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Multidimensional sustainability assessment of pig production systems at herd level – The case of Denmark

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HIGHLIGHTS

- Pig production systems can be linked to sustainability dimensions at herd level.
- There is a trade-off between different sustainability dimensions.
- Notably, high animal welfare and low environmental impact are potentially at odds.
- Therefore, those who sell and buy pork will have some hard choices to make.

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ABSTRACT

Pig production systems vary in their ability to meet key sustainability goals such as lowered environmental impact, lowered climate impact, reduced land use, economic viability, and improved animal welfare. These goals are not fully aligned and may require trade-offs to be made. The aim of the paper is to quantify these potential trade-offs.

Using Denmark as the study case, we assess the standard pig production system and four existing alternative systems, and in addition the impact of a range of manure handling technologies. Drawing on farm data from an almost industry-wide certification scheme, environmental and climate impact are estimated per kg live weight using the life-cycle approach. Antibiotic use is assessed by calculating weighted average doses consumed within the herd, and animal welfare is assessed with a recently developed benchmarking tool. Finally, productions costs are estimated using herd-level production data combined with farm-level cost estimates.

We find that the five pig production systems perform differently in the sustainability dimensions at herd level. We also find that there is a trade-off between the sustainability dimensions, as no one production system dominates the others in all dimensions.

Across the systems analysed, reduced climate impact goes to some extent hand-in-hand with cost effectiveness. However, there are negative correlations between animal welfare and production costs and, especially, animal welfare and the environment.

These dilemmas affect both regulatory and market-driven schemes, and where the production and marketing of niche products is concerned difficult decisions will need to be made. Improvements in environmental impact will reduce performance in animal welfare or vice versa – and it will do so regardless of cost.

1. Introduction

The notion of sustainability has been high on the global political agenda since publication of the 1987 Brundtland report 'Our Common Future' at least (World Commission on Environment and Development, 1987). This defined *sustainable* development as development that

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satisfies the needs of the present generation without compromising the ability of future generations to satisfy their own needs. The focus was on ensuring that vital renewable natural resources were used wisely and not exhausted. However, with its growing political importance, the concept was gradually broadened to include a wide range of concerns including nature protection, global equity and human health.

With the broadened notion of sustainability dilemmas may arise requiring trade-offs to be made (Gamborg and Sandøe, 2005). This is reflected in sustainable development goals (SDGs) (United Nations, 2020). The achievement of one SDG may have adverse effects on other SDGs. The processes are mapped as conflicts in Nilsson et al. (2016). Conflict between SDG 2, Zero Hunger, which implicitly means food production, and other development goals are emphasised by Nilsson et al. (2016). The lesson is that food production may come into conflict with several other development goals.

An especially critical issue here is animal production. This was first brought out clearly in 2006, when the Food and Agriculture Organization of the United Nations (FAO) published the report 'Livestock's long shadow'. The report stressed the serious impact of animal production on climate and environmental sustainability (FAO, 2006). It was followed by publications from the Stockholm Resilience Centre emphasising the need to improve production and consumption patterns globally (Rockström et al., 2009; Steffen et al., 2015) in order to avoid crossing 'planetary boundaries'.

Although the concept of sustainability is broad, one concern about animal production has, until recently, only occasionally (Bonneau et al., 2014) been a prominent part of the sustainability debate: animal welfare. This has now changed, however. For example, Keeling et al. (2019) found that although animal welfare is not listed as an SDG, understanding the relationship between it and the recognised SDGs helps to highlight the importance of animal welfare when implementing these goals in practice. This is also recognised in the large EU-funded research project Q-Pork Chains evaluating the sustainability of contrasted pig farming systems (Bonneau et al., 2014). Recently, major stakeholders have argued that animal welfare is part of SDG 12: Responsible Consumption and Production (Cox and Bridgers, 2019). The UN Environment Programme has also acknowledged that protecting and improving animal welfare will be important if we are to meet the requirements of the SDGs (Otieno, 2020).

Li & Kallas (2021) support the argument that the goal of sustainable agricultural production should encompass several environmental, social and economic aspects, including, for example, food quality and safety. This view is supported by Broom (2019), who emphasises that sustainability analyses must incorporate multiple sustainability dimensions, including impact on global climate and the environment, the obligation to care for human health and animal welfare, and the challenges posed by increasing antimicrobial resistance. Broom (2019) also points to the need for sound scientific information on each component. He states that we need to find ways to assess and compare positive and negative impacts of various actions while taking into account the fact that priorities differ across the world and change over time.

Animal production has been debated extensively because it contributes to greenhouse gas emissions, as we have already mentioned, but also has connections with animal welfare and healthy eating patterns. It has become clear that the climate impact of pork and chicken meat is significantly lower than that of beef (Clune et al., 2017; Röös et al., 2013). This is important for pig-producing countries like Denmark. In particular, Denmark has a large, competitive pig production sector, with 90% of the production for export, which contributes to the Danish economy and offers jobs to many Danes (Danish Agriculture and Food Council, 2022). A survey conducted in 2020 indicated that two-thirds of Danish consumers think about sustainability when they buy food, and that almost all want to change their behaviour to act more sustainably (Danish Agriculture and Food Council, 2020). The survey also showed that the main reasons Danish consumers give for buying food that is more sustainable include taking care of nature, leaving our planet in a good condition for future generations, avoiding pollution, and improving animal welfare and health.

Today, organic products are seen by many consumers as a sustainable choice (Bosana and Gebresenbet, 2018). The word 'sustainable' is often used in connection with organic production, although actually organic standards and certification do not include requirements on climate impact. No products in Denmark are directly marketed as being more sustainable than standard products, but a number of labelled products claim to offer improvements in single dimensions that are sustainability-related. Thus, in addition to conventionally produced pork, niche products are marketed in Denmark on the basis of improved indoor animal welfare, improved outdoor animal welfare, organic production and reduced antibiotic use. Each niche product is marketed as 'better' in specific attributes, but there is little knowledge about their overall sustainability impacts or the extent to which one dimension enjoys synergies with, or is detrimental to, other dimensions. This is what we set out to analyse in the present paper, using Danish pig production as a case study of the ways in which dilemmas relating to different aspects of sustainability play out in practice.

