Environmental and economic consequences of pig-cooling strategies implemented in a European pig-fattening unit

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Abstract:	The increased frequency of hot days due to climate change can potentially impair the environmental and economic performance of pig-fattening farms. Several pig-cooling strategies have been proposed to address these impacts, however their implementation is not always economically viable and the potential environmental-economic trade-offs not well understood. Here, we propose and implement a novel framework for environmental and economic evaluation of pig-cooling strategies in a whole farm context. We also demonstrate through a sensitivity analysis how such models can be integrated with projected climate data to investigate how climate change may affect the assessment of capital investments that are made over significant timescales. We considered two strategies implemented in a pig-fattening farm in south Sweden: pig-cooling with showers and with increased air velocity. Operation of the farm under non-cooling conditions was considered as the baseline system against which the analysis was conducted. We calculated whole-farm annual equivalent values (AEV) with the implementation of each strategy through a discounted cash flow analysis and annualised system environmental impact through a life cycle assessment. Both cooling strategies significantly reduced system environmental impact across all categories except water footprint. Acidification potential was reduced the most, exhibiting a -3.28% reduction with pig showers and -1.51% with increased air velocity. Farm profitability improved by +6.79% with showers and +3.37% with increased air velocity. Ambient temperature increase under non-cooling conditions significantly increased all impact categories with acidification being affected the most (+2.24%), and caused a -4.43% decrease in AEV. Both pig-cooling strategies mitigated these effects on system environmental performance. With increased air velocity we observed a +0.718% increase in acidification, while pig showers were the more resilient option exhibiting a +0.690% increase. The study represents a case-in-point for how to rationalise economically environmental management technologies in pig housing systems based on their cost-effectiveness in mitigating environmental impacts.

Environmental and economic consequences of pig-cooling strategies implemented in a European pig-fattening unit

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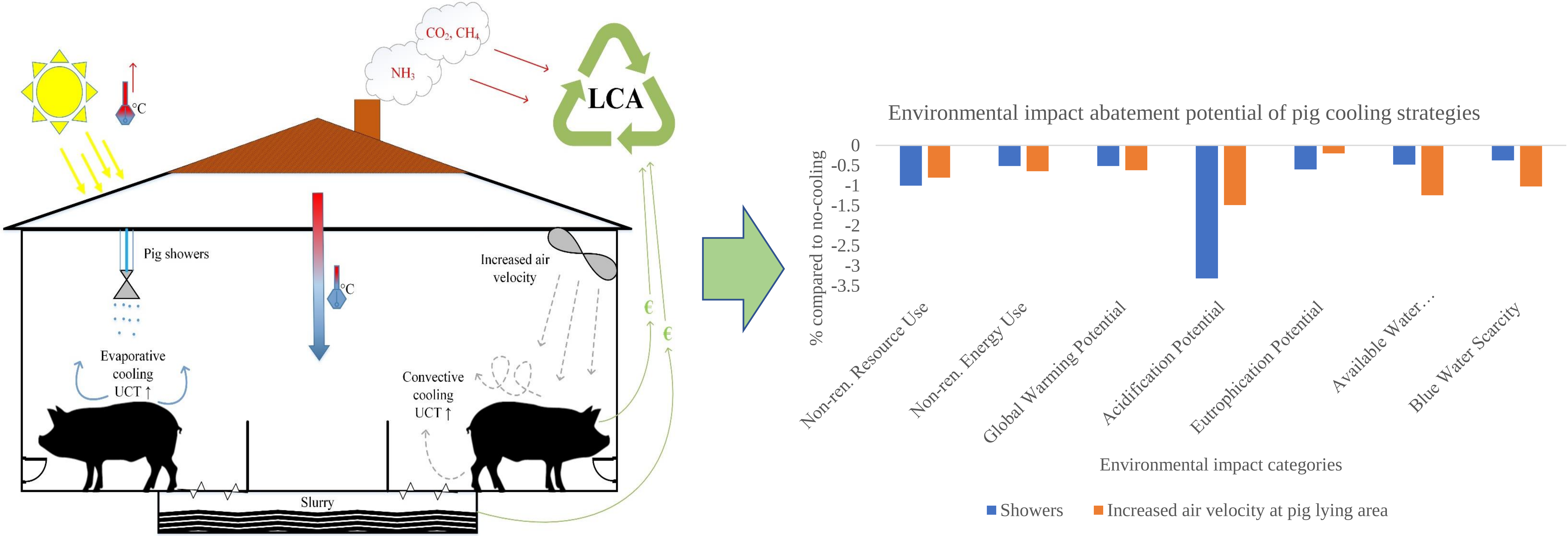
Highlights

- The environmental and economic impacts of two pig-cooling strategies were evaluated
- We considered pig-cooling with showers and increased air velocity at pig lying area
- Both strategies improved farm environmental performance for AP, EP and NRRU
- Both strategies mitigated heat stress, improved pig welfare and farm profitability
- The strategies mitigated the effects of global warming on pig farm sustainability

Graphical Abstract



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Abstract

The increased frequency of hot days due to climate change can potentially impair the environmental and economic performance of pig-fattening farms. Several pig-cooling strategies have been proposed to address these impacts, however their implementation is not always economically viable and the potential environmental-economic trade-offs not well understood. Here, we propose and implement a novel framework for environmental and economic evaluation of pig-cooling strategies in a whole farm context. We also demonstrate through a sensitivity analysis how such models can be integrated with projected climate data to investigate how climate change may affect the assessment of capital investments that are made over significant timescales. We considered two strategies implemented in a pig-fattening farm in south Sweden: pig-cooling with showers and with increased air velocity. Operation of the farm under non-cooling conditions was considered as the baseline system against which the analysis was conducted. We calculated whole-farm annual equivalent values (AEV) with the implementation of each strategy through a discounted cash flow analysis and annualised system environmental impact through a life cycle assessment. Both cooling strategies significantly reduced system environmental impact across all categories except water footprint. Acidification potential was reduced the most, exhibiting a -3.28% reduction with pig showers and -1.51% with increased air velocity. Farm profitability improved by +6.79% with showers and +3.37% with increased air velocity. Ambient temperature increase under non-cooling conditions significantly increased all impact categories with acidification being affected the most (+2.24%), and caused a -4.43% decrease in AEV. Both pig-cooling strategies mitigated these effects on system environmental performance. With increased air velocity we observed a +0.718% increase in acidification, while pig showers were the more resilient option exhibiting a +0.690% increase. The study represents a case-in-point for how to rationalise economically environmental management technologies in pig housing systems based on their cost-effectiveness in mitigating environmental impacts.

Keywords: Pig cooling; Climate change; Economic assessment; Environmental impact; Life cycle assessment; Cost effectiveness

1. Introduction

European pig production predominantly occurs in large-scale units controlled by mechanically ventilated and well-insulated buildings (Gerber et al., 2013). Due to the high heat load produced by the animals over the summer period, indoor temperature and humidity in such systems can reach high levels similar to those of tropical conditions even when the farm is located in temperate climatic zones (Schauberger et al., 2019). Evidence in literature suggests that prolonged hot (>27 ℃) and humid environmental conditions have direct consequences on animal productivity with reported reductions in growth rate (-38.7%) and feed intake (-17.2%) of growing and finishing pigs for the duration of such environmental conditions (Myer and Bucklin, 2001; Wellock, Emmans & Kyriazakis, 2003; Huynh, Aarnink, Truong, Kemp & Verstegen, 2006).

Pig production is regarded among the largest contributors to acidification of ecosystems and eutrophication of fresh water bodies, arising from livestock (De Vries and De Boer, 2010). Suboptimal farm productivity under ‘hot’ conditions can potentially increase the system environmental impact as it is associated with inefficient use of resources such as on-farm energy and feed use (Gerber et al., 2013). An increase in ambient temperature, can also significantly affect ammonia emissions at the pig housing and manure management component (Rigolot et al., 2010; Pexas, Mackenzie, Wallace & Kyriazakis, 2020a). Potential economic losses associated with the impaired performance of animals in pig farming systems have also been previously identified. Farm profitability can be significantly impacted by heat stress, since the feed and pig meat are major costs and revenues respectively (St-Pierre, Cobanov & Schnitkey, 2003; Dittrich, Wreford, Topp, Eory, & Moran, 2017; Hoste, 2017). System economy can also be impacted by variations in the efficiency (nitrogen, phosphorus, potassium concentration) of manure as an organic fertiliser (Pexas, Mackenzie, Wallace & Kyriazakis, 2020b).

