limiting global warming, and other forms of social injustice (UN 2015). In addition, a growing segment of the population assesses product quality not just by intrinsic attributes but also by extrinsic attributes connected with sustainability (Jawad et al. 2018; Benoit-Norris et al. 2012). Although consumers of pork are concerned about direct personal benefits such as their health and safety, they are also concerned about the health and welfare of pigs (Grunert et al. 2018). Grunert et al. (2014) showed that consumers in northern Europe are more concerned about social than environmental and economic sustainability. Hence, there is a need for actors in the food value chain to address not only environmental aspects but also social sustainability. A useful methodology for assessing social impacts from a product perspective is Social Life Cycle Assessment (S-LCA). The S-LCA has been standardized in the guidelines for Social Life Cycle Assessment of a Product (UNEP 2009), henceforth referred to as the 'guidelines'. The guidelines conform to the ISO 14040 implementation steps: definition of goal and scope, life cycle inventory, life cycle impact assessment, and interpretation.

Previous S-LCA studies have focused on various agricultural products including bananas (Feschet et al. 2013), broilers (Tallentire et al. 2019), cane sugar (Nemarumane and Mbohwa 2015), citrus fruits (De Luca et al. 2015), eggs (Pelletier 2018), honey (D'Eusanio et al. 2018), milk (Chen and Holden 2017; Revéret et al. 2015), tomatoes (Petti et al. 2018; Bouzid and Padilla 2014; Andrews et al. 2009), and wine (Arcese et al. 2017). However, most of the studies to date only include *workers* and *local community* as stakeholder categories, few are quantitative (Traverso et al. 2018), and to our knowledge, no S-LCA study has been conducted for pork. Animal ethics is increasingly being regarded as an important aspect of social sustainability in life cycle assessment (Neugebauer et al. 2014). Nevertheless, only one S-LCA study has included animals as stakeholders (Tallentire et al. 2019). Two other S-LCA studies have included animal welfare aspects (Pelletier 2018; Revéret et al. 2015), but their focus was on animal caretakers, not the animals themselves. Animal caretakers and animals are both important stakeholders and need to be included in a sustainability assessment (Neugebauer et al. 2014).

The objective of the study is to assess the risk of negative social impacts in organic and conventional pork systems. This study contributes to the literature on the S-LCA for livestock systems in two respects: (i) by quantitatively focusing on pork originating from two production systems, (ii) by including several major relevant stakeholders: *workers*, *farmers*, *consumers*, *local community*, *society* as a whole, and *pigs*.

2 Materials and methods

Following the guidelines, our S-LCA was undertaken in four main steps: definition of goal and scope of the study (Section 2.1), life cycle inventory (Section 2.2), life cycle impact assessment (Section 2.3), and life cycle impact interpretation (Section 2.4), as shown in Fig. 1.

2.1 Definition of goal and scope of the study

2.1.1 Goal of the S-LCA

The goal was to assess risks of negative social impacts in organic and conventional production systems in Sweden, using high-performance crossbred animals in both systems. In this study, risks of *potential* social impacts were assessed and not *actual* social impacts, which requires case-specific and primary data for the systems under study and also an establishment of cause-effect relations between activities affected by the production and the outcomes in terms of impacts on human health and life expectancy etc. (Macombe et al. 2013). Results are presented using different levels of aggregation for each stakeholder and subsystem, i.e. life cycle step, separately in order to enable identifying hotspots in pork production.

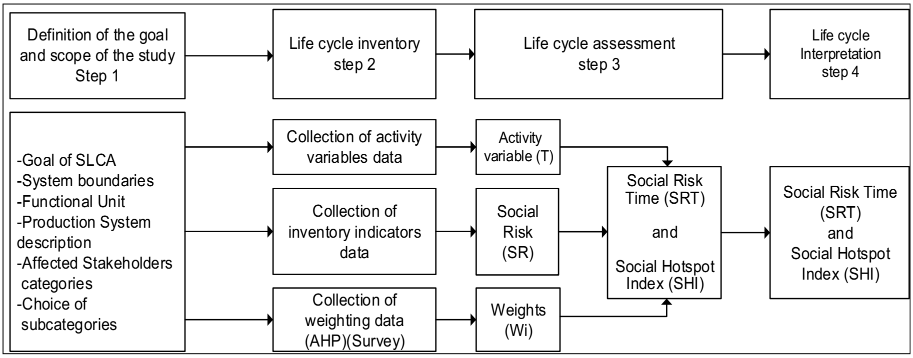

Fig. 1 The framework of the social life cycle assessment performed in this study showing the stages and the activities involved

2.1.2 Functional unit

The functional unit was 1000 kg of pork for consumption in Sweden (i.e. 'on the fork', excluding bones and not including waste at the consumer level). A pig slaughtered at 120-kg live weight results in 43-kg pork for consumption (Åsa Öberg Jordbruksverket personal communication 26 May 2020). All social risks were allocated to pork since pork is the main product from pig production.

2.1.3 System boundaries

The system boundaries are presented in Fig. 2. They include the following processes: on and off farm feed production, pig production, slaughter of pigs, and consumption of pork. The main feed crops used in Swedish pork production are wheat, barley, soybean, and rapeseed (LRF 2015). Swedish pork production uses local and imported protein sources, together with local cereal commonly produced at the pig farm. The feed requirements in the production of the functional unit are different for the two pork systems because organic pigs have higher maintenance energy requirements due to more space allowed for movements. *Pig production* refers to the rearing of parent stock (excluding grandparents) and rearing of young pigs for slaughter. *Slaughter* refers to the slaughtering of pigs and the cutting of the carcass into meat at a slaughterhouse for the market, and *consumption* is the eating of pork by consumers. The soybean farm, rapeseed farm, pig farm, slaughterhouse, and consumption are subsystems in the production systems. The cultivation of wheat and barley is accounted for in the pig farm subsystem because these are produced at the pig farm. Table 1 shows the stakeholders included for each subsystem.

To limit the scope of this study, that is, already comprehensive considering the multitude of stakeholders included, impacts related to the production of buildings, machinery, fertilizers, and transports, and energy use in retail and for cooking, feed processing, and minor nutrients in pig diets were not included. We assumed these processes have a lower relative importance owing to their low contribution to the functional unit, i.e. low values of the activity variables for these processes in the production of the functional unit 1000-kg pork (see Section 2.2.1).

2.1.4 Pig production system description

Typical conventional and organic pig farms were modelled for one production round (farrowing to finishing) based on Swedish data (Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019; Agriwise 2018; Nils Lundeheim Swedish University of Agricultural Sciences (SLU) personal communication 12 November 2018; AHDB 2017; Gård och Djurhälsan 2017). We modeled farms with integrated pig production including sows, piglets, gilts, and slaughter pigs at the same farm. We excluded the boars as most farms use artificial insemination. The characteristics in Table 2 depict a typical farm of each production system.

2.1.5 Stakeholder categories

This study examines social risks on *workers*, *farmers*, *consumers*, *local community*, *society*, and *pigs* separately within the system boundary. *Workers*, *consumers*, *local community*, *value chain actors*, and *society* are stakeholders suggested by the guidelines. Considering that there are many small and large *value chain actors* and that data collection would be very challenging, we did not include *value chain actors*, such as manufacturers and retailers in order to limit our already broad scope. *Pigs* and *farmers* were added, as they are central stakeholders in pork production. We identified *workers* as those directly involved in work for a salary in crop production (used for feed), pig husbandry, and slaughter. We defined *farmers* as the owners of pig production enterprises in Sweden. *Farmers* and *workers* were treated as separate stakeholders in order to take into account that social sustainability issues important for *farmers* do not necessarily affect *workers*

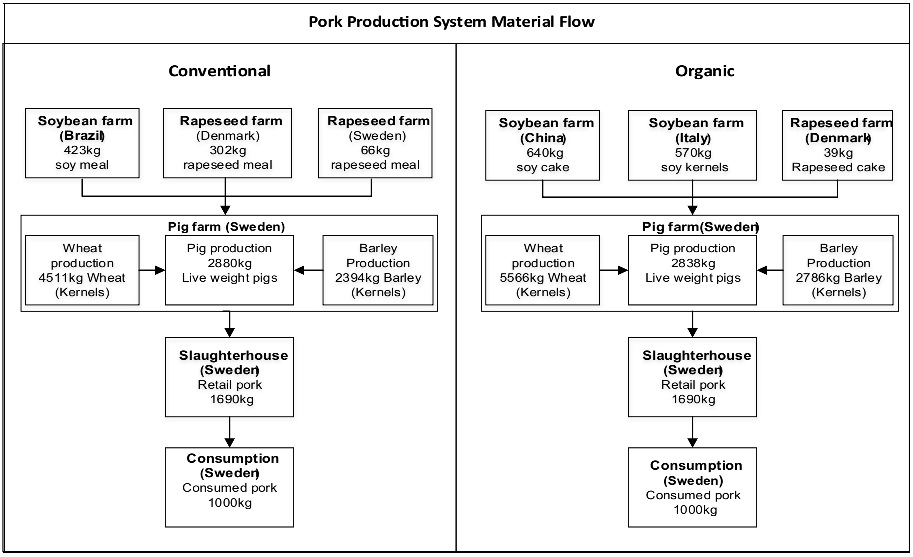

Fig. 2 System boundary and the production system material flow showing the inputs required per round of production of 1000 kg of pork for consumption (the functional unit) in terms of retail pork, live pigs, soybean, rapeseed, wheat, and barley (including co-products and waste)

at the *pig farm* and vice versa. *Local community* was, based on the study by Sarr et al. (2010), defined as residents living within 3 km^2 of the farms (soybean, rapeseed, and pig farms) and slaughterhouses. *Pigs* refers to sows, gilts, piglets, and growing pigs. Boars were not included, as their impact, with the low amount of semen required to produce the functional unit, can be considered marginal. *Consumers* were defined as people who eat pork in Sweden. Finally, based on a study on rural commuting in the UK (Champion et al. 2009) and assuming that people living within a radius of 25 km would reflect society, *society* was defined as people living within an area of 2000 km^2 around the farms. Table 1 shows the stakeholders and subsystems included.

2.1.6 Choice of subcategories

This is, to our knowledge, the first S-LCA study on pork, so it was necessary to identify subcategories of potential relevance to

Table 1 Included stakeholders and subsystems

Subsystem	Stakeholders					
	Workers	Farmers	Local community	Pigs	Consumers	Society
Soybean farm	X	-	X	-	-	X
Non-GMO conventional soy—Brazil; organic soy—China and Italy						
Rapeseed farm	X	-	X	-	-	X
Conventional rapeseed—Denmark and Sweden; organic rapeseed—Denmark						
Pig farm	X	X	X	X	-	X
Rearing pigs, and cereal production included—Sweden						
Slaughterhouse, Sweden	X	-	X	X	-	-
Consumption, Sweden	-	-	-	-	X	-

The stakeholder categories analyzed are annotated with an (X) while those with a (-) were either not applicable (e.g. pigs at soybean farm) or not included for the purpose of simplifying the model (soybean farmers and rapeseed farmers) or not included because no social sustainability issues were raised (slaughterhouse in society)

Table 2 Characteristics of conventional and organic pig production in Sweden

	Conventional	Organic	Source
Sow			
Number of litters/sow per year	2.3	2.1	(Nils Lundeheim SLU personal communication 12 November 2018; AHDB 2017)
Live born piglets per littre	14.6	12.4	(Gård och Djurhälsan 2017; Agriwise 2018)
Mean daily weight gain pre weaning nursery (kg/day)	0.3	0.3	(Nils Lundeheim SLU personal communication 12 November 2018)
Weaning age (days)	33	42	(Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019; AHDB 2017)
Mortality piglets nursery (% of total of live born pigs)	18	21	(Gård och Djurhälsan 2017)
Piglets live weight at weaning (kg)	10	13	(Nils Lundeheim SLU personal communication 12 November 2018; AHDB 2017)
Mortality sows (%)	7	7	(Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019)
Culled sows in % of total number of annual sows	50	40	(Nils Lundeheim SLU personal communication 12 November 2018)
Gilt age at first farrowing (days)	354	367	(Nils Lundeheim SLU personal communication 12 November 2018)
Gilt weight at first insemination (kg)	140	140	(Nils Lundeheim SLU personal communication 12 November 2018)
Mean sow weight (kg)	240	240	(Nils Lundeheim SLU personal communication 12 November 2018)
Growing and finishing pig			
Mean daily weight gain 11–35-kg weaners (kg/day)	0.6	0.57	(Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019)
Post weaning nursing period (days)	42	38.5	(Nils Lundeheim SLU personal communication 12 November 2018)
Mean daily weight gain 36–60-kg growers (kg/day)	0.68	0.65	(Nils Lundeheim SLU personal communication 12 November 2018)
Growing period (days)	37	38	(Nils Lundeheim SLU personal communication 12 November 2018)
Mean daily weight gain 61–110-kg finishers (kg/day)	0.9	0.85	(Nils Lundeheim SLU personal communication 12 November 2018)
Finishing period (days)	67	68	(Nils Lundeheim SLU personal communication 12 November 2018)
Mortality weaners (% of total number of weaners)	2	4	(Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019)
Mortality growing pigs (% of total number of growers)	1	1.9	(Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019)
Mortality finishers (% of total number of finishers)	1.8	1.6	(Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019; Nils Lundeheim SLU personal communication 12 November 2018; Agriwise 2018)
Live weight at slaughter (kg)	124	120	(Nils Lundeheim SLU personal communication 12 November 2018; Ingvar Eriksson Gård och Djurhälsan personal communication 16 August 2019)

pork. We adopted a bottom-up approach as suggested by the guidelines in which we first identified the major social sustainability issues associated with pork based on a literature search and an expert workshop, and then classified the identified social sustainability issues found into subcategories suggested in the guidelines and additional ones applicable to the social sustainability issue in question. To gather social sustainability issues, we selected articles from peer-reviewed journals and publications from international non-governmental organizations (NGOs) using Google Scholar. Web of Science and Scopus databases were checked for potential additional issues but no issues not already captured by the search using the Google Scholar were found.

Search strategy The search terms were social, problem(s), challenge(s), impact(s) or issue(s), swine production, pig production or pork production, and consumption. The first search used the terms soci* AND (problem* OR challenge* OR impact* OR issue*) AND (swine OR pig OR pork) AND product* AND consum*. In a second search, the terms were soci* AND (problem* OR challenge* OR impact* OR issue*) AND soy* OR rapeseed* OR canola. In the third search, the terms were soci* AND (problem* OR challenge* OR impact* OR issue*) AND (swine OR pig OR pork) AND (slaughter* OR abattoir*). The three searches resulted in 17,600; 18,900; and 18,000 citations, respectively.

Inclusion criteria A publication was included if it (i) was written in English; (ii) was a peer-reviewed article, commentary from a journal or NGO publication focusing on subject areas (e.g. The Dutch Soy Coalition); (iii) was published between 1998 and June 2019; (iv) had online full text available; and (v) had a title, excerpt, or statements with socio-economic issues related to one or more of the following: soy in Asia or South America, crop production in Europe, pig production in Europe or North America, and the slaughtering of pigs in Europe or North America. In addition, the reference lists from the identified publications were screened for any relevant literature.

Full-text assessment In the first screening, articles were excluded if they did not meet the inclusion criteria. The most common reason for exclusion was that the title did not refer to crop production, pig production, slaughter, or consumption. Pig production and slaughter issues were restricted to systems in developed countries. The first screening resulted in the selection of 14, 60, and 3 publications for the first, second, and third searches, as described above. The second screening was based on the full text of the articles. After duplicates had been excluded, the relevant publications were narrowed down to 2, 27, and 1 publications for the first, second, and third searches. In total, 30 publications were finally used to identify social sustainability issues. The social sustainability issues identified from the literature subsequently used in the computation of social risks are presented in Tables 3, 4, 5, 6, 7, and 8. (See the full list of social sustainability issues in the Online Resource, Tables 1–6).

Expert workshop A workshop with 13 experts in Swedish pork production, especially feeding, husbandry, pig health, and slaughter, was organized to verify social sustainability issues identified from the literature search, and to identify potentially relevant additional issues. Before the workshop, the experts were informed about the goal of the study and the social sustainability issues of pork production identified from the literature.

In the verification process, the experts first assessed the relevance of social sustainability issues in the context of Swedish pork production. Following group discussion, they reached a consensus on which of the issues identified in the literature search that were not relevant in the current context. These were excluded from the subsequent steps of the investigation. The experts also suggested additional social sustainability issues not captured by the literature search.

The social sustainability issues collected from literature review and stakeholder workshop were classified into subcategories based on the guidelines, as shown in Tables 3, 4, 5, 6, 7, and 8. The literature review and workshop together resulted in 35 subcategories (including subcategories for pigs) and 156 social sustainability issues (social sustainability issues Tables 1–6 in the Online Resource).

2.2 Life cycle inventory

2.2.1 Activity variables

To relate the impacts from the different subsystems to the functional unit, different activity variables (T) were used (UNEP 2009; Section 2.3.3). The activity variable for *workers* and *farmers* was work hours, i.e. the number of hours of work for one person at the farm and the slaughterhouse needed to produce the functional unit. In the calculation of the activity variables (T) for the pig farm, we added (T) for home-grown cereals with (T) for pig production. For example, work hours needed to produce the functional unit for the *workers* in the organic pork system are 7.4 h (6.17 h for pig production and 1.18 h for home-grown cereals). For *pigs*, the unit was life days at the *pig farm* and the *slaughterhouse*. Pig life days are given by the number of pigs needed to produce the functional unit multiplied by days at *the farm* or at *the slaughterhouse*. We assumed mortality was on the first day for piglets and at 50% of production time for weaners, growers, fatteners, gilts, and sows. For *local community* and *society*, the activity variables were people hectare days calculated as the number of people in an area (defined in square kilometers see Section 2.1.5) multiplied by the number of hectares used in the production process and the number of days of the production process used to produce the functional unit.

Table 3 Issues from the literature and experts for the stakeholder category *workers*

Subsystem	Subcategory	Inventory indicator	Social sustainability issue
Soybean farm	Freedom of association and collective bargaining	Global Rights Index workers	Organization freedom and union[a]
	Child labour	Child labour percentage	Poor application of the UN Convention on the Rights of the Child[a]
	Fair salary	Minimum wage	Low wages (The Dutch Soy Coalition 2008)
	Working hours	Work hours per week	Long working hours[a]
	Forced labour	Global Slavery Index	Slavery (The Dutch Soy Coalition 2008)
	Equal opportunities/discrimination	Gender Equality Index	Gender inequality at farms[a]
	Health and safety	Hospital beds per 1000 inhabitants Physicians per 1000 inhabitants	Limited access to health services (The Dutch Soy Coalition 2008)
		Percentage of DNA damage in leucocytes of farm and office workers	Risk of cancer from pesticide use (Walker et al. 2005)
		Adult literacy rate	Poor training of workers on management of chemicals, safety, first aid and waste management on farms[a]
	Social benefits and security	Percentage of unemployed receiving social security unemployment benefits Public social protection expenditure on benefits	Unsatisfactory social benefits (Zortea et al. 2018)
Rapeseed farm	Fair salary	Lowest wage	Low wages[b]
	Working hours	Work hours per week	Long working hours[b]
	Forced labour	Global Slavery Index	Slavery[b]
	Equal opportunities/discrimination	Gender Equality Index	Gender inequality at farms[b]
	Health and safety	Hospital beds per 1000 inhabitants Physicians per 1000 inhabitants	Limited access to health services[b]
Pig farm	Fair salary	Average wage per month	Lower salary for pig caretakers due to rise of industrial pig production (Honeyman 1996)
	Working hours	Work hours per week	Long working time (Porcher 2011)
	Health and safety	Percentage with respiratory disease	Respiratory diseases (Donham et al. 2006; Preller et al. 1995)
		Risk of antibiotic resistance	Antibiotic resistance (methicillin-resistant *Staphylococcus aureus*—MRSA) (Van Boeckel et al. 2015)
		Percentage of farm workers with musculoskeletal disorders (MSD)	Musculoskeletal disorders (MSD)[a]
		Accidents per 1000 workers	Accidents[a]
	Social benefits and security	Percentage of unemployed receiving social security unemployment benefits Public social protection expenditure on benefits	Rare paid sick leave on pig farms (Porcher 2011)
Slaughter house	Fair salary	Average wage per month	Low wages (Dillard 2008)
	Working hours	Work hours per week	Long working time (Dillard 2008)
	Equal opportunities	Ratio of females to males employed Percentage gender salary gap	Gender inequality[a]
	Health and safety	Accidents per 1000 workers	Accidents—physical danger from sharp knives (Dillard 2008)
		Work related sickness per 1000 workers	Work related sickness (musculoskeletal disorders, tendonitis, carpal tunnel syndrome, white finger, psychological traumatic stress) (Dillard 2008)

[a] Input from the workshop (subcategories without the footnote are from the guidelines and social sustainability issues without the footnote are from the literature search)

[b] All social sustainability issues identified for the soybean farm were also listed for the rapeseed farm

Table 4 Issues from experts for the stakeholder category *farmer* (new stakeholder)

Subsystem	Subcategory	Inventory indicator	Social sustainability issue
Pig farm	Freedom of association	Difference in proportion of farmers with freedom of association	Organization freedom and union[a]
	Fair income[a]	Average income per year	Lower income[a]
	Working hours	Work hours per week	Long working time[a]
	Health and safety	Risk of antibiotic resistance	Antibiotic resistance (methicillin-resistant *Staphylococcus aureus*)[a]
		Percentage of farmers with musculoskeletal disorders (MSD)	Musculoskeletal disorders (MSD)[a]
		Accidents per 1000	Accidents[a]
	Social benefits and security	Proportion of farmers with access to social benefits	Rare paid sick leave on pig farms[a]
	Work satisfaction[a]	Percentage of farmers with low status	Low status and recognition in society[a]

[a] Input from the workshop (subcategories without the footnote are from the guidelines and social sustainability issues without the footnote are from the literature search)

Standard pig diets for the two systems were used to compute the time needed for the production of 1000-kg pork. For the conventional pork system, the pig diet was obtained from Cederberg et al. (2009) as this was the best available estimate. The organic diet, for which there is no official published data available, was provided by a feed company with good knowledge about feeding practices in organic pork production in Sweden (anonymous, so as to respect confidentiality). Consumption is indicated by the number of people consuming pork (without bones) in one day and is obtained by dividing 1000-kg pork by the average pork consumption per capita per day, which is 40 g in Sweden (Åsa Öberg Jordbruksverket personal communication 26 May 2020). The activity variable for consumers was people consumption days. Soybean and rapeseed production produce oil as a co-product. Economic allocation was used for these co-products for the allocation of social risk. We used a factor of 0.60 for soybean meal/cake (Cremaschi et al. 2015) and 0.24 for rapeseed meal/cake (Bernesson 2004). Table 9 shows the activity variables associated with the production and consumption of 1000-kg pork for different stakeholders.

2.2.2 Inventory indicators

Data for the inventory indicators for social sustainability issues were collected from case-specific and generic sources. Case-specific data were collected from interviews, survey data, published articles, reports, and websites. Data for the subsystems *pig farm* and *slaughterhouse* were mainly case-specific. For imported feed, which was not possible to trace to a very specific origin, generic data were used. For some *soybean farm* and *rapeseed farm* inventory indicators, we used national data (rather than sector specific) as a proxy due to lack of data. For example, for social benefits and security at *soybean farm*, the percentage of unemployed receiving social security unemployment benefits in the soy-producing country was used as a proxy. The national data were collected mainly from reports and databases from international organizations such as ILO (International Labour Organization), the World Bank, United Nations agencies, and third party certification agencies.

