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The effects of progress in genetics and management on intensities of greenhouse gas emissions from Norwegian pork production

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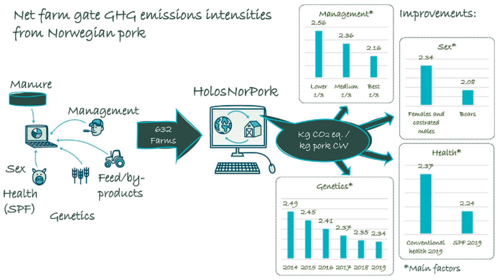
HIGHLIGHTS

- The HolosNorPork reflected the effects of the progress in genetics and management.
- Estimated emissions decreased from 2.49 to 2.34 kg CO_2eq. kg^{-1} CW from 2014 to 2019.
- Results imply 3.30 kg CO_2eq. kg^{-1} edible meat and 1.74 kg CO_2eq. $(100\ g)^{-1}$ protein.
- Progress in genetics and management contributes to a sustainable production of pork.

GRAPHICAL ABSTRACT



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ABSTRACT

The environmental sustainability of food production systems, including net greenhouse gas (GHG) emissions, is of increasing importance. In Norwegian pork production, animal performance is high in terms of reproduction, growth, and health. The development and use of an IPCC methodology-based model for estimating GHG emissions from pork production could be helpful in identifying the effects of progress in genetics and management. The objective was to investigate whether an IPCC methodology-based model was able to reflect the effects of the progress in genetics and management in pork production on the GHG emissions per kg carcass weight (CW). It is hypothesized that this progress has led to low GHG emissions intensities in Norwegian pork compared to global levels and that expected improvements will give a lasting reduction in GHG emissions intensities. A model 'HolosNorPork' for estimating net farm gate GHG emissions intensities was developed, including allocation procedures, at the pig production unit level. The model was run with pig production data from in average 632 farms from 2014 to 2019. The estimates include emissions of enteric and manure storage methane, manure storage nitrous oxide emissions, as well as GHG emissions from production and transportation of purchased feeds, and direct and indirect GHG emissions caused by energy use in pig-barns. The model was able to estimate the effects on net GHG emissions intensities from pork production on the basis of production characteristics. The estimated net GHG emissions intensity was found to have decreased from on average 2.49 to 2.34 kg CO_2 eq. kg^{-1} CW over the investigated period. For 2019 the net GHG emission for the one-third lower performing farms was estimated to 2.56 kg CO_2 eq. kg^{-1} CW, whereas for the one-third medium and one-third best performing farms the estimates were 2.36 and 2.16 kg CO_2 eq. kg^{-1} CW, respectively. The net GHG emissions intensity for pork carcasses from boars was estimated to be 2.07 kg CO_2 eq. kg^{-1} CW. For the health regimes investigated, Conventional and Specific-Pathogen Free (SPF), the estimated GHG emissions intensities for 2019 were 2.37 and

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2.24 kg CO_2 eq. kg^{-1} CW, respectively. The effects on net GHG emissions intensities of breeding and management measures were estimated to be profound, and this progress in pig production systems contributes to an on-going strengthening of pork as a sustainable source for human food supply.

1. Introduction

The environmental sustainability of food production systems, including net greenhouse gas (GHG) emissions, is of increasing importance for diet recommendations (*e.g.* Willett et al., 2019). Thus, to preserve a proportion of animal-based food in such recommendations, it is necessary to further reduce the net GHG emissions intensities from animal husbandry systems. As monogastric animals, pigs have low enteric methane (CH_4) production compared to ruminants, and the largest sources of net GHG emissions from pig production systems are manure storage, including nitrous oxide (N_2O) and CH_4, and feed production, both N_2O and carbon dioxide (CO_2).

In Norwegian pork production, animal performance is high both in terms of reproduction and growth, and following the introduction of genomic selection in the pig breeding program in 2014 (Nordbø et al., 2014), the progress in animal performance has been further increased (Ingris, 2019). Animal health status is high due to the closed national population of animals, *i.e.* with no import of animals, which has contributed to the eradication of many swine diseases common in the rest of the world (Grøntvedt et al., 2016a, 2016b). The production of 1.6 million finishers is organized within a hierarchical pyramid of approximately 2000 herds, with 70 genetic nucleus and multiplier herds at the top level. This has spread the high genetic basis and the good health status to pig farms at all levels. Commercial pig units are organized as independent family farms with either specialized piglet production, grower-finisher production, or combined production. From 2016, the aim has been that by 2024 all nucleus farms will have converted to a specific pathogen free (SPF) health regime as a first step towards further improvement of the animal health status for the entire national pig population (Animalia, 2020). It is expected that by introducing the SPF health regime, animal losses due to health issues will be minimized.

MacLeod et al. (2013) classified pig production systems into backyard, intermediate, and industrial systems, where industrial systems featured the lowest GHG emissions intensities. However, industrial production systems tend to obscure environmental and resource costs, as the livestock-crop factors in such systems are generally delinked (Naylor et al., 2005). To counteract this, government agricultural policy in Norway aims to preserve the links between animal production and the natural resource base of the farms by legislations. For pig production units, this has been accomplished by implementing quotas for the number of pigs (Norwegian Ministry of Agriculture and Food, 2004), manure disposal requirements, and compulsory planning of manure use; currently a maximum of 35 kg P from manure per ha (Norwegian Ministry of Agriculture and Food, 2002). The result is relatively small-scale and dispersed pig production units; typically, with 105 sows in piglet production or maximum 2100 finishers slaughtered per year (Norwegian Ministry of Agriculture and Food, 2004). This small-scale and scattered structure is well suited for both minimizing risk of disease transmission and consequences of infections. Other management measures in Norwegian pig production with the potential of reducing GHG emissions intensities are the use of food by-products for feed and efforts to increase the finishing of entire boars.

The development and use of IPCC based models for the estimation of GHG emissions at the production unit level has been useful in detecting mitigation options in dairy and beef production systems (*e.g.* Beauchemin et al., 2010; Bonesmo et al., 2013; Samsonstuen et al., 2019). Similar development and use of an IPCC based model for estimating GHG emissions from pork production could be helpful in identifying the effects of progress in genetics and management. With this as a background, the objective of the current study was to investigate whether an IPCC methodology-based model was able to reflect the effects of such progress in Norwegian pork production on the GHG emissions per kg carcass weight (CW). Further, it is hypothesized (1) that the on-going progress in genetics and management has led to low GHG emissions intensity in Norwegian pork compared to global levels and (2) that expected improvements in production methods will give a lasting reduction in GHG emissions intensity, such that Norwegian pork will remain a valuable source of protein in a sustainable food production.

2. Materials and methods

The following sections describe a pork production model ‘HolosNorPork’ for estimating net GHG emissions intensities, including allocation procedures, at the herd level. Thereafter, the data used in the current investigation of the effects of progress in genetics and management on net GHG emissions intensities from Norwegian pork production are presented.