Several alternative management strategies and technologies have been proposed to tackle the effect of increased ambient temperature on animal performance and emissions at pig housing (Vitt et al., 2017; Mikovits et al., 2019). Among the practices that can potentially achieve combined benefits for mitigation of heat stress and ammonia emissions, is cooling of the pigs (Botermans, Gustafsson, Jeppsson, Brown, & Rodhe, 2010). During hot periods, pigs alter their behaviour to combat heat stress and tend to lie in the slatted, excretory area of the pen, increasing fouling in the solid, lying area. Consequently, ammonia emissions at pig housing increase due to the larger surface of manure exposed to air and high temperature (Aarnink, Schrama, Heetkamp, Stefanowska, & Huynh, 2006). Increased air velocity at pig lying area affects the immediate thermal vicinity of the animals, causing increased convective heat losses from their bodies and therefore expanding the thresholds of their perceived thermo-neutral zone (wind-chill effect) (Wellock et al., 2003; Zhang and Bjerg, 2017). Cooling can also be achieved with frequent showers over the slatted area of the pen during ‘hot’ periods. This way, animals lie less in the excretory area and pen cleanliness is improved. Furthermore, evaporative cooling is increased from pig wet skin, which can potentially reduce the effect of heat stress (Wellock et al., 2003; Aarnink et al., 2006; Huynh et al., 2006). The implementation of such cooling strategies has direct (i.e. slurry dilution from showers) and indirect effects (i.e. more nitrogen in manure due to reduced NH_3 emissions) on manure composition. Therefore, to evaluate their environmental performance accurately we should adopt a whole-farm approach, considering interactions between all system components (Pexas et al., 2020a).

Pig-cooling strategies can also increase farm related costs (i.e. investment in technological equipment, running costs) and so thorough cost-effectiveness assessments should be performed prior to their implementation (Mikovits et al., 2019, Pexas et al., 2020b). Some studies have attempted to evaluate the effectiveness of similar strategies to improve farm economic performance and animal welfare conditions at growing and finishing pig farming systems (Vitt et al., 2017; Schauberger et al., 2019).

With an increase in ambient temperature and the frequency of hot days due to climate change, the resilience of confined pig farming systems to heat stress, as well as the mitigation of their potential environmental and economic impacts are of increasing concern (Valiño, Perdigones, Iglesias, & García, 2010; Beniston, Stoffel, & Guillet, 2017; Mikovits et al., 2019). In the present paper, we have addressed a gap in thorough whole-farm environmental impact assessments of the system under heat stress conditions, and for the first time we evaluated the potential environmental and economic impact trade-offs associated with the implementation of pig-cooling strategies that target heat stress and ammonia emissions mitigation in a European pig-fattening unit. We also investigated the implications of projected ambient temperature increases for Sweden caused by global heating on the environmental impact mitigation provided by pig-cooling scenarios. In doing so, we demonstrated a novel framework for farm level environmental and economic evaluation of animal housing technologies that can be integrated with projected to provide insight as to how global heating may affect the cost-effectiveness of capital investments based on their potential to mitigate environmental impacts in the long term.

2. Materials and Methods

The primary aim of this study was to evaluate trade-offs in the environmental impacts and economic implications associated with the implementation of pig-cooling strategies that target ammonia emission reductions at a pig-fattening unit. To achieve this aim we worked through the following specific steps:

i) We described the pig production system under assessment and modelled indoor climate, animal growth and heat stress related parameters as a function of outdoor climate data and specific to the system, climate control properties.

ii) We developed scenarios to simulate the operation of the pig production system with the implementation of two pig-cooling strategies: (1) cooling with showers over the slatted pen area and

(2) cooling with increased air velocity at the pig lying area. These strategies were contrasted with a baseline (‘non-cooling conditions’) comprising a standard management system without novel cooling technologies deployed.

iii) We estimated the annualised system environmental impact for each scenario, through an environmental life cycle assessment framework.

iv) We estimated the financial performance of each scenario using whole-farm annual equivalent values derived from a discounted cash flow analysis over a 25-year time horizon.

v) We evaluated potential environmental and economic trade-offs by assessing the cost-effectiveness of each pig-cooling strategy in reducing system environmental impact.

vi) We performed a sensitivity analysis to estimate the effect of climate change as an increase in ambient temperature on the system environmental and economic performance under varied cooling conditions.

2.1. Description of the study area and pig farming system

Analyses were performed on a typical pig-fattening unit for Sweden, located near Malmö, southern Sweden (55.6050° N, 13.0038° E). The case study was purposefully selected as it demonstrates how projections for increased temperatures across all seasons may indicate the need for animal cooling even in places where it was not traditionally used (Ruosteenoja, Markkanen & Räisänen, 2020), and on the basis of data availability regarding the effect of pig cooling on ammonia emissions at housing. Although Sweden is located in northern Europe, its climate is similar to that of the largest part of Central Europe, where a big portion of pig production takes place (Vitt et al., 2017; Mikovits et al., 2019). The specific climatic type is temperate, with summers characterised by warm temperatures and moderate humidity (Cfb type according to Köppen-Geiger climate classification). Relevant data to describe the system under assessment were obtained from the Swedish University of Agricultural Sciences (SLU), and from published reports on the specifications for pig-fattening units by the Swedish Board of Agriculture (Swedish Board of Agriculture, 2018). The unit reared pigs for approximately 90 days and completed an average of three production cycles per year. Animals reared in the pig farming system were offspring of Topigs Norsvin 70 sows x Hampshire sires. They entered the fattening unit at 30 kg and under normal climate and management conditions, they reached an approximate slaughter weight of 115 kg. Farm production capacity was 1320 animals per batch with equal number of entire males and females.

Pig housing comprised a barn of six rooms (23.5 m length x 11.6 m width x 3 m height per room) with 120 pens (20 per room) accommodating an average of 11 pigs per pen. The building consisted of concrete walls, well-insulated with polyurethane boards, a flat ceiling insulated with fiberglass, concrete partially slatted floors (30% slatted: 70% solid) and under-barn slurry pits, complying with the Best

Available Techniques guidelines for rearing of pigs (Santonja et al., 2017). Cleaning, disinfecting and barn preparation activities occurred at the end of each production cycle and lasted four days; the building remained unoccupied during this period. Manure was stored outside in concrete, covered slurry tanks and applied by trail-hose tanker to replace synthetic fertiliser for crop production. We estimated the amount of manure applied as organic fertiliser, based on nutrient substitution rates, which were assumed 75% for nitrogen, 97% for phosphorus and 100% for potassium, representing the national average (Nguyen, Hermansen & Mogensen, 2011). Although derived from modelling of Danish pig systems, these figures represent the best estimates with respect to pig systems in Northern Europe for implementing the convention of accounting for mineral fertiliser replacement in LCA through system expansion (Hanserud, Cherubini, Øgaard, Müller & Brattebø, 2018).

2.2. Indoor climate modelling

Indoor climate conditions were regulated by a low-pressure ventilation system (SKOV LPV system). To estimate indoor climate parameters relevant to the system environmental and economic impact for any given day in production (indoor temperature and ventilation rate), we worked through the sensible heat balance principle $s_A + s_B + s_V = 0$ (Schauberger et al., 2000). In the model, s_A represents the sensible heat release from the animal calculated as a function of animal body mass. s_B is the sensible heat loss due to transmission through the building calculated as a function of insulation, building surface and indoor-outdoor temperature differential. s_V is the sensible heat flow due to the ventilation system calculated as a function of the indoor-outdoor temperature differential and climate control system properties (i.e. minimum & maximum ventilation rates). Temperature set points for the specific climate control system ranged from 19.4 ℃ in the first week of production to 16.5 ℃ before the animals reached slaughter weight. The unoccupied barn was heated prior to animal introduction and therefore, the starting temperature was 19.4 ℃ on the first day production. Indoor temperature and ventilation rate for a day in production (t) were estimated using indoor climate parameters for the previous day (t-1) and animal body mass, temperature set points, and daily outdoor temperature averages corresponding to t. Air velocity at pig lying area was approximately 0.15 m / s. An average of 40 Watts pig^{-1} was used for heat supply purposes during the first three weeks of a winter production cycle. Values were averaged for the 90-day production cycle to provide context for the environmental and economic impact assessments.

To account for the operation of the production system under the different seasons of the year, we used daily outdoor temperature averages for the period 1971 to 2019 collected from the nearest meteorological station at Sturup, Sweden (55.5231° N, 13.3787° E) (SMHI, 2020). As expected, winter was reported as the coolest season of the year with a mean of 0.42 ℃ (± 4.08 ℃), followed by spring (6.49 ℃, ± 4.96 ℃), autumn (8.63 ℃, ± 4.51 ℃) and summer (16.0 ℃, ± 2.82 ℃). The effect of seasonal ambient temperature variations on indoor climate parameters, energy consumption for climate control and heat stress related parameters was simulated using the indoor climate model described above. We also modelled potential direct and indirect effects on methane, ammonia, nitrous oxide and dinitrogen monoxide emissions using temperature-specific variations factors for methane and ammonia emissions from literature (Rigolot et al., 2010; Pexas et al., 2020a).

2.3. Animal growth and manure management related emissions

Animals were reared from 30 kg to 115 kg (slaughter weight) in approximately 90 days. During this weight range a total of 238 kg of feed was consumed by each animal. Two cereal-based diet formulations were used in the production cycle: a ‘growing’ diet from 30 kg to 65 kg and a ‘finishing’ diet from 65 kg to 115 kg. Using specific feed conversion ratio for fattening pigs as reported by SLU, we estimated that 97.8 kg of ‘growing’ feed was allocated during the first weight interval, and 140.2 kg of ‘finishing’ feed during the second one. Due to data limitations on water consumption, a 2:1 water-to-feed ratio was assumed according to the guidelines for welfare of pigs (DEFRA, 2020).