We took as our starting point five existing production systems with well-defined differences and documented differences in productivity. We obtained access to data on antibiotic use, climate and environmental impact and animal welfare from the vast majority of Danish pig herds. This access to quantitative registered herd-level data allowed us to quantify synergies and conflicts amongst the different production systems. We were also able to assess how widespread each of the production systems is, and thus to assess the sustainability implications of the present distribution of production systems and of potential future distributions (e.g. if the market share of organic pork were to increase).

We chose to evaluate the five production systems against their relative climate impact, environmental impact and impact on animal welfare. As a fourth measure of sustainability, we included use of antibiotics, because this, together with the risk of antimicrobial resistance, is seen as a significant risk to human health (O'Neill, 2014; World Health Organization, 2020). We also included a fifth measure, production costs, as this is essential for economic sustainability and is likely to affect consumer prices, making it an important dimension of food security. We could have considered other dimensions of sustainability but we have chosen the dimensions for which we have empirical data and in which we have seen market developments in Europe.

In short, the purpose of the study was to quantify the performance of, and trade-offs between, five aspects, or measures, of sustainability in five of the pig production systems operated in Denmark today.

2. Materials

We define the *Standard* pig production system, together with the four additional market-driven systems: *Raised without antibiotics, Animal welfare* pork, *Free range* and *Organic*. The names set here in italics are used consistently throughout the present paper. All are divided into three stages: 1) sows with piglets, 2) weaners, and 3) finishers. The data structure is not balanced across the three stages as the starting point of the data collection is the finisher producers as a consequence of the data being collected by a slaughterhouse company. Sow and weaner herds are only included in the data set if these herds are co-owned with a finisher herd. Hence, the share of the total Danish production represented in the data is substantially lower for sows and weaners (30 percent) compared to finishers (approx. 76 percent).

Below the five production systems are described in more detail. Following this, the various data sources and methods we used to quantify the scores of the pig production systems across the five dimensions of sustainability – environmental impacts, climate impacts, animal welfare, antibiotic use and production cost – are also described.

2.1. Production systems

The *Standard* system is the conventional method of pig production widely used in Denmark with intensive indoor rearing and fattening facilities with national improvements above EU requirements (Tamstorf, 2023). Turning to the other four systems, *Animal welfare* production and *Organic* production are certified by government agencies, whereas *Raised without antibiotics* and *Free range* production are certified by the industry (Danish Crown, 2022[1]).

Obviously, the production systems differ in quite a number of ways. Here we will concentrate on differences affecting their impact on the five dimensions of sustainability. In *Animal welfare*, sows are loose-housed all the time, the minimum weaning age is 28 days without derogation for batch weaning. The total space requirements are 30% higher for weaners and finisher than those given to a standard pig, amount of straw (in all Stages) is supposed to cover (almost) the full rest area for all pigs, double antibiotic retention time before slaughter (Danish Crown, 2023). In *Raised without antibiotics*, no antibiotics is allowed. Pigs that have been individually treated are precluded from the scheme and not eligible for its additional payments. Further, all-vegetarian feed is required and pigs should be born, raised, and slaughtered in Denmark (Danish Crown, 2022). *Raised without antibiotics* production for growing pigs requires increased infection protection, increased hygiene, use of probiotics and more vaccines. For this, increased labour is required. These elements are included in the calculation of the increased costs. The *Free range* production system requires outdoor farrowing huts with minimum space requirements within the hut of 3.8 m^2 and at least 300 m^2 as total area per sow, and a minimum weaning age of 35 days on average across all weaners. During gestation, the sows are normally housed outdoor with access to a gestation hut, with minimum 1.3 m^2 per sow and an area of approx. 500 m^2 per sow. Weaners and finishers roam inside with access to an outdoor run, and there are approx. 41 percent greater total space requirements than those given to standard pigs whereof approx. 42 percent is required to be outside. The sows are housed indoor a short period around mating (Dyrenes Beskyttelse, 2023). Requirements in *Organic* pig farming are in many ways the same as those in the *Free range* scheme, but with greater space requirements especially for the weaners and finishers, with a total space requirements approx. 75 percent greater than those given to standard pigs, whereof approx. 42 percent is required to be outside. There is a minimum average weaning age of 49 days, pigs may only be treated with antibiotics a limited number of times before they no longer can be sold as organic and there is double antibiotic retention time before slaughter. Further, 95% of feed must be organic, and as of 2020 a minimum of 20% must be locally grown. This also implies that no artificial fertilizers are allowed. To meet these rules the feed for the *Organic* production system uses Danish grain, broad beans (i.e. fava, or faba beans), rapeseed cake and conventional soybean meal. Roughage such as grass-clover or barley whole crop silage has to be fed in all stages (straw is not classified as roughage).

It is assumed that the feed items are identical in the four non-organic production systems, and that these – barley, rape-, sunflower- and soybean meal – are adjusted in the appropriate proportions, respectively, for sows, weaners and finishers, in order to meet Danish standards for energy and protein (Børsting and Hellwing, 2021). Feed for weaned pigs is often supplemented with probiotics and because preventive treatment is prohibited in Denmark everyone uses low-risk feed.

The types of housing facility used in the five production systems are described in Table A1 in the Appendix. Hence the housing facility and hence also the manure handling as well as feed consumption was system level generalisations but productivity levels, mortality, and antibiotics consumption was based on herd level data.

2.2. Herd level data

All of the farmers in this study were delivering pigs to Danish Crown slaughterhouses and were certified in 2018–2019 as part of Danish Crown's sustainability certification scheme (Danish Crown, 2021). The farms account for approximately 90% of pigs slaughtered in Danish Crown slaughterhouses in Denmark, corresponding to approximately 76% of the pigs slaughtered in Denmark.

Information on each farm was obtained by telephone interviews to which the farmers could prepare by filling out a questionnaire sent to the farmers in advance. Danish Crown's sustainability certification scheme was gathered by the independent certification company Baltic Control. The certification included information about production facilities, antibiotic use, manure management and storage, use of climate and environmental technologies, and production volume. It also involved production data such as litter per sow, finishers produced per sow, mortality, and feed conversion ratio measured as feed consumed to increase live weight gain by one kg for weaners and finishers. This information was used to estimate the sustainability status from the production systems.

Information on the use (sale) of antibiotics was from the farmers who obtained the information from the VetStat database, which is a publicly maintained database (Danish Veterinary and Food Administration, 2023). Danish pharmacies are required by law to report prescriptions, which are ascribed to unique herd-numbers, directly to the database. If veterinarians use antibiotics during a visit, this is also reported to the database.