2.1. The model

HolosNorPork estimates net GHG emissions per kg pork CW leaving the farm. All GHG emissions are expressed as CO_2 equivalents to account for the global warming potential of the respective gases given a time horizon of 100 years: CH_4 kg × 25 + N_2O kg × 298 + CO_2 kg × 1 (IPCC, 2007). They are presented as intensities per produced unit, *i.e.* kg CO_2 equivalents per kg pork CW from sows and finishers, and per weaner sold. The following GHG sources are considered: enteric CH_4, manure-derived CH_4 and N_2O, the pork production unit CO_2 emissions from energy used on-farm, and off-farm CO_2 and N_2O emissions from feed production. The scope of the current investigation was GHG emissions per kg pork CW leaving the farm such that the estimation of GHG emissions from the farm’s crop production are not included in the model. In the Norwegian feed production system, close to all of the grains produced are delivered to feed mills for concentrate, *i.e.* compound feed, production. Consequently, to ensure representativeness, independent estimates at national level of GHG emissions intensities of concentrate feeds for pigs are used as input. These GHG emissions intensities are based on the report of Johansen and Hjelkrem (2018) which is the only available life cycle assessment (LCA) calculated as appropriate of concentrate feed for pigs in Norway. Further, emissions of GHGs from fixed investments are not included such that the model takes into account only the effects of management variations at the operational and tactical levels. Consequences of variations at the strategic level, such as variations in buildings construction or other technical equipment, are not assessed.

Enteric CH_4 emissions are calculated for four categories: Sows, from the first insemination resulting in a litter and with a live weight (LW) higher than approximately 160 kg; Gilts, from approximately 120 to 160 kg LW; Weaners, from weaning at approximately 10 kg LW and until they enter the finisher stage at approximately 30 kg LW; Finishers, from approximately 30 to the time of slaughter at approximately 120 kg LW, this category also includes the animals destined for piglet production until entering the Gilts category. Following the approach of Philippe and Nicks (2015), enteric CH_4 is calculated as the product of age category specific factors accounting for fermentation in the large intestine and the level of fibre intake, the so-called digestible residues (Table 1). The digestible residues are defined as the difference between digested organic matter and digested protein, fat, starch and sugar.

Estimates of manure management CH_4 emissions from the pig-barn are based on volatile solids (VS) production, according to IPCC (2006)

Table 1
Methodology, with sources, for the calculation of yearly enteric CH_4 emission for four categories of pigs: Sows, Gilts, Weaners, and Finishers.

Variable name	Equations and factors with units	Source
Enteric_methane_total_CO_2_eq	Enteric_methane_total_CH_4, kg CH_4 * 25 CO_2 eq. (kg CH_4)$^{-1}$	IPCC (2006)
Enteric_methane_total_CH_4	Enteric_methane, kg CH_4 head^{-1} day^{-1} * animals, head * 365, day	Tables 5–7
Enteric_methane	dRes_intake, g head^{-1} day^{-1} * dRes_factor / 1000 g kg^{-1}	Philippe and Nicks (2015)
dRes_intake	Feed_intake, kg head^{-1} day^{-1} * 1000 g kg^{-1} * dRes_percentage,%	Philippe and Nicks (2015)
dRes_percentage	12.5% in feed for sows; 7.66% in feed for weaners; 10.83% in feed for finishers and gilts	Typical numbers
dRes_factor	0.021 for sows; 0.012 for others	Philippe and Nicks (2015)
Feed_intake_sows	3.8 kg head^{-1} day^{-1} with 9.3 MJ_NE kg^{-1} concentrate	Typical number
Feed_intake_others	FCR, MJ_NE (kg LW)$^{-1}$ *ADG, g LW day^{-1} / 1000 g kg^{-1} * 9.68 MJ kg^{-1}	Tables 6 and 7

Animals = the number of animals in each category calculated as the sum of days an individual animal is defined as 'Sows', 'Gilts', 'Weaners', or 'Finishers', respectively, and divided by 365. dRes_intake = The level of fibre intake, the so-called digestible residues (deRes), defined as the difference between digested organic matter and digested protein, fat, starch, and sugar.

Table 2
Methodology, with sources, for the calculation of yearly manure CH_4 emission from four categories of pigs; Sows, Gilts, Weaners, and Finishers; taking into account the gross energy intake of the animal and the digestibility of the diet.

Variable name	Equations and factors with units	Source
Manure_methane_total_CO_2_eq	Manure_methane_total_CH_4, kg CH_4 yr^{-1} * 25 CO_2 eq. (kg CH_4)$^{-1}$	IPCC (2006)
Manure_methane_total_CH_4	Manure_methane, kg CH_4 head^{-1} day^{-1} * animals, head * 365 days	Tables 5–7
Manure_methane	VS, kg head^{-1} day^{-1} * B0, m^3 (kg VS)$^{-1}$ * MCF,% * 0.662 kg m^{-3}	Morken et al. (2013), IPCC (2006)
VS	VS_percentage,% * (DM_urine, kg + DM_faeces, kg)	Morken et al. (2013), Dämmgen et al. (2012)
DM_urine	Feed_intake, kg head^{-1} day^{-1} * DM_feed,% * 2.5 kg urine (kg feed DM)$^{-1}$ * 0.02 kg DM (kg urine)$^{-1}$	Karlengen et al. (2012)
DM_faeces	Feed_intake, kg head^{-1} day^{-1} * DM_feed,% * (1 - Feed_digestibility,%)	Karlengen et al. (2012)
Feed_digestibility	81% for feed for sows; 83% for feed for others	Typical numbers
MCF	3.5%	Morken et al. (2013), IPCC (2006)
B0	0.3 m^3 (kg VS)$^{-1}$	Morken et al. (2013), Dämmgen et al. (2012)
VS_percentage	88%	Morken et al. (2013), IPCC (2006)
DM_percentage_feed	89%	Typical number

VS = volatile solids; DM = dry matter; MCF = methane conversion factor; B0 = methane potential.

(Table 2). The VS production is multiplied by a maximum CH_4 producing capacity of the manure (Dämmgen et al., 2012), a conversion factor from volume to mass of 0.662 kg m^{-3}, and a CH_4 conversion factor specific to the manure management practice (Morken et al., 2013). The VS production is calculated as a percentage of the dry matter content (DM) of manure (Morken et al., 2013), which is calculated separately for faeces and urine on the basis of DM feed intake and digestibility (Karlengen et al., 2012).