2.2.3 Weighting

Expert weighting of subcategories was used in the assessment for each subsystem for each stakeholder. For example, for the stakeholder category *workers* in the subsystem *pig farm*, the four subcategories, fair salary, working hours, health and safety, and social benefits and security, were used (Table 3). These subcategories were then weighted using Analytical Hierarchical Processing (AHP) (Saaty 1990). AHP was conducted through a questionnaire for each stakeholder category and subsystem. In total, 15 stakeholders-subsystems were included in the study (Table 1), and with only one subcategory for *local community* for *slaughterhouse*, 14 questionnaires were used in total. The experts were selected based on purposive sampling with requirements of a minimum of two and a half years' work experience in the subject area. The experts included farmers and staff from advisory services, authorities, academia, and NGOs. Invitations to respond to a web-questionnaire using Netigate (a Swedish web-based survey tool) were sent by email to 10 experts for each questionnaire. The aim was to obtain at least three responses for each questionnaire. Experts with suitable expertise were invited to answer several questionnaires. Examples of invitation emails and questionnaires can be found in Questionnaires 4.1–4.4 in the Online Resource. The pairwise comparisons made by experts were used to make geometric mean vectors using AHP in the R package (AHP).

The consistency ratio for an expert should ideally be ≤ 0.1 according to Saaty (2003, 1990), but a consistency ratio ≤ 0.2 can be accepted in applied sciences (Dolan 2008). For any

Table 5: Issues from the literature and experts for the stakeholder category *local community*

Subsystem	Subcategory	Inventory indicator	Social sustainability issue
Soybean farm	Access to material resources	Percentage change in forest area 2000–2010	Deforestation (deVisser et al. 2014; The Dutch Soy Coalition 2008)
	Delocalization and migration	Land holding inequality Gini Index	Delocalization due to expanding soybean farms and land grabbing/land speculation (The Dutch Soy Coalition 2008)
	Cultural heritage	Food production diversity score	More cash crop production by small-scale farmers at the expense of more traditional crops (The Dutch Soy Coalition 2008)
	Safe and healthy living conditions	Active ingredient per ha	Human and environmental pesticide toxicity from pesticides and herbicides (The Dutch Soy Coalition 2008)
Rapeseed farm	Delocalization and migration	Percentage employed in the agricultural sector	Delocalization to urban areas due to fewer and larger farms[b]
	Safe and healthy living conditions	Active ingredient per ha	Human and environmental toxicity from pesticides and herbicides[b]
Pig farm	Access to material resources	Percentage of farms below 100 ha	Community assistance from farmers, for example snow clearance[a]
		Percentage of farms above 100 ha	Large farms results in improved infrastructure (installation of internet infrastructure etc.)[a]
		Percentage of farms with stores	Access to farm stores[a]
	Delocalization and migration	Percentage change in farms above 100 ha	Reduction in number of family farms due to industrial pig production (Honeyman 1996)
	Cultural heritage	Percentage of pigs kept indoors throughout life	Pigs kept indoors and not seen outside (Boogaard et al. 2011)
Slaughter house	Access to material resources	Average of water use per tonne pork	High amount of water use (Gerbens-Leenes et al. 2013; Urlings et al. 1992)

[a] Input from the workshop (subcategories without the footnote are from the guidelines and social sustainability issues without the footnote are from the literature search)

[b] All social sustainability issues identified for the soybean farm were also listed for the rapeseed farm

expert with a consistency ratio > 0.2, we used the R package Ahpsurvey to develop an error matrix iteration (Harker 1987) to replace inconsistent values in order to reduce the consistency ratio until this was ≤ 0.2. In the aggregation of individual weights, we used the geometric mean of all respondents (within the same questionnaire), as this is more appropriate for the AHP method than the arithmetic mean (Forman and Peniwati 1998). Between 3 and 6 responses per questionnaire were obtained from the 10 invited experts.

2.3 Life cycle impact assessment

2.3.1 Social Risk

In this study, the Social Risk (SR) is a measure of the risk of negative social impacts for each of the inventory indicators related to the social sustainability issues listed in Tables 3, 4, 5, 6, 7, and 8. SR corresponds to the risk weighting factor R_i representing the risk of negative social impacts in Tallentire et al. (2019) and Benoit et al. (2012). SR also corresponds to the normalized value for an indicator N_i used by Chen and Holden (2018) in the assessment of sustainability. SR is not corrected for the functional unit. SR, ranging between 0 and 1, is a normalization of the inventory indicator using reference points (see computation of social risk in the Online Resource in Tables 10–24). A reference point denotes a baseline situation for a certain aspect. SR is 0.5 when the inventory indicator is at the reference point. If for a certain inventory indicator, the situation is worse than for the reference point, the value of SR will be between 0.5 and 1. Hence, a low value of SR is preferable, as it means a low risk of negative social impacts. For example, for the social sustainability issue 'long working hours', the inventory indicator is work hours per week. If the work hours per week is above the average in Europe (the performance reference point), that would give a score above 0.5. If the inventory indicator is better than the reference, the SR will be between 0 and 0.5. The formulas used to calculate SR were:

1) $SR = 1 - EXP(LN(0.5) \times IND/REF)$ when a *higher* value than the reference point reflects a more negative impact, and
2) $SR = EXP(LN(0.5) \times IND/REF)$ when a *lower* value than the reference point reflects a more negative impact.

where IND is the inventory indicator for the subsystem and REF is the reference point.

The reference points used in this study were based on European averages (reference frame Table 8 in the Online Resource). The reference points were collected from the literature; see Tables 10–24 in the Online Resource. For example, the number of hospital beds per 1000 inhabitants in Europe, 5.6 beds (World Bank 2019), was used as the reference point

Table 6 Issues from the literature and experts for the stakeholder category *consumers*

Subsystem	Subcategory	Inventory indicator	Social sustainability issue
Consumption	Health and safety	Meat consumption per capita	Health Obesity due to pork consumption (Walker et al. 2005) Cardiovascular disease due to excessive meat consumption (Walker et al. 2005) Type II diabetes due to excessive meat consumption (Walker et al. 2005) Cancer due to excessive meat consumption (Grunert et al. 2018)
		Risk seroprevalence of *Toxoplasma gondii* infected meat	Food safety *Listeria* sp. infection from meat (Davies 2011; Mcglone 2013) *Escherichia coli* infection from meat (Hansen et al. 2013; Mcglone 2013) *Salmonella* sp. infection from meat (McGlone 2013) *Campylobacter* sp. infection from meat (McGlone 2013) *Yersinia enterocolitica* infection from meat (Drummond et al. 2012) Hepatitis E virus infection from meat (Wacheck et al. 2012) *Toxoplasma gondii* infection from meat (Kijlstra et al. 2004) Antibiotic resistance from meat (Van Boeckel et al. 2015)
	Perception of value[a]	Price per kg carcass	Low economic value of pork meat[a]
	Affordability[a]	Price per kg carcass	High price of pork (Mcglone 2013)
	Extrinsic attributes[a]	Percentage of pork products with a label indicating extrinsic quality	Known origin of the meat (Bernués et al. 2003)
	Eating quality[a]	Ultimate pH (pork)	Low quality of meat (Boogaard et al. 2011)

[a] Input from the workshop (subcategories without the footnote are from the guidelines and social sustainability issues without the footnote are from the literature search)

to compare access to health services in China, Brazil, and Italy for soy workers. European reference points were used because Europe is, in an international context, a champion of sustainability (European Commission 2019). However, for fair wage, which depends on the living costs in a specific country, national minimum wages in each country were used as reference points. Where average values were not available, control values were used as reference points. For example, percentage of DNA damage of leucocytes in sedentary workers was used as a control for DNA damage of leucocytes in farm workers using pesticides. The reference point for each inventory indicator is described in more detail in the Online Resource (computation of social risk Tables 10–24). Where no performance reference points could be found in the literature, for example, as happened with average prevalence of Listeria species in Europe, expert judgement was used for estimating the SR. These estimates were based on an ordinal scale: very low risk = 0.1, low risk = 0.3, average risk = 0.5, high risk = 0.7, and very high risk = 1.

To calculate SR in subsystems with two subprocesses producing the same product, for example, the *soybean farm* in the organic pork system, where soybean produced both in Italy and China was used, we used mass allocation factors in calculating SR for the *soybean farm*, i.e. 0.47 for Italy and 0.53 for China (feed company, anonymous personal communication 1 November 2018). For the rapeseed farm in the conventional pork system, we used 0.18 for Sweden and 0.82 for Denmark (Cederberg et al. 2009) as mass allocation factors for SR. The factors are based on the ratios of the soybean and rapeseed in the diets.

2.3.2 Weights

The weight for a subcategory (see Section 2.2.3 on how weights were collected from AHP) was multiplied by the weight for the inventory indicator (all inventory indicators under subcategory were assigned equal weight), giving the final weight (W) for each inventory indicator. For example, the subcategory health had a weight of 0.370 and had four inventory indicators (percentage of workers with respiratory diseases, risk of antibiotic resistance, percentage of workers with musculoskeletal disorders, and accidents per 1000 workers) as shown in Table 12 in the Online Resource. Thus, the final weight (W) for each inventory indicator would be $0.370 \times 0.25 = 0.0925$.

2.3.3 Social Risk Time

The social risk depends on the extent an input is used or the magnitude of 'exposure'. The social risk related to an input used in either of the two systems will differ depending on the quantity of the input used to produce the functional unit (for example, 4511 kg of wheat is required in the feed in order to produce 1000 kg of pork in the conventional pork system while 5566 kg of wheat is required in the organic pork system). This is true not only for quantities but can also refer to the magnitude of exposure, for example, the number of days a pig is exposed to negative social impacts in different subsystems vary between pork production systems. In accordance with Tallentire et al. (2019), the social risk for subsystems and stakeholders was

Table 7 Issues from the literature and experts for the stakeholder category *pigs* (new stakeholder)

Subsystem	Subcategory	Inventory indicator	Social sustainability issue
Pig farm	Animal-friendly housing[a]	Percentage of pigs with access to daylight	Daylight for pigs (Boogaard et al. 2011)
		Percentage of pigs with slatted floors	Slatted floors (Pedersen 2017)
		The indoor space per pig	Freedom to move (Boogaard et al. 2011)
		Percentage of time a pig spends in an outdoor environment	Outside access (Boogaard et al. 2011)
		Percentage of pigs provided enrichment material	Distraction material straw (Boogaard et al. 2011)
		Months per year a sow spends in a crate	Crated sows[a]
	Possibility to express natural behavior[a]	Percentage of pigs provided roughage as feed	Absence of roughage (Boogaard et al. 2011)
		Percentage of pigs with bitten tails	Evidence of tail biting (Sinisalo et al. 2012; Walker and Bilkei 2006; Valros et al. 2004)
		Access outdoor area or deep straw bed	Possibility to express natural behaviour—rooting, playing, and lying in the mud (Boogaard et al. 2011)
	Free from fear, pain, and injuries[a]	Injuries per pig	Scared, stressed, injured, and ill animals (Boogaard et al. 2011)
	Good animal health[a]	Percentage of pigs with osteochondrosis	Osteochondrosis[a]
		Percentage of pigs with Erysipelas	Swine erysipelas[a]
		Pig mortality	Piglet mortality (Bergstra et al. 2017)
		Percentage of pigs with pneumonia	Lung disease[a]
		Percentage of pigs with internal parasites	*Ascaris suum* (Sutherland et al. 2013)
		Prevalence of shoulder lesions	Shoulder lesions[a]
		Weaning age	Weaning age (Bergstra et al. 2017)
	Animal friendly management[a]	Percentage of tail docked pigs	Tail docking (Bergstra et al. 2017; Boogaard et al. 2011)
		Percentage of pigs with nose rings	Use of nose rings (Boogaard et al. 2011)
Slaughterhouse	Free from fear, pain and injuries[a]	Percentage of pigs with injuries	Injuries due to fighting at slaughter house especially overnight[a]
	Animal friendly management[a]	Ultimate pH	Stress in pigs at slaughter, poor meat quality (an indicator of stress), fear/stress due to transport, and handling before slaughter (Carlsson et al. 2007)

[a] Input from the workshop (subcategories without the footnote are from the guidelines and social sustainability issues without the footnote are from the literature search)

computed as Social Risk Time (SRT) using the activity variables (T) needed in each subsystem to produce the functional unit, the score for each inventory indicator (SR), and the weight of each inventory indicator (W). The SRT were summed over inventory indicator to give the SRT for stakeholder i (e.g. *worker*) and subsystem j (e.g. *soybean farm*) as:

$$\mathrm{SRT}_{ij} = \sum_{k=1}^{K} \left(T_{ij} \times \mathrm{SR}_{ijk} \times W_{ijk} \right)$$

where k denotes inventory indicator (e.g. $k = 1\ldots.12$ for *workers* at *soybean farm*), SRT_{ij} denotes Social Risk Time for stakeholder i in subsystem j, T_{ij} denotes the activity variable in subsystem j for stakeholder i (e.g. work hours), SR_{ijk} denotes the Social Risk for inventory indicator k in subsystem j for stakeholder i, and $W_{ijk}$is the weight of inventory indicator k in subsystem j for stakeholder i. SRT for all relevant subsystems were also summed to a total SRT for each stakeholder as shown in Table 9.

2.3.4 Social Hotspot Index

The Social Hotspot Index (SHI) indicates the risk of negative social impacts relative to the maximum possible risk of negative social impacts for a given stakeholder in one of the systems (Benoit et al. 2012). Following Tallentire et al. (2019) and Benoit et al. (2012), we calculated the SHI based on the assessed SRT relative to the worst potential SRT for a system, $\widehat{\mathrm{SRT}}$, which occurs when SR = 1. SHI values range between 0 and 1, and a low value of SHI is preferable as it indicates a low potential of negative social impact. The formula for the Social Hotspot Index for stakeholder i in subsystem j is:

$$\mathrm{SHI}_{ij} = \mathrm{SRT}_{ij} / \widehat{\mathrm{SRT}}_{ij}$$

Table 8 Issues from the literature and experts for the stakeholder category *society*

Subsystem	Subcategory	Inventory indicator	Social sustainability issue
Soybean farm	Public commitment to sustainability	Ecosystem status	Commitment to environmental sustainability: deforestation, loss of biodiversity, erosion, and degradation
	Contribution to economic development	Hours per hectare	Low employment due mechanization of crop cultivation (The Dutch Soy Coalition 2008)
	Contribution to food production/security[a]	Yield per hectare	Low productivity per hectare[a]
Rapeseed farm	Public commitment to sustainability	Ecosystem status	Commitment to environmental sustainability: deforestation, loss of biodiversity, erosion, and degradation[b]
	Contribution to economic development	Hours per hectare	Low employment due mechanization of crop cultivation[b]
	Contribution to food production/security[a]	Hectares per tonne	Low productivity per hectare[b]
Pig farm	Public commitment to sustainability issues	Proportion of human edible component	High food/feed competition (Walker et al. 2005)
		Percentage of farms with resistant *E. coli*	Contribution to antibiotic resistance[a]
		Cross Local Index	Reduction of the animal genetic variability (Nardone and Gibon 2015)
	Contribution to economic development	Percentage of farmers less than 35 years	Aging of pig farmers (Honeyman 1996)
		Hours per tonne pork	Low employment (work hours per 1000-kg pork)[a]
	Contribution to food production/security[a]	Carcass meat production (kg) per sow	Low productivity per sow[a]

[a] Input from the workshop (subcategories without the footnote are from the guidelines and social sustainability issues without the footnote are from the literature search)

[b] All social sustainability issues identified for the soybean farm were also listed for the rapeseed farm

where SRT_{ij} denotes Social Risk Time for stakeholder i in subsystem j, and $\widehat{\mathrm{SRT}}_{ij}$ denotes the worst SRT for stakeholder i in subsystem j. The SHI for each stakeholder was then obtained by summing over subsystems taking into account the proportion of the total time in each subsystem such that $\mathrm{SHI}_i = \frac{\sum_{j=1}^{J} \mathrm{SHI}_{ij} \times T_{ij}}{\sum_{j=1}^{J} T_{ij}}$. An example of how SRT and SHI were calculated is presented in Table 9 in the Online Resource.

2.4 Interpretation

The interpretation step analyzed SR, SRT, and SHI to draw out conclusions on the risk of negative social impacts of pork systems in Sweden. SR shows social risks for different inventory indicators in relation to the reference without relating the impact to the functional unit, which is done for SRT and SHI. The fundamental difference between SRT and SHI is that SRT increases with the activity variable (e.g. work hours or pig life days) needed to produce the functional unit, while SHI only uses the activity variable to aggregate impacts from different subsystems.

3 Results

3.1 Social Risk

SR measures the risk of negative social impacts when relating the value of an inventory indicator in relation to a reference point. A value lower than 0.5 indicates a better situation than the reference, which is the average European social conditions. For stakeholder *workers* at the *soybean farm*, 8 of 12 inventory indicators had a value of SR > 0.5 in the conventional pork system and 5 of 12 had a value of SR > 0.5 in the organic pork system (Table 9). This was due to aspects related to human rights and social security in the countries in which the soy is produced (see details in Table 10 in the Online Resource). For example, for the inventory indicator *percentage of unemployed receiving social security unemployment benefits*, the conventional pork system had higher values of SR than the organic due to lower social security in Brazil (conventional soy) than in China and Italy (organic soy). For *workers* at the *slaughterhouse*, 2 out of 6 inventory indicators had a value of SR > 0.5 in both pork systems. However, the highest value of SR of all 32 inventory indicators (in all subsystems) for *workers* was at the *slaughterhouse* for both

Table 9 Activity variables, Social Risk (SR), Social Risk Time (SRT), and Social Hotspot Index (SHI) for stakeholders for 1000 kg of consumed pork

Stakeholder category and subsystem	Activity variables		Number of inventory indicators with Social Risk > 0.5 out of total inventory indicators		Social Risk Time		Social Hotspot Index	
	Conventional	Organic	Conventional	Organic	Conventional	Organic	Conventional	Organic
Workers	13	79	16/32	13/32	5.7	29	0.40	0.31
Soybean farm	1.6	58	8/12	5/12	0.64	20	0.24	0.27
Rapeseed farm	0.18	0.13	2/6	2/6	0.07	0.05	0.11	0.10
Pig farm	9	19	4/8	4/8	3.7	7.9	0.42	0.42
Slaughterhouse	2.7	2.6	2/6	2/6	1.3	1.3	0.48	0.48
Farmers	29	61	3/8	3/8	15	29	0.52	0.48
Local commun.	4900	24,000	7/12	2/12	2200	5,000	0.42	0.20
Soybean farm	250	1900	3/4	0/4	120	360	0.27	0.14
Rapeseed farm	310	160	1/2	1/2	160	57	0.13	0.09
Pig farm	4300	22,000	3/5	1/5	1900	4,600	0.45	0.21
Slaughterhouse	47	47	0/1	0/1	15	15	0.32	0.32
Consumers	25,000	25,000	2/16	2/16	9000	7500	0.36	0.30
Pigs	5000	5300	5/21	3/21	1700	1200	0.34	0.22
Pig farm	5000	5300	5/19	3/19	1700	1200	0.34	0.22
Slaughterhouse	0.51	0.51	0/2	0/2	0.25	0.15	0.48	0.30
Society	3,200,000	16,000,000	7/12	5/12	1,700,000	7,600,000	0.48	0.46
Soybean farm	170,000	1,300,000	1/3	0/3	59,000	380,000	0.21	0.23
Rapeseed farm	210,000	110,000	2/3	2/3	130,000	68,000	0.17	0.15
Pig farm	2,900,000	15,000,000	4/6	3/6	1,500,000	7,200,000	0.53	0.49

Values for the workers and farmers for the pig farm include wheat and barley production

systems, specifically for the inventory indicator *accidents per 1000 workers* (0.95), which was due to the high risk of accidents from sharp knives (Table 13 in the Online Resource). For *farmers* at the *pig farm*, 3 out of 8 inventory indicators had a value of SR > 0.5 in both pork systems. This was due to low income, long working time and musculoskeletal disorders (Table 14 in the Online Resource). For *local community*, there were 5 inventory indicators for the *pig farm.* Three of these inventory indicators had a value of SR > 0.5 in the conventional pork system while only one had a value of SR > 0.5 in the organic pork system because of low SR related to community assistance, access to farm stores and pigs on pasture (Table 17 in the Online Resource). The highest value of SR for the *local community* was for the social sustainability issue *access to farm stores* at the *pig farm*. Of the 19 inventory indicators for stakeholder *pigs* at the *pig farm*, 5 in the conventional pork system and 3 in the organic pork system had a value of SR > 0.5. This was attributable to piglet mortality and other animal welfare issues (Table 20 in the Online Resource). The highest value of SR (0.91) for *pigs* was observed for the inventory indicator *percentage of pigs provided roughage as feed* in the conventional pork system. Roughage provides both nutrients and enrichment of the pigs' environment indoors. It is not provided in the conventional system while this is a requirement according to the organic certification. Of the 6 inventory indicators for stakeholder *society* at the *pig farm*, 4 in the conventional and 3 in the organic pork system had a value of SR > 0.5. This concerned sustainability issues related to farm animal genetic diversity, food/feed competition, and low productivity for both systems and also to aging farmers in Sweden for the conventional system (Table 24 in the Online Resource). The highest value of SR of all inventory indicators for the stakeholder *society* was for the social sustainability issue *reduction of animal genetic variability* at the *pig farm* and this was due to the lack of local, traditional breeds in Swedish pig production.

3.2 Social Risk Time

SRT relates the risk of negative social impacts to the functional unit taking the magnitude of 'exposure' and the weights of the inventory indicators into account. For *workers* in the organic pork system, the *soybean farm* had substantially higher value of SRT than all other subsystems (Table 9). This was due to organic production of soybean being time-consuming and carried out in countries with poor social security. For the stakeholder *workers* in the conventional pork system, the *pig farm* had the highest value of SRT because most of the work time for *workers* in the conventional pork production occurs at the *pig farm*. For the stakeholder *pigs*, SRT was dominated by the effects at the *pig farm* since pigs spend very little time at the *slaughterhouse*. For *local community* in both systems, the *pig farm* had the highest value of SRT because more land was required to produce wheat and barley than for soybean and rapeseed. For *consumers*, the inventory indicator for the subcategory 'extrinsic attributes' had the highest weight. The SR for the indicator in this subcategory was lower than 0.5 for both systems due to all organic production and 55% of conventional production being certified with a certification guaranteeing added extrinsic values for the consumer (Table 19 in the Online Resource).

3.3 Social Hotspot Index

SHI indicates the risk of negative social impacts relative to the worst case scenario for a given stakeholder and/or subsystem. Note that the activity variable in the calculation of SHI for each subsystem is cancelled out (see example in Table 9 in the Online Resource). This is illustrated by the SHI for *workers* at the *pig farm*, where SHI is the same for both systems (0.42) although SRT has a much higher value in the organic pork system due to longer work time needed to produce organic pork in comparison with conventional pork. In the conventional pork system, SHI > 0.5 slightly for *farmers* as well as *society* at *pig farm* which means a similar risk of negative social impacts with the average European social conditions. In the organic pork system, SHI < 0.5 (i.e. better than the average European social conditions) for all stakeholders and subsystems. Furthermore, the organic pork system had substantially lower values of SHI than the conventional pork system for *pigs* at *pig farm* and *slaughterhouse*. The organic pork system also had substantially lower values of SHI than the conventional pork system for stakeholder *local community* at *soybean farm* and *pig farm*. For *local community* at the *pig farm*, all 5 inventory indicators had approximately the same weight and the organic pork system had equal or lower values of SR for four of them (as compared with the conventional pork system). They were related to infrastructure, farm stores, reduction in family farms, and pigs seen outdoors (Table 17 in the Online Resource). These low values of SR resulted in a SHI for *local community* at *pig farm* of 0.21 in the organic pork system, as compared with 0.45 in the conventional pork system. Looking at the pork systems at an aggregated stakeholder level (in Table 9), the results show that *farmers* and *society* had the highest value of SHI in both systems.