Methane (CH_4) emissions and nutrient excretion (N, P, K) associated with animal growth and the feed nutrient composition were estimated by tracking nutrient flows through the system components according to the mass balance principle. Following the same approach, we modelled CH_4, NH_3, NO_x, N_2 and N_2O emissions from slurry at pig housing (pen and slurry pits), slurry storage and field application. The IPCC guidelines were used for nutrient rates and methane emission factors (Dong et al., 2006). Emission factors for nitrogen and phosphorus related emissions were derived from relevant literature (Sommer et al., 2006; Botermans, et al., 2010; Pexas et al., 2020a).

2.4. Heat stress

We estimated the upper critical temperature for the average animal in the production cycle weighing approximately 72.5 kg, according to the method of Wellock et al., (2003). In addition to animal body mass and indoor temperature for the calculations, we accounted for energy intake from feed, indoor relative humidity, voluntary pigskin wetting (~15%) and air velocity at pig lying area (~0.15 m/s). If the predicted indoor temperature remained above the estimated higher critical temperature for more than three consecutive days, indoor conditions were characterised as ‘hot’. When ‘hot’ conditions were identified, we simulated a heat stress effect on animal performance applying a 17.2 % reduction in daily feed intake and a 38.7% reduction in average daily gain (Myer and Bucklin, 2001). Indirect heat stress effects on nutrient excretion, manure composition and related emissions at pig housing, manure storage and field application were modelled according to the mass balance approach.

Table 1 summarises the main variables used by the indoor climate control model and the model used to estimate the effect of heat stress on animal performance. Modelling of indoor climate, animal growth and heat stress related parameters was performed in R Studio v1.1.383 (R Core Team, 2020).

Variable (unit)	**Value**
Animal	
Body weight (kg)	30.0 – 115
Daily feed intake (kg)	1.30 – 2.70
Pig barn characteristics	
Surface area of building oriented on the outside (m^2)	2800
Mean thermal transmission coefficient, U ($W\ m^{-2}\ K^{-1}$)	0.500
Indoor climate	
Temperature set points, T_c (℃)	16.5 – 19.4
Minimum – Maximum ventilation rate ($m^3\ h^{-1}$)	8.50 – 95
Temperature bandwidth of control unit (℃)	4.00
Air velocity at pig lying area (m / s)	0.15
Heating required per animal, ~3 weeks during winter season (W)	40

Table 1: *Key variables describing the production cycle under thermo-neutral conditions. Data sources: Swedish Board of Agriculture (2018); Jeppsson & Olsson (2020, February)*

2.5. Scenario analysis

We evaluated the annualised potential environmental and economic impacts associated with the operation of the pig-fattening unit under non-cooling conditions and with the implementation of two pig-cooling strategies that aim to reduce ammonia (NH_3) emissions at pig housing and improve pen hygiene, through a decrease in pen fouling. The scenarios were developed using real data on the performance of the specific pig-cooling strategies, implemented in the system under consideration during the 2017-2019 period. Data were provided by experts in Swedish pig farming (Jeppson & Olsson, 2020 February, personal communication) (Table 2).

2.5.1. Cooling with showers

Showering over the slatted area of the pen was set to start whenever indoor temperature (T_i) exceeded the trigger point $T_{trig.shower} = T_c + 0.5$ ℃, where T_c the variable temperature set point (Table 1). Shower duration increased linearly, starting from 1’ every 45’ for $T_i = T_c + 0.5$ ℃, to a showering maximum of 2’ every 20’ for $T_i = T_c + 3$ ℃. One flat nozzle per pen sprayed water at a 0.5 litre per minute capacity (Fig.2). Normal operating hours for the shower cooling system were between 9:00 h and 20:00 h, plus any time outside of this range (i.e. during night) when the outdoor temperature was higher than 19 ℃. With this cooling strategy the percentage of pig wet skin increased from ~15% to >50% and therefore, evaporative cooling of the animals increased. The average operating time observed for this cooling strategy was 44’ during a production cycle that occurred in winter (December, January, February), 2420’ during spring (March, April, May), 6790’ during summer (June, July, August) and 4232’ during autumn (September, October, November). Under these cooling conditions, ammonia emissions at pig housing reduced by 18% during spring, 54% during summer and 35% during autumn. No significant reductions were observed during winter.

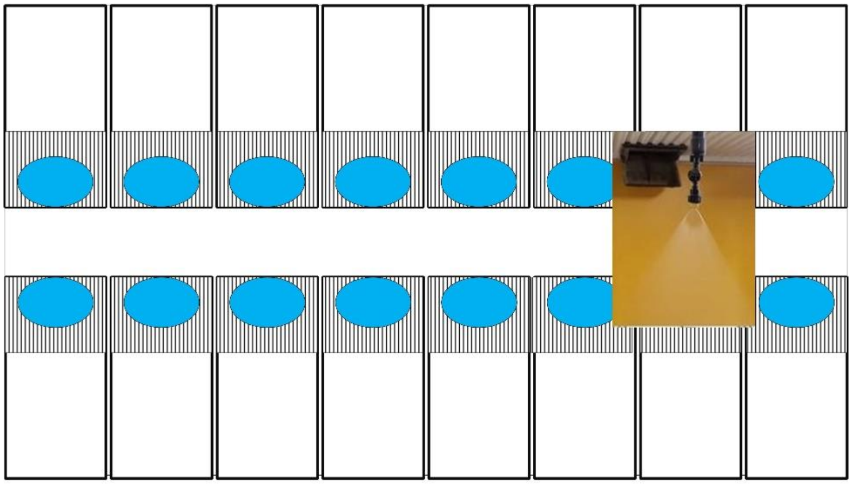

Figure 1: *Schematic representation of the ‘shower’ cooling system. One flat nozzle per pen sprays over the slatted (dunging) area of the pen, as illustrated by the elliptical shapes.*

2.5.2. Increased air velocity at pig lying area

Convective cooling with increased air velocity at pig lying area was achieved by adjusting the angle of the air inlets in the barn from 75% open to 100% open (Fig.3). Air velocity was increased at pig lying area from 0.15 m / s under non-cooling, to approximately 1 m / s. The increased air velocity cooling strategy was triggered when the incoming air was higher than a threshold temperature, which decreased from 27 ℃ for the first week of production to 17 ℃ after the 7th week of production in increments of approximately 1 ℃ per week. The operating time observed for the ‘increased air velocity’ strategy was 0’ during winter, 13620’ during spring, 53280’ during summer and 7890’ during autumn (total of 74790 minutes per year). This cooling strategy achieved 9% reductions in ammonia emissions at pig housing during spring, 21% during summer and 5% during autumn.

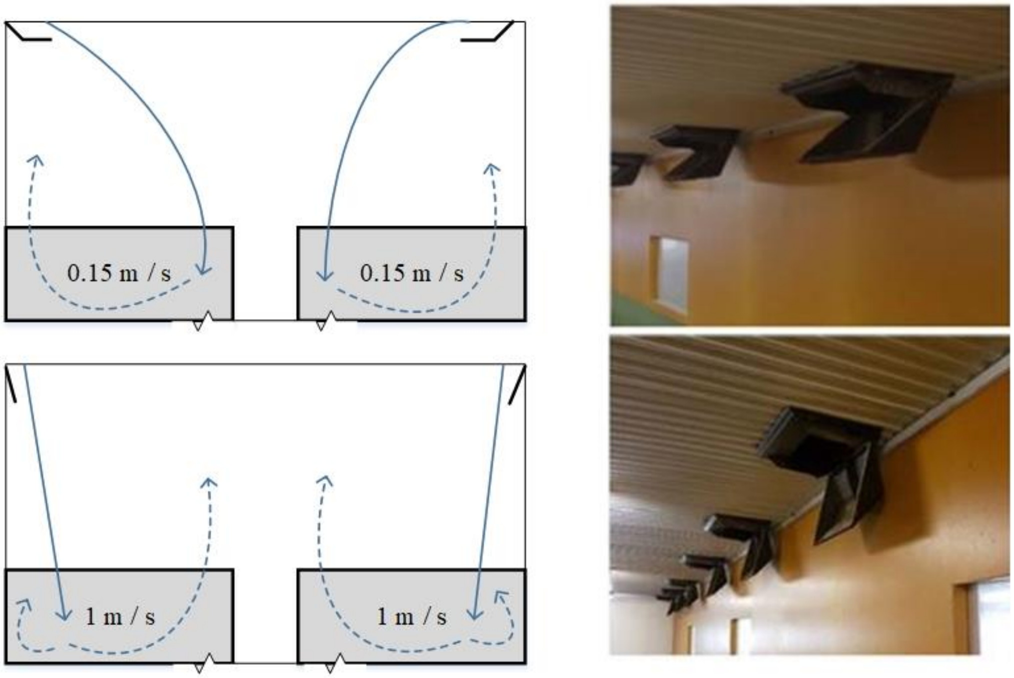

Figure 2: *Schematic description of the operation of the 'increased air velocity at pig lying area' pig-cooling strategy. The top figure illustrates air distribution with a maximum 75% air inlet opening, while the bottom figure illustrates air distribution with fully open (100%) air inlets. Irregular lines depict the slatted, excretory area of the pen.*

Variable (unit)	**Value**
Pig cooling with showers	
No-cooling pig wet skin (%)	15.0
Cooling pig wet skin (%)	>50.0
Cooling strategy operating time during autumn (minutes)	4,232
Cooling strategy operating time during winter (minutes)	44.0
Cooling strategy operating time during spring (minutes)	2,420
Cooling strategy operating time during summer (minutes)	6,790
Ammonia emission reductions achieved during autumn (%)	35.0
Ammonia emission reductions achieved during winter (%)	0.00
Ammonia emission reductions achieved during spring (%)	18.0
Ammonia emission reductions achieved during summer (%)	54.0
Pig cooling with increased air velocity	
No-cooling air inlet opening (%)	75.0
Air inlet opening with cooling implemented (%)	100.