For losses of N_2O-N from manure storage, the handling specific emission factors (EF) given in the IPCC (2006) guidelines are used (Table 3). For direct N_2O-N emissions, the EF can be assumed to be 0, as pig manure typically does not form a natural crust (Derikx et al., 1997; Chambers, 2004). However, if a sufficient amount of bedding is added to manure, a type of crust here may be formed and lead to some N_2O emissions (Smith et al., 2007). Thus, the Norwegian emissions inventory uses an EF of 0.0005 for direct N_2O-N, which accounts for a natural crust formation of 10%. However, to be in line with comparable studies (*e.g.* McAuliffe et al., 2017), an EF of 0.002 for direct N_2O-N is used in the current study. This conservative approach is also recommended in the Netherlands (Lagerwerf et al., 2019). The indirect N_2O-N emissions through volatilization are calculated as proportions of NH_3 and NO_x losses from animal housing and the storage of manure. As slurry is the predominant type of pig manure stored in Norway (Gundersen and Heldal, 2015), this study limits the calculations to slurry. Losses of N_2O-N from leaching/runoff during storage are not included, as leakage-free manure stores are required by law in Norway (Norwegian Ministry of Agriculture and Food, 2002). For losses of $NO_{x,}$ the default EF value given in EMEP/EEA (2016) is used and applied to the NH_3 content of the stored manure (Table 3). Emissions of NH_3-N from storage are calculated based on the unabated emission factors sourced from EMEP/EEA (2016). For the calculation of manure NH_3 emissions, all animal categories are grouped together, using the EF for fattening pigs, 8–110 kg (Table 3), which is considered to be a conservative approach. To account for the effect of manure handling system, an abatement factor related to manure storage systems (Bittman et al., 2014) is included in the model (Table 3). Further, as recommended by Carbon Limits (2018) for the Norwegian Environmental Agency, a temperature correction factor (Table 3) is applied to the EMEP/EEA (2016) EFs, reflecting the fact that the latter are based on studies representing climatic conditions different from those in Norway. Following the approach proposed by Grönroos et al. (2017), the difference of 4.5°C in the annual average outdoor temperature between Norway and Central Europe results in a reduction of 15% in ammonia volatilization. The estimated pool of NH_3-N in manure storage is increased by assuming that 10% of the excreted N entering storage is converted to NH_3-N during storing (Table 3), as recommended in EMEP/EEA (2016) based on studies by Dämmgen et al. (2007). Losses of NH_3-N from the livestock housing are calculated by using EFs sourced from EMEP/EEA (2016) (Table 3). It is assumed that although there is no significant difference between countries in the indoor temperatures of pig-houses, the higher outdoor temperatures in Central Europe result in an increased need for ventilation of facilities, which is likely to increase emissions (Grönroos et al., 2017). This results in a temperature correction factor of 0.93 for pig-houses in Norway. The content of N in excreta is estimated for each animal category from the DM intake (DMI), the crude protein (CP = 6.25 N) content of the diet, and the N retention by the animals based on Karlengen et al. (2012) (Table 3).

The composition of typical concentrate feeds used in Norway for weaners, finishers and sows, and feed GHG emission intensities expressed as CO_2 equivalents per kg dry matter (DM) were presented in a LCA study of Norwegian pig production (Johansen and Hjelkrem, 2018). The functional unit was set to 1 kg concentrate feed delivered from the feed mill. The LCA study included crop production, transport to and processing at the feed mill. Emissions from the production of buildings and machinery were not included. Sources used were the Ecoinvent database for imported crops, and Korsaeth et al. (2014) and Korsaeth

Table 3
Methodology, with sources, for the calculation of yearly manure N_2O emission from four categories of pigs; Sows, Gilts, Weaners, and Finishers; taking into account the N content in the diet and the N retention by the animals.

Variable name	Equations and factors with units	Source
Manure_direct_ N_2O _total_CO_2_eq	N_excreted_rate, (kg N) head^{-1} day^{-1} * EF_direct, kg N_2O-N (kg N)$^{-1}$ * animals, head * 365 days * 44/28 * 298 CO_2 eq. (kg N_2O-N)$^{-1}$	IPCC (2006), Tables 5–7
Manure_indirect_ N_2O _total_CO_2_eq	(NH_3-N_total_loss, N + NO_x-N_loss) kg head^{-1} day^{-1} * EF_N_2O-N_indirect * animals, head * 365 days * 44/28 * 298 CO_2 eq. (kg N_2O-N)$^{-1}$	IPCC (2006), Tables 5–7
EF_direct	0.002 kg N2O-N * (kg N)$^{-1}$	IPCC (2006), Lagerwerf et al. (2019)
EF_N_2O-N_indirect	0.01 kg N_2O-N * (kg NH_3-N + NO_x-N)$^{-1}$	IPCC (2006)
NO_x-N_loss	NH_3-N_storage * EF_NO_x_storage	
EF_NO_x_storage	0.0001 kg NO_x - N (kg NH_3-N)$^{-1}$	IPCC (2006)
NH_3-N_total_loss	(NH_3-N_storage, kg N * EF_NH_3-N_storage * 100% - Abatement_factor_storage * Temperature_correction_storage) + NH_3-N_loss_from_livestock_housing	
EF_NH_3-N_storage	14%	EMEP/EEA (2016)
Abatement_factor_storage	57%	Bittman et al. (2014), handling system specific*
Temperature_correction_storage	0.85	Grönroos et al. (2017)
NH_3-N_storage	NH_3-N_excreted, kg NH_3-N head^{-1} day^{-1} - NH_3-N_loss_from_livestock_housing, kg NH_3-N head^{-1} day^{-1} + NH_3-N_mineralised, kg NH_3-N head^{-1} day^{-1}	
NH_3-N_mineralised	0.1 * (N_excreted_sows, kg N head^{-1} day^{-1} * (1 – TANp_sows) + N_excreted_others, kg N head^{-1} day^{-1} * (1 – TANp_others)	EMEP/EEA (2016), Dämmgen et al. (2007)
NH_3-N_loss_from_livestock_housing	NH_3-N_excreted, kg NH_3-N head^{-1} day^{-1} * EF_NH_3-N_housing,% * Temperature_correction_housing	
NH_3-N_excreted	N_excreted_sows, kg N head^{-1} day^{-1} * TANp_sows + N_excreted_others, kg N head^{-1} day^{-1} * TANp_others	Karlengen et al. (2012), SSB 2018
EF_NH_3-N_building	28%	EMEP/EEA (2016)
Temperature_correction_housing	0.93	Grönroos et al. (2017)
N_excreted_rate_sows	(Feed_intake_N, g N head^{-1} day^{-1} - Retained_growth_sows_N, g N head^{-1} day^{-1} - Retained_piglets_N, g N head^{-1} day^{-1}) / 1000 g kg^{-1}	Karlengen et al. (2012)
Retained_growth_N_sows	175 g head^{-1} day^{-1}	
Retained_piglets_N	Weaned_piglets, heads sow^{-1} yr^{-1} * 365 days yr^{-1} * LW_weaned_piglets, kg * Retained_N_ADG, g kg^{-1}	Tables 6 and 7
N_ExcretedRate_others	ADG, g head^{-1} day^{-1} * (Feed_intake_N, g N head^{-1} day^{-1} - Retained_N_ADG g kg^{-1} head^{-1} / 1000 g kg^{-1})	Tables 6 and 7
Feed_intake_N	Feed_intake, kg head^{-1} day^{-1} * Feed_protein_conc, g kg^{-1} / 1000 g kg^{-1} / 6.25	Table 5
Retained_N_ADG	Sow, 25 g N (kg ADG)$^{-1}$; Weaners, 26 g N (kg ADG)$^{-1}$; Finisher, 28 g N (kg ADG)$^{-1}$; Gilt, 28 g N (kg ADG)$^{-1}$	Typical numbers
Feed_protein_conc	Sows and gilts, 140 g kg^{-1}; Weaners, 190 g kg^{-1}; Finishers, 165 g kg^{-1}	Typical numbers

EF = emission factor; N = nitrogen; N_2O = nitrous oxide; NH_3 = Ammonia; NO_x = Nitrogen oxide; ADG = average daily growth; TANp_sows, TANp_others = proportion of ammonium N in N excreted for 'Sows' and the other pig categories, respectively; * the specific abatement factors are calculated on the basis the distribution of types of manure storages in Norway (Gundersen and Heldal, 2015) and the corresponding abatement factors from Bittman et al. (2014).