4 Discussion

To our knowledge, this is the first S-LCA study of pork production. This is also the first study that includes the animals themselves (*pigs*) and *farmers*, together with stakeholders suggested by the guidelines (*workers*, *local community*, *consumers*, and *society*). Scherer et al. (2018) and Tallentire et al. (2018) presented studies where integration of animal welfare into social sustainability assessments has been done but these did not include any other stakeholders. It may be argued that considering animals as stakeholders in S-LCA is questionable since the area of protection in the S-LCA is humankind. However, as Tallentire et al. (2019) discuss, excluding animals in a sustainability assessment of the agrifood sector potentially excludes significant issues. Similarly, it can be argued that 'nature' (wild animals, plants and other species) should also be included as a stakeholder in the S-LCA (Chapron et al. 2019). Nature as such was not included in this S-LCA, but our plan is to combine social and environmental life cycle assessments of animal production systems in the future in order to identify potential synergies and goal conflicts between the environmental and the social dimensions of sustainability. Relating the potential social impacts to a functional unit in the S-LCA, as we did here, will facilitate a combined assessment of social and environmental sustainability.

In this study, we used three types of measures to quantitatively assess social risk: SR, SRT, and SHI. SR shows the risk of negative social impacts without relating to the functional unit. It can be valuable for identifying social sustainability issues that have a high risk of negative social impacts which do not show up in the overall assessment (e.g. due to a low value of the activity variable in the subsystem where they exist). For example, a single inventory indicator with a high value of SR can be enough to cause distrust in the system if this social sustainability issue is related to a claimed added value. In SRT, the SR values of different inventory indicators are weighed and aggregated at stakeholder and subsystem level, taking activity variables (e.g. work hours or pig life days) into account. SHI can help decision-makers to prioritize their efforts for increased social sustainability between stakeholders and subsystems. The results in this study suggest that *workers*, *farmers*, and *society* have the highest value of SHI in both systems.

In our study, we used the average European social conditions as the reference and SHI > 0.5 therefore means higher risks of negative social impacts than the average European social conditions. What is considered an acceptable level of negative social impact is highly normative and differs between stakeholders. In Sweden, Swedish pork is often marketed as being more sustainable than imported meat (see LRF 2015, for example). European pork production has advantages in a global perspective but there are still challenges (ATF 2019), and the average European production might not be considered 'good enough' as a bench mark for the conventional production system from a national perspective. Decision-makers working with pork systems with added values need to make a strategic choice; how far from the conventional pork system do they want to position their system (Rydhmer and

Slagboom 2017). The European organic movement has high ambitions in terms of animal welfare (IFOAM EU 2010). This is reflected in SRT and SHI for *pigs* at *pig farm* and *slaughterhouse* in the organic pork system. However, since their vision for food and farming is 'a fair, environmentally conscious, healthy and caring system' (Barabanova et al. 2015) one could expect lower values on SRT and SHI also for *farmers* and *society*. The difference in SRT between the organic and the conventional pork system is strongly related to the activity variables and thus resource efficiency, and potential goal conflicts between efficiency and sustainability needs further research.

The results of this study rests on the assumption that certification of soy (here the organic KRAV certification or the Round Table of Responsible Soy and ProTerra for conventional soy) can effectively decrease negative social risks when it comes to child labour, working hours, wage levels, and deforestation in Brazil, Italy, and China. However, these certifications have been criticized for being too weak to guarantee the preventions of negative impacts, especially for child labour (Jia et al. 2020). That is why we tested how results would be affected if we assume that this certification is not effective (see Table 10 and Table 15 for details). We found that the number of inventory indicators with a value above 0.5 increased from 16 to 17 and 13 to 15 for the conventional and organic systems respectively for the stakeholder *workers*. In terms of the SHI for *workers*, this increased to 0.42 for both systems (from 0.40 for the conventional and 0.31 for the organic). This indicates that if soybean certification is not effective, the SHI for *workers* in the two pork systems is closer to the European average. If certification of soybean does not work, for the stakeholder *local community* for the subsystem *soybean farm* for the conventional system, deforestation in Brazil emerged as a concerning issue scoring the worst possible, while the risk for deforestation is considerably lower in the countries from which organic soybean is sourced (China and Italy). Hence, results are sensitive to how well certification of soybean works.

When looking at the risk of negative social impacts in one system relative to another system, in some cases, it is sufficient to focus on SHI; while in other cases, it may be necessary to consider several measures including the activity variable (*T*) and the Social Risk Time (SRT), and examine how they interact with SHI. For example, a certain number of work hours (farmers and hired labour) are required in order to produce the functional unit of 1000-kg pork. This work can be more or less problematic from a social point of view. In our study, a resource-efficient production system, requiring fewer hours of work, but with a type of work associated with a more severe negative impact for some social sustainability issue (e.g. high rate of accidents), would result in a higher value of SHI than a system that requires more work hours but has less severe negative impacts for these social sustainability issues. SHI does not reflect the time of exposure for a certain impact. Tallentire et al. (2019) assess the welfare of broilers in four production systems (four countries) and they state that SHI is useful for identifying the risk of negative social impacts of a production system. The activity variable used in their study was, however, similar for the different systems whereas many of the activity variables (*T*) used in this study differed considerably between the conventional and the organic pork system. When the activity variables of two systems are not similar, then SHI and SRT provide complementary information important in assessing which of the systems has a relatively higher risk of negative social impacts. There are several possible outcomes to consider when comparing two systems, A and B, in case the activity variable is of greater magnitude for system A. If system A has a higher value of SHI and a higher value of SRT, this indicates that system A has a higher risk of negative social impacts. Conversely, if system A has a lower value of SHI and a lower value of SRT, this indicates that system A has a lower risk of negative social impacts. However, if system A has a lower value of SHI and a higher value of SRT, this indicates that the systems have similar risk of negative social impacts. If SHI is similar in both systems and the difference in SRT is small, then this indicates similar risk of negative social impacts.

The risk of negative social impacts has, in previous S-LCA studies on livestock products (eggs and dairy), been found to be largest for the stakeholders' *workers* and *local community* according to Pelletier (2018) and Chen and Holden (2017). The result of this study indicates that *farmers* and *society* are the stakeholders associated with the highest risk of negative social impacts. Our study differs from previous S-LCA on livestock products in that we included *farmers* as a separate stakeholder. In addition, we used different references; while previous studies have used the producing countries as reference; our reference was Europe. Since the reference is crucial for SR and thus the results of the evaluation, a sensitivity analysis of how different reference systems affect the results should be the next step.

For some social sustainability issues, neither case-specific nor generic inventory indicator data were available. The cost-benefit of collecting the data made us decide not to include all social sustainability issues in the final computation (e.g. the magnitude of noise at a pig farm for health and safety of workers). Of the 156 social sustainability issues identified in the literature search and expert workshop, 62% were finally used in this study. More inventory data would need to be collected and used in order to improve the quality of the S-LCA and to assure that the omission of social sustainability issues in this study does not mask substantial negative social impacts. We have reported all of the social sustainability issues collected from the literature and experts (social sustainability issues Tables 1–6 in the Online Resource), hoping that the long list will inspire other researchers to identify additional inventory indicators.

An important issue related to data on inventory indicators is change over time. Most production systems develop over time, and the use of old data on inventory indicators could therefore lead to problems of temporal conformance (Eisfeldt and Ciroth 2017). Discussions with different experts were conducted to mitigate this potential bias. Secondary data can also be influenced by other factors, unique to a study at a given time, and this increases uncertainty. A sensitivity analysis of how using different data sources affects the result is the next step in the improvement of this work.

The aggregation of various impact categories into an overall score requires the impact categories to be weighted. Ideally, the stakeholders—e.g. *farmers* and *consumers*—should do the weighting. Experts can also provide reliable results that are similar to those produced by stakeholders (Kamali et al. 2017). We used experts as proxy respondents because this was cheaper and faster than involving a large number of representatives of all stakeholders, and because obviously, the *pig*, as a stakeholder, cannot speak for itself. The results of this study may be influenced by the panel used. Future studies could check the robustness of our panel by using randomized large samples of the actual respondents—e.g. farmers or consumers. In the AHP, a consistency ratio ≤ 0.2 is desirable (Dolan 2008), but some experts' consistency ratios were larger than 0.2. Improving consistency by asking respondents to reconsider their choices could have offered a better way forward. However, there is a risk that the experts will get the impression that they are being pressed to revise their weighting in accordance with the researchers' preferences and lose interest in the whole study as a result. Hence, inconsistency was reduced with the method of Harker (1987), although this does not necessarily increase the validity of the matrix.

Ideally, the study of a system should include all inputs and outputs, but time and costs are always considered when defining system boundaries. Our system included wheat, barley, soy, rapeseed, and pig production. Future studies could expand the boundary, e.g. by including fertilizers which constitutes a major difference between organic and conventional pork systems. Fertilizers were not included in this study because we used the activity variables to cut off the system boundary. In future studies, production of fertilizers could be included by additional data on social sustainability issues and inventory data associated with fertilizer production. Farmers in conventional pork production use different diet compositions depending on the availability and price of feed ingredients during the course of the year. Data from a livestock feed inventory provided the best estimate currently available. Better and later data on the feed used would improve the quality of the study but requires a major study to collect such data. Family farms involving both the farmer and workers are common in Swedish pig production, and since they, to some extent, are concerned with different sustainability issues, both *farmers* and *workers* were included as stakeholders. In view of the difficulty of calculating the actual work hours for farmers in the other subsystems, we only included farmers for the pig farm. In future studies, we recommend that farmers are included for all subsystems.

In this study, we quantitatively examined the risk of negative social impacts in two pork production systems. Additional primary data is required in order to improve the assessment of the two systems and in particular to assess actual social impacts. This study does, however, show how the risk of negative social impacts of a functional unit in two different systems can be quantitatively analyzed and compared using the measures SR, SRT, and SHI. The findings can guide decision-makers within industry and society in their efforts to improve the social sustainability of livestock products.

5 Conclusions

The objective of this study was to assess the risk of negative social impacts in two pork production systems. An S-LCA was conducted on Swedish conventional and organic pork systems with high-performance crossbred pigs. The social risk was examined for stakeholders at two levels, the system and the subsystem. At the system level, the results indicate that for stakeholders' *workers*, *pigs*, *local community*, and *consumers*, both organic and conventional Swedish pork production have lower risk of negative social impacts than the average European social conditions. The risk of negative social impacts for the stakeholders' *farmers* and *society* was found to be the same as the average European social conditions.

At the subsystem level, the results indicate that *workers* as well as *society* at *soybean* farm have higher risk of negative social impacts in the organic pork system than in the conventional pork system. *Pigs* at *pig farm,* as well as *slaughterhouse*, and *local community* at the *rapeseed farm* and *consumers* have higher risk of negative social impacts in the conventional pork system than the organic system.

We conclude that Social Risk Time (SRT) and Social Hotspot Index (SHI) are measures useful for assessing the risk of negative social impacts within system and for comparing different production systems. A precise comparison between systems would however require additional primary data. The results from this study highlight social sustainability challenges in pork production and can help decision-makers prioritize between improvement opportunities. However, for the dependence of the results of the chosen reference level, the reliance on certification, and the indicators included, results should be interpreted and used with care. This study however provides useful information for future S-LCA of two or more livestock production systems.

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Research article

A life cycle sustainability assessment of organic and conventional pork supply chains in Sweden

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A B S T R A C T

Most existing life cycle assessment studies that have compared the sustainability of organic and conventional pork supply chains are environmental assessments. The economic and social sustainability dimensions of pork supply chains are currently under-researched. The study reported here was designed to assess the environmental, economic and social sustainability of conventional and organic pork in Sweden. Life Cycle Sustainability Assessment was undertaken using 20 indicators expressed per unit product (1000 kg pork fork weight) and per unit area (1000 ha of farmland) for the four main subsystems in pork supply chains: (1) farm and feed production, (2) slaughter, (3) wholesaling and retailing, and (4) consumption. The organic pork supply chain out-performed the conventional chain in 11 of the 20 indicators expressed per unit product and 18 of the 20 indicators expressed per unit area. It was therefore the more sustainable of the two chains in nearly all the indicators expressed per unit area. However, the organic supply chain was less sustainable in some of the indicators expressed per unit product because, more feed per kg of pork was required in organic pork production. Pig welfare improvement leads to higher production costs and environmental impacts. Assessment of all three sustainability dimensions – environmental, economic and social – helps to identify trade-offs between these three pillars of sustainability. However, the selection of indicators influences results, and obtaining environmental, economic and social data simultaneously is challenging.

1. Introduction

Pork is the most produced terrestrial meat product in the world today with production having quadrupled over the last 50 years (FAO 2021). In 2021, global pork production is expected to increase by 2% to 103.8 million tonnes of pork with China being the largest producer with 40% of the world's production and at the same time being the largest consumer (USDA 2021). Sweden is one of the leading countries in terms of socially sustainable pork production (Zira et al. 2020), with low use of antibiotics (SVA 2020) and high animal welfare supported by law (SFS 1988). Aiming for a sustainable pork production, there is room for improvement in Sweden as well as other countries, but multidisciplinary analyses of environmental, economic and social sustainability issues on pork supply chains are generally lacking (Gunnarsson et al. 2020; Bonneau et al. 2014).

The European Green Deal sets out strategies to address these sustainability issues. In it, reductions in the use of pesticides, antibiotics and fertilizers are proposed, as well as other strategies including reduced food waste, increased focus on innovation and improved provision of information to society (e.g. through labelling) (EP 2020). The food industry also engages in improving sustainability of food, for example by the use of private certification schemes and providing its own environmental and social information on production practices. For example, there is certification of organic products for which both EU regulations exists (EC 2007) and private certification schemes which augment the EU regulations (e.g. KRAV in Sweden). These allow citizens to make more informed purchasing decisions when buying food products (Kanis et al. 2003).

Life cycle assessment (LCA) has been used in the past to assess the sustainability impacts of various livestock products, including pork. Much of the focus has been on assessing the environmental

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Nomenclature

APOS	at point of substitution
B_0	methane generation potential
BDP	biodiversity damage potential
$CD_{W/R}$	costs of distribution for wholesaler and retailer (excluding salaries, interest, depreciation, rent, and taxes)
CMA_P	costs of product manufacturing at the farm (excluding wages, salaries, interest, depreciation, rent, taxes)
CO_S	costs of operating the slaughterhouse (excluding salaries, interest, depreciation, rent, and taxes),
CPA_S	costs of packaging for slaughterhouse
$CRE_{W/R}$	costs of retail for the wholesaler and retailer (excluding salaries, interest, depreciation, rent, and taxes)
CTR_P	costs of transport for the farmer
CTR_S	costs of transport for the slaughterhouse
$CTR_{W/R}$	costs of transport for the wholesaler and retailer
FDP	fossil depletion
FEP	freshwater eutrophication potential
FET	freshwater ecotoxicity
GWP100	global warming potential over 100 years
HTP	human toxicity potential
IND_{conv}	environmental, economic or social indicator values for the conventional supply chain
IND_{org}	environmental, economic or social indicator values for the organic supply chain
ISO	international standard organization
LCC	life cycle costs
LCC_P	life cycle costs of the farmer
LCC_s	life cycle costs of the slaughterhouse
$LCC_{W/R}$	life cycle costs of the wholesaler and retailer
LCSA	life cycle sustainability assessment
MCF	methane conversion factor
MEP	marine eutrophication potential
MET	marine ecotoxicity
PET	polyethylene terephthalate
RSP	relative sustainability points
SCL100	soil carbon loss over 100 years
SEK	swedish krona (around 0.1 euro)
SR	social risk
SRT	social risk time
T	activity variable
TAP100	terrestrial acidification potential over 100 years
TET	terrestrial ecotoxicity
VA	value added
VS	volatile solids

impacts in environmental LCA (E-LCA). More studies with a holistic approach, like the Life Cycle Sustainability Assessment (LCSA), which incorporates all three sustainability dimensions, are required for pork supply chains to identify opportunities for improvement and enable a shift towards more sustainable business models.

Therefore, the present study was designed to perform an LCSA for two contrasting pork supply chains in Sweden, one conventional and one organic, in order to identify the elements, or prerequisites, of more sustainable pork supply chains. The study's results are important in determining appropriate management strategies in the quest for fair, healthy and environment-friendly pork production under the European Green Deal (EP 2020).

2. Literature review

2.1. Environmental, social and economic concerns of pork production

Pig production systems drive deforestation in South America because they rely on soybean feed (approximately 20% of soybean exports from Brazil to the EU are linked with deforestation (Rajão et al. 2020)). They contribute to extensive land use in the production of feed crops (zu Ermgassen et al. 2016), and to water and soil pollution through their dependence on fertilizers and pesticides in crop production. Fertilizer use, together with the manure production and management, fossil fuel use for crop production, and the transportation of products from production sites to markets, all contribute to greenhouse gas emissions (Gerber et al. 2013). In terms of social sustainability, Zira et al. (2020) found that pork supply chains had issues including accidents at the slaughterhouse, unsatisfactory social benefits for workers at soybean farms, gender inequality for soybean workers in Brazil, health risks to workers stemming from pesticide use in soybean production, musculoskeletal disorders in farmers and workers at pig farms, and limited opportunities for pigs to express their natural behavior as a result of intensification. On the economic front, the sustainability issues that pork supply chains face include low incomes for farmers (Zira et al. 2020; van Wagenberg et al. 2017).

Several LCA studies on European pork supply chains have been published to date. Most are E-LCA and have system boundaries up to either the farm gate or slaughter gate, i.e. they are limited to the environmental impacts of pork production before the pork gets to the retailers (e.g. Monteiro et al. 2019; Noya et al. 2017; Sonesson et al. 2016). However, a few have included the retail and consumption stages (Bonou et al. 2020; Moberg et al. 2019; Head et al. 2014). To date, although sustainable business models require not only on environmental sustainability but also economic and social sustainability (Gunnarsson et al. 2020; Lin et al. 2020), only a few studies have examined the economic (Lotti and Bonazzi 2014) and social (Zira et al. 2020) sustainability of pork production.

2.2. Life Cycle Assessment

Life Cycle Assessment (ISO 14044) is a standardized method of assessing impacts of a product/service (ISO 2006). Life Cycle Assessment was conceived in the 1960s in response to concerns about environmental degradation and use of resources (Bjørn et al. 2018). The first LCA in the 1960s focused on packaging of food (Agrifootprint 2020) and later in the 1970s much focus was on energy (Andersson et al. 1994). The first LCA on agricultural products was on tomatoes in 1990 (Agrifootprint 2020) and LCA broadened to include animal products in the early 1990s in Europe (Andersson et al. 1994). Life cycle costing was first performed in the 1960s by the United States Department of Defense (Guinée et al. 2011). There is no standardization of life cycle costing methods and many applications are on durable products such as buildings (Settanni et al. 2010). Very few life cycle costing studies on food products have been performed (Konstantas et al. 2019). S-LCA is relatively new, as LCA experts formed the Life cycle initiative in 2002 to broadened LCA to include the social dimension and the guidelines for S-LCA were published in 2009 (Huertas-Valdivia et al. 2020). Using the guidelines, the first S-LCA on animal products was on milk (Chen and Holden 2017).

In LCA, impacts are commonly assessed per kg of product produced. A mass-based functional unit is useful for calculating the total emissions from total human food consumption. However, Salou et al. 2017 recommend the use of both a mass-based unit and assessing impacts per area, e.g. per hectare of land used, when performing LCA on agricultural systems. The use of mass-based comparisons alone miss important aspects related to intensification of production, e.g. that point pollution might increase when the use of inputs increase per hectare, hence risking non-optimal decision making (Muller and Schader 2017). These two units of comparisons, so called 'functional units' in LCA vocabulary, also reflects different perspectives of sustainability in food systems. The traditional mass-based unit relates to the dominant 'efficiency' perspective that focuses on increasing productivity in order to decrease emissions per unit product, while demand is considered largely given by current trends (Garnett 2014). The efficiency perspective does not deal with potential overconsumption of livestock products with a low impact per kg resulting in higher impact in absolute terms. In the contrasting 'sufficiency' perspective, focus is put on the possibility and need to manage demand to reduce overall emissions and resource use (Garnett 2014). The sufficiency perspective hence views the available agricultural land as the boundary condition rather than the need to produce a certain exogenously determined amount of meat (van Zanten et al. 2018). For this perspective, a per area functional unit is also relevant as here the focus is on the efficient use of land (Röös et al. 2021).

2.3. Life Cycle Sustainability Assessment

Conceptually, LCSA has three components: environmental (E-LCA), economic (Life Cycle Costing) and social (Social Life Cycle Assessment, or S-LCA) (Finkbeiner et al. 2010; Kloepffer 2008). LCSA provides a foundation for sustainable business models (Chen and Holden 2018; Bocken et al. 2014). Most LCSA studies have been conducted in connection with energy and buildings (Wulf et al. 2019). The challenge of connecting social impacts to the functional unit in S-LCA has been a barrier to LCSA development (Lin et al. 2020; Kloepffer 2008), and only a few LCSA studies on agricultural food products have been performed. LCSA on animal food products is still in its infancy, and the lack of a standardized framework for LCSA makes progress challenging. However, there are now a few LCSA publications on animal food products. These work with different frameworks to address some challenges in LCSA, such as lack of data. Valente et al. (2020) performed an LCSA study on pig slaughter using a framework with different system boundaries for E-LCA, S-LCA and Life cycle costing. Chen and Holden (2018) performed an LCSA study on dairy production using a tiered approach, and Scherer et al. (2018) presented a framework for the integration of animal welfare into LCSA that was applicable to cattle, pigs, poultry, salmon, shrimps and insects.

3. Material and methods

The methodology applied, in accordance with ISO 14040 LCA, comprised the following steps:

1 Goal and scope definition - We described the goal, scope of study, supply chain system, delimitation, functional units, allocation and impact categories.
2 Inventory – We collected data on the four subsystems (farm and feed production, slaughter, wholesaling and retailing, and consumption) for the organic and conventional pork supply chains.
3 Impact assessment – We analyzed the environmental, social and economic impacts for the two pork supply chains.
4 Interpretation – We presented this step as the result and discussion, and conclusion.

3.1. Goal and scope definition

The goal was to perform a Life Cycle Sustainability Assessment (LCSA) of conventional and organic pork supply chains in Sweden, comparing the two supply chains' environmental, economic and social impacts per 1000 kg pork fork weight as well as per 1000 ha farmland used, and to provide suggestions as to how the overall sustainability of pork production can be improved.

3.1.1. System description

Swedish pork production is divided into two supply chains, conventional and organic, both using the same crossbred breed, the chains' relative volumes are 98% and 2%, respectively (Jordbruksverket 2017). In the organic supply chain, the following requirements are imposed: pigs must have outdoor access all year and grazing during summer, inorganic chemicals in fertilizers and pesticides must not be used in crop production, slaughter pigs should not stay overnight at the slaughterhouse, drivers should use fuel-efficient driving techniques, and electrical energy from renewable sources like wind, solar and hydro should be used (KRAV 2019). In the conventional pork supply chain, by contrast, farmers are not obliged to provide an outdoor area for the pigs, inorganic fertilizer and pesticides are used, slaughter pigs can stay overnight at the slaughterhouse, and any source of electrical energy can be used. Feed ingredients also differ between the two systems, and there are further differences in input resources such as capital, land and labor.

Two typical pig farms were modelled, one conventional and one organic. These represented the production systems in Sweden for both an organic pig farm (according to the KRAV regulation: KRAV 2019) and a conventional one. We assumed that the typical farms were located in Västra Götaland in Sweden. In the conventional pork supply chain the pigs were assumed to be 100% indoors, and in the organic supply chain they were 50% indoors with outdoor access, and 50% outdoor on pasture yearly (Carlsson et al. 2009). We also modelled theoretical slaughterhouses using different sources of electricity. The slaughterhouse in the conventional supply chain used the Swedish electricity mix, whereas the slaughterhouse in the organic supply chain used electricity from renewable energy sources complying with KRAV regulations (KRAV 2019). We modelled the farms using certified conventional soybean in Brazil and KRAV certified organic soybean in China assuming that these meet regulations prohibiting child labor (children under 15 years) and forced labor, and also guarantee normal working hours per week and a fair salary as in Roundtable on Responsible Soy (RTRS 2017) and KRAV (KRAV 2019) certified products.