No-cooling air velocity at pig lying area (m/s)	0.15
Air velocity at pig lying area with cooling implemented (m/s)	1.00
Cooling strategy operating time during autumn (minutes)	7,890
Cooling strategy operating time during winter (minutes)	0.00
Cooling strategy operating time during spring (minutes)	13,620
Cooling strategy operating time during summer (minutes)	53,280
Ammonia emission reductions achieved during autumn (%)	5.00
Ammonia emission reductions achieved during winter (%)	0.00
Ammonia emission reductions achieved during spring (%)	9.00
Ammonia emission reductions achieved during summer (%)	21.0

Table 2: *Key parameters that describe the implementation of the pig cooling with showers and pig cooling with increased air velocity scenarios. Data sources: Jeppsson & Olsson (2020, February)*

2.6. Environmental life cycle assessment (LCA)

A life cycle assessment framework was developed in SimaPro 8.5.0.0 (PRé Consultants, Amersfoort, The Netherlands) according to Pexas et al., (2020a). The goal of the framework was to model and compare the operation of the Swedish pig-fattening unit described earlier, for the baseline ('non-cooling conditions') and with each of the pig-cooling strategies implemented. Within the whole-farm system boundaries (Fig.3) we modelled the following components: i) feed production (i.e. diet formulations used), ii) animal growth at pig barn (30kg to 115 kg), iii) manure management at pig barn, storage and field. Tables S1-S3 of the Supplementary Material, present the average environmental impact of inputs and outputs associated with the three scenarios modelled in this study, and characterisation factors for emissions identified at pig housing and manure management. To model relevant processes within the system boundaries, we used databases provided along with the SimaPro software. Agri-footprint and Agribalyse v1.3 were primarily used to model the feed production component, and the Ecoinvent 3 database was mainly used for processes related to pig housing and manure management (Colomb et al., 2013; Vellinga, Blonk, Marinussen, Van Zeist & Starmans, 2013; AGRIBALYSE, 2016; Wernet et al., 2016; Agri-footprint, 2017). System expansion was used to avoid co-product allocation. When this was not possible, economic allocation was used (Weidema and Schmidt, 2010; Mackenzie, Leinonen & Kyriazakis, 2017). We estimated the environmental impact for production cycles that occurred during the four different seasons of the year. The functional unit of the analysis was the production of 1 kilogram of live weight pig at slaughter weight adjusted for mortality rates. The annualised environmental impact for the pig farm was calculated as the summation of the equally weighted environmental impacts for each production cycle. The environmental impacts assessed were chosen based on the FAO guidelines for the environmental impact assessment of pig supply chains (FAO, 2018a) and the FAO guidelines for water use in livestock production (FAO, 2018b). Specifically, we used the CML Baseline v3.05 calculation method to estimate Non-Renewable Resource Use (**NRRU**) expressed in grams of antimony (Sb) equivalents, Non-Renewable Energy Use (**NREU**) expressed in mega-joules (MJ), Global Warming Potential (**GWP**) expressed in tonnes of carbon dioxide (CO_2) equivalents, Acidification Potential (**AP**) expressed in tonnes of sulphate (SO_2^-) equivalents and Eutrophication Potential (**EP**) expressed in tonnes of phosphate (PO_4^{3-}) equivalents. System water footprint was estimated through the Water Use (**AWARE** v1.01) and Blue Water Scarcity Index (**BWSI**) methods expressed in cubic meters of water used (m^3). Finally, we used the ReCiPe 2016 Midpoint v1.01 method to assess agricultural Land Use (**LU**), expressed in square meters of crop land converted (m^2). Each environmental impact category was assessed individually; we did not aggregate across categories.

A Monte Carlo (MC) method (one thousand parallel simulations for each scenario compared against the baseline) was used for the quantification of uncertainties related to data inputs and to distinguish between uncertainties specific to each scenario or shared between scenarios. Whenever uncertainty information was not available for a variable relevant to any of the scenarios we assumed that the variable was normally distributed with a standard deviation equal to 10% of the mean (Groen, Heijungs, Bokkers & de Boer, 2014). The same Monte Carlo simulations method was used to perform pairwise comparisons and assess significance of differences in environmental impact between any two scenarios considered. If a scenario exhibited different (lesser or greater) environmental impact than the baseline for more than 95% of iterations, we considered the results to be significantly different (Mackenzie, Leinonen, Ferguson & Kyriazakis, 2015; Pexas et al., 2020a).

2.7. Economic impact analysis

Differences in farm economic impact between non-cooling and cooling scenarios were evaluated through a discounted cash flow over a 25-year time horizon (Pexas et al., 2020b). All cost and revenue streams within the system boundaries defined by the environmental LCA, were identified and linked to the best available financial information. In this way, the modelling approach we followed is consistent with the Life Cycle Cost Analysis method, except that a zero end-of-life disposal value of capital equipment was assumed in our study due to lack of data (Norris, 2001; Hunkeler et al., 2008; Swarr et al., 2011).

For the purposes of this analysis, a comprehensive list of economic data was compiled to describe all relevant processes (Table 3). Input and output prices were normalised whenever possible, using mean values over the 2012 – 2019 period, to smooth inter-year variability. Differences in specific costs and revenues for production cycles occurring in different seasons were included in the model.

Capital costs were calculated and amortised over a 25-year lifetime for building related components and a 12.5-year lifetime for technological equipment. Technological reinvestments were considered for equipment that was expected to be renewed at intervals more frequent than the time horizon. Costs related to the pig housing (i.e. building infrastructure, climate control, feed & water delivery and slurry removal technological equipment) and manure management component i.e. slurry storage and field application equipment) were considered. Working capital comprised the purchasing of piglets at 30 kg and direct veterinary/medical inputs.

Operational expenses included animal, pig housing management and manure management related costs such as feed, electricity and diesel fuel, technological equipment maintenance and labour. Annual maintenance costs for the building and technological equipment including the pig showering system were estimated as 2.50% of the relevant capital costs. Because no capital investment was required for the implementation of the increased air velocity strategy, we considered a 50% increase in maintenance of the ventilation system to maintain good air distribution and operation of this strategy (Pexas et al., 2020b).

Total revenues consisted of live weight pig meat sold and avoided costs of synthetic fertiliser at crop production replaced by the field application of manure.

To evaluate investment feasibility we estimated two farm financial metrics commonly used to compare the economic performance of alternative investments; the whole-farm Annual Equivalent Value (AEV) and the whole-farm Internal Rate of Return (IRR). To estimate these it was necessary to first calculate the whole-farm Net Present Value (NPV) (Eq.1). AEV is a measure of the annualised monetary return of an investment (Eq.2) and can be used as a proxy to estimate the annual profitability of the farm as a whole. IRR represents an investment's expected percentage return on capital over the time horizon.

$$Eq.1: NPV = \sum_{t=1}^{T} \frac{Rev_t - OpEx_t - RenC_t}{(1+d)^t} - ICI$$

$$Eq.2: AEV = \frac{d(NPV)}{1-(1+d)^T}$$

Where, *d* = discount rate, *T* = total number of years in time horizon, *t* = each individual year, *Rev* = revenues, *OpEx* = operating expenses, *RenC* = renewal costs for technological equipment whenever its lifetime was less than the time horizon, and *ICI* = initial capital investment.

IRR is also estimated through Eq.1, by solving for the discount rate that satisfies the condition "*NPV = 0*".

Variable	Unit	Value	Data Sources
Main economic analysis assumptions			
Discount rate	%	7.00	Larsson (2020, February)
Building lifetime	years	25.0	Pexas et al. (2020b)
Technological equipment lifetime	years	12.5	> >
Costs			
Piglet at 30 kg	€ per pig	63.9	Larsson (2020, February)
Growing feed, complete formulation	€ per kg	0.427	Statistics Sweden (2019)
Finishing feed, complete formulation	€ per kg	0.260	> >
Water	€ per litre	Free of charge	
Labour, trained farm worker	€ per hour	22.3	Statistics Sweden (2018c)
Veterinary / medicine	€ per pig	0.950	Statistics Sweden (2019)
Electricity, household, grid-mix	€ per kWh	0.168	Statistics Sweden (2018b)
Diesel fuel	€ per litre	1.14	Statistics Sweden (2019)
Cost of installation for technological equipment (incl. labour, machinery, consumables)	% capital cost	20.0	Adapted from Pexas et al. (2020b); Jeppsson & Olsson (2020, February)
Annual maintenance of buildings and technological equipment	% capital cost	2.50	> >
Flat nozzle shower cooling system, purchasing	€ per pen	21.0	Statistics Sweden (2019)
Insurance (building, technological equipment)	% capital cost	0.250	Pexas et al. (2020b)
Revenues			
Pig meat sold	€ per kg live weight	1.61	Statistics Sweden (2019)
Urea fertiliser	€ per kg	0.314	Adapted from FAO (2019)
Di ammonium phosphate fertiliser	€ per kg	0.460	> >
Potassium chloride fertiliser	€ per kg	0.339	> >

Table 3: *Main costs associated with the operation of a typical pig-fattening unit in southern Sweden that produces slaughter pigs to 115 kg.*

The cost of abatement for each individual environmental impact category associated with each pig cooling strategy was then estimated. This was calculated through the following equation (Eq. 4):

$$Eq.3: € \, per \, unit \, of \, pollutant \, abated = \frac{\Delta AEV}{\Delta EI} \times -1$$

Where, ΔAEV = difference in AEV between a cooling and the baseline, no-cooling scenario, and ΔEI = difference in environmental impact between cooling and no-cooling scenarios.