and Roer (2016) for small grains and field beans produced in Norway. However, the GHG emission intensity used by Johansen and Hjelkrem (2018) for soya meal (0.39 kg CO_2 equivalents per kg DM) is lower than those recommended in Denmark (Mogensen et al., 2018) and Sweden (Woodhouse, 2019), and that of Hörtenhuber et al. (2011) for soya used in Austria. Further, the recent focus on soya has led to an effort to reduce its content in concentrate feeds, resulting in a lower use of soya meal in a typical concentrate for sows and its complete removal in a typical concentrate for finishers. Thus, the GHG emission intensity of soya meal, including soil C change but excluding transportation, is set to 0.45 kg CO_2 equivalents per kg DM in the current study, in accordance with Mogensen et al. (2018), and to reflect the current trend in feed composition the proportion of soya meal is reduced from 0.1 to 0.05 in the concentrate for sows and from 0.07 to 0 in the concentrate for finishers (Table 4). To meet the nutrient requirement of the feed, the content of rapeseed cake was enhanced correspondingly. In addition to emissions caused by on- and off-farm emissions from fuel and manufacturing of input factors, the GHG emissions intensities for Norwegian grown small grains presented in Table 4 encompasses indirect N_2O emissions, trough volatilization and leaching, and direct N_2O emissions from the use of synthetic fertilizer, and from plant residues. The estimates of GHG intensities for grains in pig feeds is based on area weighted national LCAs calculated for the main crop growing agro-ecozones in Norway. It is noteworthy that these LCA calculations were for farms without animals. However, Johansen and Hjelkrem (2018) conducted a case LCA study for a typical farm with pigs resulting in considerably lower GHG emissions in crop production than for farms without animals. Thus, the results from the area weighted national LCAs for the main crop growing agro-ecozones can be considered to provide adequate and conservative estimates for pig feeds in Norway. Yet, to avoid a seemingly negligence of the inclusion of emissions from the application of animal manure to crops for production of concentrate, an addition 0.01 kg CO_2 equivalents per kg grain to the estimated GHG intensities for grains from Johansen and Hjelkrem (2018) was included in our estimates for GHG emissions per kg CW pork. The additional emissions from manure spreading were calculated as follows: Using *exo*-farm estimates, *i.e.* representative estimates at national level, for emissions form feeds requires that emissions from the spreading of manure from all husbandry animal types are to be included. According to the 2020 National Inventory Report for Norway (Norwegian Environment Agency, 2021), indirect losses of N_2O-N from atmospheric deposition from manure application to land was estimated to, in tonnes, 115.84, and indirect losses of N_2O-N from leaching and runoff during

Table 4

Composition of typical concentrate feeds for sows and gilts, weaners, and finishers, and the GHG emission intensities expressed as CO_2 equivalents per kg dry matter (DM) and per MJ net energy (NE), in accordance with Johansen and Hjelkrem (2018), with enhanced value of GHG emission intensity and reduced proportion for soya meal in the feeds for sows and finishers.

Ingredient	Country of origin	CO_2 eq. kg^{-1} DM	Feed for sows and gilts		Feed for weaners		Feed for finishers	
			proportion	CO_2 eq.	proportion	CO_2 eq.	proportion	CO_2 eq.
Wheat	Norway	0.59	0.22	0.130	0.45	0.266		
Barley	Norway	0.56	0.28	0.157	0.19	0.106	0.44	0.246
Oat	Norway	0.49	0.21	0.103	0.05	0.025	0.25	0.123
Field beans	Norway	0.80					0.07	0.056
Soybean meal	Brazil	0.45	0.05	0.023	0.09	0.041		
Rapeseed cake	Baltic states	0.54	0.10	0.054	0.01	0.005	0.13	0.070
Corn gluten	China	0.60	0.02	0.012	0.04	0.024		
Molasses	Poland	0.07	0.02	0.001	0.01	0.001	0.02	0.001
Acidifier	China	2.88					0.005	0.014
Salt, vitamins, minerals, amino acids	_	1.80	0.05	0.090	0.06	0.108	0.03	0.054
Unspecified	Norway	0.37	0.05	0.019	0.10	0.037	0.055	0.020
Transportation to processing unit, kg CO_2 eq. kg^{-1} DM			0.035		0.035		0.035	
Energy to processing, CO_2 eq. kg^{-1} DM				0.011		0.011		0.011
Concentrate feed, CO_2 eq. kg^{-1} DM				0.63		0.66		0.63
Concentrate feed, CO_2 eq. MJ^{-1} NE				0.057		0.060		0.057

manure application to land, in tonnes, 92.32. Of these losses 16% of the N_2O-N from atmospheric deposition and 22% of N_2O-N from leaching and runoff were from arable crop land. Grains were cultivated at about 90% of the arable crop land. This results in total indirect emissions of 16, 695,873 kg CO_2 equivalents from manure spreading at fields for grain crops. By the use of manure, the total N applicated will be higher than by solely use of synthetic fertilizer. Of the total N excreted per year (Norwegian Environment Agency, 2021), 18,160.93 tonnes per year can be allocated to fields for grain crops. Assuming a substitution factor of 0.6 for N from manure to N from synthetic fertilizer, the increase in direct N_2O-N loss from fields for grain crops due to the use of manure will be 34 016 138 kg CO_2 equivalents. However, substituting synthetic N with manure N will reduce the emissions caused by the production of synthetic fertilizer. Using the relatively low factor of 3.6 kg CO_2 equivalents per kg N in synthetic fertilizer, similar to that used by Johansen and Hjelkrem (2018), this will decrease the emissions attributed to grains with 39,225,443 kg CO_2 equivalents. Adding up the increase in indirect and direct N_2O emissions caused by spreading of manure and the decrease in the emissions attributed to grains from the production of synthetic fertilizer and dividing it on the 1 200 000 tonnes of grains produced in Norway, 0.01 kg CO_2 equivalents per kg grain used in pig feeds can be added to the LCA for pig feeds of Johansen and Hjelkrem (2018) presuming all other inputs not changed.

Whilst most of the feed to pigs in Norway comes from grain-based concentrate feed, 4414.8 mill MJ NE (Norwegian Agriculture Agency, 2019), a significant amount also comes from feeds based on various by-products. Feeds based on recycling from food production, retailing and consumption, contribute with at least 232.2 mill MJ NE, and by-products from the dairy industry, whey and surplus milk, contribute with at least 264.0 mill MJ NE. Thus, a very conservative estimate is that feed, based on these by-products, contributes 10% of the total amount of feed to pigs in Norway. Emissions from food-based by-products encompasses emissions from transportation and processing. The cost of the unconsumed food is negligible, and this part is set to zero in accordance with Landquist et al. (2020). Consequently, assuming the same contribution for transportation and processing per MJ NE of feed from by-products as that used for grain-based concentrate feed, the emission estimates from the typical feeds used in the current work are 0.054 CO_2 equivalents per MJ NE for weaners, and 0.052 CO_2 equivalents per MJ NE for finishers, gilts, and sows.