We assumed feed waste was 2% (Schell et al. 2002) and that food waste as a percentage of what enters each stage was 5% loss at slaughter and meat processing, 4% at retail, and 11% at the consumption stage (FAO 2011). An inventory of the inputs used in crop and feed production, pig production, slaughter, wholesaling and retailing, and consumption was performed. The inventory also included environmental, economic and social data. The environmental data included emissions into soil, air and water. The economic data included full costs for goods purchased at the pig farm, life cycle costs downstream and labor costs. The social data included labor hours spent on the farm working in feed production and pig rearing, and in producing bought-in feed and at the slaughterhouse, people consumption days (i.e. the number of people consuming the functional unit in one day) and pig life days for the pigs at the pig farm and slaughterhouse (i.e. the number of days' pigs live corresponding to the functional unit) (both in line with Zira et al. 2020).

System boundaries

The pork LCA included the following four main subsystems: 1) farm and feed production (crop cultivation, feed production and pig production), 2) slaughter, 3) wholesaling and retailing, and 4) consumption, except for Life cycle costing, which ended at retailing. Inputs included fertilizer, electricity, diesel, tap water, light oil

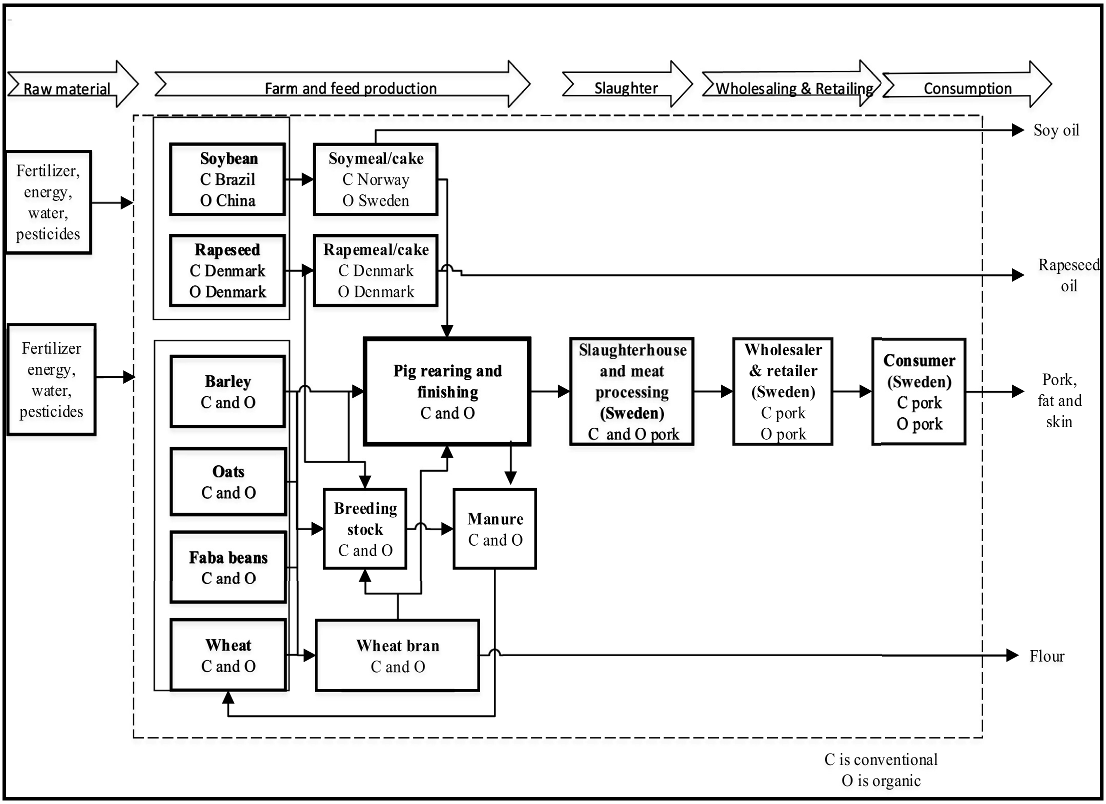

Fig. 1. The Swedish pork supply chains for conventional and organic production with the four subsystems farm and feed production, slaughter, wholesaling and retailing, and consumption.

and pesticides. The electricity used in the organic supply subsystems was from renewable energy sources (except for the wholesaling and retailing, and consumption subsystems). Farm and feed production included i) the cultivation of the feed crops: conventional soybean without genetic modification in Brazil and organic soybean in China, rapeseed in Denmark, wheat, oats, faba beans and barley grown at the pig farm in Sweden; ii) the production of soybean meal/cake, rapeseed meal/cake and wheat bran; iii) the grinding of wheat, oats, faba beans and barley; iv) the mixing of soybean meal/cake, rapeseed meal/cake and wheat bran with grains produced at the pig farm; and v) pig husbandry: the rearing of sows, gilts and slaughter pigs. Manure management was taken into account via impacts associated with manure storage and application. Slaughter included the stunning, bleeding, scalding, evisceration, splitting and chilling of the carcass as well as meat processing. Wholesaling and retailing included the distribution and sale of pork to consumers. Consumption covered the shopping, preparation and nourishment of people at a household. Transport events were included in the study, with impacts assigned to the goods produced. Truck driving in the organic supply chain was based on fuel-efficient driving techniques (KRAV 2019). The system boundary for both pork supply chains is shown in Fig. 1.

NB: Organic excludes pesticides and inorganic fertilizers as inputs.

3.1.1.1. Delimitation. To simplify the study, farm buildings and machinery were omitted. We assumed that impacts from the production of farm buildings were small for the two pork supply chains. Minor feed ingredients such as inorganic minerals, vitamins and crystalline amino acids in diets in the conventional supply chain were not included; nor were pharmaceuticals.

3.1.1.2. Functional units. Two functional units were used in parallel: 1000 kg of cooked bone- and fat-free meat at the consumer's fork and the use of 1000 ha of farmland for pork production.

3.1.2. Allocation

Economic allocation was used for the byproducts soybean oil, rapeseed oil and wheat flour (see Fig. 1). The allocation factors were 0.68 for soymeal/cake (World bank 2020a), 0.26 for rapeseed meal/cake (Soca v1 - Greendelta 2017) and 0.04 for wheat bran (Cederberg and Flysjö 2004). We did not allocate any impacts on lard or other pork byproducts used to make rubber, plastic, softeners, etc. (Mora et al. 2019). Allocating all impact from the pigs to the pork is a simplification, since approximately 6-10% of the total value of slaughtered pigs is related to such byproducts and these make up 25% of the live weight (Marti et al. 2011).

3.1.3. Assessment indicators

Assessment for E-LCA was based on mid-point impact indicators for climate change (GWP100), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial acidification (TAP100), fossil depletion (FDP), biodiversity damage potential (BDP), freshwater ecotoxicity (FET), marine ecotoxicity (MET), terrestrial ecotoxicity

(TET), human toxicity (HTP) and land degradation (Soil Carbon Loss - SCL100) (see section 3.3.1). Life Cycle Costing was based on the impact indicators Value Added (VA)/(Life Cycle Costs (LCC) + labor costs) ratio for the farm, slaughterhouse, and wholesaler and retailer (see section 3.3.2). S-LCA assessment was based on the indicator Social Risk Time (SRT) for the stakeholders *workers, local community, society, consumers, value chain actors* and *pigs* (see section 3.3.3). A list of the topics for social sustainability concerns used in the S-LCA based on the availability of indicators in Soca v.1 (Greendelta 2017) is shown in Table S1 in the supplementary.

3.1.4. Computation

The environmental and social impacts were computed using OpenLCA 1.10.2 (Greendelta 2019). Ecoinvent 3.3 (APOS) (Ecoinvent 2016) was used as a database for inventory data for background processes and characterization, and the Soca v.1 database (Greendelta 2017) was used for the social impacts. The economic impacts were calculated using Microsoft Excel.

3.2. Life cycle inventory

We conducted an inventory for the four production subsystems. We started with an inventory of inputs to the subsystems, and then made inventories for environmental, economic and social outputs. We assumed the same quantity of inputs per kg pork meat in both supply chains for the slaughter, wholesaling and retailing, and consumption, because the processing and preparation of pork was the same in both systems. The input inventory is shown in Table S2 in the supplementary. Details of the farm and feed production, slaughter, wholesaling and retailing and pork consumption are described below.

3.2.1. Environmental inventory

3.2.1.3. Farm and feed production. **Pig production**

Pig production was assumed to take place on an integrated pig farm, i.e. one producing both weaners and slaughter pigs. Crossbred pigs of the same breeds were used in both conventional and organic pork supply chains in the assessment. Gilts were assumed to be sourced from a nucleus herd 200 km from the pig production farm and transported by a 14-tonne truck. The slaughter pigs were produced at the integrated pig farms with the production characteristics shown in Table 1. These figures are the same as those previously used by Zira et al. (2020) for a S-LCA. The electricity use required per sow place per year, and per slaughter pig place per year, was assumed to be 738 kWh (Länsstyrelsen Västra Götalands län 2018a; Edström et al. 2005) and 62 kWh (Länsstyrelsen Västra Götalands län 2018a), respectively.

For the organic pork supply chain, 20% grass-clover leys (according to KRAV regulations) was included in the calculation of land use to assess biodiversity impacts and soil carbon loss. The inventory for environmental data is presented in Table S3-S5 in the supplementary.

Enteric methane emissions for pork were calculated assuming emissions of 1.5 kg per pig per year (IPCC 2019a). Methane emissions from manure storage were calculated based on volatile solids (VS), methane generation potential (B_0) and the methane conversion factor (MCF) for Sweden. In the organic pork supply chain VS were calculated to be 410 kg per sow place and year, and 150 kg per slaughter pig place and year. In the conventional pork supply chain VS were assumed to be 320 kg per sow place and year, and 120 kg per slaughter pig place and year. In both cases, a digestibility value of 75%, urinary energy value of 2% and ash value of 5% were applied (Berglund et al. 2013; IPCC 2006a). B_0 was assumed to be 0.45 kg/kg VS for all pigs (IPCC 2019a). It was assumed that the liquid manure system was used in the conventional pork supply chain, and that the solid manure system was used in the organic pork supply chain. MCF was set at 3.5% for pigs in the conventional supply chain to reflect the use of a slurry manure management system (Lantz and Björnsson 2016). The MCF for the pigs in the organic pork supply chain was set at 2% (Berglund 2017) for pig housing to reflect the use of a solid manure management system there, and at 1% for outdoor/grazing (Ingela Löfqvist Hushållningssällskapet personal communication 2020).

For direct nitrous oxide (N_2O) emissions from manure storage, we estimated 0.005 kg N_2O-N/kg nitrogen (N) for N deposited in the slurry for pigs in the conventional pork supply chain and 0.010 kg N_2O-N/kg N for N deposited in solid manure for pigs in the organic pork supply chain with solid manure management (IPCC 2019a). The emission factors for indirect N_2O emissions are presented in Table 4. Ammonia emissions during housing are influenced by the manure system used; a liquid manure system has more emissions than a solid system. Ammonia emissions for pig housing were assumed to be 14% of the N that is excreted by pigs in the conventional pork supply chain and 10% in the organic pork supply chain (Berglund 2017). Emissions from storage were assumed to be 10% of the N stored in the storage facility in the conventional pork supply chain and 20% in the organic pork supply chain due to the dilution effects of water in liquid manure (Berglund 2017). The N balance and fluxes from which the emissions were calculated are shown in Tables S4 and S5 in the supplementary and the other emission factors used are shown in Table 4.

Crop and feed production

The diets consisted of seven main ingredients, as shown in Table 2. We left out agri-byproducts from the food and energy industry because their proportion in the pig diets varies between farms and over time, ranging from non-use to approximately 31 kg of total feed intake of a slaughter pig on dry matter basis (RISE 2020), depending on availability. We replaced agri-byproducts with oilseed meals and faba beans to balance the nutrient requirements of the animals. The cereal ingredients and faba beans were assumed to be produced at the pig farm in Sweden, whereas soybean and rapeseed meal and cake were taken to be imported. In the organic pork supply chain, we included the use of forage, as this is a requirement imposed by the organic regulations (KRAV 2019); the diet for a sow included 200 kg forage dry matter per year and the diet for a slaughter pig included 20 kg dry matter per animal lifetime (Länsstyrelsen Västra Götalands län 2018b). Input requirements for crop production are shown in Table 3 (Länsstyrelsen Västra Götalands län 2018a; 2018b). The feed intake for pigs in the organic pork supply chain, especially sows, was larger than it was in the conventional pork supply chain because organic sows require more energy for thermoregulation and have heightened locomotion and a longer lactation period (Eskildsen et al. 2020).

Pesticides including herbicides, insecticides, molluscicide and fungicides are used for crop production in the conventional pork supply chain. The total mass of the active ingredients is shown in Table 3. Quantities of individual pesticides per hectare per feed crop (Nordborg et al. 2017) are shown in Table S6 in the supplementary.

We estimated emissions of N compounds from N application using the (IPCC 2019b; 2019c) emission factors summarized in Table 4. N in crop residues was calculated using IPCC (2019b) formulas. Carbon dioxide emissions from lime applications were assumed to be 12% of the lime applied (IPCC 2006b).

For conventional production, we assumed that ammonium nitrate was used as the nitrogen source, potash as potassium source and single super phosphate as the phosphorous source to retrieve impacts from fertilizer production from Ecoinvent 3.3 for each region (Ecoinvent 2016). Modern fertilizer plants in Europe are now equipped with N_2O reduction technology and emissions from ammonium nitrate production are 3.5-3.6 kg CO_2 eq per

Table 1
The characteristics of the two average pig farms in Sweden.

	Conventional	Organic	Source
Sow			
Number of litters/sow per year	2.3	2.1	Nils Lundeheim pers comm (2018); Agriculture Horticulture Development Board (2017)
Live born piglets per litter	14.6	12.4	Gård and Djurhälsan (2017); Agriwise (2018)
Mean daily weight gain pre weaning nursery (kg/d)	0.3	0.3	Nils Lundeheim pers comm (2018)
Weaning age (days)	33	42	Ingvar Eriksson pers comm (2019); Agriculture Horticulture Development Board (2017)
Mortality piglets nursery (% of total of live born pigs)	18	21	Gård and Djurhälsan (2017)
Piglets live weight at weaning (kg)	10	13	Nils Lundeheim pers comm (2018); Agriculture Horticulture Development Board (2017)
Mortality sows (%)	7	7	Ingvar Eriksson Gård djurhälsan pers comm (2019)
Culled sows in % of total number of annual sows	50	40	Nils Lundeheim pers comm (2018)
Gilt age at first farrowing (days)	354	367	Nils Lundeheim pers comm (2018)
Gilt weight at first insemination (kg)	140	140	Nils Lundeheim pers comm (2018)
Mean sow weight (kg)	240	240	Nils Lundeheim pers comm (2018)
Growing and finishing pig			
Mean daily weight gain 11-35kg weaners (kg/day)	0.60	0.57	Ingvar Eriksson pers comm (2019)
Post weaning nursing period (days)	42	38.5	Nils Lundeheim pers comm (2018)
Mean daily weight gain 36-60kg growers (kg/day)	0.68	0.65	Nils Lundeheim pers comm 2018)
Growing period (days)	37	38	Nils Lundeheim pers comm (2018)
Mean daily weight gain 61-110kg finishers (kg/day)	0.9	0.85	Nils Lundeheim pers comm (2018)
Finishing period (days)	67	68	Nils Lundeheim pers comm (2018)
Mortality weaners (% of total number of weaners)	2	4	Ingvar Eriksson pers comm (2019)
Mortality growing pigs (% of total number of growers)	1.0	1.9	Ingvar Eriksson pers comm (2019)
Mortality finishers (% of total number of finishers)	1.8	1.6	Ingvar Eriksson pers comm (2019); Nils Lundeheim pers comm (2018); Agriwise (2018)
Live weight at slaughter (kg)	124	120	Nils Lundeheim pers comm (2018); Ingvar Eriksson pers comm (2019)

Note: Data from Zira et al. (2020 p 1961)

Table 2
The pork supply chains' feed ingredients as a percentage of raw feed diet and the feed intake in kg.

	Dry sow		Lactating sow		Piglet		Slaughter pig	
	Conventional	Organic	Conventional	Organic	Conventional	Organic	Conventional	Organic
Wheat, %	40	34	44	34	43	34	42	27
Barley, %	29	34	37	34	38	34	32	27
Oats, %	17	21	5.7	5	8	5	5.3	0
Wheat bran, %	3.4	6.5	3.4	6	0	6	1.1	14
Faba bean, %	1	0	0	0	1	0	11	19
Rapeseed[1], %	3	1	3	1	0	1	4.6	1
Soybean[2], %	6.6	3.5	6.9	20	10	20	4	12
Feed intake (kg)	840[3]	880[3]	710[3]	890[3]	47[4]	46[4]	250[4]	270[4]

Diets in the conventional pork supply chain based on Cederberg et al. (2009) and RISE (2020); modified to reflect current conventional pig feed diets not including agri-byproducts

Diets in the organic pork supply chain (Ingela Löfqvist Hushållningssällskapet personal communication 2020). In organic production pigs are also fed with forage (not presented in the table)

[1] Rape meal in the conventional supply chain and rape cake in the organic supply chain

[2] Soybean meal in the conventional supply chain and soybean cake in the organic supply chain

[3] Feed per sow per year

[4] Feed per pig per life time

kg N in ammonium nitrate (Yara 2020; Berglund 2017). We assumed that the ammonium nitrate fertilizer on the Swedish market had an average 5.0 kg CO_2 eq per kg N in ammonium nitrate (Greppa näringen 2011) because imports from old plants are also used. We assumed phosphorous leaching from crop fields to be 0.72 kg/ha/year for the farm, the average in Västra Götaland (Johnsson et al. 2019), 3 kg/ha/year in Brazil (Cederberg and Flysjö 2004), 2.2 kg/ha/year in China (Li et al. 2015) and 0.5 kg/ha/year in Denmark (Heckrath et al. 2005).

3.2.1.4. Slaughter. It was assumed that live pigs were transported 50 km from the farm by a 16-tonne truck. At the slaughter subsystem, the pigs were slaughtered and the carcasses were cut, chilled and packaged. Pig carcasses are often used to produce various pork products (e.g. smoked pork, cooked sausages and fermented sausages), but for simplicity we assumed that all meat was sold as fresh raw meat in units of 500 g pork cuts. The pork was packaged in Polyethylene Terephthalate (PET) meat trays weighing 18.43 g each, with a volume of 1 liter (Maga et al. 2019). In terms of energy use, 797 kWh of electricity and 317 kWh oil was assumed to be required per 1000 kg live weight pigs (Edström et al. 2005). Further, it was assumed that 80 g of nitrogen and 8 g of phosphorous per slaughter pig were emitted into water (Naturvårdsverket 2009). Chemical Oxygen Demand (COD)

Table 3
Yields and inputs in conventional (Conv.) and organic (Org.) crop production.

	Soybean		Wheat		Oats		Faba beans		Barley		Rapeseed	
Origin	Conv. Brazil	Org. China	Conv. Sweden	Org. Sweden	Conv. Sweden	Org. Sweden	Conv. Sweden	Org. Sweden	Conv. Sweden	Org. Sweden	Conv. Denmark	Org. Denmark
Seed (kg/ha)	56[4]	55[7]	210[8]	230[9]	190[8]	230[9]	280[8]	280[9]	180[8]	210[9]	5[8]	5[9]
N applied (kg/ha)	8[2]	1.5[3]	155[8]	80[9]	90[8]	38[9]	0[8]	0[9]	115[8]	80[9]	205[8]	140[9]
P applied (kg/ha)	31[2]	2.3[3]	18[8]	11[9]	17[8]	8[9]	9[8]	7.5[9]	12[8]	10[9]	25[8]	52.5[9]
K applied (kg/ha)	57[11]	7.5[3]	20[8]	4[9]	13[8]	2[9]	15[8]	10[9]	10[8]	2[9]	25[8]	87.5[9]
Lime (kg/ha)	0	0	150[8]	100[9]	150[8]	100[9]	150[8]	100[9]	150[8]	100[9]	150[8]	100[9]
Diesel (liter/ha)	65[4]	35[7]	86[8]	105[9]	77[8]	108[9]	79[8]	82[9]	77[8]	108[9]	86[8]	87[9]
Yield (kg/ha)	3000[4]	2800[7]	7000[8]	4200[9]	5500[8]	3500[9]	3000[8]	2300[9]	5000[8]	4000[9]	4000[8]	3500[9]
Pesticides (g active ingredient/ha)	2200[10]	0[3]	500[10]	0[9]	520[10]	0[9]	630[10]	0[9]	280[10]	0[9]	1600[10]	0[9]
Work time (hours/ha)	7.5[4]	326.0[7]	5.2[8]	5.6[9]	4.3[8]	5.3[9]	5.0[8]	6.2[9]	5.3[8]	6.4[9]	5.3[8]	5.5[9]
Electricity drying (kWh/ha)	0[3]	0[3]	98[2]	59[2]	77[2]	49[2]	42[2]	32[2]	77[2]	56[2]	56[2]	49[2]
Oil drying (MJ/ha)	780[2]	840[3]	2100[2]	1260[2]	1650[2]	1050[2]	900[2]	690[2]	1650[2]	1200[2]	1200[2]	1050[2]

1 Agriwise (2018)
[2]Organic requires low energy for drying as a result of low yields per hectare. Cederberg and Flysjö (2004); [3]Cederberg et al. (2011); [4]Cremaschi et al. (2015)
[5]HIR Malmöhus (2015)
[6]Jordbruksverket 2019
[7]Knudsen et al. (2010)
[8]Länsstyrelsen Västra Götalands län (2018a)
[9]Länsstyrelsen Västra Götalands län (2018b)
[10]Nordborg et al. (2017)
[11]SOCA v.1 (Greendelta 2017)

Table 4
The emission factors for ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O) and nitrogen (N) leached from the soil from synthetic fertilizers and bio fertilizers, slurry spreading and excreta from grazing pigs.

Emission factors	kg (NH_3-N)/kg N	kg (NO_x-N)/kg N	kg N_2O-N/kg N (direct)	kg N_2O-N/kg N (indirect)	kg N leached/kg N
Synthetic fertilizer (ammonium nitrate)	0.03	0.029	0.01	0.01 (NH_3) + 0.011 (N leaching)	0.24
Bio fertilizer and slurry spreading	0.197	0.015	0.01	0.01 (NH_3) + 0.011 (N leaching)	0.24
Crop residues	0.197	0.015	0.01	0.01 (NH_3) + 0.011 (N leaching)	0.24
Excreta from grazing pigs	0.197	0.015	0.004	0.01 (NH_3) + 0.011 (N leaching)	0.24

Note: Data from IPCC (2019c)

is a measure of the oxygen consumed by water due to bacterial activity. The discharge of slaughterhouse waste results in increased demand for oxygen by water, which was assumed to be 1800 g per slaughter pig (Naturvårdsverket 2009). We assumed that a slaughterhouse in Sweden uses 0.45 m^3 water for a pig weighing 120 kg liveweight (Naturvårdsverket 2009).

It was assumed that the meat was transported 50 km from the slaughterhouse to the distribution point in a refrigerated truck with carbon dioxide refrigeration. Emissions and resource use for 1000 kg of pork fork weight were retrieved from Ecoinvent 3.3 (Ecoinvent 2016).