Figure 3 below summarises the main components identified within the system boundaries of the pig farming system assessed, and graphically describes the methodological flow we followed to evaluate whole-farm environmental and economic consequences under 'no-cooling', 'cooling with showers' and 'cooling with increased air velocity' scenarios.

2.8. Integration of the environmental-economic models with projected climate data

A sensitivity analysis was carried out to investigate the implications of projected ambient temperature increases for Sweden caused by climate change on the relative cost-effectiveness of the environmental impact mitigation provided by pig-cooling scenarios. We evaluated the effect of increasing ambient temperature on the system environmental and economic impact for the three different scenarios considered. Specifically, we incrementally increased ambient temperature to simulate the effect of climate change on the environmental and economic performance of the production cycle during the warmest season of the year. Five increments of +0.52 ℃ were used to simulate a total +2.6 ℃ average temperature increase as projected by the Representative Concentration Pathway (RCP) 4.5 scenario (IPCC, 2014). A Monte Carlo method (1000 iterations) was used to simulate the model for each step of the sensitivity analysis. Significance of difference between scenarios for the different cooling conditions was evaluate using the pairwise Monte Carlo comparisons method described in the previous sections.

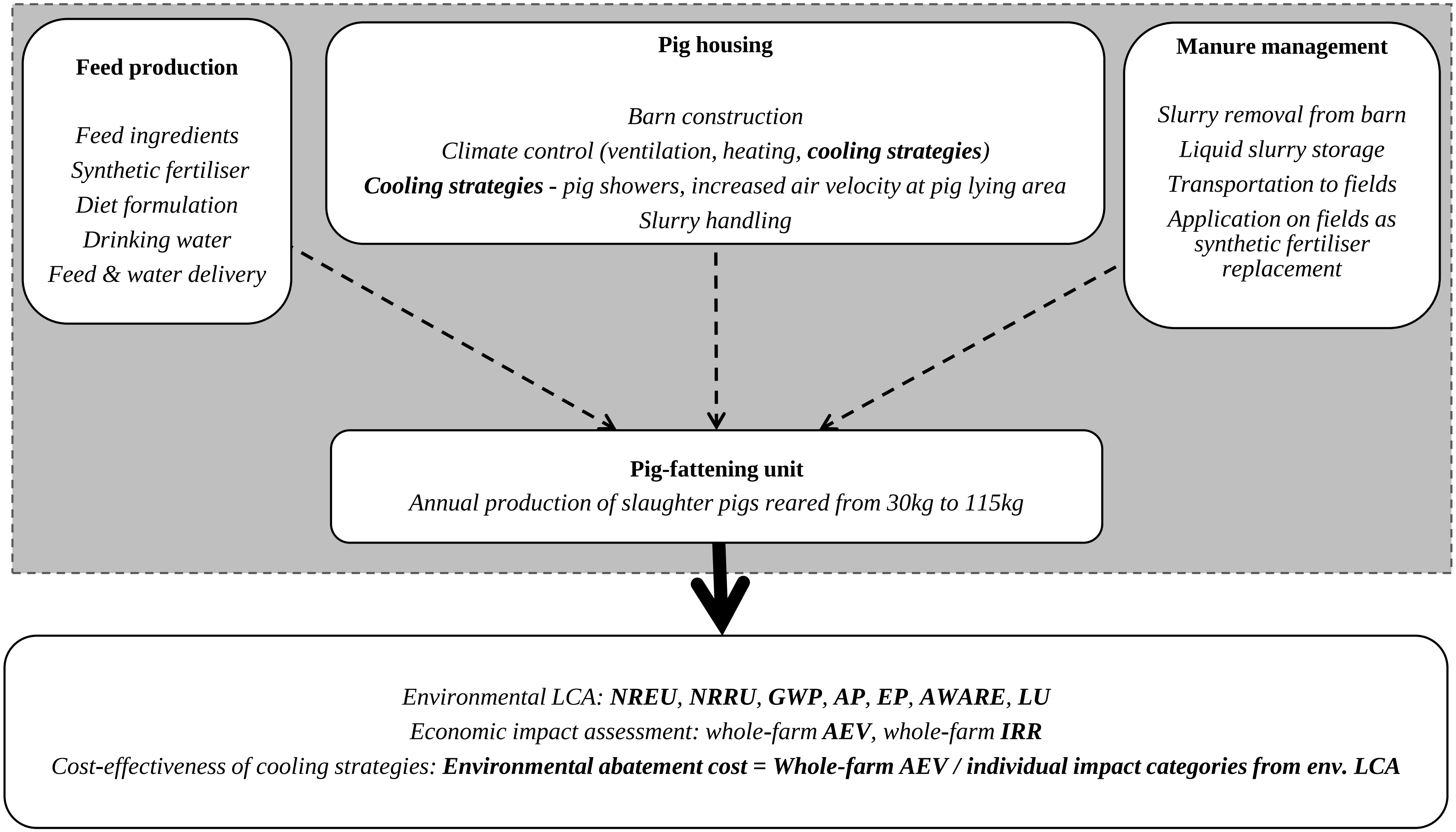

Figure 3: *Schematic representation of the main components identified within the system boundaries of the analysis. The grey shaded area represents the life cycle inventory description phase (system description), which was the basis for the development of the integrated, life cycle based cost-effectiveness framework. LCA = Life cycle assessment, AEV = Annual equivalent value, IRR = Internal rate of return, NREU = Non-renewable energy use, NRRU = Non-renewable resource use, GWP = Global warming potential, AP = Acidification potential, EP = Eutrophication potential, AWARE = Available water resources, LU = Land use.*

3. Results and Discussion

We first present the outcomes of the indoor climate and heat stress models that provided context for the environmental and economic impact analyses. We then present the environmental life cycle assessment and the whole-farm financial performance of the Swedish pig-fattening unit under ‘non-cooling’ conditions and the two cooling scenarios considered. The results of the integration of the framework with projected climate data to investigate the effect of ambient temperature increase on system environmental and economic performance are presented last.

3.1. Indoor climate and heat stress

Indoor climate and heat stress relevant parameters were estimated for the average animal of the pig-fattening unit, weighing approximately 72.5 kg on the 45th day of the production cycle. Sensible heat production from the average pig was estimated at ≅289 W. Our specific indoor temperature and ventilation rate estimates through the sensible heat balance model followed seasonal variations of outdoor temperature. The warmest period of the year was during the summer production cycle with average indoor temperatures of approximately 23.0 ℃. Under such conditions, the ventilation system operated at a maximum capacity providing approximately 95 m^3 / h per animal. The average indoor temperature for the autumn production cycle was estimated at ~18.5 ℃, and at ~18.0 ℃ and ~16.5 ℃ for spring and winter respectively. Average ventilation rates were estimated at approximately 30.1 m^3 / h, 19.3 m^3 / h and 8.50 m^3 / h per animal for autumn, spring and winter respectively. Average sensible heat losses due to transmission through the building were ≅5880 W during a summer production cycle, ≅6180 W during autumn, ≅7200 W during spring and ≅10100 W during winter.

We estimated an upper critical temperature for the average pig at approximately 26.8 ℃, beyond which the effects of heat stress on animal performance become noticeable. According to the indoor climate and heat stress models, ‘hot’ conditions were observed only for approximately 10.0 % of the duration of a summer production cycle and resulted in a 3.50 kg reduction in feed intake and a 4.00 kg reduction in slaughter weight for the specific production cycle. Upper critical temperature increased with the implementation of both pig-cooling strategies. Pig-cooling with showers allowed the animals to wet more than 50% of their skin increasing evaporative cooling and therefore, increased the perceived upper critical temperature from 26.8 ℃ to higher than 32.2 ℃. When we simulated pig-cooling with increased air velocity (1 m/s) at pig lying area, upper critical temperature was raised at 31.5 ℃. Both pig-cooling scenarios completely removed the effects of heat stress on growth rate and feed intake, since indoor temperature never exceeded the upper critical temperature thresholds for prolonged periods in the south Swedish pig-fattening unit and therefore, animals did not experience ‘hot’ conditions.