The estimates of emissions caused by direct energy use in pig-houses and off-farm energy use related to pig production are taken from Johansen and Hjelkrem (2018). These emissions are added as constant values per kg pork CW delivered both for finishers and sows: 0.0173 kg CO_2 equivalents per kg CW from the use of electricity in pig-houses; 0.0407 kg CO_2 equivalents per kg CW from fuel used in transportation of concentrate feed, bedding materials, and veterinarian visits; and 0.0057 kg CO_2 equivalents per kg CW from production of bedding materials. The activity data base for the assessment of emissions from direct and indirect energy use was the Norwegian agricultural accountancy survey (NIBIO, 2020)

According to the methodology used, the GHG emissions are calculated for each age group as described. However, a pig production unit delivers carcasses and/or live animals including weaners. Thus, the emissions are allocated to the main products; pork carcasses from finishers (CW_finishers), carcasses from sows (CW_sows), and the intermediate product 30 kg LW weaner (LW_weaners) (Fig. 1). For the assessment of emissions for the products, the emissions from all relevant age groups are included as follows: For CW_finishers, in addition to the emissions in the Finishers and the Weaners age categories, the emissions from the finisher's mother in gestation and lactation periods are also included (Fig. 1). Such that the emissions calculated for the Sows category after first insemination and their further lifetime, are distributed to the weaners produced and sequentially allocated to the CW_finishers. For the CW_sows, the emissions are assigned as all emissions from when the gilt herself was conceived until she is inseminated for the first time. For the intermediate 30 kg LW weaner, all emissions from the Sows category, *i.e.* after the first insemination, are allocated to piglet production, in addition to the emissions from the Weaners category.

2.2. *Pig production data*

The data source for this work was Norwegian litter recording system (Ingris) (Norwegian Meat and Poultry research Centre, 2021). This is a web-based management system for pigs and is the predominantly used registration system for pig management in Norway. Data from Ingris are published annually and encompass about 75% of the sows and gilts, 12% of the weaners and 29% of the finishers (Ingris, 2014). For the GHG intensity assessment, the Ingris data were divided into the categories: Sows, Gilts, Weaners, and Finishers. The number of animals in each category is calculated as the sum of the number of days over individual animals in the category divided by 365 days.

To estimate the development in GHG emission intensities over time, annual averages from 2014 to 2019 of key production characteristics were used (Tables 5–7). The 2019 data were split into low, medium, and high efficiency performance groups based on the numbers of piglets weaned per sow per year (Table 5), the growth of weaners (Table 6) and the feed efficiency for finishers (Table 7). For 2019, all animal categories were also split into two health regimes: Conventional health and Specific-Pathogen Free (SPF) (Tables 5–7). In Norway, pig health status

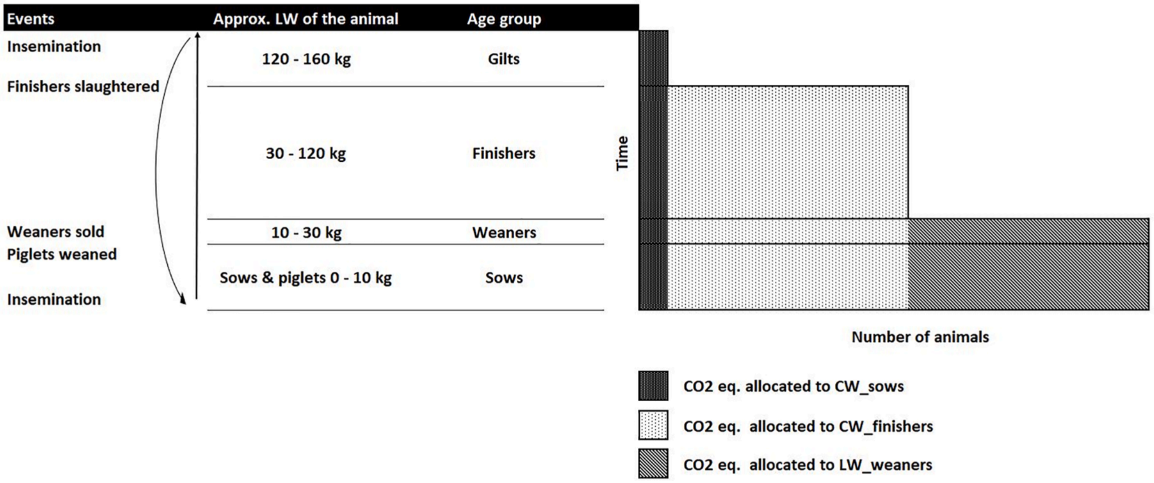

Fig. 1. General description of the method developed for allocating estimated emissions from pigs in four age categories to pork CW from sows and finishers and 30 kg LW weaners sold; framed horizontal areas represent the estimated emission per age category; patterned vertical areas represent the allocated emissions to pork CW from sows (darkest shaded), pork CW from finishers (lightest shaded), and 30 kg LW weaners sold (intermediate shaded).

Table 5
Key production characteristics for pigs in the categories Sows and Gilts as: yearly averages from 2014 to 2019; low, medium, and best efficiency performance groups for the year 2019; and for conventional health regime and Specific-Pathogen Free (SPF) health regime for the year 2019.

Sows and gilts, piglets production	2014	2015	2016	2017	2018	2019	Lower 1/3 2019	Medium 1/3 2019	Best 1/3 2019	Conventional health 2019	SPF 2019
Number of sows	43 450	41 945	41 269	39 254	39 695	38 190	7 754	14 824	15 610	14 869	4 866
Number of herds	368	363	349	344	340	332	111	111	110	214	38
Litters per herd	247	244	251	243	252	250	142	287	320	153	273
Weaned piglets per sow and year	24.3	25.2	25.9	26.9	27.1	27.9	23.6	27.5	30.4	27.7	27.7
Litters per sow and year	2.16	2.16	2.17	2.20	2.19	2.20	2.03	2.20	2.28	2.17	2.15
Live piglets born per sow and year	13.2	13.4	13.6	13.9	14.1	14.5	13.6	14.5	15.1	14.7	14.4
Total piglets born per sow and year	14.3	14.5	14.6	14.9	15.2	15.7	14.8	15.6	16.1	15.9	15.5
Weaned piglets per litter	11.3	11.6	11.8	12.2	12.3	12.7	11.7	12.5	13.3	12.8	12.9
Age at weaning, days	32.9	33.1	33.1	33.1	33.3	33.5	34.1	33.1	33.5	33.8	33.2
% first litter	38.9	38.0	38.6	37.5	37.8	36.1	38.5	37.1	34.0	34.6	40.8
Farrowing rate,%	80.0	81.1	81.7	83.0	83.4	84.8	78.5	84.0	88.7	83.4	84.0
Age at first farrowing, days	359	356	359	356	355	361	354	362	363	365	357
CW, kg	151	152	152	152	153	152	ND	ND	ND	ND	ND
Mortality sows,%	15.8	11.3	10.7	10.9	9.5	11.0	10.3	10.1	12.2	9.7	8.1
SPF,%		9.3	11.6	13.6	12.6	15.8	14.8	16.3	15.8	0	100

CW = carcass weight, SPF = specific pathogen free, ND = no data.

Table 6
Key production characteristics for pigs in the Weaners age category as: yearly averages from 2014 to 2019; lower, medium, and best efficiency performance groups for the year 2019; and for conventional health regime and Specific-Pathogen Free (SPF) health regime for the year 2019.