3.2.1.5. Wholesaling and retailing. It was assumed that pork from the slaughterhouse was sold to a vertically integrated retailer (i.e. wholesaling and retailing were done by the same actor), that 10 days would elapse between slaughter and consumer purchase, and that the meat was transported 50 km in a truck with carbon dioxide refrigeration from the distribution point to the retail store. The electricity required for meat storage was set at 11.7 kWh per m^3 (Carlsson-Kanyama 1999). We also assumed that pork would require 2.23 m^3 of space per tonne during transportation and storage (Baker et al. 2012). Emissions and resource use for transportation were calculated per tonne km using emission factors retrieved from Ecoinvent 3.3 (Ecoinvent 2016).

3.2.1.6. Consumption. The cooked fork weight of pork was assumed to correspond to 36% of the live weight of the slaughtered pigs (Åsa Öberg Jordbruksverket personal communication 2020). We assumed that consumers need to travel 200 km per 1000 kg of pork live weight (retail weight 59% of live weight) (Edström et al. 2005), and that each consumer used a small petrol (1.6 liter engine capacity) car for shopping. We also assumed that 195 kWh of electricity would be used for 1000 kg pork live weight (590 kg of pork retail weight) in cooking and refrigeration (Edström et al. 2005), together with 5 kg of water to wash dishes for every 1 kg pork fork weight prepared. The emissions to air and water and resource use were calculated using emission factors from Ecoinvent 3.3 (Ecoinvent 2016).

3.2.2. Economic inventory

Costs for the inputs required to produce 1000 kg of pork fork weight were calculated based on the input requirements in the four subsystems and each input's unit cost (see Table S7 in the supplementary). The costs include the operational costs and are presented in Table S8 in the supplementary. For labor costs, we multiplied the cost of labor (salary and social benefits) per hour, i.e. 260 SEK per hour for farm labor, which was indexed from 206 SEK in 2012 (LRF 2012) to the cost in 2017 and 370 SEK per hour for the slaughterhouse, wholesaler and retailer as the average labor cost per hour in 2017 (Ekonomifakta 2020) by the work hours calculated for crop production from Table 3 and pig production work hours described in section 3.2.3.

3.2.3. Social inventory

Social Risk Time (SRT), an indicator of risk used in an S-LCA, is calculated based on i) the activity variable (T), and ii) the Social Risk (SR) (Greendelta 2017) – see section 3.3.3. For the stakeholders *workers, value chain actors, local community* and *society* the activity variable was the work hours needed either to produce 1000 kg pork fork weight or to produce pork from 1000 hectares of land. The activity variables were used as input in Soca v1. The Soca database includes a range of indicators to capture social impacts of different sectors on different stakeholders. Values for the indicators are collected from primary or secondary sources for the list of social sustainability concerns shown in Table S1 (Greendelta 2017). For example, the percentage of children in employment, is an inventory indicator for the stakeholder *workers*. Social Risk is the risk assigned to the inventory indicator. The Social Risk value indicates the potential negative social impacts based on a reference scale (from 0 – no risk, to 100 – very high risk). Hence, it provides a way of normalizing indicator values so that social impacts can be aggregated. In most cases, the reference scale has six performance points: no risk (0), very low risk (0.01), low risk (0.1), medium risk (1), high risk (10) and very high risk (100) (Greendelta 2017). Continuing with our earlier example (% of children in employment), the value in Brazil's soybean sector was 4.2% in Soca v.1 (Green Delta 2017). This meant that the Social Risk (SR) was low and equal to 0.1, because Soca v.1 defines low risk when the percentage of children in employment varies between 2.5 and 5(Greendelta 2017). We used the Soca v.1 database for the SR and inventory indicators for the stakeholders *workers, local community, society* and *value chain actors*. For the activity variable on the farm, we used work hours spent in crop production in Table 3. To calculate the work hours for pig production, we assumed 15 hours per sow and year and 0.2 hours per slaughter pig in the conventional pork supply chain (Länsstyrelsen Västra Götalands län 2018a) and 33 hours per sow and year and 0.8 hours per slaughter pig in the organic pork supply chain (Länsstyrelsen Västra Götalands län 2018b). For the slaughterhouse, the total labor hours for the production of the retail weight that results in 1000 kg pork fork weight were assumed to be 2.7 hours (Zira et al. 2020). We assumed that work hours were 1 hour per 1000 kg pork fork weight for the wholesaler and retailer, because it was difficult to ascertain actual time given the huge assortment of goods handled at wholesale and in the supermarket.

The activity variables for *pigs* and *consumers* were calculated (see Table S9 in the supplementary) and used as input in the calculation of social impact in Excel. The activity variable for pigs was pig life days calculated as the product of the number of pigs required to produce the functional unit and number of life days on the farm and at the slaughterhouse. The activity variable for *consumers* was people consumption days, which is the quotient of the functional unit (1000 kg pork fork weight), and average pork consumption per capita per day in Sweden, which is 40 g. (Åsa Öberg Jordbruksverket personal communication 2020; Zira et al. 2020). Social impacts on *pigs and consumers* could not be calculated in Soca (Greendelta 2017) as the indicators for these were not present in Soca. We, therefore, used inventory indicators (see column *Inventory indicators for each subsystem and reference scale*) and Social Risk values (see column *Conventional SR = z and Organic SR = z*) in Table S10-S12 in the Supplementary (same as in Zira et al. (2020)), but the performance reference scales were aligned with those in Soca to calculate social risk using the method in Zira et al. (2020). Soca has data for 189 countries in it, close to 15,000 sectors, detailed and differentiated by their commodities and industries. We created sectors for the wheat bran, slaughterhouse, wholesaler, retailer and consumers because these did not exist in Soca. We also created a sector for soybean production in China, adjusting the social parameters to suit Chinese production conditions. For the soybean production sector in Brazil, we used the existing sector in Soca. We also used existing sectors in Europe for cereal crops, faba bean, rapeseed, rapeseed meal, soybean meal expeller and mechanical extraction methods, ammonia nitrate, single super phosphate, potash, pesticides, tap water, light oil and diesel, and for pig housing. When data from Sweden was missing in Soca, we used the country most similar in production and structure (e.g. for cereal crops we used Germany). We used the Swedish electricity mix for electricity supplies in Sweden in the conventional pork supply chain and for the wholesaler, retailer and consumers in the organic pork supply chain. For electricity in the organic pork supply chain, we used Norway's electricity mix, because Norway has the highest proportion of renewable electricity in its electricity mix in the world, 96.54% (Global Petrol Prices 2020). We used Swedish solar electricity for pig housing in the organic pork supply chain. We adjusted inputs and outputs for crops, pig production, slaughter, wholesaling and retailing and consumer according to our inventory data from Sweden.

3.3. Impact assessment

We used mid-point impacts in the characterization of the environmental and social indicators. This section gives a detailed description of the characterization methods for environmental, economic and social impacts.

3.3.1. Environmental Life Cycle Assessment

Recipe midpoint 2016 (H) V1.13 was used for characterization (Goedkoop et al. 2013). The environmental impacts of pork production are a result of emissions of environmentally damaging compounds into soil, water and/or air, as well as use of resources such as land and fossil resources. We analyzed contribution to climate change (the global increase in temperature due to greenhouse gases) as Global Warming Potential over 100 years, including feedback loops (IPCC 2013). Eutrophication, i.e. the pollution state of aquatic ecosystems leading to increased biomass growth, was characterized as freshwater eutrophication (FEP) and marine eutrophication (MEP). Acidification, i.e. the decrease in pH values in the natural environment, was characterized as terrestrial acidification (TAP100). Fossil resource depletion, i.e. the reduction in the quantity of fossil resources, was characterized as fossil depletion (FDP). See Goedkoop et al. (2013) for descriptions of FEP, MEP, TAP100 and FDP in Recipe midpoint 2016 (H) V1.13. We analyzed the impact categories listed above because these are the most important impacts for pork (Noya et al. 2017; Reckmann et al. 2012). We also included potential species loss, marine, freshwater, terrestrial and human ecotoxicity, and agricultural land degradation, because these are important factors in the comparison of conventional and organic product supply chains (Van der Werf et al. 2020). Potential species loss, i.e. the difference in species richness between a reference ecosystem over time and an area with a given land use type, was characterized as Biodiversity Damage Potential (BDP) (Knudsen et al. 2017). BDP for a supply chain was the sum of the area required for cropping, where BDP for crop production was a product of the characterization factor for crop production multiplied by time and area used for crop production. The characterization factors were derived by dividing the species richness for the given land use by the reference ecosystem's species richness. Characterization factors relating to the potentially damaged fraction of plant species per square meter for different types of land uses are shown in Table S18 in the supplementary. The model has several limitations, e.g. it does not incorporate urban land use, and the biodiversity of species such as reptiles, mammals and birds is measured only indirectly.

Environmental toxicity (the negative effects of chemicals on organisms in their natural environments) was included as FET, MET, TET and HTP. Terrestrial ecotoxicity is dominated by the impacts of agricultural soil pesticide emissions (Borrion et al. 2012). By contrast, freshwater ecotoxicity is dominated by impacts from emissions of pesticide applied to agricultural soil and heavy metals leaked into freshwater bodies (Nemecek et al. 2016). Marine ecotoxicity is dominated by impacts of heavy metals emissions into marine water bodies (Borrion et al. 2012). With regards to toxicity in the human environment, human toxicity (carcinogenic) deals with carcinogenic substances using the World Health Organization evaluation of carcinogenic substances. The mid-point characterization factors for all the ecotoxicity indicators and human toxicity are 1.4 dichlorobenzene equivalents. In other words, the effects of substances emitted are divided by the effects of the chemical 1.4-dichlorobenzene (DCB), which is used as a reference (Goedkoop et al. 2013).

Agricultural land degradation, captured here by gain/loss of soil organic carbon, was included as soil carbon changes over 100 years in accordance with the Introductory Carbon Balance Method (ICBM) presented in Moberg et al. (2019). We used the ICBM method in our assessment of soil carbon changes. Thus we calculated the amount of carbon the soil stores, or loses, until it reaches a steady state when cereals, legumes, rapeseed and grass-clover ley are each cultivated on a hectare of land and then subtracted the steady state soil carbon amount from 100 tonnes carbon per ha, which is the reference carbon content in Swedish soils. The difference was then divided over a period of 100 years to obtain an annual change, i.e. the potential annual soil carbon changes per ha. Based on this it was assumed that cereals had a loss of 150 kg carbon per year per hectare, that soybeans and faba beans had each a loss of 190 kg carbon per year per hectare, and that rapeseed had a loss of 160 kg carbon per year per hectare. Grass-clover mixture production was assumed to lead to carbon capture of 270 kg carbon per year per hectare (Moberg et al. 2019). The land used for the different crops is shown in Table S18 in the Supplementary Material. This is a simplified assessment of soil carbon that does not account for differences in crop yields and the amount of manure between the two systems.

3.3.2. Life Cycle Costing

We used the method of Life Cycle Costing given by Konstantas et al. (2019). This was adjusted to include labor costs as outlined in section 3.2.2, as there is a large difference in the farm's labor requirements in conventional and organic pork supply chains, as shown in Table 3 and section 3.2.1. Under LCC we included operational costs excluding wages, interest, depreciation, rent, and taxes, and VA was then the amount that can be used for these excluded costs thus calculated as the difference between the product price and the LCC for each supply chain stage (Konstantas et al. 2020, 2019). The impact indicator used to investigate economic sustainability was the VA/(LCC + labor costs) ratio for each stage in the supply chain, i.e. farm, slaughterhouse, and wholesaler and retailer. The VA/(LCC + labor costs) ratio indicates whether the supply chain actor has a potentially viable business. This is not relevant for a consumer, and therefore we omitted consumers from the life cycle costing. The VA/(LCC + labor costs) ratio represents the value created at that particular stage in the chain. A higher VA/(LCC + labor costs) ratio is desirable and means more value is created by a supply chain actor.

3.3.2.7. Life Cycle Costs. These costs were calculated according to Konstantas et al. (2019) as follows:

$$LCC_P = CRM + CMA_P + CTR_P \tag{1}$$

$$LCC_S = CPA_S + CO_S + CTR_S \tag{2}$$

$$LCC_{W/R} = CD_{W/R} + CRE_{W/R} + CTR_{W/R} \tag{3}$$

where CRM denotes the costs of raw materials (fertilizer, seed, pesticides, diesel etc.),

CMA_P the costs of product manufacturing at the farm (excluding wages, salaries, interest, depreciation, rent, and taxes),

CTR_P the costs of transport for the farmer,

CPA_S the costs of packaging for the slaughterhouse,

CO_S the costs of operating the slaughterhouse (excluding salaries, interest, depreciation, rent, and taxes),

CTR_S the costs of transport for the slaughterhouse,

$CD_{W/R}$ the costs of distribution for the wholesaler and retailer (excluding salaries, interest, depreciation, rent, and taxes),

$CRE_{W/R}$ the costs of retailing for the wholesaler and retailer (excluding salaries, interest, depreciation, rent, and taxes),

$CTR_{W/R}$ the costs of transport for the wholesaler and retailer,

VA can be defined in more than one way. In the LCC approach by Konstantas et al. (2019) that we follow, VA is the benefit to a specific value chain actor arising from the difference between the price and the input costs of production. From another perspective, value added in a business can be described as the surplus beyond the customers' expectations and the gain in a company's share value, but this was not the perspective taken in our study.

3.3.3. Social Life Cycle Assessment

We used Social Risk Time (SRT) for all stakeholders as an impact indicator. The formula for calculating SRT is shown in equation (4).

$$SRT_{ij} = \sum_{k=1}^{J} \left(T_{ijk} * SR_{ijk}\right) \tag{4}$$

Where *i* denotes the stakeholder (e.g. workers), *j* denotes the inventory indicator (e.g. fair salary for workers), *k* denotes the subsystem (e.g. slaughterhouse) and *SRT* denotes Social Risk Time for stakeholder *i*, *Tijk* denotes the activity variable for stakeholder *i* for indicator *j* and subsystem *k* and *SRijk* denotes the Social Risk for stakeholder *i* for indicator *j* and subsystem *k*. The lower the SRT, the less risk there is of negative social impacts. Hence, low SRT is better when we are comparing two supply chains.

3.3.4. Life Cycle Sustainability Assessment

The organic pork supply chain's environmental, economic and social indicators were compared with those in the conventional pork supply chain using Relative Sustainability Points (RSP). An RSP score below 0.5 for the organic pork supply chain means that the chain is performing better than the conventional pork supply chain for the indicator in question, and an RSP score above 0.5 indicates the opposite. The RSP score for an indicator ranges from 0-1. Formulas (5) and (6) were used to calculate RSP: when a *higher* value for an indicator reflects a more negative impact, for example GWP100, and

$$RSP = 1 - EXP(LN(0.5) * INDorg/INDconv) \tag{5}$$

when a *lower* value for an indicator reflects a more negative impact of an indicator, for example VA/(LCC + labor costs)

$$RSP = EXP(LN(0.5) * INDorg/INDconv) \tag{6}$$

where INDorg and INDconv are the environmental, economic or social indicator values for organic and conventional pork production, respectively.

3.3.5. Sensitivity Analysis

We carried out twelve sensitivity analyses using the product functional unit: i) inclusion of agri-byproducts as feed, ii) change in crop yields, iii) change of nitrogen leaching during grazing, iv) change in soil carbon method, v) change of fuel type used in the car used by the consumer, vi) change in the biodiversity model, vii) change in the mineral fertilizer production emission factor, viii) access to the outdoor environment in the conventional system, ix) change of country producing soybean, x) increase or decrease in the international market price of soybean, xi) change in the producer price for slaughter pigs and xii) increase in salary by 5% on the farm. For the sensitivity analyses, a change in crop yields and pigs' access to the outdoor was carried out across all the three sustainability pillars.

In the diet for slaughter pigs, we did not consider the use of agri-byproducts from the food and energy industry (e.g. wheat distillers can be used in conventional pig diets as a protein source, especially for slaughter pigs). For the environmental impacts per unit product, we conducted sensitivity analyses of the effect of inclusion of 31 kg dry matter of agri-byproducts from the food and energy industry in the total feed intake of a slaughter pig between 30 kg and the slaughter weight by substituting 80% of the soybean, 77% of the rapeseed and 44% of the faba bean used. We assumed that the agri-byproducts came free from environmental burden, i.e. their environmental impact was zero. We also examined the effect of a ±20% higher yield change for one crop at a time and a change to the lowest value of nitrogen leaching during grazing described in IPCC (2019c).

Soil carbon change is an indicator of soil quality, but it is difficult to assess because it depends on climate, on soil type and on agricultural land-use practices. We used a different model, supplied by the IPCC to be used in national greenhouse gas inventories (IPCC 2019b), which is based on multiplication of the reference carbon stock with the negative carbon stock change factors from land use, management factors and inputs, and thereafter added the amount of carbon stored to the reference stock, to see how the results would be affected by a change in the model. The consumer's car was switched from one using a fossil fuel to one running on electricity to analyze the change in impacts, since an electric car was assumed to be more environment-friendly than an internal combustion engine car. An alternative biodiversity model, proposed by Chaudhary and Brooks (2018), was used, because it assesses biodiversity for reptiles, mammals and birds, tracking potential species loss directly and not indirectly as the model by Knudsen et al. (2017). However, the Chaudhary and Brooks (2018) model is set on a larger spatial scale and thus does not specifically capture the differences in organic and conventional production.

About 66% of nitric acid plants in Europe have low-temperature tail-gases in the production process. This rules out high-temperature-dependent decomposition of nitrous oxide (IPCC 2006c). However, modern plants using catalytic cleansing technology, which cuts up to 90% of nitrous oxide emissions in nitric acid production, have low greenhouse gas emissions for ammonium nitrate fertilizer manufacturing (3.5–3.6 kg CO_2 eq per kg N in ammonium nitrate (Yara 2020; Berglund 2017)) than the average of ammonium nitrate on the Swedish market (5 kg CO_2 eq per kg N in ammonium nitrate (Greppa näringen 2011)). We therefore analyzed the change to entire use of ammonium nitrate from a modern plant.

In our sensitivity analyses for the social impacts we asked whether importing soybean from a European country would affect the results. The change in social impacts of allowing pigs access to the outdoor environment were studied for the conventional supply chain.

We carried out sensitivity analyses of the economic impacts of a change in soy prices i.e. ±32% change according to the changes in the last five years (World bank 2020a), ±20% change in pork producer price, also according to changes in the last five years (Jordbruksverket 2020), ±20% change in crop yields and access to the outdoor environment for the product indicators, all in the same fashion as the environmental and social impacts. We also performed a sensitivity analysis for a 5% increase in salary on the farm and also a total removal of labor costs from VA/(LCC + labor ratio).

4. Results and discussion

4.1. Environmental Life Cycle Assessment

The environmental impacts per 1000 kg pork fork weight showed that the conventional pork supply chain had 7-23% lower environmental impacts than the organic pork supply chain for FEP, MEP, TAP100 and FDP. The organic pork supply chain had 4-54% lower environmental impacts than the conventional pork supply chain for BDP, FET, MET, TET, HTP and SCL100. GWP was the same for both supply chains. Results of the environmental analysis are shown in Table 5. When the environmental impacts were expressed per 1000 ha of farmland used, the organic pork supply chain had 38-80% lower environmental impacts than the conventional pork supply chain in all impact categories. The lower environmental impacts in organic production per area are due to fact that organic agriculture uses less inputs per hectare besides fuel. In the organic supply chain, the use of renewable sources of electricity such as wind, solar and hydro, fuel-efficient driving techniques and non-use of inorganic fertilizers and pesticides did not offset the increased environmental impacts created by lower yields and more polluting manure handling for the indicators FEP, MEP, TAP100 and FDP. However, as a result of the avoidance of synthetic pesticide use in organic production the toxicity indicators (FET, MET, TET and HTP) were lower in organic production both per kg product and per hectare.

Feed production substantially influences most of the environmental impacts on the two pork supply chains and therefore it is a hotspot. With GWP100, for example, the biggest impact factor was feed production (i.e. crop inputs, cultivation and processing), which was 67% for the conventional pork supply chain and 68% for the organic pork supply chain, as shown in Fig. S1 in the supplementary. These results are consistent with conclusions from previous European studies reporting that feed production contributed between 50% and 85% of the impacts of GWP100 in pork production (Six et al. 2017; González-García et al. 2015; Reckmann et al. 2013; Pelletier et al. 2010; Dalgaard et al. 2007). By contrast, post-farm stages (slaughter, wholesaler and retailer, and storage and preparation by the consumer) contributed only 9% and 8% to total GWP100 in conventional and organic pork supply chains, respectively.

GWP had the same value for both pork supply chains because the low yields in crop production, high feed intake by pigs and higher use of diesel for mechanical operation in crop production in the organic pork supply chain annulled the avoided emissions from the production of inorganic fertilizers.

The organic pork supply chain exhibited lower impacts for FET, MET, TET and HTP because no pesticides were used in it for crop production. However, both pork supply chains led to emissions of toxic metals such as copper, nickel, chrome and zinc caused by the mining of raw minerals (e.g. the copper used for electricity generation and transmission). Heavy metals such as cadmium, similarly, were emitted in deposition, with the organic supply chain having slightly higher levels of deposition as a result of its greater land use. Soil liming products used in both pork supply chains also contributed heavy metals such as cadmium in the soil.

The lower BDP in the organic pork supply chain can be explained by lower biodiversity losses on the organic cropland (Table S18). This is in line with previous research, which has found, on average, a 30-50% higher plant species richness in organic farming systems than in conventional farming systems (Tuck et al. 2014; Bengtsson et al. 2005). However, if the model described by Chaudhary and Brooks (2018) is applied, the conventional pork supply chain performs better than its organic counterpart in poten-

Table 5
Environmental impacts for production of 1000 kg pork fork weight and 1000 ha of farmland in the pork supply chains (higher of the two marked in bold).

Impact category	Units	Impacts per 1000 kg pork		Impacts per 1000 ha farmland	
		Conventional	Organic	Conventional	Organic
Global warming potential 100	kg CO_2 eq	7 100	7 100	**3 900 000**	1 800 000
Freshwater eutrophication	kg P eq	2.7	**3.1**	**1 500**	800
Marine eutrophication	kg N eq	110	**130**	**61 000**	33 000
Terrestrial acidification 100	kg SO_2 eq	200	**260**	**110 000**	68 000
Fossil depletion	kg oil eq	1 300	**1 400**	**720 000**	360 000
Biodiversity damage potential	Potential disappeared fraction	**12 000**	9 000	**6 700 000**	2 300 000
Freshwater ecotoxicity	kg 1.4 DCB eq	**85**	80	**47 000**	21 000
Marine ecotoxicity	kg 1.4 DCB eq	**77**	74	**43 000**	19 000
Terrestrial ecotoxicity	kg 1.4 DCB eq	**10**	4.6	**5 500**	1 100
Human toxicity potential	kg 1.4 DCB eq	**2 000**	1 700	**1 100 000**	430 000
Soil Carbon loss 100	tonne carbon	**0.29**	0.26	**160**	66

GWP100 does not include emissions associated with soil carbon losses

tial biodiversity loss, because there is less difference in characterization factors between the different land-use management practices in this model. The model variance here is a result of lower resolution in Chaudhary and Brooks (2018) that does not capture the difference between organic and conventional land use. This is a valuable reminder of the significant influence of the method used to assess impacts of biodiversity and the need for further research in this area.

The organic pork supply chain used twice as much land at the farm, as shown in Table S18 in the supplementary. All the land used for feed production at the farm in the conventional pork supply chain was for annual crop production, whereas this was 80% in the organic pork supply chain, with the remaining 20% being used for grass-clover leys in rotation. The carbon sequestrating from the grass-clover leys compensated for the cropping's carbon loss per kg of meat. Soil carbon changes are difficult to capture and model, as they are highly site-specific and influenced by a range of factors that are seldom available for all the land involved in the supply chain (e.g. different fields at the farm and fields used for imported feed). In the soil model used here (ICBM), the soil carbon changes for different crops can be calculated. This is not possible using the IPCC model owing to the blanket stock change factors for all cropping. The IPCC model shows that SCL was 0.55 tonnes carbon per 1000 kg pork fork weight in the conventional pork supply chain and 0.88 tonnes carbon per 1000 kg pork fork weight in the organic pork supply chain. The conventional pork supply chain performs better than its organic counterpart. The results also heavily depend on the proportions of annual crops and leys. Without the 20% ley in crop rotations the organic pork supply chain has a soil carbon loss of 0.49 tonnes carbon per 1000 kg pork fork weight and this is higher than in the conventional pork supply chain.