Similarities in climatic conditions between southern Sweden and Central European countries, provide a potential explanation for agreement of specific results with past studies that used temperature-humidity indices to estimate heat stress thresholds in different European pig-fattening units (Vitt et al., 2017; Mikovits et al., 2019). Diet composition and growth rate specific to different management systems play an important role in the estimation of heat stress parameters. Herd and pig housing management choices such as stocking density or the provision of bedding in the pen can also affect estimates for critical temperature thresholds. While in this study we compared indoor climate and heat stress parameters for scenarios that referred to one specific pig-fattening unit, variations in such factors should be considered to ensure reliability when performing ‘between – pig farm’ comparisons (Wellock et al., 2003).

3.2. Environmental impact assessment

Table 4 summarises the system environmental performance over the different impact categories for the three cooling scenarios considered. Differences between scenarios are presented at a 95% significance level. When pig-cooling with showers was implemented the largest reduction of -3.28% was observed for acidification potential. Non-renewable resource use and eutrophication potential were also significantly reduced by -1.14% and -0.960% respectively. Smaller but also significant reductions were observed for global warming potential (-0.508%), non-renewable energy use (-0.500%), and agricultural land use (-0.395%). The water footprint assessment did not reveal any significant differences for either blue water scarcity or water use when pig-cooling with showers was compared to the non-cooling baseline. Increased air velocity achieved its largest abatement potential also for acidification potential (-1.51%). Significant reductions were also observed for non-renewable resource use (-0.789%) and non-renewable energy use (-0.636%). Smaller, but significant reductions were achieved for eutrophication potential (-0.564%), global warming potential (-0.606%), and agricultural land use (-0.229%). Water footprint was not significantly different when implementing the increased air velocity strategy either. Comparisons between the environmental performances of the two pig-cooling strategies revealed significant differences only for acidification potential, eutrophication potential and non-renewable resource use. More specifically, pig-cooling with showers significantly outperformed the increased air velocity strategy, achieving 1.76%, 0.396% and 0.349% larger abatement potential for acidification, eutrophication and non-renewable resource use respectively. For all other impact categories assessed, the two pig-cooling strategies exhibited approximately the same performance.

		Non-cooling (baseline)	**Showers**	**Increased air velocity**
Non-renewable resource use (g Sb eq.)	Mean	499.	494.*[a]	495.
	% ≤ baseline		100	100

Non-renewable energy use (GJ)	Mean	3,874	3,854$^{n.s}$	3,849
	% ≤ baseline		100	100
Global warming potential (ton CO_2 eq.)	Mean	971.	966.$^{n.s}$	965.
	% ≤ baseline		100	100
Acidification potential (ton SO_2 eq.)	Mean	8.74	8.45*^{a}	8.61
	% ≤ baseline		100	100
Eutrophication potential (ton PO_4 eq.)	Mean	10.0	9.94*^{a}	9.98
	% ≤ baseline		100	100
Land use (km^2)	Mean	1.31	1.31$^{n.s}$	1.31
	% ≤ baseline		100	100
Water use (m^3)	Mean	43,514	43,306$^{n.s}$	42,972
	% ≤ baseline		32.0	30.7
Blue water scarcity index (m^3)	Mean	1,860	1,853$^{n.s}$	1,841
	% ≤ baseline		29.3	28.7

Table 4: *Annualised (three production cycles) environmental impact of the pig-fattening unit under non-cooling conditions (baseline) and with the implementation of pig-cooling with showers and pig-cooling with increased air velocity (1000 Monte Carlo simulations). Significance of difference between pig-cooling with showers and pig-cooling with increased air velocity (1000 Monte Carlo simulation pairwise comparisons) is indicated by asterisk (*) and alpha (a) if impact of showers was smaller than increased air velocity or beta (b) for the opposite case. Non-significant between pig-cooling with showers and pig-cooling with increased air velocity are indicated by "n.s" superscript (significance level = 95%).*

Several factors can explain the observed differences in system environmental impact under the different cooling scenarios. When indoor temperature is relatively high, pigs change their lying and dunging behaviour, and exhibit fouling on the solid area of the pen. As a result, the larger slurry surface that is exposed to air allows for increased ammonia volatilisation and emissions at pig housing (Aarnink et al., 2006). Ammonia emissions largely contribute to acidification potential, eutrophication potential and even global warming potential (Dong et al., 2006; De Vries and De Boer, 2010). The use of frequent showers and increased air velocity at pig lying area during 'hot' conditions can help prevent animals from excreting on the lying, solid area or lying on the excretory area of the pen, and therefore improve the system environmental performance through reduced ammonia emissions (Botermans et al., 2010). Reductions in system environmental impact when implementing pig-cooling with showers could also be explained by the large potential for mitigation of ammonia emissions achieved when slurry is diluted and the concentration of ammoniacal nitrogen reduced (Rigolot et al., 2010; Pexas et al., 2020a). Variations in slaughter weight from impaired animal performance critically affect environmental impact allocation over the functional unit in the life cycle assessment framework and could also explain the observed differences in environmental performance. Under non-cooling conditions, heat stress resulted in delivery of lighter pigs during the summer production cycle and reduced feed intake. Increasing air velocity at pig lying area from 0.15 m/s (non-cooling baseline) to 1 m/s, or implementing frequent pig showers to increase evaporative cooling from pig wet skin, resulted to mitigation of the effect of ‘hot’ conditions on animal growth rate and feed intake, which resulted in the improved system environmental performance. On the other hand, because feed production is among the largest contributors in environmental impact arising from pig production (FAO, 2018a) the increased feed intake under cooling conditions might have acted against the maximum abatement potential associated with the operation of either cooling strategy. Increased feed intake could explain the better environmental performance for non-renewable resource use with the implementation of increased air velocity and pig showers. More feed consumed resulted in higher concentrations of nutrients available in manure to replace synthetic fertiliser for crop production, a main contributor to this impact category (Pexas et al., 2020a).

Contrary to our expectations, the system water footprint did not significantly change with the implementation of pig-cooling with showers. While the production of water and electricity for on-farm use contribute to both the water use and blue water scarcity index impact categories, the additional requirements for the operation of the showering system were not large enough to significantly increase the system water footprint. High uncertainties associated with specific data and methods used for the water footprint assessment could also explain the observed inconsistencies.

While the environmental abatement potential of the pig cooling methods tested here is small relative to other potential farm interventions (Pexas et al., 2020a), it is important to emphasize that the implementation of cooling strategies may have implications also on animal health and welfare, and by extension to the input of medication in pig systems (Silva et al., 2008). Although in our experiment we did not see any change in the use of antimicrobials, increased environmental temperature and humidity has been associated with increase in the incidence of respiratory conditions and vice, such as tail biting (Velarde and Dalmau, 2012; Scollo, A., Contiero, B., & Gottardo, 2016; Jukan, Masip-Bruin & Amla, 2017; Lovarelli, Bacenetti & Guarino, 2020). We suggest that in future research and prior to the implementation of such strategies, considerations of potential effects on animal health and welfare are taken into account.

3.3. Economic impact assessment

Table 5 summarises the major financial performance metrics estimated for the ‘non-cooling’ baseline and the two pig-cooling scenarios. Under non-cooling conditions the whole-farm annual equivalent value was equal to € 52,961 and the internal rate of return equal to 16.4%. The discounted cash flow analysis showed that the implementation of the pig-cooling with showers strategy was the most profitable system configuration overall. More specifically, whole-farm annual equivalent value with this pig-cooling strategy was € 56,558 (+6.79% compared to 'non-cooling conditions') and its internal rate of return 17.0%. Pig-cooling with increased air velocity was less profitable with whole-farm annual equivalent value estimated at € 54,747 (+3.37% compared to 'non-cooling conditions') and internal rate of return at 16.8%. In terms of cost of production per kg of live weight pig meat, the costliest scenario was the non-cooling baseline at € 1.36. When pig-cooling with increased air velocity was implemented, cost of production per kg of pig meat produced reduced by -1.02% (€ 0.0139). Pig-cooling with showers reduced this further, by -1.10% (€ 0.0150) compared to the non-cooling baseline.

The main sources for the observed differences in farm profitability between the cooling scenarios can be identified by breaking down the cost and revenue streams. Increased air velocity required a +0.451% increase in cash overheads from additional annual maintenance of the housing component. With the mitigation of heat stress effects on feed intake and animal growth rate, feed related costs increased by +0.904% (€ 2,776), and revenues from pig meat sold and manure application by +0.664% (€ 4,824), when compared to the non-cooling baseline. Specifically, urea fertiliser discounts increased by +0.904% (€ 15.5), di-ammonium phosphate by +0.954% (€ 16.4) and potassium chloride by +0.586% (€ 10.1). Consequently, budgeted cash margins increased by +0.267% (€ 1,938) with this strategy. Relatively high additional capital and operating costs were associated with the implementation of the shower cooling strategy. When compared to the non-cooling scenario, pig-cooling with showers required a +0.378% (€ 2,749) higher investment in capital costs at year 0, +0.378% (€ 2,749) higher costs associated with the renewal of technological equipment at year 12.5 and +0.904% (€ 2,776) feed related costs. However, revenues from pig meat sold increased by +0.664% (€ 4,824), urea fertiliser discounts increased by +1.08% (€ 18.7), while di-ammonium phosphate and potassium chloride discounts were identical to the ones achieved with the implementation of increased air velocity. Therefore, whole-farm budgeted cash margins were +0.584% (€ 4,246) higher compared to the non-cooling baseline.