Weaners	2014	2015	2016	2017	2018	2019	Lower 1/3 2019	Medium 1/3 2019	Best 1/3 2019	Conventional health 2019	SPF 2019
Number of weaners	101 295	123 331	111 096	128 354	143 324	181 220	519 24	545 35	747 61	127 851	53 369
Number of herds	49	55	45	49	60	71	25	23	23	53	18
LW weaned piglets, kg	10.7	10.6	10.7	10.8	10.7	10.6	10.6	10.4	10.7	10.4	11.1
LW out, kg	31.9	32.6	33.3	32.7	32.7	32.1	30.8	31.8	33.1	32.2	31.8
ADG, g LW day^{-1}	521	551	579	582	595	585	497	583	649	567	628
FCR, MJ_NE (kg LW)$^{-1}$	16.5	15.9	15.7	15.0	15.0	15.2	15.8	15.8	14.6	15.5	14.3
Days in period	41	40	39	38	38	37	41	37	35	39	33
Mortality,%	1.8	1.3	1.3	1.1	1.3	1.1	1.7	1.0	0.8	1.4	0.5
SPF,%	ND	ND	ND	31.8	27.0	29.5	9.6	32.2	41.2	0	100

LW = live weight, ADG = average daily growth, FCR = feed conversion ratio, SPF = specific pathogen free, MJ_NE = Mega Joule net energy, Feed concentration: 10.1 MJ_NE kg^{-1} concentrates; ND = no data.

Table 7
Key production characteristics for pigs in the Finishers age category as: yearly averages from 2014 to 2019; lower, medium, and best efficiency performance groups for the year 2019; and for conventional health regime and Specific-Pathogen Free (SPF) health regime for the year 2019.

Finishers	2014	2015	2016	2017	2018	2019	Lower 1/3 2019	Medium 1/3 2019	Best 1/3 2019	Conventional health 2019	SPF 2019
Number of groups	262	332	362	422	442	442	137	137	136	345	97
Number of pigs	271 622	351 702	392 517	416 462	437 457	441 840	147 150	145 373	128 031	329 871	111 969
Number of herds	192	255	281	322	326	321	103	103	102	247	74
LW, kg	31.4	31.9	32.4	32.0	31.9	31.7	32.3	31.6	30.8	31.6	31.9
CW, kg	79.1	82.7	81.6	81.5	80.0	80.2	80.3	80.2	80.0	80.0	80.7
ADG, g LW day^{-1}	955	980	996	1018	1032	1051	1005	1059	1100	1034	1101
FCR, MJ_NE kg^{-1}	24.1	23.9	23.6	23.6	23.3	23.3	24.9	23.3	21.6	23.6	22.5
Days in period	89	92	88	87	83	82	86	82	79	83	79
Mortality,%	1.78	2.1	2.21	1.95	1.83	1.7	1.99	1.6	1.48	1.72	1.64
Not approved carcasses,%	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.2	0.1
SPF,%	ND	ND	ND	18.6	24.8	25.3	10.8	23.4	43.8	0	100

Numbers of groups: Finishers are not recorded individually but in groups; LW = live weigt, CW = carcass weight, ADG = average daily growth, FCR = feed conversion ratio, SPF = specific pathogen free, MJ_NE = Mega Joule net energy, Feed concentration: 9.7 MJ_NE kg^{-1} concentrate, ND = no data.

is generally high and all herds with conventional health are free from Porcine Reproductive and Respiratory Syndrome (PRRS), Transmissible Gastroenteritis (TGE), Swine influenza (H1N1, H1N2 and H3N2) and *Mycoplasma hyopneumoniae* (enzootic pneumonia). Most herds with conventional health are also free from Toxin-producing *Pasteurella multocida* (Atrhropic rhinitis), *Brachyspira hyodysenteriae* (swine dysentery), and *Sarcoptes scabei*. All SPF herds are free from all the earlier mentioned pathogens in addition to all serotypes of *Actinobacillus pleuropneumoniae* (APP, contagious pleuropneumonia). The use of antibiotics in Norwegian pig production is low and no antibiotics are given prophylactically (NORM/NORM-VET, 2018).

Production characteristics based on about 40,000 annual recordings for individual sows were available for the period 2014 to 2019 (Table 5). There was an increased performance of Weaned piglets sow^{-1} year^{-1} of 15%, Weaned piglets litter^{-1} of 12%, live-born of 11% and total born of 10%, and consequently the frequency of piglet mortality has decreased by 10%. In addition, mortality for sows had decreased by 30%. Further, there were similar differences between lowest and highest preforming herds in 2019, and 29% more Weaned piglets sow^{-1} year^{-1} for the highest performing herds compared to the lowest preforming herds. This was because of the higher number of litters sow^{-1} year^{-1}, more piglets born and lower piglet mortality.

Age at first farrowing (Table 5) is the characteristic with the largest impact on the number of days and feed intake for gilts, as the number of days in this age category is calculated as age at first farrowing minus the gestation length of 115 days. Average daily gain (ADG), feed conversion rate (FCR), and mortality are not specified for the gilts category in the recording system. Thus, estimates of 0.75 kg per day in growth, an FCR of 23.8 MJ NE kg^{-1} growth, and a mortality of 2% are used for this category. The gilts category accounts for less than 3% of the entire production, so the use of fixed factors has negligible effects on the results.

For Weaners there have been improvements in both ADG, with 12% increase, and FCR, with 7% decline, from 2014 to 2019 (Table 6). In 2019, the difference between herds with the high and low ADG was 31%, and between farms with the high and low FCR the difference was 7%. The SPF health regime achieved 11% higher ADG and 7% better FCR than the conventional health regime in 2019. Weaner mortality follows the same pattern; it has improved over time and it is lower in the high performing group and for the SPF health regime.

The number of animals in the category Finishers in the Ingris recording system increased from 2014 to 2019. In 2019, the base for the production characteristics was more than 440,000 animals (Table 7). As for Weaners, there were improvements in ADG and FCR from 2014 to 2019 of 10% and 3%, respectively. Between farms with high and low efficiency the differences in these factors) were 9% and 13%, respectively, for farms with different health status they were 6 and 4%, respectively. The mortality was generally low, but still improving over time and lower for better performing herds and herds with higher health status.

Further, a separate assessment of GHG emissions intensities was performed for finishers as boars, *i.e.* entire males. Data for this group were from the Norsvin central boar test station. The breed was Norsvin Duroc and information collected in 2019 was used, based on 1537 animals. The boars ADG was 1133 g day^{-1} and FCR was 19.9 MJ NE kg^{-1} growth^{-1}. Compared with data from 2019 for Finishers (Table 7), the efficiencies for boars were 8% and 15% higher for ADG and FCR, respectively. Commercial finishers in Norway are 98% females and castrated males, so there is a large difference between the composition of finishers at the boar test station and that at commercial farms. Even so, it is noteworthy that the boars at the Norsvin central boar test station do not have the benefit of heterosis that most commercial pigs have, as commercial finishers in Norway generally have Norsvin Duroc sires and TN70 dams. It is difficult to determine the exact effect of health status, as the boars have the advantage of higher health from nucleus farms, but still have the disadvantage of being mixed with farms from several herds.

2.3. Upscaling to national numbers and sensitivity tests

Of the emissions estimated for pork production in the current work, the enteric emissions and the emissions from manure in buildings and storage are those that are attributed to the agricultural sector in national GHG inventories (*e.g.* Norwegian Environment Agency, 2021). A challenge for GHG inventory reporting is to provide reliable data as a basis for the calculations. Whereas the farmers' reported numbers of animals may be subject to considerable uncertainty, the number of animals registered at slaughter in Norway is very reliable. Using the 2019 Ingris consistent dataset for estimating the number of animals and the number of days in each of the four animal categories related to the number of finishers slaughtered, it was possible to upscale the estimated emissions to the national level in combination with the 1,572,021 finishers registered as slaughtered in Norway in 2019 (Animalia, 2020).