In general, the climate impact of pork found in this study compares well with previous E-LCA studies on pork. Most of these studies have the farm gate as a system boundary and use a functional unit of live weight or slaughter weight (75% of live weight). Our value at the farm gate was GWP 2.5 kg CO_2 eq per kg slaughter weight when agri-byproducts are included and 2.6 kg CO_2 eq per kg slaughter weight when agri-byproducts are not included – a finding that was in the same range as a recent study by RISE (2020). Compared with other European studies, GWP was comparable for conventional pork for a kg of slaughter weight at farm gate (Reckmann et al. 2013; Dalgaard et al. 2007 and Williams et al. 2006). Concerning GWP at the retail gate, our GWP value of 3.6 kg CO_2 eq per kg retail weight (59% of live weight) was in the range found in another recent study (Moberg et al. 2019). Our results for FEP, MEP, TAP100, FET, MET and TET were also in line with a recent LCA study from Spain by Noya et al. (2017), which calculated 18 environmental indicators for pork. In the conventional pork supply chain having the slaughter gate as the system boundary in order to compare with Noya et al. (2017), indicates that 94-99% of the total impacts of FEP, MEP, TAP100, TET, FET, MET and HTP come from inputs, crop cultivation and pigs as shown in Fig. S2 to S8 in the supplementary. Our results for FDP are a departure from Noya et al. (2017). We had lower fossil fuel use for the farm and feed production stage (see Fig. S9) when compared with Noya et al. (2017) as a result of differences in distances travelled for transportation of farm inputs such as fertilizer, seeds and also pigs to the slaughterhouse. The distances in Spain are much longer than the distance we assumed for Sweden, so more fuel is required per kg pork. However, temperatures in Sweden are much lower, requiring more heating at the slaughterhouse per kg pork.

The sensitivity analysis results show that an increase in wheat and barley yields, together with the inclusion of agri-byproducts, reduced all environmental impact categories (Table S13). Replacement of soybean, rapeseed and faba beans in the total feed intake with agri-byproducts has a larger effect than increasing the yields for wheat and barley yields, especially on FEP, BDP, TET and SCL100. The large reductions in FEP were due to reduced leaching as a result of less soybean production and faba bean production, and in BDP the reductions in impacts were largely due to lower land use in the savanna biome for soybean production. The tropical savanna biome has higher species richness than temperate biomes (Cherubini et al. 2015). The reductions in carbon loss were associated with fewer losses resulting from less legume production. However, agri-byproducts are not free from impacts as such, and reductions in total impacts are not as high when the impacts of the agri-byproducts are taken into account. Thus, for example, when the GWP impact for agri-products was considered using economic allocation, GWP impact per kg pork was reduced by only 1%, whereas when the agri-byproducts were treated as free of environmental burden, the reduction was 7% (RISE 2020). The differences between our value of 4% when agri-byproducts are assumed to be free from environmental burden and 7% (RISE 2020) was that in our sensitivity analysis we replaced feed for slaughter pigs only and did not consider agri-byproduct use for the dry sows.

The use of an electric car decreased HTP by 5%, FEP by 3%, FDP by 2% and GWP by 1% in the conventional pork supply chain. The corresponding reduction figures for the organic pork supply chain were: HTP 6%, FEP 3%, FDP 2% and GWP 1%. Access to an outdoor environment increased MEP by 27%, TET by 17%, FEP by 3%, GWP by 1%, HTP by 2% and TAP100 by 9% in the conventional pork supply chain. This means that the provision of outdoor access increases negative environmental impacts, especially for MEP, as a result of N leaching caused by spatial and temporal distribution of N following pig movements in the outdoor area. The sensitiv-

Table 6
Value Added over Life Cycle Costs plus labor costs ratio (expressed in Swedish krona) for 1000 kg pork fork weight and 1000 ha of farmland in the pork supply chains.

	Impacts per 1000 kg pork		Impacts per 1000 ha farmland	
Indicator	Conventional	Organic	Conventional	Organic
VA/(LCC + labor costs) farm	1.1	0.83	1.1	0.83
VA/(LCC + labor costs) slaughterhouse	5.1	4.9	5.0	4.9
VA/(LCC + labor costs) wholesaler and retailer	13	27	13	26

VA- value added
LCC – Life Cycle Costing

ity analysis indicates that GWP emissions are 4% lower when all the ammonium nitrate used is produced using the N_2O reduction technology that reduces nitrous oxide emissions by 90%.

4.2. Life Cycle Costing

Our results showed that the VA/(LCC + labor costs) ratio for pig farmers in the conventional pork supply chain was higher than that for farmers in the organic pork supply chain. Farm production in the conventional pork supply chain generates more value than the organic equivalent for every SEK invested in LCC + labor costs per 1000 kg pork fork weight and 1000 ha of farmland used, as shown in Table 6. The VA/(LCC + labor costs) ratio for the pig farm in the organic pork supply chain was less than 1, suggesting that a farmer creates less value compared to the amount invested for LCC and has less money remaining to meet expenses such as interest, depreciation and also make a profit in the end. However, here we considered neither the value of ecosystem services provided by the farm nor the fact that farmers often work without remunerating themselves. The later however cannot be considered economically sustainable. When the results were expressed per 1000 ha farmland used instead of per 1000 kg pork fork weight, the conventional pork supply chain still performed better than its organic counterpart at the farm, reflecting greater economic activity (i.e. higher production) per hectare. There was no difference between VA/(LCC + labor costs) ratio for the 1000 kg pork fork weight and 1000 ha farmland used, because the increases in value added and costs were proportional. The conventional pork supply chain has the higher VA/(LCC + labor cost) for the farmers, and the organic pork supply chain has the higher VA/(LCC + labor cost) for other supply chain actors, indicating that the increased willingness to pay for organic meat among consumers does not reach the farmer. However, it should be noted that for the wholesaler and retailer, VA/(LCC + labor costs) was larger than it was for other chain actors, partly as a consequence of vertical integration (i.e. one and the same actor performing wholesaling and retailing).

Measured per 1000 kg pork fork weight, the LCC + labor costs at the farm were 1.5 times more in the organic pork supply chain owing to higher labor cost and costs related to lower efficiency (e.g. more feed required per kg pork and lower crop yields in the organic supply chain: see Table S8 in the supplementary). Moreover, value-added (VA) at the farm was almost twice as high in the organic pork supply chain than it was in the conventional pork supply chain as a result of the higher price for organic pork (see Table S14 in the supplementary). Measured per 1000 ha of farmland, the organic pork supply chain had 19% higher costs at the farm than the conventional pork supply chain (see Table S8 in the supplementary). Value-added was also 8% higher at the conventional farm (see Table S14 in the supplementary) and there was a large difference between the conventional and the organic pork supply chain in labor costs at the farm (Fig. S10).

The organic pork supply chain had higher VA/(LCC + labor costs) for the slaughterhouse, and for the wholesaler and retailer, than the conventional pork supply chain. This can be explained by the substantially higher selling prices both at the slaughterhouse (17 SEK/kg slaughter weight for conventional and 35 SEK/kg slaughter weight for organic) and at wholesaler and retailer (respectively, 42 SEK/kg retail weight and 67 SEK/kg retail weight) (Lars Jonasson personal communication 2020) when these are compared with LCC which are the same for both supply chains (see Table S8 in the supplementary). There was also a huge increase in value at the end of the supply chain because low costs were associated with vertical integration, post farm actors had higher margins and also because we did not consider processed meats but only fresh raw meat. The results emphasize that farmers do not generate value as other chain actors do. The large difference in VA/(LCC + labor cost) ratio between the wholesaler and retailer and the farmer is an example of the unequal distribution of profits across food chain actors in the EU reported by Kelly (2019), an inequality we found to be especially pronounced in the organic pork supply chain.

The VA/(LCC + labor costs) farm results for this study show that conventional pig production created more value than the life cycle and labor costs when compared to organic pig production, indicating a higher opportunity of profitability than in organic pig production. However, profits in organic production vary: some farmers report higher profits while others have indicated lower profits when compared to conventional production (Larsson 2014). Confidentiality issues mean that we have no empirical studies to the best of our knowledge indicating gross profit margins or net profits for pig production in Europe generally.

Change in pork producer price has the greatest effect on the VA/(LCC + labor costs) ratio, followed by soy price change (Table S15). Change in wheat and barley yields have a notable effect in comparison with other crops produced at the farm because they are the main feed ingredients. The conventional pork supply chain still performs better than the organic pork supply chain at the farm when soybean price and pork producer price are altered in the sensitivity analyses. Access to an outdoor environment decreased the VA/(LCC + labor costs) ratio for the conventional farm by 11%. This means that providing pigs access to outdoor environment has a negative economic effect, given that it is not used in marketing conventional pork, which could raise the consumer price of the pork. A 5% increase in salary decreased the VA/(LCC + labor costs) ratio for the farm by 2% in both pork supply chains. Removing labor costs (as they vary from farm to farm) and thus having the VA/LCC ratio, results in both supply chains creating more value than the amount invested for LCC. The conventional pork supply chain has VA/LCC equal to 1.7 and organic pork supply chain has VA/LCC equal to 1.4 at the farm, but these are still below the other value chain actors.

4.3. Social Life Cycle Assessment

The social assessment per 1000 kg of pork fork weight produced showed that the organic pork supply chain performs better (i.e. has a smaller SRT) than the conventional pork supply chain for *value chain actors, society, consumers* and *pigs* (see Table 7). In

Table 7
The Social Risk Time for 1000 kg pork fork weight and 1000 ha of farmland in the pork supply chains (higher of the two marked in bold).

Stakeholder	Units	Impacts per 1000 kg pork		Impacts per 1000 ha farmland	
		Conventional	Organic	Conventional	Organic
Workers	Medium risk hours	52 000	**56 000**	**29 000 000**	14 000 000
Local community	Medium risk hours	74 000	**93 000**	**43 000 000**	24 000 000
Value chain actors	Medium risk hours	**48 000**	31 000	**27 000 000**	8 600 000
Society	Medium risk hours	**69 000**	46 000	**39 000 000**	12 000 000
Consumer	Risk people days	**44 000**	19 000	**25 000 000**	4 900 000
Pigs	Risk pig life days	**280 000**	130 000	**160 000 000**	32 000 000

contrast, the conventional pork supply chain had smaller SRT for *workers* and the *local community*. This is explained by higher values of the activity variables in the organic pork supply chain (where more working hours are needed to produce 1000 kg of pork fork weight than are needed for the conventional pork supply chain) and the larger SRs in the organic pork supply chain. An increase in working hours has a positive impact on employment, which is favorable from a societal point of view, but when the work is associated with higher social risks, as captured by the SRs, this gives a large SRT, and this is unfavorable. The social assessment per 1000 ha of farmland confirmed that the organic pork supply chain performs better for all stakeholders. This outcome was due to there being less economic activity per hectare, giving lower output and hence lower activity variables.

The higher SRT for *workers* for the organic pork supply chains resulted from differences in values relating to the gender wage gap, trade unionism and risk of violation of employment laws and regulations, as shown in Table S16 in the supplementary. Most of the impacts in the organic pork supply chain emanate from soybean production (Fig. S11). Soybean is imported from China in the organic pork supply chain, whereas in the conventional pork supply chain it is sourced in Brazil. If certification schemes such as the Roundtable on Responsible Soy (RTRS) for conventional soybean and KRAV for organic soybean are not working properly, the risks become higher. Assuming the schemes are not working properly, SRT increases by 2% for *workers* in Brazil and 16% for *workers* in China. These results were expected given China's lower human freedom rankings than Brazil's (Vásquez and Porčnik 2019).

The differences in SRT for the *local community* were caused by difference in fossil fuel consumption, international migrant stock and non-fatal accidents in electricity generation and distribution. The use of renewable energy from solar sources at the pig farm in the organic pork supply chain resulted in higher social impacts for *workers* and the *local community* because there are more accidents in renewable energy production (Fig. S11). This has also been reported by Stamford and Azapagic (2012) in a life cycle sustainability assessment of electricity in the United Kingdom. The organic pork supply chain used more diesel, especially for wheat and barley production due to mechanical weed control, since pesticides were not used. The yields were lower here, and more feed per kg pork was required. More light fuel oil for drying crops was also required, because of more feed as well.

The differences in SRT for *value chain actors* were caused by differences in values for corruption in Brazil and China. These results accord with Brazil's lower transparency rankings than China's (Transparency International 2020). For *society*, the differences in SRT were caused by differences in literacy and health expenditure between Brazil and China. These are indicators which, on a general level, capture the social situation in different countries. The results here were expected, because Brazil has a lower literacy rate than China (World Bank 2020b), and also because in Brazil the government contribution to health expenditure is lower, as a percentage of health spending per capita, than in China (World Health Organization 2020).

For some of the key inputs in the pork supply chain, Sweden was not fully represented in all sectors in Soca, and here, therefore, we used alternative countries with production conditions similar to those in Sweden. For example, for wheat production we used German social risk indicators. Obviously, this method relies on national similarities and can lead to the underestimation or overestimation of social impacts, so our results must be read with caution.

SRT depends on the weight of the indicators. In Zira et al. (2020) an expert panel was used in setting the weightings of the indicators. Here, no explicit weighting was undertaken, and all indicators were weighted equally. However, the way the scales are set up can create an indirect weighting. Thus, consider the indicator *percentage of pigs with bitten tails* (Table S12). This indicator has six levels of risk on the reference scale: no risk (0), very low risk (0.01), low risk (0.1), medium risk (1), high risk (10) and very high risk (100). Five percent of the pigs have bitten tails and this was assigned a low risk level, the activity variable for the indicator will hence be multiplied by 0.1, meaning a low contribution to SRT. Now compare an indicator like *percentage of tail-docked pigs* with just two levels, where no docking is set at no risk (0) and docking is set at very high risk (100). Here, if 5% of the pigs are tail-docked, the activity variable is multiplied by 100. It can be seen that the indicator *percentage of tail-docked pigs* has more weight because it has fewer performance reference points but the same starting point and endpoint as a normal reference scale with six reference points. The reference scales are context-specific and expert opinion was used to define them so that a weighting in between indicators was also performed. Defining different endpoints or risk levels for the worse option can be seen as an alternative to the differential weighting of different indicators employed by Zira et al. (2020) in a previous S-LCA on pork.

In Zira et al. (2020) a linear scale (with risk values between 0 and 1) was used. This resulted in the activity variable T (*i.e.* the time of exposure) having a large effect on SRT in comparison with social risk. Hence prolonged exposure at low social risk could result in considerably higher SRT than a high but brief social risk. As this may, in some cases, disfavor systems which require more time but have low social risk, Zira et al. (2020) used an index, the Social Hotspot Index, in which each system was compared with its respective worst-case scenario (when SR was at its maximum value) thereby cancelling the effect of T. In the present study, however, there was less need to do this, because an exponential reference scale (with risk values between 0-100) was used for SR, decreasing the importance of T at high social risk values.

As for *pigs* and *consumers*, the results we report here are comparable with those presented in our previous study (Zira et al. 2020). In other words, the organic pork supply chain has lower social risk for pigs and consumers than the conventional pork supply chain, because organic pigs have outside access and more opportunities to express natural behavior, and because organic pork meat is valued more highly by consumers. The results are less comparable for *workers, local community* and *society*, because in our previous study we dwelt on *direct* social sustainability issues raised against pork production that were collected for all the stakeholders whereas in this study we focus on a general social inventory of indicators for pork supply chains presented in Soca (Table S1). The general social inventory of indicators in Soca omits indicators of work-related ill health specifically associated with pork production, such as musculoskeletal disorders and direct assessment of pesticide toxicity for soybean production. Pesticide toxicity is, however, partly taken into account in *'presence of safety measures'*. They also do not include gender equality as measured by the number of males/females employed, the status of the production activity in society (e.g. pig farming may be considered a low status employment in Sweden), age discrimination, and access to products (e.g. through on-farm stores). All of these were considered in our previous study (Zira et al. 2020). Another reason for the discrepancy for *local community* and *society* is that the same activity variable, *work hours*, is used for all these stakeholders. In contrast, in our previous study (Zira et al. 2020), we used different activity variables for different stakeholders. We recognize that the change of the activity variable from *hectare days* in Zira et al. (2020) to *work hours* in the present study led to a decrease in SRT in the organic pork supply chain. In other words, there was a change from a larger activity variable based on the area of land used multiplied by *work hours* to a smaller activity variable based on *work hours* alone, and this resulted in the organic pork supply chain coming out, in respect of its impacts on society, than the conventional pork supply chain, when the two were compared per 1000 kg of pork fork weight, in a way that was not observed in Zira et al. (2020). It is arguably better to use *hectare days* because the social risk impact for *society* from crop production is influenced more by the amount of land used and the time between planting and harvesting for a crop than it is by *work hours*. This suggests that the best practice in assessing social risk impacts in S-LCA involving crop production might be to use *hectare days* for *society* as well as *local community* and *work hours* for workers and farmers as the activity variables. But more research is needed in this area.

The sensitivity analysis (Table S17) suggests that a change in the soybean source to a high-income country has a largely favorable effect on the social risk on *workers* and the *local community* in the organic pork supply chain but no effect in the conventional pork supply chain. This result indicates the difference in the social conditions of labor and human rights between China and Switzerland. It also illustrates the change in social risk that might occur if the soybean source is changed. We selected Switzerland because it produces organic and conventional soybean and is present in Soca. However, such a country may not be viable in reality, as low quantities of soybeans are produced in Switzerland (and indeed in Europe generally). There was no notable difference between Brazil and Switzerland for social impacts because trade unionism in Brazil is similar to that in Switzerland, according to the information in Soca. Brazil has 18 000 unions, and these can negotiate for better working conditions (Menezes-Filho et al. 2008). However, in China there is a single trade union system, the All-China Federation of Trade Unions (ACFTU), and its genuine willingness, or ability, to represent workers' interests has been contested, especially since its office holders are not elected themselves (Lambert and Webster 2017). There was also no notable difference between Brazil and Switzerland because Soca misses the indicators on work-related sickness, such as pesticide effects on deoxyribonucleic acid, which were captured in Zira et al. (2020). Change in the soybean source alters the result pattern: with this change, the organic pork supply chain performs better than the conventional pork supply chain for all stakeholders. The improvement of social conditions in China, or replacement of soybean with other protein sources produced in Europe, could reduce social risk impacts in the organic pork supply chain.

Increased access to the outdoor environment resulted in an 8% increase in impacts each for *workers* and *local community*, a 5% increase for *society*, and a 16% decrease in the impacts for *pigs*. Although providing access to the outdoor environment has some favorable effects for the pigs, it negatively affects other stakeholders since it raises work hours. The +20% yield change in wheat and barley (one at a time), each reduced impacts for all stakeholders by 2% and the -20% yield change in wheat and barley, each increased impacts for all stakeholders by 3% for the conventional pork supply chain. For the organic pork supply chain, the ±20% yield change in barley, changed impacts for all stakeholders by ±1%.

4.4. Life Cycle Sustainability Assessment

Relative Sustainability Point (RSP) scores range from 0 to 1, and the conventional pork supply chain is the benchmark (at 0.5) (Fig. 2). Low RSP (< 0.5) therefore means that the organic pork supply chain is more sustainable than the conventional pork supply chain. The organic pork supply chain performs worse than its conventional counterpart in 9 out of 20 product-based indicators when these are compared for the production of 1000 kg pork fork weight, mostly as a result of environmental indicators (Fig. 2). The organic pork supply chain outperforms the conventional for 18 of the 20 indicators when the results are expressed per unit area (Fig 2). This means that if decision makers emphasize the negative impacts pork supply chains have on the ecosystem per unit area of land, the organic system is preferable. However, for indicators such as eutrophication and acidification, the lower yields of the organic pork supply chain result in higher impacts on a product basis.

Access to outdoor environment improves social performance for pigs in the conventional pork supply chain. However, it leads to higher environmental impacts such as GWP and MEP per kg of pork, and to an increased risk of diseases such as toxoplasmosis (Kijlstra et al. 2004), higher social risk for workers, and greater feed costs (because more feed is required per kg pork) (Stern et al. 2003). This is in accordance with (Rossi and Garner (2014), Appleby (2005) and Hendrickson and James (2005), all of whom argue that animal welfare generates environmental costs and more expensive meat for society. This points up the difficulties involved in making improvements in all three sustainability pillars. The complexities here are due to unavoidable trade-offs between social and environmental sustainability and social and economic sustainability.

Improving soybean sustainability by increasing the cultivation of soybean in Southern Europe (Chancellor 2018) may reduce the social risk for the stakeholder category *workers* in the pork supply chain, as shown in the sensitivity analysis for soybean origin in the organic pork supply chain. This may not affect environmental impacts such as GWP and FDP, but it will lead to a reduction of the VA/(LCC + labor costs) ratio for pig farmers, as indicated in the sensitivity analysis for increased soybean price. This may also lead to loss of income opportunities for soybean producers in Brazil and China, an effect that our analysis of social impacts failed to capture. The use of robots in the pork supply chain, at the slaughterhouse (Valente et al. 2020) and possibly at the farms in Brazil or China, could reduce the social risk for labor-intensive activities, reduce labor costs and provide more jobs for educated and skilled labor, but it could also reduce employment for the less skilled (Marinoudi et al. 2019). This remains difficult to capture with attributional S-LCA and may be best captured by consequential S-LCA (Zamagni et al. 2011).

Incorporating agri-byproducts in the pigs' diets and increasing yields (without increased use of fertilizers) can improve the en-

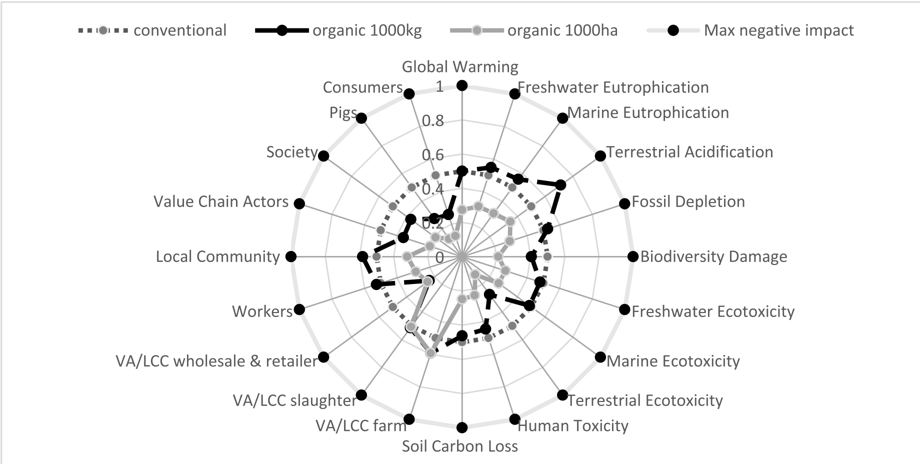

Fig. 2. Life cycle sustainability assessment in Relative Sustainability Points (RSP) for the organic pork supply chain for 1000 kg pork fork weight and 1000 ha of farmland with the conventional pork supply chain as the reference (RSP=0.5) with VA/LCC being the Value Added over Life Cycle Cost + Labor Costs.

vironmental impacts per kg pork, such as GWP, and the economic impact through a higher VA/(LCC + labor costs) ratio and lower social risk for *workers*, especially for soybean. Agri-byproducts exhibit a synergy between social, environmental and economic impacts. However, competition for byproducts for other uses, the cultural acceptability of byproduct use, and the fact that the availability of byproducts is driven by the main product, all limit the potential of using byproducts (van Zanten et al. 2018; Röös et al. 2016). Having more byproducts in pig diets going forward may therefore be difficult. Adjusting the pig population so that it is commensurate with ecological limits and the availability of byproducts could be a solution here (van Zanten et al. 2018). However, there will always be an opportunity cost, because byproducts are used or can be used for other purposes as well.

