Livestock Science 260 (2022) 104929

Contents lists available at ScienceDirect

Livestock Science

journal homepage: www.elsevier.com/locate/livsci

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

S. Zira[a,*], E. Röös[b], E. Ivarsson[c], J. Friman[c], H. Møller[d], S. Samsonstuen[e], H.F. Olsen[e], L. Rydhmer[a]

[a] *Department of Animal Breeding and Genetics, Swedish University of Agricultural Sciences, SLU Box 7023, 75007 Uppsala, Sweden*
[b] *Department of Energy and Technology, Swedish University of Agricultural Sciences, SLU Box 7032, 75007 Uppsala, Sweden*
[c] *Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, SLU Box 7024, 75007 Uppsala, Sweden*
[d] *NORSUS, Stadion 4, 1671 Kråkerøy, Norway*
[e] *Department of Animal and Aquaculture Sciences, Norwegian University of Environmental and Life Sciences, PO Box 5003, N-1432 Ås, Norway*

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*.

ARTICLE INFO

Keywords:
One Health approach
Future pig production
Pig breeding
Yeast protein
Environment
Silage

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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[*] Corresponding author at: Animal Breeding and Genetics, Swedish University of Agricultural Sciences: Sveriges lantbruksuniversitet, 26 Ulls väg, 75007 Uppsala, Sweden.

E-mail address: stanley.zira@slu.se (S. Zira).

https://doi.org/10.1016/j.livsci.2022.104929
Received 26 November 2021; Received in revised form 3 April 2022; Accepted 6 April 2022
Available online 10 April 2022
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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

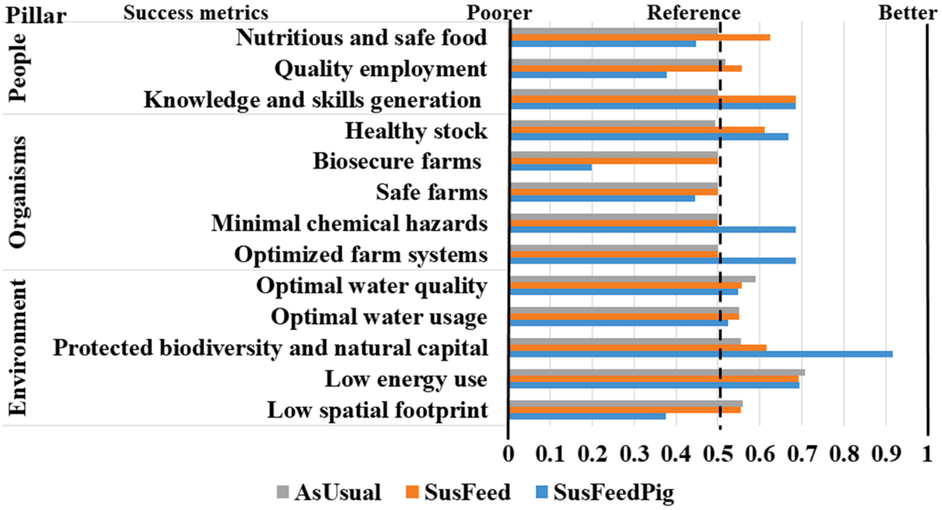

Fig. 1. The One Health framework results for three future scenarios, presented with relative sustainability points (RSPs). By definition, the Reference case has an RSP score of 0.5 (broken line in Figure 1). RSPs above 0.5 indicate negative impacts lower than the Reference case, and RSPs below 0.5 indicate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

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**

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

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.

Acknowledgement

This work was supported by the European Commission as a part of the ERA-Net Cofund SusAn project called SusPig (grant nr. 696231) and supported by funds from The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) (grant nr. 2017-00153) and the research platform Future Food at SLU (years 2018-2022), and the Research Council of Norway through Sustainable Livestock Production (LIVESTOCK) (grant 295189).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.livsci.2022.104929.

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