For the sensitivity tests, the base-case was set to be the weighted GHG emissions intensity taking into account the proportions of carcasses from both sows and finishers. The key production characteristics were changed by one standard deviation of one parameter at the time. The standard deviations for the key production characteristics were calculated from the complete Ingris dataset for 2019. To investigate effects beyond those of progress in genetics and herd management, the emission intensities of 2019 were recalculated, both individually and overall, for (1) expected future change in global warming potential for CH_4 from

25 to 34 (Myhre et al., 2013), (2) the effects of the recommended national aim of 100% manure indoor storage using the abatement factor of 80% from Bittman et al. (2014), (3) an increase in the proportion of by-products in feed from 10% to 15%, (4) a resetting of the implemented effects of lower temperatures under Norwegian conditions and (5) the factor accounting for the effect of limited crust formation in pig manure.

3. Results

The GHG emissions per kg pork CW produced in Norway in 2019 were estimated to be 2.34 kg CO_2 eq. kg^{-1} CW for pork from finishers and 2.47 kg CO_2 eq. kg^{-1} CW for pork from sows based on animal and management data from 632 farms (Table 8). The emissions estimated per kg pork include emissions from the animal's entire lifetime. The emissions that follow the animal from the Weaner category, including the Sow category, to the Finisher category was for 2019 estimated to be 51.9 kg CO_2 eq. per weaner of 30 kg LW. There was a marked annual decrease between 2014 and 2019 in the emissions estimated for pork from finishers, resulting in 6.0% lower emissions in 2019 than in 2014. Estimated emissions per 30 kg LW weaner showed a similar distinct pattern over time with 11.1% lower emission in 2019 than in 2014. The emissions estimated for pork from sows also indicated a decrease in the gilt growth production phase, as all years following 2014 had lower emission per kg pork CW from sows. For the split in the 2019 data, the emissions estimated per kg pork CW from finishers on farms with one-third lower performance were 7.8% higher than those with one-third medium performance, whilst the farms with one-third higher performance had 7.7% lower estimated emissions from finishers than the latter group (Table 8). Similarly, the lower performance farms had 7.8% higher estimated emissions per 30 kg LW weaner and the higher performance farms had 6.7% percentage lower emissions than the middle performance farms. However, for pork CW from sows the estimated emissions were 3.5% lower for the lower performance farms and 1% higher for the higher performance farms compared with the one-third of farms with medium performance.

Based on the 2019 data, the estimated emissions per kg CW pork were lower under the SPF health regime than under the Conventional health regime. These emissions were 5.7% lower for pork CW from finishers, 7.1% lower for pork CW from sows and 9.6% lower for 30 kg LW weaners (Table 9). The quantification of a possible impact on GHG emissions of the higher growth and feed efficiency of boars, resulted in 11.2% lower estimated emissions per kg pork CW from finishers and 3.3% lower for 30 kg LW weaners of boars only compared with those of females and castrates.

Table 9
Estimated pork GHG emission intensities, kg CO_2 eq. kg^{-1} CW, from finishers (CW_finishers) and sows (CW_sows) and weaners GHG emission intensities, kg CO_2 eq. kg^{-1} LW, for live 30 kg weaners (LW_weaners), for conventional health regime, the specific pathogen free (SPF) health regime, and boars for Norwegian pork production in 2019.

	Unit	Conventional health 2019	SPF 2019	Boars
CW_finishers	kg CO_2 eq. kg^{-1} CW	2.37	2.24	2.08
CW_sows	kg CO_2 eq. kg^{-1} CW	2.48	2.30	2.43
LW_weaners	kg CO_2 eq. 30 kg^{-1} LW	52.8	47.8	50.2

Table 10
GHG emissions presented per kg CW, with percentage distribution, and for the total Norwegian pig production with a volume of 132 539 ton of pork CW in 2019. The CW from finishers (CW_finishers) and sows (CW_sows) are weighted together based on the volume they contribute.

Sources and type of GHG emissions	Estimated GHG emissions, kg CO_2 eq. kg CW^{-1}	Percentage distribution	Estimated GHG emissions from the Norwegian pig population, ton CO_2 eq.
Overall	2.35		311 439
Feeds	1.89	81%	250 774
Electricity and Transport	0.11	4%	13 975
Enteric CH_4	0.14	6%	18 137
Manure CH_4	0.11	5%	14 915
Manure N_2O	0.10	4%	13 637

As much as 95% of the pork produced in Norway comes from finishers, and only 5% from sows. The pork GHG emission intensity per kg CW, including the contribution from animals in all animal categories and carcasses from both finishers and sows, was estimated to be 2.35 kg CO_2 eq. per kg CW, giving sums of 311,467 tonnes CO_2 eq. for the 132,539 tons (Animalia, 2020) of pork carcasses produced in Norway in 2019. Emission from production and processing of the feed contributed most to the total emissions and was estimated to be 1.89 kg CO_2 eq. kg^{-1} pork CW, *i.e.* 81% of the total emissions. The second largest source was the animal related emissions that were estimated at 0.36 kg CO_2 eq. kg^{-1} CW, accounting for 15% of the total emissions. Emissions of 0.14, 0.11, and 0.10 kg CO_2 eq. kg^{-1} pork CW were related to enteric CH_4, manure storage CH_4, and manure storage N_2O, respectively. Estimated emissions from electricity usage, the production various input factors and transport related to on farm activity accounted for only 4% of the total weighted emissions (Table 10).

Of the 2.35 kg CO_2 eq. kg^{-1} CW pork, 0.43 kg CO_2 eq. kg^{-1} CW pork is from the category Sows, 0.26 kg is from Weaners, 1.60 kg is from Finishers, and 0.06 kg is from Gilts. The animal categories differ with regard to their proportions of enteric and manure CH_4 and manure N_2O. The category Sows has a higher proportion of enteric CH_4 but lower proportions of manure CH_4 and N_2O than the Finishers and Gilts categories. For Weaners, there is relatively less enteric CH_4 but relatively more manure CH_4 and N_2O than for the Finishers and Gilts categories. These differences reflect the higher fibre digestion of the sows and the higher N-content in the diet of weaners compared to finishers and gilts (Table 11).

Estimated emissions per animal per year for each age category were multiplied by the time (years) in each category needed to produce one slaughtered finisher, and upscaled to an estimate of the total emission per age category for 1,572,021 slaughtered finishers in 2019 (Table 11). The sum of the estimated emission from animals and manure over all age categories was 46,836 669 kg CO_2 eq. which represents the contribution that can be attributed to the agricultural sector from pork production units in the total national GHG inventory for Norway.

The sensitivity tests revealed that the change in the FCR for finishers was the single most important of the investigated parameters to the

Table 8
Estimated pork GHG emission intensities, kg CO_2 eq. kg^{-1} CW, from finishers (CW_finishers) and sows (CW_sows) and weaners GHG emission intensities, kg CO_2 eq. kg^{-1} LW, for live 30 kg weaners (LW_Weaners), from 2014 to 2019, and for the one-thirds with lower, medium, and best performance in 2019; based on data from 925 Norwegian farms.