Assuming equal importance of economic, environmental, and social life-cycle indicators (i.e., equal weights), the most sustainable supply chain, when comparing different supply chains, is the one with lower RSP for most indicators. From an indicator expressed per unit area perspective, the organic pork supply chain is more sustainable (RSP organic < RSP conventional for 18 of 20 indicators). The increased competition for agricultural land and the increased demand for animal products are reasons for a product-based perspective, and then the assessment result is less clear (RSP organic < RSP conventional for 11 of 20 indicators). Another way to compare different pork supply chains is to define the most sustainable one as the one with most indicators with lower RSP for *both* indicators expressed per unit area and unit product. In this LCSA, the organic pork supply chain has lower RSP for 11 indicators expressed both per unit area and unit product, and the conventional pork supply chain has lower RSP for 1 indicator expressed both per unit area and unit product.

This study's results provide a basis for future planning of a new business model for reducing negative impacts of pork production without focusing on food provisioning alone. The pork supply chain, as envisaged in the new business model, should improve social welfare for stakeholders, including pigs, maintain or improve economic benefits and mitigate environmental impacts. Elements of the new model are likely to include allowing pigs access to distraction material or an outdoor environment, optimizing the use of by-products in pig diets, obtaining higher yields in organic production, and ensuring there is a viable producer price for slaughter pigs. Kelly (2019) reports challenges in food supply chains in the EU caused by the unfair distribution of profits in the supply chain. Our results could help farmer organizations in the pork supply chain to lobby for better conditions, and returns, for farmers in future.

Life Cycle Sustainability Assessment has the advantage of integrating environmental, economic and social indicators, and thereby showing the trade-offs between these three pillars of sustainability. However, the identification of suitable indicators is a challenging task, and indicator selection and scaling heavily influence results of the assessment. In addition, social and economic data are not available at the same level of detail as environmental data. A degree of arbitrariness remains in the design of the algorithm to calculate impacts, especially where social impacts are concerned. Other challenges revolve around the communication of results to decision-makers and the question whether the weighting and aggregation of the indicators enhances the overall interpretation. These should be further researched.

5. Conclusions

Assessed with the 20 indicators used in this LCSA, the organic pork supply chain is clearly more sustainable than its conventional counterpart when the assessment is based on indicators expressed per unit area (agricultural land). On the other hand, the greater quantity of feed required to produce a kg of pork and the lower yields in the organic pork supply chain cause the organic pork supply chain to perform less well for indicators expressed per unit product. Inevitably, the picture is complex. The organic pork supply chain performs better than the conventional one in terms of human toxicity and ecotoxicity, biodiversity loss, better pig welfare, lower social risk for *consumers, society* and *value chain actors*, and in delivering more value added at the slaughterhouse, and wholesaler and retailer, than the conventional pork supply chain. However, it performs less well than the conventional pork supply chain on a per kg pork basis for eutrophication, acidification, fossil resources use, and in the value added when a comparison is made with life cycle costs and labor costs at the farm, and the social risks for *workers* and *local community*. The organic pork supply chain promotes social well-being for pigs, but it consumes more resources, especially land, and has a higher leakage of nitrogen as a result of the greater amount of feed required to produce a kg of pork together with lower crop yields. The conventional pork supply chain is more resource-efficient, in that more pork is produced per unit area and in terms of the financial resources used, but pesticide use results in higher human toxicity and ecotoxicity.

The redesign of both pork supply chains is required to make them more sustainable, and this could include consideration of the following three points. Firstly, the need for an increase in wheat and barley yields (through improvements in managements and with limited additional inputs) because higher yields for these feed crops reduce environmental, social and economic impacts in both pork supply chains. Secondly, the need for improved animal welfare in the conventional pork supply chain in order for welfare to approach the organic pork supply chain, where pigs have indicated better welfare due to outdoor access, access to distraction material and the possibility to express natural behavior. Lastly, the farmers need to receive a fair slaughter price that results in at least Value Added over Life Cycle Costs plus labor costs ratio (VA/(LCC + labor costs)) equal to one, which is currently not the case for the studied organic pork supply chain. Trade-offs between environmental, economic and social sustainability should be considered in the redesigning of the pork supply chains.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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An assessment of scenarios for future pig production using a One Health approach

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HIGHLIGHTS

- A One Health framework can be used to analyse negative impacts of pig production.
- The impact of yeast protein on the *environment* was highly dependent on nitrogen source.
- Alternative protein including yeast was predicted to reduce impact for farmed *organisms* and *environment.*
- Access to a veranda and silage were predicted to reduce impacts on *environment, people* and farmed *organisms*.
- Access to pasture was predicted to reduce impacts on farmed *organisms* through better welfare but not on *environment* and *people*.
- A changed breeding goal was predicted to reduce impacts on the *environment, people* and farmed *organisms*.

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ABSTRACT

One Health is an approach to achieve better health and well-being outcomes for *people*, farmed *organisms* and their shared *environment.* The One Health approach was used to analyse the impacts on the *environment, people* and *organisms* (including the pigs) of three scenarios for future pig production to ascertain their strengths and weaknesses when compared with a Reference case reflecting today's pig production. The scenarios were: Business as usual scenario (AsUsual), Sustainable Feed scenario (SusFeed), and Sustainable Feed and Pigs bred for feed efficiency and better animal welfare scenario (SusFeedPig). In SusFeed, the pig diets were without soybean meal but with locally produced feed ingredients including yeast protein. The pigs had access to an outdoor veranda, silage and straw for enrichment, and were selected using today's breeding goal. In SusFeedPig, pigs had the same feed as in SusFeed, had access to pasture during summer and were selected using an alternative to today's breeding goal with focus on overall feed efficiency and improved animal welfare. In AsUsual, pigs were fed current diets including soybean meal, had no access to a veranda and silage, and pigs were bred based on today's breeding goals. The different scenarios were assessed using a One Health framework with 13 success metrics. The selection and scoring of indicators for success metrics may be subjective because they depend on individual assessments that can be variable. SusFeed performed better than the Reference case on nine success metrics, SusFeedPig on eight and AsUsual on six. Sustainability in all the future scenarios was improved when compared to the Reference case but SusFeed with the alternative breeding goal was the most preferable scenario due to reduced negative effects for the *environment, people* and farmed *organisms*.

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1. Introduction

Pig production accounts for 33% of global meat production and is the second largest meat production sector by volume after poultry (FAOSTAT, 2020). Pork contains important nutrients, but pig production and consumption also have negative health and welfare effects on people, such as farmers, workers and consumers, and also on the pigs. Pig production also contributes to raised antimicrobial resistance (Kempf et al., 2017). Future challenges in pig production include land scarcity and the need to mitigate negative effects on biogeochemical cycles i.e. carbon (C), nitrogen (N) and phosphorous (P) cycles.

Most of the environmental impacts of pork production arise from feed production (Zira et al., 2021). Thus, selection for increased feed efficiency is one way to reduce the environmental footprint of pork (Rauw et al., 2020). Soybean (*Glycine max*) meal and cake are important protein ingredients in livestock feed in Europe owing to their high crude protein content and favourable amino acid composition, especially with regards to lysine, the first limiting amino acid for pigs (Rauw et al., 2020). However, soybean cultivation has been associated with deforestation and high pesticide use (Landquist et al., 2020), therefore there is an urgent need for alternative protein sources. Yeast *(Cyberlindnera jadinii* and *Candida utilis)* is an interesting protein source because it can be produced from forest residues and thus reduce food-feed competition (Karlsson et al., 2021). The digestion process in pigs, manure management, and energy use at the farm also contribute to environmental emissions. A shift to renewable energy sources, such as second generation biodiesel (Holmgren and Hagberg, 2009), electricity generated from wind (Liu, 2017), and the use of ammonia as a marine fuel (Al-Aboosi et al., 2021), could reduce environmental impacts.

Indoor pig production is associated with controlled husbandry environment, N and P leakage, automatic routines, high growth rate and feed efficiency as well as easy detection and treatment of unhealthy animals. On the other hand, indoor pig production has animal welfare problems, such as increased risk of tail biting, and fewer opportunities to express "natural behaviour" like rooting. Pigs that do not have access to forage are more likely to develop abnormal behaviours (Brunberg et al., 2016), and thus fundamental changes in animal rearing, such as allowing outdoor access using a veranda, straw, or other roughage (e.g. silage), have been proposed (Sørensen and Schrader, 2019).

Despite its welfare benefits, outdoor pig production, with large space allowance and unhindered exercise, is associated with poor leg health in commonly used breeds (Wallenbeck et al., 2020), and with higher feed costs (Edwards, 2003). In addition, the expansion of wild boar (*Sus scrofa*) populations in Europe has increased the risk of infection by African Swine fever especially in the absence of strong biosecurity measures for outdoor pigs (Bonardi et al., 2019).

Negative impacts on the environment, economy and society have been evaluated for current pork production systems (Zira et al., 2021) and future pork production scenarios (Cederberg and Flysjö, 2004a) using life cycle assessment (LCA). The One Health approach has been suggested as a method of evaluating the sustainability of livestock systems (Stentiford et al., 2020). One Health is an approach to achieve better health and well-being outcomes recognizing the interconnections between *people*, farmed *organisms* (animals and plants) and their shared *environment* (One Health Commission, 2021), focusing on zoonotic and non-zoonotic diseases, occupational health, food safety and security, antimicrobial resistance, and environmental contamination (CDC, 2018). As a result of the health implications of changes in the interactions between people, animals and the environment, e.g. as a result of the intensification of farming, the One Health approach has become more important in recent times. The One Health approach has to date been applied mainly in studies of zoonotic diseases. However, Stentiford et al. (2020) have also applied it in designing a novel framework to capture a wide range of aspects relevant to the sustainability of aquaculture production.

The aim of this study was to use the One Health framework to quantitatively analyse and compare the strengths and weaknesses of three future scenarios (year 2040) of improved pig production. The study will contribute by providing new knowledge which can be used to develop sustainable pig production systems.

2. Material and methods

2.1. The One Health framework

We adapted the One Health framework for pig production, employing the success metrics used by Stentiford et al. (2020) for *people*, farmed *organisms* and the *environment*. The framework originally had 13 success metrics concerning policy and legislation. Here, we instead applied a set of indicators and a scoring method to assess outcomes related to these metrics in more detail. We describe the system and scenarios used, the indicators selected, and the scoring method in more detail in Sections 2.2–2.5.

2.2. Scenario description

We constructed three scenarios for pig production in the year 2040: Business as usual (AsUsual), Sustainable Feed (SusFeed) and Sustainable Feed and Sustainable Pig bred for high feed efficiency and improved animal welfare (SusFeedPig). The scenarios were intended to reflect future changes to pig production in Europe that could be anticipated at present (Table 1). They were compared with a Reference case designed to capture the conventional production system operating in Sweden in 2019/20.

AsUsual assumed that several current trends continue, such as continued use of soybean meal from certified Brazilian soybeans in the pig diets. Also, renewable electricity and third-generation biodiesel from forest waste products were used as energy sources, following an anticipated transition to fossil-free energy. The pigs were assumed to have undergone continuous genetic gain between now and 2040 reflecting the breeding goal used in today's pig production (Section 2.3.4). Feeding and housing were assumed to remain the same as today, with all pigs reared indoors.

In SusFeed, the soybeans were replaced by a local protein source in terms of yeast produced from second-generation sugar derived from hydrolysis of lignocellulosic biomass from low-value forest residues from spruce (*Picea abies*) (Øverland and Skrede, 2017; Cruz et al., 2019, 2020). Silage was fed to growing pigs as a total mixed ration and to sows as a separate feed to improve pig welfare. The breeding goal was the same as in AsUsual. Due to the assumption of low acceptance for indoor production in 2040, growing pigs were assumed to have access to an outdoor veranda.

The diets in SusFeedPig were the same as in SusFeed, but the breeding goal was changed to further improve feed efficiency and animal welfare. In addition, the pigs were kept on pasture during the summer season (Table 1). The relative economic weights used for breeding in SusFeedPig aimed for increased overall feed efficiency and improved animal welfare (Table S1). This resulted in increased growth, increased feed efficiency, and healthier pigs in SusFeedPig, whereas the current weights, as used in SusFeed, gave increased litter size (Table 2). In addition, meat quality was included in the breeding goal in SusFeedPig, to satisfy the consumer demand for quality as of today. The economic weights in SusFeedPig were adjusted so that none of the traits displayed an unfavourable genetic trend.

In SusFeed and SusFeedPig, silage was included as both a nutrient source and as enrichment for the pigs. In addition to the feed ingredients presented in Table 1, rapeseed *(Brassica napus)* meal, rapeseed cake, potato *(Solanum tuberosum)* protein and synthetic amino acids were present in all scenarios. It was assumed that there was a high competing demand for by-products or waste streams from the food industry, therefore, the diets in SusFeed and SusFeedPig contained only wheat *(Triticum aestivum)* bran and no other by-products like e.g. spent grain or

Table 1
Description of Reference case and three future scenarios in pork production

	Reference case	AsUsual scenario	SusFeed scenario	SusFeedPig scenario
Feed	Soybean meal	Soybean meal	No soybean meal	No soybean meal
	No yeast meal	No yeast meal	Yeast meal	Yeast meal
	Maize meal	Maize meal	No maize meal	No maize meal
	Wheat bran and other by-products	Wheat bran and other by-products	Wheat bran	Wheat bran
	Cereals, rapeseed, legumes produced at farm	Cereals, rapeseed, legumes produced at farm	Cereals, rapeseed, legumes and silage mixed to a total mixed ration produced at the farm	Cereals, rapeseed, legumes, and silage mixed to a total mixed ration produced at the farm
	Sows and growing pigs have no access to silage	Sows and growing pigs have no access to silage	Sows have access to silage and growing pigs have silage as a total mixed ration	Sows have access to silage and growing pigs have silage as a total mixed ration
Rearing and breeding	Pigs have no outdoor access	Pigs have no outdoor access	Pigs have outdoor access in the form of a veranda all seasons	Pigs are on summer pasture and have access to a veranda during winter
	Pigs receive a small daily amount of straw	Pigs receive a small daily amount of straw	Pigs receive a large daily amount of straw	Pigs receive a large daily amount of straw
	Todays' pigs (no genetic improvement)	Pigs selected in a conventional way	Pigs selected in a conventional way	Pigs selected for traits important for animal welfare and feed efficiency
Energy	Electricity from both non-renewable and renewable energy sources in Europe	100% of electricity from a renewable energy source in Europe	100% of electricity from a renewable energy source in Europe	100% of electricity from a renewable energy source in Europe
	100% diesel used as fuel in Sweden	100% Fischer-Tropsch (third generation) biodiesel produced from wood as feed stock	100% Fischer-Tropsch (third generation) biodiesel produced from wood as feed stock	100% Fischer-Tropsch (third generation) biodiesel produced from wood as feed stock
	100% heavy fuel oil as marine fuel	100% ammonia as marine fuel	100% ammonia as marine fuel	100% ammonia as marine fuel

dairy residuals. Full details of the diets are shown in Table S2. We assumed 2% feed waste in all scenarios (Schell et al., 2002).

2.3. System description

2.3.1. Pig production

Four theoretical pig production farms were modelled, one for each scenario. Each farm consisted of 100 sows, integrated with production of piglets and growing pigs, and all produced gilts for replacement. The growing pigs were housed in pens in groups. The pens were similar in all scenarios with a feeding, resting (solid floor) and defecating area (slatted floor). Straw was placed on the solid floor every day. In addition, the pigs in SusFeed and SusFeedPig had access to an outdoor veranda (Table 1). Pregnant sows were housed in groups in pens with deep straw bedding in all scenarios. The farms were assumed to be located in southern Sweden.

2.3.2. Pig feed and farm activities

Off-farm feed production involved eight foreground processes: the cultivation of soybean meal in Brazil, rapeseed meal and cake in Sweden, yeast meal in Sweden, maize (*Zea mais*) grain in Denmark, monocalcium phosphate in Germany, synthetic crystalline amino acids in Denmark, potato protein in Sweden, fish meal processing in Sweden, and two background processes – energy and transport (see Table S3 for more details).

The pig farms included four activities. i) The on-farm cultivation of feed crops – wheat, triticale (*Triticosecale*), oats (*Avena sativa*), barley (*Hordeum vulgare*), faba beans (*Vicia faba*), peas (*Pisum sativum*), rapeseed to be included as whole seed in the diet, and grass (*Lolium perenne*) and clover (*Trifolium pratense*) (grass clover and grass were only present in SusFeed and SusFeedPig). ii) Milling and mixing to make concentrate feed ingredients (all scenarios), and the fine cutting of silage and mixing with concentrate into a total mixed ration for finisher pigs, as well as the feeding of silage as a separate roughage feed for sows (SusFeed and SusFeedPig). iii) Pig husbandry (sows, gilts, and growing pigs) and pig grazing (SusFeedPig in the summer), and iv) Manure management.

2.3.3. Energy and fertilizer

In all three scenarios, electricity from 100% renewable sources was used because Sweden is aiming for 100% renewable electricity by 2040 (IRENA, 2020). Also, it was assumed that Fischer-Tropsch biodiesel was made using forest residues as feedstock (Holmgren and Hagberg, 2009). Ammonium nitrate for fertilizer was produced from green ammonia (Bicer et al., 2016), and a catalyst that reduced nitrous oxides emissions by 90% was used (Yara, 2020). We assumed ammonia was used as a marine fuel in internal combustion engines for ships in place of heavy fuel oil (Al-Aboosi et al., 2021). In the Reference case, 50% renewable electricity i.e. Swedish production mix today (IRENA, 2020), fossil diesel and ammonium nitrate with ammonia from hydrogen produced from steam methane reforming process were used. Transport included transportation of goods used and produced in and by the activities described above. To simplify, we excluded impacts for machinery and buildings in all scenarios.

2.3.4. Pig breeding

A terminal three-breed cross ((Yorkshire x Landrace) x sire breed) is common in pig production to take advantage of maternal and individual heterosis. In our theoretical breeding model, we created a synthetic breed representing all three breeds and their breeding goals. The fictitious pig farms used artificial insemination and we assumed that the impacts from boar husbandry were small owing to a high number of semen straws per boar. A breeding scheme was simulated with *SelAction* (Rutten et al., 2002) to estimate average values for production, reproduction and health traits in 2040. The breeding goal for AsUsual and SusFeed included litter size, growth rate, feed efficiency, leanness, and leg strength, with economic weights that reflected the current breeding goal. For SusFeedPig, a breeding goal aiming for improved animal welfare and reduced environmental impact was constructed with 12 selection traits. The goal was based on results presented in articles by Ottosen et al. (2020), Rauw et al. (2020), Soleimani and Gilbert (2020, 2021) and Wallenbeck et al. (2016). We estimated the response to selection in one generation and extrapolated the response for 10 generations to reach 2040. The selection traits and their relative economic weights (i.e. the selection pressure put on each trait) are presented along with the breeding schemes in Table S1. The phenotypic averages resulting from selection according to the different breeding goals are shown in Table 2. The input data for *SelAction* were genetic standard deviations and relative economic weights (Table S1), heritabilities, and correlations between traits (Table S4).

2.4. Choice of indicators

Our assessment of effects on *people* included farmers and workers at a pig farm in Sweden, and consumers at the point of consumption (e.g. a

Table 2
Characteristics of the pig production in the Reference case and the three future scenarios AsUsual, SusFeed, and SusFeedPig (average values)

	Reference case 2020	Influenced by selection[1]	AsUsual 2040 and SusFeed 2040[2]	SusFeedPig 2040
Gilts, sows and piglets				
Number of litters/ sow and year	2.2		2.2	2.2
Lactation period, days	33		33	33
Gestation period, days	115		115	115
Dry period (non-productive days), days	15		15	15
Interval weaning to service ≤7 days, % of sows	90.0	X	88.8	90.4
Litter size, number of live born piglets	14.6	X	16.7	15.1
Piglet mortality, % of live born	18.0	X	20.2	16.7
Piglet weight at weaning, kg	10		10	10
Productive life length (sow longevity), days	570	X	615	669
Sows with shoulder ulcers, % of sows	20	X	20	18
Replacement rate, %	47	X	44	41
Gilt age at first farrowing (days)	354		354	354
Weight at first insemination kg	140		140	140
Energy requirement lactating sows, MJ ME/d	120		142	142
Energy requirements non-lactating sows and gilts, MJ ME/d	37		37	37
Growing pigs				
Weaners' mean growth rate, weaning to 35 kg, g/d	600	X	636	667
Weaners' energy requirement, MJ ME/d	15.7	X	15.7	16.4
Weaners' mortality, %	2.0		2.0	2.0
Growers' mean growth rate, 35 to 120 kg, g/d	834	X	1070	1090
Growers' energy requirements, MJ ME/d	31.0	X	34.3	34.1
Overall feed conversion, MJ/ kg growth	33.5	X	29.9	29.4
Growers' mortality, %	2.78		2.78	2.78
Live weight at slaughter	120		120	120
Leg strength at performance test, points from 1 to 5, 5 best	3.5	X	4.2	4.3
Growing pigs treated for disease, % of pigs	20	X	20	18
Leanness, meat in carcass, %	58.6	X	62.8	59.3
Meat quality, drip loss, % (lower drip loss = better quality)	5	X	7	5

[1] Traits influenced by selection in the model are marked with an X
[2] Assuming the same input production data in the AsUsual 2040 and SusFeed 2040 scenarios, but different output due to differences in feeding and rearing

household or restaurant in Sweden). For *organisms* our system boundary was pig production, i.e. sows, growing pigs and gilts at a pig farm in Sweden. For the *environment*, the boundaries were fertilizer and energy production, soybean production in Brazil, feed production in Sweden and Denmark, and pig production at farms in Sweden.

Effects on *people, organisms* and *environment* were assessed through the success metrics shown in Table 3. Different sources for social indicators were used in six steps. The identification of indicators was a process where new indicators were added in the following order: the first source was Zira et al. (2020; *people* and *organisms*), but indicators that do not apply to the success metrics listed in the framework suggested by Stentiford et al. (2020) were omitted. The second was 19 experts from industry and academia (*people* and *organisms*), and the third was two groups of pig advisors with a total of seven advisors (*organisms)*. The fourth was the article by Stentiford et al. (2020; *people*), the fifth was a veterinary and public health expert (*people* and *organisms*), and the sixth was the authors (*organisms*). The social indicators and sources are shown in Tables S5 and S6. For the environmental indicators (*environment*), the authors used environmental impact categories used in LCA (Table 3).