On-farm water consumption is free-of-charge in Sweden and so the variable costs associated with the operation of pig-cooling with showers could be higher if the system was implemented in a different country, further reducing farm profitability. For example, if water prices were included instead (e.g. € 0.00840 per litre as is the case in neighbouring Denmark) the observed difference in whole-farm AEV between the pig showers strategy and 'non-cooling conditions' would be smaller, at +3.81% (€ 2,016).

Potential economic impacts associated with the implementation of animal cooling strategies, may finally be identified in relation to their implications for animal health and the reductions they can cause in welfare. Reducing costs for medication and treatments required on such occasions, can further improve farm economic performance (Velarde and Dalmau, 2012; Sneeringer, MacDonald, Key, McBride & Mathews, 2015).

	Unit	Non-cooling	Showers	Increased air velocity
Financial performance				
Whole-farm Annual Equivalent Value	€	52,961	56,558	54,747
Whole-farm Net Present Value	€	670,149	715,663	692,740
Whole-farm Internal Rate of Return	%	16.4	17.0	16.8
Cost of production	€ / kg pig live weigh	1.36	1.35	1.35
Cost of abatement				
Non-renewable resource use	€ / g Sb eq. abated	N.A	$-8.36e^{-04}$	$-7.54e^{-04}$
Non-renewable energy use	(€ / GJ abated)	N.A	$-2.85e^{-03}$	$-4.71e^{-03}$
Global warming potential	(€ / ton CO_2 eq. abated)	N.A	$-7.25e^{-04}$	$-1.12e^{-03}$
Acidification potential	(€ / ton SO_2^- eq. abated)	N.A	$-4.21e^{-05}$	$-2.53e^{-05}$
Eutrophication potential	(€ / ton PO_4^{3-} eq. abated)	N.A	$-1.42e^{-05}$	$-1.08e^{-05}$
Land use	(€ / km^2 abated)	N.A	$-7.64e^{-07}$	$-1.45e^{-06}$

Table 5: *Financial performance metrics are presented for the operation of the pig-fattening unit under 'non-cooling conditions' and with the implementation of each pig-cooling strategy, as evaluated over the 25-year time horizon. The cost-effectiveness of each pig-cooling strategy is presented as the cost of abatement they exhibited for environmental impacts they significantly mitigated. A negative cost indicates that profit was generated along with the mitigation of the specific impact category.*

3.4. Environmental and economic trade-off assessment

Although both investments were cost-effective in mitigating the system environmental impact for most impact categories considered, important trade-offs were identified. Pig-cooling with showers was the more cost-effective scenario for non-renewable resource use, acidification and eutrophication potential generating €8.36e^{-04} of profit per g Sb eq., €4.21e^{-05} per ton SO_2^- eq., €1.42e^{-05} per ton PO_4^{3-} eq. mitigated respectively. For the same impact categories, increased air velocity generated €7.54e^{-04} of profit per g Sb eq., €2.53e^{-05} per ton SO_2^- eq., €1.08e^{-05} per ton PO_4^{3-} eq. mitigated. An opposite trend was observed for mitigation of non-renewable energy use, global warming potential and land use, where increased air velocity was the more cost-effective option. More specifically, it generated €4.71e^{-03} of profit per GJ, €1.12e^{-04} per CO_2 eq. and €1.45e^{-06} per km^2 mitigated, while pig-cooling with showers generated smaller profits of €2.85e^{-03} per GJ for non-renewable energy use, €7.25e^{-04} per CO_2 eq. for global warming potential and €7.64e^{-07} per km^2 for land use mitigation. Further analysis on the potential synergies between the two pig-cooling strategies, could provide alternative options through combinations that prioritize on specific objectives (i.e mitigation of acidification potential).

3.5. Sensitivity analysis for climate change consequences on system environmental impact

Figures 4a-4f present the effect of ambient temperature increase on system environmental impact, for categories that were significantly affected in one or more of the cooling scenarios considered. When we increased ambient temperature under non-cooling conditions, system environmental impact increased significantly in a linear way, for all categories except water footprint (water use and blue water scarcity index). For a +2.6 ℃ increase in ambient temperature, acidification potential was +2.24% significantly higher compared to the baseline climate conditions. Significant increases were observed also for non-renewable resource use (+1.05%), global warming potential (+1.05%) and eutrophication potential (1.05%). Land use was affected less but also significantly, exhibiting a +0.605% increase. Both pig-cooling strategies greatly mitigated these effects, and significant changes were only observed for non-renewable resource use, acidification potential and eutrophication potential. Specifically, when we tested the performance of increased air velocity strategy under increasing ambient temperature conditions, we observed a significant increase of +0.718% for acidification, +0.136% for eutrophication potential, and +0.0526% for non-renewable resource use. Pig-cooling with showers was more robust and exhibited even smaller but significant increases of +0.690% for acidification, +0.261% for eutrophication potential, and +0.0171% for non-renewable resource use.

The direct effect of temperature on ammonia and methane emissions at pig housing could provide an explanation for the observed significant effects of ambient temperature increase on system environmental impact (Rigolot et al., 2010; Pexas et al., 2020a). Ammonia emissions are among the largest contributors to acidification potential associated with pig production and therefore, we expected that the main effect would be observed for this impact category. These findings highlight the importance of such strategies for the mitigation of system environmental impact under the threat of climate change and increasing temperatures.
As anticipated, the amount of days perceived as ‘hot’ during the warmest season also increased linearly with ambient temperature. Intense confined livestock systems are particularly sensitive to prolonged ‘hot’ climatic conditions due to the inability of ventilation system alone to maintain indoor temperatures low for animals and the effects of heat stress on animal performance are amplified in such environments. Further reduction of slaughter weight could explain the observed increases in system environmental impact across all impact categories, and that cooling strategies, which mitigate heat stress, were more resilient to ambient temperature increase than the non-cooling baseline. When ambient temperature

increased by +2.6 ℃ under non-cooling conditions, slaughter weight reduced to 109 kg. The ‘wind-chill’ effect achieved by the increasing the air velocity at pig lying area and the increased evaporative cooling caused by the pig showers, increased the perceived upper critical temperature at ~31.5 ℃ and ~32.2 ℃ respectively. Therefore, with the implementation of either strategy in the temperature range we tested, the animals did not experience any heat stress related effects on growth rate and feed intake.

No significant effects were observed for either of the water footprint impact categories. Water use, feed production and electricity consumption would be the main contributors to system water footprint. Reductions in feed intake caused by the prolonged heat stress did not result to consistent differences in system water footprint, which might be attributed to data and method related uncertainties for the specific impact categories. Changes in electricity consumption for indoor climate control were negligible and did not cause a significant effect on model outcome for water use and blue water scarcity.

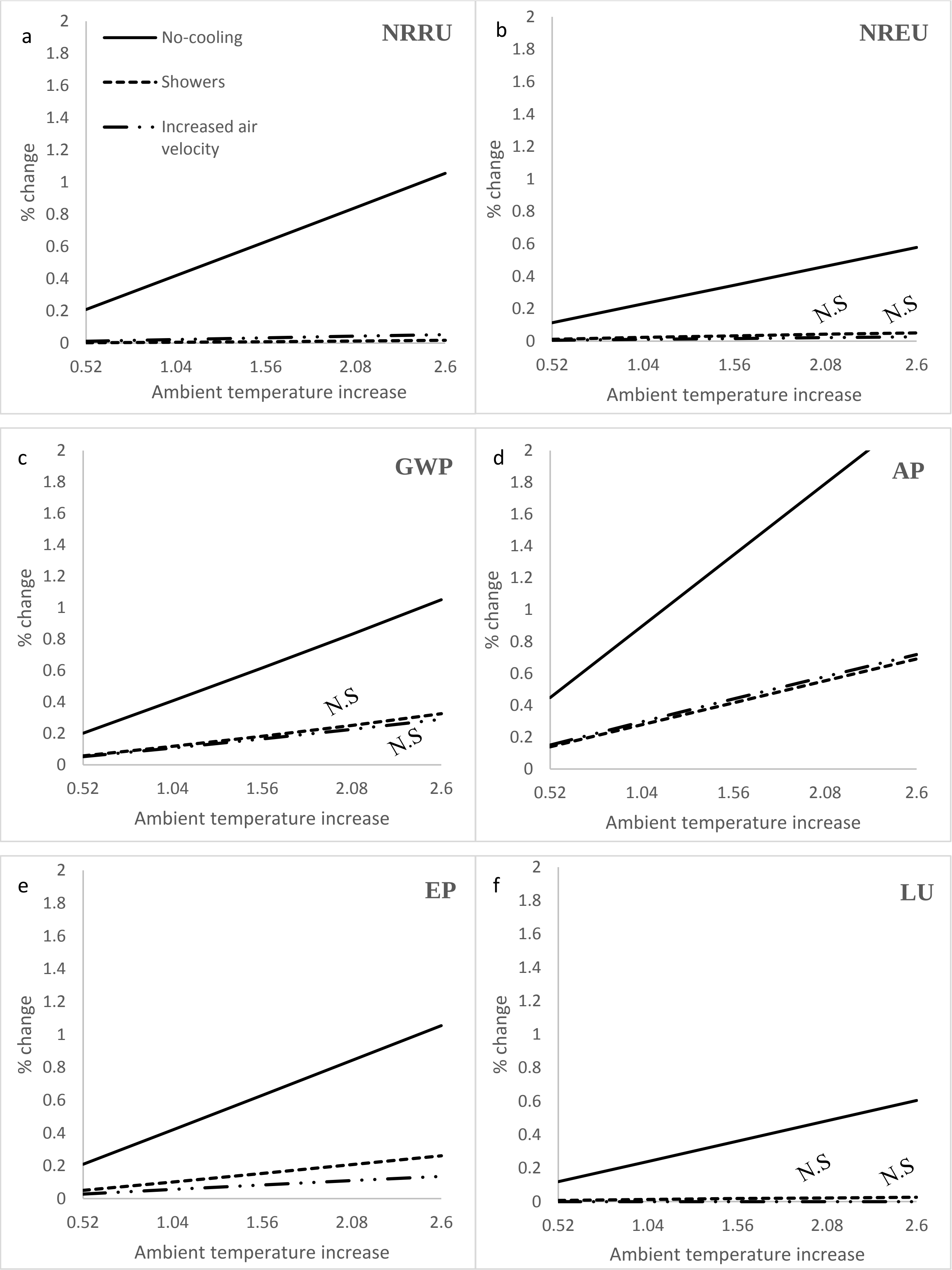
a
NRRU
No-cooling
Showers
Increased air velocity
% change
Ambient temperature increase
0.52
1.04
1.56
2.08
2.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
b
NREU
N.S
N.S
c
GWP
N.S
N.S
d
AP
e
EP
f
LU
N.S
N.S