3. Methods

The indicators for the five dimensions are described in turn below.

3.1. Environmental and climate impacts

Climate impact was measured in CO_2-eq as global warming potential and environmental impacts were measured in three categories: eutrophication, acidification potential measured in mol H^+-eq., and land occupation measured in m^2 over one year. Eutrophication was subdivided into marine eutrophication (g N-eq.), freshwater eutrophication (g P-eq.), and terrestrial eutrophication (mmol N-eq.). These four impacts together are labelled environmental and climate impacts and the five production systems were assessed by Life Cycle Assessment (LCA) based on the principles and model documented in Dorca-Preda et al. (2021).

The present study investigated the changes in production system and use of manure technologies due to local N and P regulations and more global climate concern including land use for feed production.

Toxicity-based impacts (e.g. ecotoxicity) related to the use of chemicals such as pesticides, fertilizers, pharmaceuticals were not included due to data unavailability for the specific systems.

The functional unit used in the analysis was kilo live weight (LW) at the farm gate. The three environmental indicators were given same weight when three individual indices were combined to one environmental index.

The grain and rapeseed used for feed were assumed to be produced in Denmark using artificial fertilisers in accordance with data originating in Mogensen et al. (2018). It was also assumed that the amount of fertiliser had been reduced by the fertilising effect of the manure produced in each pig production system. Environmental and climate emissions related to manure management vary according to housing system as well as storage facilities and technologies. Use of fossil energy, and hence the emissions from production processes such as light, ventilation, feeding and manure handling, were assumed to be a standard across the systems

[1] Danish Crown is a cooperatively owned slaughterhouse based in Denmark but with multinational engagements. The slaughterhouse is the dominant slaughterhouse in Denmark, slaughtering about 80% to 85% of the finisher pigs produced in the country.

because we had no differentiating data. Impacts from feed production were updated with respect to organic production, though, using Mogensen et al. (2018). Environmental and climate impacts of the construction of buildings, and the manufacture of machinery and similar, were not included in the LCA.

The model presented by Dorca-Preda et al. (2021) was developed to handle pig farming systems with indoor housing. Impacts of the two production types in our study with partly outdoor housing were estimated outside the model by taking into account manure emission factors in *Organic* and *Free range* derived from Kai & Adamsen (2017).

3.2. Environmental and climate mitigating technologies

We apply the term 'technology' in a broad sense to a group of environmental and climate mitigating technologies widely used in Danish pig production: production of biogas using manure, acidification of slurry in the stable, slurry cooling in the stable, and frequent sluicing of slurry[2] from the stable. The estimated effect here included both the direct effect of technology on emissions of N and CH_4 and indirect effects due to change in fertiliser value and energy production (only for biogas) (Dorca-Preda et al., 2021).

3.3. Animal welfare

Quantification of animal welfare in the production systems built on the methodology presented in Sandøe et al. (2020), where a panel of international academic experts on animal behaviour rate the animal welfare effects of features found in different production systems. The experts were asked 19 questions about how a given aspect of a production system – e.g. space per animal, or access to environmental enrichment of various kinds – affects the welfare of the pigs in that system. The answers were scores ranging from 0 to 10. The experts were then asked how important each aspect is from a welfare perspective, with responses ranging from 1 to 5. The average score was multiplied by average weight given by the five experts from Sandøe et al. (2020), and the score for a production system was then calculated as points divided by the maximum points attainable.

The implicit assumption of this approach is that the experts have assessed the relative welfare effects of resources provided to the piglet, the weaner, the finisher and the sow. It is also assumed that the increased welfare from a better in-house environment for four subsequent finisher pigs during a year is equivalent to the increased welfare for a single finisher pig for a whole year.

Thus, animal welfare outcomes of the five production systems analysed in this study were estimated with the mentioned methodology (Sandøe et al., 2020). For the quantification of animal welfare outcomes the experts assessed the importance for the pigs of resources provided but were not able to include problems of non-compliance or the impact of quality of management and stockmanship.

3.4. Antibiotic use

The use of antibiotics to produce one kg of pork was measured in average daily doses (ADD), which is defined as the average quantity of antibiotics 100 pigs have been prescribed per day over the last 9-months. The calculation principles are stated in the legislation (Ministeriet for Fødevarer, Landbrug og Fiskeri, 2023). With the prescriptions being attributed to a specified age groups, the use of antibiotics can be calculated relative to herd size.

Different antibiotic products have different amounts of active substance that make up 'one dose', just as the amount of antibiotics making up 'one dose' depends on the weight of the animal. However, at the time of prescription, the weight of the animal is unknown to the veterinarian and the pharmacy, so standard weights for the age group are used to calculate dosage.

Each of the five production systems includes three age groups, and these have different ADDs. Therefore the levels of consumption of antibiotics in the age groups needed to be weighted together to create an overall index for the production system. The weighting of antibiotic use for the different age groups was done on the basis of an aggregated standard weight of the animals on a given day. The standard weights used in the calculation of the doses were the same in all production systems: 200 kg for a sow, 15 kg for a weaner pig and 50 kg for a finisher pig. This implies, for example, that a standard dose for a weaner pig represents only 7.5% of the standard dose for a sow.

3.5. Cost of production

The cost of producing a pig from birth to slaughter varies and depends on production system. The estimate of the cost of production in the standard production system used in our study was based on calculations of investments and the costs of production in Danish pig production (Udesen, 2020). In essence, the calculation of investment and production costs in the sow weaner operation, as well as in the finisher production, is the basis for a fair price of a weaner pig traded by Danish farmers. We assumed that the prices and investment levels were trustworthy, since the representatives have conflicting interests when settling the price with reference to empirical investments and costs. The calculated price for a weaner pig is the price that equates the return on assets for the hypothetical seller and buyer.

Several cost components are linked with the *Animal Welfare* system. Production systems with a requirement of 100% loose-housed sows have increased investment costs. The requirement of 30% more space in weaner and finisher sections is also estimated to be associated with additional costs.[3] Finally, the higher workload and higher costs of straw and other manipulable materials increases costs in comparison with the *Standard* production system.