2.5. *Indicator scoring*

2.5.1. *Relative sustainability points*

Relative sustainability points (RSPs) are scores for the indicators for each success metric, derived by comparing the performance of a scenario with the Reference case (Table 3). For *people* and *organisms*, RSPs

Table 3
One health framework for sustainable pig production

Pillar	Success metrics	Indicators for the success metrics (topics)
People	Nutritious and safe food	Microbe prevalence, meat quality
	Quality employment	Working conditions, social recognition, health
	Knowledge development	Technical knowledge, management skills development
	Gender equalization	No data
	Equitable income generation	No data
Organism	Healthy stock	Pig environment enrichment, health, hygiene
	Biosecure farms	Injuries from predators and epizootic diseases
	Safe farms	Antibiotic resistant microbes
	Minimal chemical hazards	Antibiotic usage
	Optimized farm systems	Breeding goal improving animal welfare
Environment	Optimal water quality	Ecotoxicity, eutrophication
	Optimal water usage	Water footprint
	Protected biodiversity, natural capital	Biodiversity damage, soil carbon loss
	Low energy use	Climate impact, fossil depletion
	Low spatial footprint	Land use

were calculated based on "social points" (see section 2.5.2) for each indicator (Table 3) based on literature and expert advice (Tables S5 and S6). For *environment*, we used a set of commonly used indicators from LCA that matched the success metrics used in Stentiford et al. (2020). The value of the indicator for the Reference case was defined as having an RSP equal to 0.5, as in Zira et al. (2021). For success metrics with more than one indicator, we used the average RSP for each indicator with equal weighting to represent the RSP for the success metric. RSPs were calculated using the following formulas:

1) $RSP_{jk} = \sum_{i=1}^{n}(1 - EXP(LN(0.5) * INDS_{ijk} / INDC_{ijk}))/n$ for *people* and *organisms* success metrics because a high value is favourable, and
2) $RSP_{jk} = \sum_{i=1}^{n}(EXP(LN(0.5) * INDS_{ijk} / INDC_{ijk}))/n$ for *environment* success metric because a high value is unfavourable

where *INDC* is the value of the indicator *i* under the success metric *j* under pillar *k* in the Reference case and *n* is the number of the indicators under a success metric. *INDS* is the corresponding value of the indicator under the scenarios. For each success metric, an RSP above 0.5 means that the scenario performs better than the Reference case for this success metric.

2.5.2. Social points

We adapted the scoring system introduced by Stentiford et al. (2020) for two reasons: partly in response to the considerable challenges of forecasting research, legislation and policy on future pig production, and partly to add additional value to the analysis using quantitative indicators where possible. In the adaptation, we used a scale with three score levels for performance of social points, 5 (very good), 3 (fair) and 1 (very poor), based on the thresholds shown in Table S5 and S6. The social points were used as indicators for *people* and *organisms* due to lack of data on success metrics, also ensuring similar scoring for the two categories. Total social points for each scenario were also calculated.

People. Based on a microbiological baseline study of Swedish pig slaughterhouses (Lindblad et al., 2007) and studies by Wallander et al. (2016) and Stødkilde et al. (2021), quantitative thresholds for five indicators were created for nutritious and safe food. Also, the veterinary public health expert created thresholds for one indicator (nutritious and safe food). For quality employment, thresholds for one indicator were based on a study by Länsstyrelsen Västra Götalands län (2018) and all other (qualitative) thresholds for the rest of the indicators were created by the authors. All the indicators and thresholds are shown in Table S5.

Organisms. The thresholds for one indicator (healthy stock) were created based on a study by Wallgren et al. (2019). The other indicators' thresholds were created by pig advisors, the veterinary and public health expert, and the authors. The social points for *organisms* are shown in Table S6. After scoring, all the success metric indicators were sent to, in total, five experts at the Swedish University of Agricultural Sciences for validation. Counts of social points equal to one (very poor) were done for each scenario. Although the count of social points equal to one was sensitive to the normatively set thresholds for the indicators, it remained a useful measurement, as it showed the number of areas that needed substantial improvement for the achievement of better health for *people* and *organisms*.

2.5.3. Environmental indicators

Inventory data to calculate environment success metric indicators were available and thus impact assessment methods from LCA were used to assess the environmental outcomes of the different scenarios. Theoretical foreground data were used for the production of soybean, rapeseed, soybean meal, rapeseed meal, cereal, feed, pigs and manure management (Zira et al., 2021), and yeast meal (Møller and Modahl, 2020). OpenLCA (v.1.10.2) with ecoinvent (v.3.3 APOS) was used for background processes, specifically for energy and transport using generic data inventories. We carried out an environmental inventory for emissions to soil, air and water for all the four scenarios using the data shown in Tables S7-S9. Recipe midpoint (H V1.13; Goedkoop et al., 2013) was used for characterization factors for environmental indicators in Table S5 (ecotoxicity, eutrophication, climate impact, fossil depletion, and land use). We used the blue and green water footprint of crops to measure water usage with data from Mekonnen and Hoekstra (2011, 2012). For crops, national data from Sweden was used, and for soybeans, data from Brazil was used. Because the required values for maize, grass-clover silage and pasture were missing in Mekonnen and Hoekstra (2011, 2012), we used data from Germany. Soil carbon loss was assessed using the introductory carbon balance model modified by Moberg et al. (2019). Biodiversity damage potential was assessed with using characterization factors from Knudsen et al. (2017).

The functional unit was 1000 kg pork retail weight at the farm gate although slaughter is outside the system boundary. Economic allocation was used for the co-products of rapeseed oil and soybean oil; 0.26 for rapeseed meal (Greendelta, 2017) and 0.32 for rapeseed cake (ISTA, 2020), and 0.68 for soybean meal (Cederberg and Flysjö, 2004b). For the yeast meal, an allocation factor of 0.35 was used as the carbon dioxide produced along with the yeast (Møller and Modahl, 2020) can be used as a gas fertilizer in green houses. For pork, an allocation factor of 0.99 was used to include other by-products from the pig production (Marti et al., 2011).

2.6. Sensitivity analysis

To investigate the robustness in results, sensitivity analyses were applied on SusFeed. First, a sensitivity analysis of the change in the breeding goal was performed to establish how much of the difference between SusFeed and SusFeedPig depended on the breeding goal. Second, we analysed the sensitivity assuming more unfavourable genetic correlations in SusFeed, using the correlation matrix shown in Table S4, as genetic correlations differ between populations and may change over time. Third, a sensitivity analysis of change in the weighting method from equal weighting to expert weighting (veterinarians and animal welfare experts) was performed for the success metric healthy stock, which included the highest number of indicators.

3. Results

3.1. Relative sustainability points

AsUsual, SusFeed and SusFeedPig, performed better than the Reference case on six, nine, and eight success metrics respectively (RSP above 0.5; Fig. 1). For AsUsual, the improvement was mostly for *environment* (Fig. 1).

3.2. Total social points for people and organisms

The totals of social points for *people* were 58 out of 90 for the Reference case, 60 for AsUsual, 70 for SusFeed and 48 for SusFeedPig (90 reflecting possible best performance). The totals of social points for *organisms* were 61 out of 115 for the Reference case, 61 for AsUsual, 79 for SusFeed and 81 for SusFeedPig (115 reflecting possible best performance). The Reference case and AsUsual scored well for quality employment, as the work hours per kg pork and amount of time spent outdoors were lower in comparison with the other scenarios. SusFeed scored well for nutritious and safe food, knowledge and skills generation, and healthy stock as a result of its low risk of *Trichinella* species in the meat. Compared with the Reference case and AsUsual, SusFeed had greater progress in technical and management skills development, plus a higher level of co-ownership of the sustainability narrative. SusFeedPig scored well for healthy stock and safe farms. This was explained by its lower proportions of growing pigs with bitten tails, pneumonia and sows with shoulder ulcers, and by outdoor access, as compared with those in the Reference case and the other scenarios. The social points for all

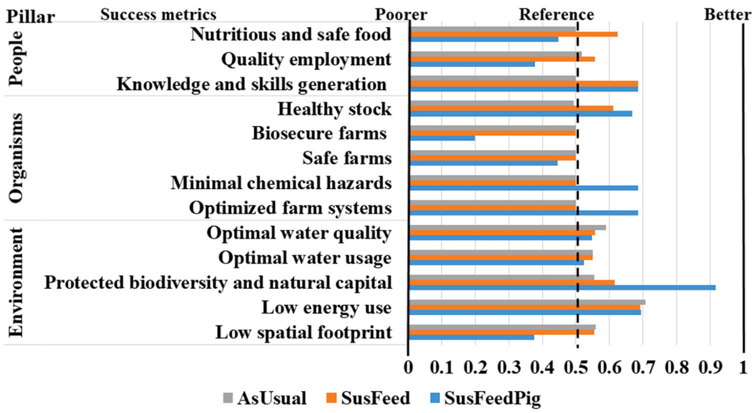

Fig. 1. The One Health framework results for three future scenarios, presented with relative sustainability points (RSPs). By definition, the Reference case has an RSP score of 0.5 (broken line in Figure 1). RSPs above 0.5 indicate negative impacts lower than the Reference case, and RSPs below 0.5 indicate negative impacts higher than the Reference case.

indicators are shown in Tables S5 and S6.

3.3. Environmental indicators

AsUsual, SusFeed and SusFeedPig had lower negative impacts on the *environment* than the Reference case (Table 4), except for marine eutrophication in SusFeed and SusFeedPig. SusFeedPig had the highest marine eutrophication as a result of ammonia production from manure from pigs on pasture and leaching from the production of on-farm protein feeds, i.e. faba beans and peas, because the quantities of faba beans and peas required in the SusFeedPig were greater than those in AsUsual and Reference case. The quantities of soybean, faba bean and peas were lower in AsUsual and Reference case because by-products from the agri-food industry, which we assumed to have no environmental impacts, provided proteins in the pig diets. SusFeedPig had the lowest soil carbon loss as a result of high carbon sequestration by grass-clover cultivation. The Reference case had a higher green and blue water footprint because it used more feed than that used in the future scenarios due to pigs' lower genetic capacity for growth rate and feed efficiency. The green and blue water footprint for SusFeedPig was higher than that in AsUsual and SusFeed because it used more land. AsUsual had the lowest freshwater eutrophication, climate impact, and green and blue water footprint because it used by-products from the agri-food industry. The biodiversity damage potential was lower for all scenarios compared to the Reference case, and SusFeed had the lowest impact due to use of less annual crops and more grass-clover silage. All future scenarios had a considerably lower climate impact than the Reference case. This was because they used less feed than that used in the Reference case. They were able to do this because they had higher overall feed efficiency associated with the pigs' genetic gain. Land use in AsUsual and SusFeed also decreased for this reason, while in SusFeedPig it increased considerably due to pasture. Contributions of the production processes to the total impacts on the environment are shown in Figures S1–S6.

3.4. Counts of social points equal to one (very poor)

3.4.1. People

Counts of social points equal to one (very poor) out of the number of indicators assessed are shown in Table 5. SusFeedPig had the highest count of social points equal to one for nutritious and safe food because outdoor pigs had a higher risk of contracting food-borne pathogens such as *Salmonella* species. SusFeedPig also had the highest count of social points equal to one for quality employment. This was partly because more labour was required for outdoor work such as shifting fences for outdoor pigs on pasture. The difficulty in monitoring animals in the outdoor environment, the raised level of work stress and of musculoskeletal disorders, and the higher risk of attack by aggressive sows, as well as sabotage, e.g. by activists, also resulted in SusFeedPig having the highest count of social points equal to one. SusFeed had no social points equal to one.

3.4.2. Organisms

Counts of social points equal to one (very poor) were lower for SusFeed and SusFeedPig than they were for AsUsual and the Reference

Table 4
Environment results for the pig production scenarios per 1000 kg of retail weight of pig meat

Success metric	Environmental indicators	Units	Reference case	AsUsual scenario	SusFeed scenario	SusFeedPig scenario
Optimal water quality	Freshwater eutrophication	kg P eq	1.40	0.87	0.81	0.88
	Marine eutrophication	kg N eq	53	46	62	69
	Freshwater ecotoxicity	kg 1.4 DCB eq	37	29	31	30
	Marine ecotoxicity	kg 1.4 DCB eq	32	25	27	26
Optimum water usage	Green and blue water use	m^3	2 900	2 500	2 500	2 700
Protected biodiversity and natural capital	Biodiversity damage potential	Potential disappeared fraction	6 300	5 300	4 800	5 400
	Soil Carbon Loss	Tonnes carbon	0.14	0.12	0.09	-0.05[1]
Low energy use	Climate impact	kg CO_2 eq	3 500	2 100	2 400	2 300
	Fossil Depletion	kg oil eq	490	200	190	200
Low spatial footprint	Land use	m^2	9 200	7 700	7 800	13 000

[1] Negative value indicates soil carbon sequestration. DCB is dichlorobenzene. Climate impact does not factor in carbon sequestration.

Table 5
Counts of social points equal to one (very poor) for people in different pig production scenarios

Success metric	No. of indicators	Reference case	AsUsual scenario	SusFeed scenario	SusFeedPig scenario
Nutritious and safe food	6	2	2	0	4
Quality employment	10	1	1	0	6
Knowledge and skills generation	2	0	0	0	0
Total count	18	3	3	0	10

case for the success metric healthy stock (Table 6). Healthy stock included indicators important for animal welfare. In SusFeed and SusFeedPig, pigs received cognitive stimulation from enrichment material (silage), more straw, and access to the outdoor environment in the form of a veranda. In SusFeedPig, pigs were on pasture during the summer season, and therefore it had the lowest count of social points equal to one (very poor) for healthy stock. The pigs' being outdoors lowered the risk of Livestock Associated Methicillin Resistant *Staphylococcus aureus* (LA-MRSA), which thrives inside the pig houses. SusFeedPig had the highest count of social points equal to one for the success metric biosecure farms because outdoor pigs had a higher risk of coming into contact with wild animals such as wild boars which could host pathogens that cause disease (e.g. African swine fever) than in the Reference case and other scenarios.

3.5. Sensitivity analysis

Changing the breeding goal so that more weight was put on traits important for overall feed efficiency and animal welfare in SusFeed increased the RSP for minimum chemical hazards and optimized farm systems because the disease resistance of the pigs improved (Table 7). This change of breeding goal also increased RSPs for all the *environment* success metrics as a result of the genetic gain of feed efficiency increasing by 10%. The use of a genetic correlation matrix with more unfavourable correlations decreased RSPs for success metrics under the *environment* because the gain in meat percentage decreased by 50%. The use of expert weighting of indicators (instead of an average of the indicators) for healthy stock resulted in changes in RSPs for SusFeed by +5% (when RSP was calculated using social indicators in Table S10), with veterinarians bringing about less change than animal welfare scientists because of their different weights for, for example, average pig space. The weights from the four experts for all health stock success metric indicators are shown in Table S10.

Table 7
Sensitivity analysis of the SusFeed scenario. Relative sustainability points (RSPs) in percentage of values in Figure 1; a higher RSP is more favourable

Success metrics	Change to the same breeding goal as SusFeedPig	More unfavorable genetics correlations
Nutritious and safe food	0	0
Quality employment	0	0
Knowledge and skills generation	0	0
Healthy stock	+4	0
Biosecure farms	0	0
Safe farms	0	0
Minimum chemical hazards	+37	0
Optimized farm systems	+37	0
Optimal water quality	+2	-3
Optimal water usage	+3	-2
Protected biodiversity and natural capital	+1	-2
Low energy use	+2	-1
Low spatial footprint	+2	-2

4. Discussion

We have shown how the One Health framework suggested by Stentiford et al. (2020), can be adapted for use in the assessment of pig production systems. The selection of indicators, thresholds and weighting moderated the results. This is one reason why transparency about all the steps is crucial. Future research using the One Health framework should focus on applying the framework to other systems with other livestock species. Results from such studies can then be used in the formulation of policy and strategies for improved system design.

Table 6
Counts of social points equal to one (very poor) for organisms in different pig production scenarios

Success metric	No. of indicators	Reference case	AsUsual scenario	SusFeed scenario	SusFeedPig scenario
Healthy stock	16	9	10	5	4
Biosecure farms	3	0	0	0	2
Safe farms	2	0	0	0	1
Minimum chemical hazards	1	0	0	0	0
Optimized farm systems	1	0	0	0	0
Total count	**23**	**9**	**10**	**5**	**7**

Some commonly used impact categories in LCA (e.g. acidification) and product quality aspects (e.g. taste and juiciness of meat), were missed in our One Health framework. These could have been added, but limiting indicators to a manageable number is crucial. The placing of indicators under different pillars also affects the interpretation of the results. The success metric optimized farm systems, which was now sorted under *organisms,* could be sorted under the *environment,* and biosecure farms, safe farms and minimal chemical hazard, which were sorted under *organisms* in the framework, could be fitted better under *people*. With all the success metrics included in *organisms*, there is a risk that the assessment of the animals' situation is overshadowed by indicators that actually have more to do with *people*. An unanswered but relevant question concerns equitable income generation, a success metric for *people* in the One Health framework (Stentiford et al., 2020). Given the challenges of forecasting the future prices of products, we did not include this success metric in this study.

Aspects such as the selection, weighting, and scoring of indicators are subjective, because they depend on individual assessments made by people at a certain point in time. For example, working in indoor production was considered good by our experts, but if the weather is fine, so is working outdoors – some people might even consider it preferable. The weightings of indicators performed by veterinarians and animal welfare experts confirmed that weighting differed considerably from one individual to another. When other data sources were missing, we used our discretion in setting some of the thresholds using our expertise. If the assessment results are to be used for political governance, the identification of thresholds (and indicators) would need to be undertaken by stakeholders.

Use of forest waste products for yeast and biodiesel production avoid feed-food competition but the availability of forest waste products rests on the biomass increment, and on the utilization and demand for main forest products. Forecasts indicate that biomass increment in Swedish forests exceed future demand for stem wood, although demand for stem wood is expected to grow in the future (Kumar et al., 2021). However, there is a huge demand for forest residues from many sectors, and therefore careful consideration of the best way to use them will be necessary.

Currently, the use of inorganic nitrogen for yeast production cause high climate impact. By using organic nitrogen from chicken offal and blood, climate impact could be reduced by an average of 27.5% (Møller and Modahl, 2020). However, availability of these nitrogen sources is not guaranteed due to other competing uses. In the SusFeed and SusFeedPig diets, some fish meal was included, because the diet composition with yeast examined by Cruz et al. (2019, 2020) had fish meal. Yeast-based diets with enzymatic hydrolysed feather meal in place of fish meal (Zhou et al., 2020) could be developed to reduce reliance on fish meal.

The genetic gains in feed efficiency, and the corresponding change in environmental impacts over time, were in keeping with a recent study that included a historical perspective on environmental impacts over the period 2005–2020 (Landquist et al., 2020). The decrease in negative impacts on the environment connected with high feed efficiency was comparable to Soleimani and Gilbert's (2020) finding of an average of 7% decrease in negative impacts on the environment when comparing pigs with low and high residual feed intake. Our results were also in line with the findings of Ottosen et al. (2020), who have indicated that changes in especially growing pig growth rate and maintenance contribute between 3-18% change to negative impacts on the environment in pig production (not considering management improvements).

The genetic progress with the current breeding goal resulted in a litter size of 17 piglets for SusFeed in 2040, indicating the possibility of 20 piglets per litter by 2050, as predicted by Merks et al. (2012). However, this is not desirable, because it could increase the need for nurse sows. Wallenbeck et al. (2016) showed that farmers want more weight to be put on sow longevity and less on litter size. Piglet survival is important for animal welfare and ethical reasons but piglet mortality is currently higher in Sweden than in many other countries. Due to unfavourable correlations, it remained high also in SusFeedPig (although lower than in SusFeed). Increased selection pressure on piglet survival should thus be considered in future studies. Using the alternative breeding goal in SusFeed improved the RSPs for eight success metrics and had no influence on the other five success metrics. Resilience to heat stress may be a relevant goal trait for 2040. We did not select pigs for this trait in the alternative breeding goal because of lack of genetic parameters, but this is important to consider in future studies.

Enrichment material and silage help to foster expressions of normal behaviour (Presto et al., 2013; Godyń et al., 2019) and reduce abnormal behaviour such as tail biting and improve the pigs' quality of life. In this study, the introduction of grass-clover ley in crop rotations also contributed to a reduction of soil carbon losses and increased biodiversity. Continuous annual cropping reduces soil biodiversity through soil compaction, e.g. earthworms and mycorrhizal populations and plant and insect populations through use of herbicides and pesticides (Berdeni et al., 2021). Wheat straw is a good enrichment material because it is a by-product that mimics the natural environment, but its hygienic status needs to be tested. Fertilizing crops with manure increase the risks of chemical compounds, such as antibiotics, and pathogens being found in wheat straw (Wagner et al., 2018). A good, enriched environment should have nutritional, sensory, physical, occupational and social features (Bracke et al., 2006). In SusFeed, silage improved nutritional, sensory and occupational features for the growing pigs, which were fed total mixed rations (Presto et al., 2013). The physical feature was improved in SusFeed, relative to the Reference case, as a result of the veranda. This feature, i.e. a larger space, is key to providing comfort to pigs (Godyń et al., 2019). Providing more indoor space is costly in terms of the buildings needed, and access to pasture had trade-offs with *people* success metrics, i.e. low nutritional and safe food and quality employment. However, access both to an indoor area with enrichment materials and to a veranda could be a way to handle the goal conflicts between biosecurity and healthy stock.

The health status of the Swedish pig population is high. At present Sweden is declared free from Africa Swine Fever, Aujeszky's Disease and PRRS that cause problems in other European countries. Further LA-MRSA has not yet been diagnosed in Swedish pigs and the incidence of Salmonella that is notifiable in Sweden has been low during the last decades. There is of course no guarantee that Sweden will remain free from these infections for ever, but they are all included in national control programs (Swedish University of Agricultural Sciences, Department of Biomedicine and Veterinary Public Health, personal communication, 18 August 2021). Leg strength was included in both breeding goals and the breeding goal used in SusFeedPig also included disease resistance and shoulder ulcers. However, there were still some weaknesses in the future scenarios, i.e. the negative health effects for *organisms* such as growing pigs treated for diseases and sows with shoulder ulcers, as indeed there are in today's pig production. These could be handled by placing more selection pressure on traits that are important for health, such as disease resistance. We did not consider measures to reduce such risks – e.g. the use of real-time disease surveillance systems, or of routines that could improve biosecurity in outdoor pig production – when calculating risk points. Doing so might have reduced many of the serious risks identified for SusFeedPig (Table 5 and 6).

The yields of crops are expected to increase (Maracchi et al., 2005) but on the other hand, some studies have projected a fall due to a shorter grain-filling stage (Dijkman et al., 2017). Therefore, as a result of conflicting projections, we did not change yields to adjust for climate change in the future scenarios. Technological advances can bring about rapid change in farming methods. In precision farming, robots, cameras, and drones and sensors recording temperature, nutrients, and moisture, as well as machines and information technology, are all being developed and used increasingly. These could reduce inputs and environmental impacts (Klerkx et al., 2019), improve animal welfare (Buller et al., 2020) and reduce heavy workloads and stress, thereby change the situation in the future.

5. Conclusion

Efforts to ensure improved health and well-being should be made within a One Health perspective, recognizing the interconnections between people, plants and animals, and their shared environment. By comparing different future scenarios of pig production using the One Health framework and the success metrics introduced by Stentiford et al. (2020), we were able to establish the strengths and weaknesses of those scenarios. A changed breeding goal with higher economic weights on traits important for pig welfare and overall feed efficiency, alongside a veranda, straw and silage, yeast protein, and renewable energy sources, can improve future pig production. It can reduce the negative effects on the *environment, people* and *organisms* that we see in today's pig production.

CRediT authorship contribution statement

S. Zira: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Data curation. **E. Röös:** Conceptualization, Methodology, Validation, Writing – review & editing. **E. Ivarsson:** Conceptualization, Methodology, Validation, Writing – review & editing, Data curation. **J. Friman:** Conceptualization, Writing – review & editing, Data curation. **H. Møller:** Conceptualization, Writing – review & editing, Data curation. **S. Samsonstuen:** Conceptualization, Writing – review & editing. **H.F. Olsen:** Conceptualization, Writing – review & editing. **L. Rydhmer:** Conceptualization, Methodology, Validation, Writing – review & editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Meat and milk are valuable foods from livestock that contribute to a good quality of life for humans but have negative environmental, social and economic impacts. Measuring sustainability is complex as it requires methods with a broad and deep focus. The overall aims of this thesis were to further develop and test sustainability assessment methods by assessing different animal production systems. The results reveal strengths and weaknesses, and contribute to the design of more sustainable animal production systems.

Stanley Zira received his doctoral education at the Department of Animal Breeding and Genetics, SLU. He obtained his MSc in Organic Agriculture at WUR in the Netherlands and MComm in Strategic Management at GZU in Zimbabwe.

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