Figure 4a-4f: *The effect of ambient temperature increase on system environmental impact for categories that were significantly affected under one or more cooling scenarios (>95% of Monte Carlo simulations). The y-axis presents the percentage change in environmental impact compared to a baseline where ambient temperature represents current climate conditions. NRRU = Non-renewable resource use, NREU = Non-renewable energy use, GWP = Global warming potential, AP = Acidification potential, EP = Eutrophication potential, LU = Land use. N.S = non-significant difference.*

Increasing ambient temperature affected farm profitability mainly in relation to revenues from sold pig meat. Due to slaughter weight reductions, when temperature increased by +2.6 ℃, pig meat revenues reduced by -0.441% (€ 3,188) under non-cooling conditions. As expected, the magnified heat stress effects also affected annual feed related costs, which reduced by -0.208% (€ 638). In terms of whole-farm annual equivalent value, the increased ambient temperature resulted to a -4.43% decrease under non-cooling conditions. The specific farm costs and revenues were unaffected when pig cooling with showers or increased air velocity were implemented.

While the main economic impact of increased ambient temperature was directly related to variability in the quantity of pig meat sold, other potential implications might arise such as batch uniformity penalties depending on policies specific to the slaughter plant, or additional costs relevant to potential increases in operating frequencies of the pig-cooling strategies. An elaboration of the analysis with the inclusion of such parameters, which we did not capture here due to data limitations, would enhance the accuracy of predictions for the economic performance of such strategies under changing climate conditions.

3.6. Methodological implications and challenges in developing integrated environmental–economic models for animal housing investments

Through the more focused study described in this paper, we have presented the potential for animal cooling strategies to improve farming system sustainability. Furthermore, we have highlighted important trade-offs that policy makers have to face when comparing the cost-effectiveness of potential farm investments to identify sustainable solutions. While Swedish slaughter pig production was used as a case-in-point, the methodological framework presented here can be applied to a range of technologies and strategies in pig production, but also on other livestock systems (e.g. broiler, dairy cow), and on a broader geographical scale (Pexas et al., 2020b). The specific results generated in this study also have wider implications for the European pig production sector. Potential environmental and economic benefits that arise from the implementation of the two cooling strategies become more relevant in warmer countries, and may even be amplified when implemented in less advanced systems in terms of climate control technologies involved at housing, where animals experience unstable climate and greater frequency of heat stress events (Valiño et al., 2010; Skuce, Morgan, Van Dijk & Mitchell, 2013).

We acknowledge that cost and revenue streams within the various scenarios modelled are dynamic and particularly sensitive to geographic and temporal variability. In cases, as in this study, where many of the economic parameters are considered static, the discounting method remains useful in accounting for decision makers' time preferences when comparing the differing life-time cash flow profiles of alternative investments. For this reason, DCF has been a standard practice in environmental life cycle costing, despite challenges with issues such as the choice of discount rates to accurately represent both business transactions and environmental considerations, and occasional inconsistencies in product economic (or useful) versus actual lifetime (Hunkeler et al., 2008; Kloepffer, 2008; Swarr et al., 2011). Availability of information about spatiotemporal variations in prices of feed and water, relevant construction materials, and batch uniformity penalties would allow for the development of a stochastic financial assessment framework enhancing reliability of comparisons, particularly in 'between-farm' analysis designs. We also recognise that qualitative, economically relevant information about the stakeholders' preferences (e.g. farm manager investment behaviour) would enable us to better predict the cost-effectiveness of potential farm investments in the future (Mackenzie, Wallace & Kyriazakis, 2017). We identified an important challenge in dealing with uncertainties when combining environmental LCAs and economic modelling, due to limited availability of resources and the sheer extent of life cycle inventory describing our models. Further investigation is suggested for the implementation of methods such as the pedigree matrix to account for data related uncertainties within integrated LCA frameworks (Ciroth, Muller, Weidema & Lesage, 2016). Such a methodological exercise requires exploration in its own right, and emphasis beyond what our resources allowed for in this study.

In our model, the number of 'hot' days during the warmest season increased linearly with ambient temperature. However, this assumption of linearity may lead to underestimation of the potential economic and environmental benefits of the pig-cooling strategies we investigated, as it does not account for climate variability. While mean air temperatures are consistently predicted to increase globally in the coming years by climate modellers (IPCC, 2014; Hausfather, Drake, Abbott & Schmidt, 2020), some also project increased variation from that mean in specific regions (Bathiany, Dakos, Scheffer & Lenton, 2018; Chen, Dai & Zhang, 2019). As predictions around temperature variability in climate projections is subject to debate among climate modellers (Huntingford, Jones, Livina, Lenton & Cox, 2013) we did not address it in our sensitivity analysis. However, increased temperature variability could potentially increase the number of 'hot' days further as mean temperature increased, and lead to increased environmental and economic benefits from investing in pig cooling strategies in the model we present. In the Swedish case study presented here, there was no need for pig cooling strategies to operate during the winter season. This situation may change if the expected winter temperature variability due to climate change materialises (Castro- Díez, Pozo- Vázquez, Rodrigo & Esteban- Parra, 2002).

While in this paper we considered the two pig-cooling strategies as mutually exclusive, we acknowledge that potential synergistic effects could be achieved to further improve system environmental performance and, provided that relevant data exists, their combined implementation should be investigated as a potential abatement scenario. Also in this study, we assumed a homogeneous air distribution for our simulations, due to data limitations about the variability of wind speed at pig lying area. We acknowledge that in order to achieve and maintain such homogeneity of air velocity throughout the pen in real conditions, novel ventilation systems should be implemented.

The development of accurate LCA models that address both the environmental and economic aspects of complex production systems in the agri-food sector is a data intensive process. Here we expected to obtain detailed data about the effects of cooling strategies on indoor climate (precise measurements of temperature and humidity across scenarios) and emissions at pig housing (ammonia levels on a high temporal resolution). Furthermore, we aimed to acquire information about potential synergies of the two cooling strategies. However, data of such quality was not always available, which is why we resorted to the specific assumptions described in this paper. Future studies should focus on the generation of primary data to facilitate modelling of novel on-farm solutions for improved sustainability.

4. Conclusions

The implementation of pig-cooling strategies that target ammonia emission reductions at pig housing have important environmental and economic implications at a whole-farm level. Here, we presented a novel environmental and economic impact assessment framework and demonstrated its potential to facilitate decision making regarding the implementation of such farm investments in a cost-effective manner. Through the presented framework, potential environmental (i.e. indoor temperature) and economic (i.e. feed and water price) impact hotspots can also be identified to help improve farm sustainability. We conclude that both pig-cooling with showers and pig-cooling with increased air velocity can significantly reduce system environmental impact, while improving farm profitability. Both pig-cooling strategies were resilient and effective in significantly reducing the effects of climate change on system environmental impact for all impact categories. Notwithstanding the challenges in adopting whole-farm, life cycle assessment approaches, this paper demonstrates the importance of using such elaborate frameworks to evaluate potential environmental and economic impacts associated with farm investments that aim to improve the system environmental performance.

Author contributions

Georgios Pexas: Conceptualization, Methodology, Formal Analysis, Writing-original draft preparation, Visualization, Project coordination. **Stephen G. Mackenzie:** Conceptualization, Methodology, Writing-

review and editing, Supervision, Project coordination. **Knut-Håkan Jeppsson:** Investigation, Resources, Writing-review and editing. **Anne-Charlotte Olsson:** Investigation, Resources, Writing-review and editing. **Michael Wallace:** Conceptualization, Methodology, Writing-review and editing, Supervision, Project coordination. **Ilias Kyriazakis:** Conceptualization, Writing-review and editing, Supervision, Project coordination, Funding acquisition.

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