The *Raised without antibiotics* system has lower costs for antibiotics but higher wage costs and raised costs for vaccines. Wage bills rise as a result of higher levels of management, handling of ear tags and hygiene levels. Costs of producing for *Free range* pigs are referenced via the same type of calculation as that used for the *Standard* system. The *Free range* production system differs from the *Standard* system in having sows outdoors and giving weaner and finisher pigs outdoor access.

Finally, the costs of producing *Organic* pigs are referenced via the same calculation as that used for the *Standard* and *Free range* systems. In addition to the requirements in the *Free range* system, pigs in the *Organic* system are required to have even more space and be fed with feed produced organically.

The estimated statuses of the five sustainability dimensions are presented in a Cobweb diagram showing relative performance compared with the best production system in each dimension. For the dimension where higher values are better (animal welfare) the calculation of the index is straightforward: the relative performance of the relevant production system's share of the production system has the highest value. For the remaining dimensions the same ratio is calculated, but as this performance measure is higher than one (e.g. 2.5) it is inverted (e.g. the result is 0.4).

3.6. Results

We begin by presenting the production characteristics for the five production systems, and the estimated sustainability scores for the five

[2] Pipes will run under the slab and outlet points through the slab will connect each section of the pit. The manure will be flushed out through the pipes by the vacuum.

[3] Christiansen, M.G. Personal communication. Special Consultant, Danish Pig Research Centre, SEGES.

selected dimensions in each production system, in turn.

Table 1 shows the weighted means for the selected parameters in the five production systems. Number of herds is considerably higher in *Standard* than it is in the other systems. The results also show that number of piglets per sow is higher in *Standard* and *Raised without antibiotics* than it is in the other production systems. In terms of production results, the biggest difference between the systems is in respect of antibiotic use and piglet mortality. The combined effect of fertility and mortality is captured in the calculated number of finishers produced per sow and kg LW produced per sow.

Table 1
Parameters in five pig production systems in Denmark, separated into sows with piglets, weaners, and finishers, based on data from the Danish Crown sustainability certification scheme. Production data are presented as weighted means with standard deviation shown in parentheses.

	Standard, no technology adoption	*Animal welfare*[1]	*Raised without antibiotics*	*Free range*	*Organic*
Sows and piglets					
Number of herds	465[3]	1	18[3]	8	16
Piglets weaned per sow per year	33.3 (3.12)	29.7	33.3 (2.82)	26.2 (2.87)	22.2 (2.83)
Mortality, sows,%	11.7 (5.54)	7.0	11.7 (4.89)	8.9 (4.99)	10.6 (6.18)
Mortality, piglets,%	13.8 (3.66)	20.0	13.9 (4.97)	23.1[4]	28.1[4]
Antibiotic use, ADD[2]	2.6 (1.82)	1.3	2.3 (4.58)	1.2 (0.86)	1.1 (2.02)
Weaners					
Number of herds	704[3]	3[3]	28[3]	9	27
Mortality for weaners,%	3 (2.04)	2.6 (1.51)	3.9 (1.89)	3.2 (1.30)	3.3 (2.43)
Feed conversion ratio, kg per kg LW gain	1.9 (0.14)	1.8 (0.24)	1.8 (0.12)	1.9 (0.08)	2.1 (0.29)
Antibiotic use, ADD[2]	8.9 (4.71)	8.4 (4.9)	3.0 (2.59)	8.0 (5.81)	2.8 (2.58)
Finisher pigs					
Number of herds	2107	33	91	18	63
Number of finisher pigs produced	11,420,000	153,000	479,000	83,000	176,000
Mortality,%	2.9 (1.62)	2.9 (1.22)	3 (1.29)	3.7 (0.84)	4.6 (2.46)
Feed conversion ratio,%	2.7 (0.12)	2.8 (0.12)	2.7 (0.11)	2.9 (0.13)	2.9 (0.15)
Production per sow, kg LW	3496	3117	3468	2747	2279
Produced finishers per sow, no.	31.4	28.1	31.0	24.4	20.5
Antibiotic use, ADD[2]	2.3 (1.36)	1.2 (1.04)	0.8 (1.26)	2.2 (1.39)	1.6 (1.18)

Source: Own calculations based on Danish Crown data.
[1] Only one herd with sows is included in this production system; hence no standard deviation is shown.
[2] Measured as average daily dose for 100 animals according to VetStat (Fødevarestyrelsen, 2022).
[3] Estimated number of observations based on the total number of sows and average herd size.
[4] Owing to lack of validity concerning piglet mortality, the mortality ratio estimation is based on an assumption of 1 fewer live births per litter for *Free range* and 1.5 fewer live births per litter for *Organic* production than the litter in *Standard* production (Christiansen[4]).

Estimated environmental and climate impacts for the five production systems are shown in Table 2. The impacts are presented per kg of live weight as the sum of all sources in the life cycle up to the farm gate. The three indoor systems are at the same level for all impact categories, as there is only a minor difference between them in the underlying production system. For all impact measures the *Free range* system sits between the three indoor systems and the *Organic* system, the latter of which has the highest impact per kg for all impact categories.

Environmental and climate impacts can be mitigated with various technologies. Altogether, more than 20% of the farms had employed one or more environmental technology. The effects of such technologies on the selected dimensions of environmental and climate impacts are shown in Table 3. They are presented as the difference from the *Standard* production system with no environmental technology adoption. Biogas is the technology with the highest mitigation potential in relation to climate, at 15%, including reduced reliance on fossil energy following the switch to energy from biogas. For eutrophication and acidification the acid application is the most effective technology, with a reduction of up to 22% across the four impact categories.

Frequent sluicing technology only affects the production of finishers. As 60% of the slurry in a full line farm is produced by the finishers, however, it can, in combination with biogas, reduce the GHG emissions by roughly the same amount as biogas from the full quantity of slurry for the entire farm does.

Impacts on fresh water and land use are not affected by the implementation of the assessed environmental technologies.

Clearly, the effects of the environmental and climate technologies shown in Table 3 will be of relevance only if the technologies are applied. Table 4 provides information about how common the technologies are in finisher production. We focused on finishers because there can be several combinations of technologies in sow herds combined with several technologies in finisher herds. We also had more data for finisher production herds, and since the technologies there relate to manure handling, and since in addition more about 60% of the manure is from finisher production, the impact from this part of the chain is also highest.

Note that not all of the technologies can be used in all five production systems. The implication is that the environmental, climate and economic performance of the production systems is impacted by the technologies presented in Table 4, based on the number and share of finisher pigs produced in each production system with environmental and climate technology. It is important to note that the shares of finisher pigs produced with a given technology are not additive across the production systems, as some herds may have implemented multiple technologies.

Table 2
Environmental and climate impacts for the five pig production systems. Per kg live weight.

	Standard, no technology adoption	*Animal welfare*	*Raised without antibiotics*	*Free range*	*Organic*
Climate (GWP), kg CO_2-eq.	2.67	2.71	2.67	2.80	2.89
Eutrophication					
Marine (N-eq., g)	13.8	13.3	13.9	15.0	19.7
Fresh water (P-eq., g)	0.71	0.72	0.71	0.77	0.84
Terrestrial (N-eq., mmol)	248	241	248	273	389
Acidification ($H+$-eq., mmol)	57	55	57	62	79
Land use (LO), m^2	4.38	4.43	4.38	4.86	6.40

Source: Danish Crown (2021).

Table 3
Environmental and climate impact of different environmental technologies in pig production. The results are presented as per kg live weight for the Standard system without any technologies and as the difference from the Standard system for the selected environmental and climatic technologies.

	Standard, no technology adoption	Biogas (all animal groups)	Acidification (all animal groups)	Slurry cooling (all animal groups)	Frequent sluicing (finishers)	Frequent sluicing + biogas (finishers)
Climate (GWP), kg CO_2-eq.	2.67	−0.39	−0.31	−0.03	−0.13	−0.41
Eutrophication						
Marine (N-eq., g)	13.87	−0.11	−0.28	−0.05	−0.02	−0.07
Fresh water (P-eq., g)	0.71	0.00	0.00	0.00	0.00	0.00
Terrestrial (N-eq., mmol)	248.0	−15.6	−53.7	−11.2	−2.4	−10.7
Acidification ($H+$-eq., mmol)	56.6	−3.5	−12.0	−2.5	−0.5	−2.4
Land use (LO), m^2	4.38	0	0	0	0	0

Table 4
Number and share of finisher pigs within each production system produced using at least one of the five technologies.

Finisher pigs produced in systems		*Standard*	*Animal welfare*	*Raised without antibiotics*	*Free range*	*Organic*
With slurry cooling	Number	2.224.508	13.200	108.188	-	58.800
	Share	19%	9%	23%	0%	33%
With biological air cleaner	Number	332.968	-	37.464	-	-
	Share	3%	0%	8%	0%	0%
With chemical air cleaner	Number	71.900	-	5.200	-	-
	Share	1%	0%	1%	0%	0%
With in-barn acidification of slurry	Number	631.704	5.600	400	-	-
	Share	6%	4%	0%	0%	0%
With biogas	Number	1.778.050	4.500	33.425	7.400	11.700
	Share	16%	3%	7%	9%	7%

Biological and chemical air cleaners, which reduce the ammonia emissions and smell, are used only in approximately 3–4% of the herds. Slurry cooling is used in 20% of the herds to reduce ammonia emissions. The net cost of this technology is relatively low because the energy derived from the cooling can be used elsewhere on the farm. Finally, frequent sluicing of slurry is a low-tech technology, with farmers sluicing the slurry at least every eighth day. Usually, it is sluiced less frequently (typically about once a month).

Frequent sluicing is not quantifiable in the same way as the other technologies in Table 3, because the alternative frequency is not known. Further, it is rather easy to scale up or scale down on the implementation of this technology, since it is mainly associated with higher labour intensity.

Results of the animal welfare quantification for the five production

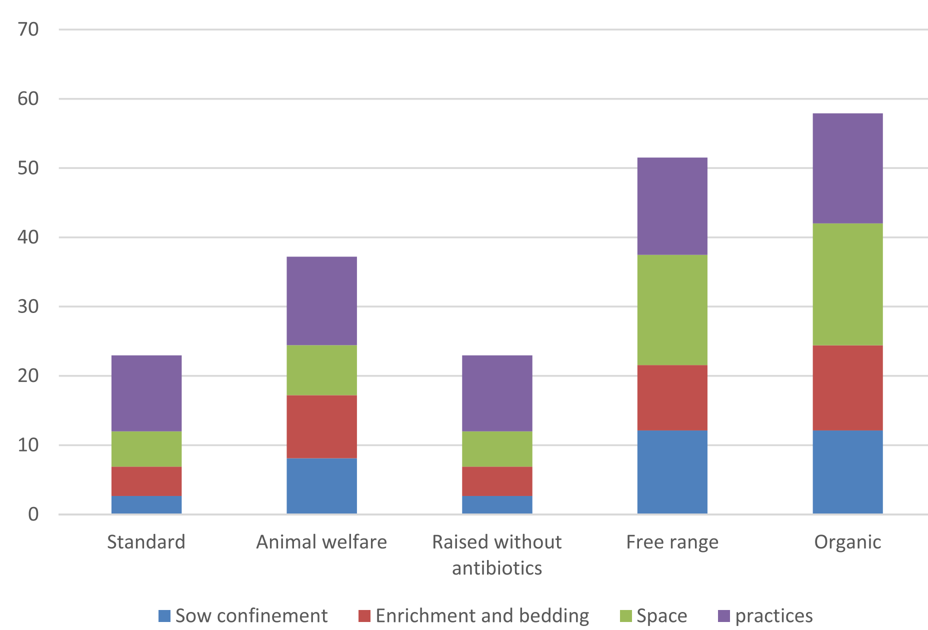

Fig. 1. Quantification of animal welfare in the five production systems. Quantification following Sandøe et al. (2020). The colours indicate the relative impact on the Benchmark score of whether sows are confined or not, of the provision (or not) of straw and others forms of enrichment and bedding material, and of space provision. 'Practices' include different practices regarding weaning, tail docking, castration, stable pen groups of pigs, transport, and slatted floors for finishers.

systems are presented in Fig. 1. The bars indicate the share of maximum points that the production system can achieve. The animal welfare status is subdivided into four components of animal welfare. As the bars indicate, the *Organic* and *Free range* production systems score high on animal welfare, mainly as a result of outdoor access and more space for the pigs (outdoor included in 'space'). The loose housing of sows throughout the whole cycle and added space in the *Animal welfare* production system is the background for higher welfare score than is achieved in the *Standard* and *Raised without antibiotics* systems. Outdoor access and much more space is heavily weighted in the method applied to assess animal welfare, which explains why animal welfare is lower in the A*nimal welfare* system than it is in the *Free range* and *Organic* systems.

Estimated antibiotic use in the five production systems is shown in the Table 5. The lowest use is found in the *Raised without antibiotics* system. The use of antibiotics there is not zero, though, as some finisher pigs which are not included in the scheme are treated with antibiotics on the farms. The sows are also treated with antibiotics. Hence, although the pigs labelled as *Raised without antibiotics* have not been treated with antibiotics, antibiotics are still used in the herd to treat sick finisher pigs (subsequently sold as standard pigs) and sows.

Finally, costs of production in the five production systems are shown in Table 6. These are inferred from the production results presented in Table 1 and not extracted directly from the farm accounts. Estimated quantities of extra straw and extra use of labour is used to calculate the costs.

It is estimated that the costs of adding environmental technologies are marginal in comparison with the cost differences across the production systems, as the different technologies incur cost increases ranging from €0.5 per pig to €2.5 per pig. The cost components of the environmental technologies are presented in Table A2 in the Appendix.

Combining all of the results for all five of the production systems, we were able to create the cobweb chart shown in Fig. 2. For each of the five dimensions, the results are normalised relative to the production system with the best practice in that dimension. A dominant production system with best practice in all five dimensions would score 100% on all five dimensions. As can be seen from the figure, there is no dominant production system amongst the five systems when they are analysed in the five selected dimensions. The *Standard* system is dominant in the cost dimension, as well as in climate impact, together with *Raised without Antibiotic*, while *Raised without Antibiotic* is dominant in the antibiotic use dimension. *Organic* is dominant in animal welfare dimension. It also performs well in the antibiotic use dimension, but scores low in the environment and cost of production dimensions. Though its name suggests that the *Animal welfare* system ought to perform well on animal welfare, this production system is well below the performance of the *Organic* production system. This mainly reflects two features of *Animal welfare*: lack of access to an outdoor area and less space than that provided in *Organic*. Turning to climate impacts, the differences between the systems here are minimal, though there are slightly higher climate impacts in the *Free range* and *Organic* production systems.

Table 5
Results from aggregated antibiotic use per sow with offspring until slaughtering.

	Standard, no technology adoption	*Animal welfare*	*Raised without antibiotics*	*Free range*	*Organic*
Sows, body weight, kg	200	200	200	200	200
Weaners – body weight, kg	76	68	75	60	50
Finishers – body weight, kg	398	355	394	313	262
Weighted ADD	3.13	3.11	1.50	2.51	1.52
Ratio to best	2.09	2.08	1.00	1.68	1.02
Inverted (score)	48%	48%	100%	60%	98%

Table 6
Costs of producing a finisher at 115 kg live weight in the five production systems, € per pig.

	Standard, no technology adoption	*Animal welfare*	*Raised without antibiotics*	*Free range*	*Organic*
Feed costs	74.1	74.1	74.1	79.3	144.6
Antibiotics costs	1.6	1.6	1.1	1.2	1.1
Other unit costs	10.9	12.1	15.0	15.3	17.4
Labour costs	12.8	18.9	14.8	22.6	31.8
Straw and other manipulable materials	0.3	1.5	0.3	3.2	3.9
Other capacity costs[1]	8.1	9.0	8.3	13.4	18.9
Total costs	124.6	139.2	130.5	156.6	251.9

[1] Includes energy, maintenance, insurance, and miscellaneous fixed costs.

4. Discussion

Historically, the main goals of Danish pig production have revolved around productivity and cost-effectiveness. Nevertheless, capitalising on consumers' willingness to pay for additional traits, market-based initiatives have evolved that focus on animal welfare, and on the avoidance of agrochemical and antibiotic use. Increased interest in a multitude of dimensions in which standard pig production can reduce its negative impacts on the environment, the climate and animal welfare, and make less use of antibiotics, means there is a greater need to investigate the trade-offs between these sustainability dimensions. Multiple other dimensions of sustainability could be considered here, including social sustainability (Zira et al., 2021). We have chosen the dimensions for which we have empirical data and in which we have seen market developments in Europe.

4.1. Strengths and limitations of our study

The five pig production systems analysed in this study are representative of trends in pig production in western countries. But although the production systems are representative and the empirical data fed into our analysis are wide-ranging, the study does not fully represent the pig farms currently operating in Denmark. This is because we have chosen to present the trade-offs between production systems that do not use environmental technology even though many farms have technology installed. This has the implication that the estimated environmental and climate impact of the *Standard, no technology adoption* system is higher than that of the average 'standard' farm in Denmark.

The trade-offs between the five dimensions in the five existing production systems could be augmented with the trade-offs that would be introduced if e.g. *Standard* production systems were to adopt some of the environmental and climate technologies that are not applicable in the *Free range* and *Organic* production systems. Implementing such technologies in *Standard* production would improve its environment and climate dimensions, and hence intensify the trade-offs between the high animal welfare score achieved by *Free range* and *Organic* production and the high score for environment and climate in *Standard* production.

The data in our analysis has high validity for the *Standard* system. The number of observations (herds) in the other systems is much lower and this compromises the reliability of especially the *Animal Welfare* production system. However, the production results of this system are aligned with our a priori expectations. Further, the reliability for the results of sows and weaners are lower than for finisher pigs because the representation in the data is substantially lower. The large dataset for

Table A1
Housing and floor type in each section and production system.

Section	Standard	Animal welfare	Raised without antibiotics	Free range	Organic
Mating and gestation	Loose housed	Loose housed	Loose housed	Free range gestations huts	Free range gestations huts
Farrowing	Farrowing crates, partly slatted floor	Loose farrowing systems, partly slatted floor, more space	Farrowing crates, partly slatted floor	Free range farrowing huts	Free range farrowing huts
Weaners	Regulated temperature, partly slatted floor	Regulated temperature, partly slatted floor, 30% more space	Regulated temperature, partly slatted floor	Partly slatted floor, access to consolidated outdoor area	Partly slatted floor, access to consolidated outdoor area
Finishers	Drained floor (33%), slatted floor (67%)	Partly slatted floor, 50–75% solid floor, 30% more space	Drained floor (33%), slatted floor (67%)	Partly slatted floor, 50–75% solid floor, access to consolidated outdoor area	Organic barns with more space

Table A2
Costs of producing a pig in standard production system with five different environmental technologies, in Euros per pig.

	Biogas[1]	Acidification	Slurry cooling	Frequent sluicing	Frequent sluicing + biogas
Feed costs	74.1	74.1	74.1	74.1	74.1
Antibiotics costs	1.6	1.6	1.6	1.6	1.6
Other unit costs	10.9	10.9	10.9	10.9	10.9
Labour costs	12.8	12.8	12.8	13.0	13.0
Energy costs	3.1	3.4	3.5	3.1	3.1
Consumables for technology	0.0	0.8	0.0	0.0	0.0
Other capacity costs[2]	5.2	5.2	5.2	5.2	5.2
Capital costs	16.9	18.1	17.0	16.9	16.9
Total costs	124.2	126.7	125.0	124.7	124.7

[1]) Capital costs for biogas have not been included. In Denmark, we have large decentralized biogas plants that normally receive manure from a larger number of farmers with different livestock production. The biogas company collects the manure free of charge and delivers the degassed manure back to the farmer free of charge.

[2]) Other capacity costs covers energy, maintenance, insurance, and miscellaneous fixed costs.

Standard, which is used as a basis for the analysis, alleviates concerns about the representativeness of our sample, though. Still, uncertainties in the analysis, related to multiple production systems within the same herd, remain. Imprecision and strategic answering by the farmers interviewed (in order to appear to have a lower impact) are also potential sources of distortion or error. The variation within the group of herds is rather wide in comparison with the differences between the systems. This is illustrated in Table 1, where the standard deviation of the production parameters are shown in the parentheses.

In addition, for *Free Range* and *Organic* the results in the dimensions environmental and climate impact are more uncertain, as these effects were estimated outside the LCA model.

Where climate impact is concerned, it is striking that the production systems we analysed showed little or no difference. This may be due to the fact that none of the systems is 'optimised' from a climate perspective. Our results suggest that implementation of biogas and frequent sluicing would reduce climate impact by up to 19% (Table 3). It is known that emissions from feed production contribute significantly to total climate impact (Dorca- Preda et al., 2021). There is large variation in the impact per kg of dry matter, which shows the potential for reductions in impacts by optimising the feed ration as a combination of cost and reduced climate impact. Mackenzie et al. (2016) have shown that a composition of feed ration designed to lower the climate impact of feed production can decrease the impact per kg LW by up to 17%, but at increased cost.

Feed for pigs in Denmark is produced in a variety of ways (home-grown, imported from different countries, etc.). If the feed used in individual herds was based on herd-level registrations, more variation across productions systems as regards climate impact could arise. However, choice of feed is, at least to some extent, in the non-organic production system expected to be independent of the production system. The Organic feed ration differs from the other feed rations.

Our study did not include the effect of global land use change (LUC). We did not possess detailed information on the feed stuff used in every production system, and therefore we assumed the same feed composition was available in each of the four conventional systems. Including LUC would be equal for the four conventional the production system analysed in this paper irrespective of the method used to estimate LUC. By contrast, the effect in the organic system would be highly dependant on the method used (Mogensen et al., 2022).

We could have incorporated biodiversity in the LCA using the

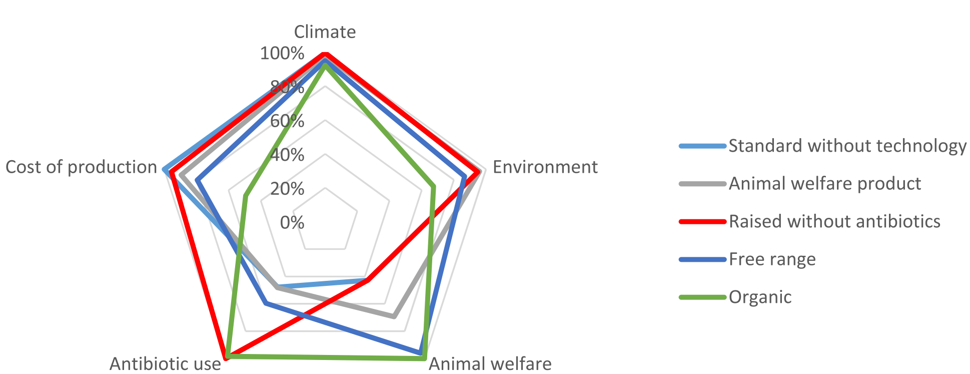

Fig. 2. Relative assessment of production systems in five dimensions. 100% is 'best' with lowest environmental and climate impact, lowest antibiotic use and cost, and highest animal welfare.

approach suggested by Knudsen et al. (2017). This would not have generated any differences in the impacts for four of the five production systems, because the same feed ration was used in all of the conventional production systems, but it might have put *Organic* production in a better position, as shown by Zira et al. (2021). As is standard in LCA the climate impact on construction of buildings is not included but as this constitutes only a minor emission this does not practically affect our results.

Our assessment of animal welfare status in the five production systems was based on concurrent research (Sandøe et al., 2020) explicitly relating animal welfare to the production system. This is done by means of the so-called Benchmark method where the welfare effects of different initiatives are being assessed by expert valuations of the resources provided to the animals. Even though the assessment is not directly animal-based it can serve as an approximation since the involved animal welfare experts aimed to assess how the resources mattered from the point of view of the affected animals. However, differences in compliance and stockmanship will not be recorded.

The antibiotic use assessment in this study was built on a solid data. However, we chose to use an index to represent the use of antibiotics with a single numeral based on the calculation of doses, and we elected to use standard weights of the animals as the basis of the weighted index of doses. If we had used the amount of active ingredients, the aggregation would have been simpler. However it would not have been as precise as regards the risk of resistance development, since some antibiotics require more active ingredients to have effect than others do. Other weights were also considered, such as the number of animals in each age group, irrespective of the weight of the animals, but this would not have been representative of the risk of resistance development.

Production costs were based on average prices and the investment levels used in industry analysis. This is not quite the true cost of production for the farms in our sample. But our costs of production were empirically based in the sense that the productivity measures and other production measures registered in the herd-level data were used in their estimation. Our data did not allow the costs to be estimated based on farm-level revenues and costs. This approach would also have introduced uncertainties about the costs of pig farming activities and other on-farm activities for joint production assets categories such as buildings.

4.2. Interpretation of our findings

We chose to use a weight-based approach, i.e. one employing per kg of product produced as the functional unit in the analysis. This approach is criticised by Zira et al. (2021), who argue that when per kg of product is used in the comparison of different production systems there is an automatic focus on intensification and efficiency. They argue that a 'per area' functional unit is more relevant, because with its use the land becomes the constraining factor. This is called a contrasting sufficiency perspective.

The question of which approach is the most suitable is closely linked with underlying assumptions about consumers' demand for pork – both in terms of the overall expected demand for pork and as regards consumer demand for pork produced with various additional product qualities. If pigs in a given country were to be produced with the lowest 'per area' impact this would, in our view, lead to that country's pig sector being outcompeted by foreign competitors because in the supermarket consumers are presented with weight-based choices. Hence, the weight-based approach is consistent with the perception that consumers in the rest of the world do not change preferences due to changes of production in Denmark. If we were to use the area-based measure instead, as suggested in Zira et al. (2021), we would assume an exogenously given change in consumer demands.

A counterargument here is that when products with higher *Animal welfare*, and thus higher environmental impact, are more expensive, consumer of pork products shopping with budgetary constraints will not impact the environment and climate as much as the mass-based measure indicates. Consumers with budgetary constraints could, however, choose to buy a lower quantity of standard products, and to spend the money they save on something else. However, given the currently small market shares enjoyed by *Organic* and *Free range* products, we believe that the mass-based measure is the more appropriate for this analysis.

Where impact on environment was concerned, there were quite large differences between the highest and lowest impacts, with the *Organic* production having highest impact, and *Standard* and *Raised without antibiotics* the lowest, per kg live weight. Substantial differences between the production systems were also found for animal welfare and antibiotic use: the animal welfare index for the *Standard* production system was only half that of *Organic* production, and antibiotic use in the *Standard* system was twice that in *Raised without antibiotics*. The differences with respect to environmental impact and animal welfare lead to trade-offs between the two sustainability dimensions based on present use of technologies. Other trade-offs can more easily be mitigated – for example, by increasing management efforts and reducing antibiotic use. This will initially lead to higher production costs, but in the long run this cost can be reduced by generally increased levels of management.

As *Standard* production displayed the lowest production costs, there are trade-offs with the production costs in all of the other production systems. Pork products of the *Organic* system were the most expensive to produce, at about twice the cost of the corresponding *Standard* products.

4.3. Comparison with the findings of other studies

In our analysis we decided to assess the impact of pig production with reference to existing production systems. The assessment was pragmatic, and the data at hand guided our ambitions as regards which dimensions to include and which measures to use. This is somewhat different from the approach taken in Bonneau et al. (2014) where the sustainability of contrasted pig farming systems were evaluated based on case observations, interviews or experts. Their findings are somewhat aligned with our findings as they find negative correlations between animal welfare and economy. Our negative relationship were between animal welfare and production costs which is not the same as economy. If consumers are willing to pay more than the extra cost of production, then it would be possible to have positive correlation between animal welfare and economy.

The impacts of environmental and climate mitigating technologies are aligned with the findings in Pexas et al. (2020), who also found that manure management and housing conditions have the potential to reduce both environmental and climate impacts of pig production.

Scherer et al. (2018) incorporated the animal welfare dimension directly into the LCA, but they include, for example, only one measure of the quality of life – which for pigs is the surface area available to each animal. We acknowledge some merits of including an animal welfare dimension in the LCA rather than, as we proposed, addressing animal welfare issues separately from the LCA analysis as this would incorporate the dimension into a respected analytical frame. On the other hand, we were able to include a more comprehensive measure of animal welfare incorporating a wide array of welfare-enriching attributes. Indeed, the Benchmark method here has an advantage, as it includes a wide range of welfare attributes systematically and transparently, and it can be used to compare the animal welfare impacts of different production systems. On the other hand, it is a limitation of the Benchmark method that, when it is used, production systems are described according to requirements formulated in national legislation, or labels, or other welfare initiatives, and thus it implicitly assumes the full compliance of all farmers.

An even more comprehensive measure of animal welfare would be obtained by the inclusion of Welfare Quality® (WQ) assessments of the animal welfare. This would be very costly, however, and there would be difficulties collecting representative data (Sandøe et al., 2020).

5 Conclusion

Based on our extensive data on current Danish pig production systems, we identified trade-offs mainly between environmental impact and animal welfare. Even with potential improvements in management in the future, this trade-off is believed to be inherent: the animal welfare dimension requires more space, and thus the pigs have lower feed conversion ratios than those in current standard production when analysed under similar feeding strategies. Further, improved indoor production systems would introduce trade-offs with production costs, albeit to a varying extent.

Whether standard production comes under tighter regulation in the future in order either to lower antibiotic use, or increase animal welfare, or reduce environmental impact (or in order to reach a combination of these goals) is a political question, but any regulation will impact production costs if it is not subsidised.

Potentially, future research and development could help to mitigate negative impacts in one dimension while improving performance in other dimensions. We have chosen to focus on technical trade-offs in existing production to guide future investments. Knowledge, and the quantification of impacts in existing pig production systems in sustainability-related dimensions, can help us to ensure that future investments in pig production increase performance in single dimensions and/or reduce the need for trade-offs. However, consumers' prioritisation of individual dimensions, their willingness to pay, and their trade-offs between dimensions, all constitute a second step on the path towards underpinning a marketing strategy that increases the sustainability of products in the pork value chain.

Authors' contributions

JVO, TC and PS: conceptualisation; HM-LA, TK, SVS, FU and JVO: data curation; HM-LA, TK, SVS, FU and JVO: formal analysis; TC and PS: funding acquisition; HM-LA, TK, SVS, FU and JVO: investigation and Methodology; JVO, TC and PS: project administration; PS: resources; HM-LA, TK, SVS, FU and JVO: Validation; JVO: writing – original draft preparation. All authors have read and agreed to the published version of the manuscript.

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Declaration of Competing Interest

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Appendix

In order to better capture differences in the sustainability dimension across the production systems those systems were subdivided into the three standard stages of the pig production process – sows, weaners and finishers. Sows includes piglets up to approx. 7 kg; weaners are 7 kg to approx. 30 kg; and finishers are 30 kg to 111.5 kg, at which point they are taken to slaughter.

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