	Unit	2014	2015	2016	2017	2018	2019	Lower 1/3	Medium 1/3	Best 1/3
CW_finishers	kg CO_2 eq. kg^{-1} CW	2.49	2.45	2.41	2.37	2.35	2.34	2.56	2.36	2.16
CW_sows	kg CO_2 eq. kg^{-1} CW	2.53	2.38	2.41	2.40	2.36	2.47	2.39	2.48	2.50
LW_weaners	kg CO_2 eq. 30 kg^{-1} LW	58.5	56.9	56.1	53.2	53.1	51.9	57.5	53.0	49.1

Table 11

Estimated yearly emissions for 2019 of enteric CH_4, manure CH_4, and manure N_2O per animal in four categories of pigs: Sows, Gilts, Weaners and Finishers; the number of animals in the categories per finisher slaughtered based on the 2019 Ingris data, and national level estimates for enteric and manure emissions on the basis of the total number of 1 572 021 finishers registered slaughtered in 2019.

Category	Enteric CH_4, kg animal^{-1} year^{-1}	Manure CH_4, kg animal^{-1} year^{-1}	Manure N_2O, kg animal^{-1} year^{-1}	Animals_year Sl_finisher^{-1}	Animals_day Sl_finisher^{-1}	Total enteric and manure emissions, kg CO_2 eq.
Sows	3.64	1.83	0.138	0.038	13.9	10,674,142
Weaners	0.30	0.40	0.027	0.106	38.6	4,241,002
Finishers	1.20	1.097	0.087	0.235	85.9	30,877,980
Gilts	1.22	1.176	0.065	0.008	3.1	1,043,545
Total						46,836,669

Animals_year Sl_finisher^{-1} = the number of animals in each category calculated as the sum of days an individual animal is in the category divided by 365 and the number of finishers registered slaughtered Animals_day Sl_finisher^{-1} = the number of animals in each category calculated as the sum of days an individual animal is in the category divided by the number of finishers registered slaughtered.

Table 12

The effect of one standard deviation (STD) improvement in key production characteristics for the estimated GHG emissions intensities for pork produced at Norwegian farms reporting to the Ingris management system in 2019.

	Current values, 2019	STD	Estimated GHG emissions intensity, kg CO_2 eq. (kg CW)$^{-1}$	Change in estimated GHG emission intensity
FCR finisher, MJ_NE kg^{-1}	23.3	1.54	2.24	−4.5%
Weaned piglets sow^{-1} year^{-1}	27.9	3.78	2.30	−2.1%
FCR weaners, MJ_NE kg^{-1}	15.2	1.97	2.32	−1.4%
Mortality finishers,%	1.7	1.33	2.32	−1.3%
Feed intake per sow, MJ_NE day^{-1}	36.8	1.84	2.33	−0.9%
Mortality sows,%	11	8.64	2.34	−0.5%
Mortality weaners,%	1.1	1.13	2.35	−0.2%

LW = live weigt, ADG = average daily growth, FCR = feed conversion ratio, MJ_NE = Mega Joule net energy.

Table 13

Sensitivity test for expected changes and implemented effects in the model used for estimating effects of GHG emission of progress in genetics and management on greenhouse gas emissions intensities for Norwegian pork production.

Investigated factors and measures	Current value	New value	Results, kg CO_2 eq. (kg CW)$^{-1}$	Change
Expected changes:				
Global warming potential CH_4	25	34	2.439	3.9%
Manure storages under tight lid, abatement factor	57%	80%	2.346	−0.2%
Feed proportion of by-products increased to 15% (from 10%) MJ_NE kg DM^{-1}	0.053	0.050	2.244	−4.5%
Expected changes, overall			2.340	−0.4%
Resetting of implemented effects:				
Temperature correction manure storage	0.85	1	2.351	0.1%
Temperature correction animal building	0.93	1	2.353	0.1%
Crust formation in pig manure, EF direct, kg N_2O-N (kg N)$^{-1}$	0.002	0.005	2.427	3.4%
Resetting of implemented effects, overall			2.432	3.5%

estimate, and the change in the FCR contributed to a reduction of 4.5% of the estimated pork GHG emission intensity if changed by one standard deviation. The second most important parameter to the estimate, was Weaned piglets sow^{-1} year^{-1} with 2.1% lower estimated value. In descending order, the ranking in importance for one standard deviation change to the estimate was, from highest to lowest, FCR for weaners, mortality in finishers, feeds per sow, mortality in sows and mortality in weaners (Table 12).

The expected change in the assessment of the global warming potential (GWP) for CH_4 from 25 to 34 will increase the estimated emissions for 2019 to 2.439 kg CO_2 eq. kg^{-1} CW (Table 13), which is 3.9% higher than the current estimate. Further, the effect of having all manure stored indoors will reduce the estimated emissions by 0.2%. An expected increase in the use of by-products in feed from 10% to 15% of the energy concentration will reduce the estimated emissions by 4.5%. If all the expected changes occur simultaneously, the overall effect will be a 0.4% lower estimate for the emissions. A resetting of the implemented country and production specific factors revealed that the temperature correction factors had a very small effect, whereas the specific emission factor for no crust formation in pig manure had an effect of 3.4% (Table 13).

4. Discussion

The results from 15 studies presented by McAuliffe et al. (2017) demonstrated a decreasing trend in estimated GHG emissions intensity per kg pork for Western European pig production from 2005 to 2017. Similarly, this decrease over time in GHG emissions intensity was steady during the whole period from 2014 to 2019 for Norwegian pork production (Table 8). Compared to the most recent studies in the compilation presenting GHGs per kg CW, the studies of Reckmann and Krieter (2015) of 3.01 kg CO_2 eq. kg^{-1} CW, farm gate, *i.e.* excluding slaughtering, and McAuliffe (2017) of 3.2 kg CO_2 eq. kg^{-1} CW, also farm gate, showed higher estimated emissions than that of Norwegian pork (Table 8). The inclusion of 10% by-products in feed, with assessed zero-emissions, explains some of this difference, but also a continuous improvement in key production characteristics has contributed considerably to the lower emissions. The GHG emission estimate of Devers et al. (2012) for Flemish pork production, 2.03 kg CO_2 eq., kg^{-1} CW excluding slaughtering, was lower than that estimated for Norwegian pork in the current study, mainly because of the lower value for estimated GHG emissions from feed, 1.0 kg CO_2 eq. kg^{-1} CW, since almost 50% of Flemish pig feed consists of wheat or wheat by-products. The estimated emissions from feed in our investigation would have been close to 2.0 kg CO_2 eq. kg^{-1} CW if the 10% use of by-products was not included. This would have been equivalent to the values for feed used by Reckmann and Krieter (2015) and McAuliffe et al. (2017). The top ten studies cited by McAuliffe et al. (2017) had 1.85 CO_2 eq. per kg CW, which is close to the GHG emissions per kg feed including 10% by-product use (1.89 kg CO_2 eq. kg^{-1} CW) in our investigation.

However, when comparing our results with results from other studies it must be taken into consideration that there are differences both in representativeness and systems boundaries. A strength of our investigation is the large dataset of industry data that encompasses a range of years and facilitates an assessment of trends in productivity. Nevertheless, it might be that the progress could be somewhat overestimated as the data recorders also could be the farmers that most quickly adopt new practices.

A worldwide analysis of pig supply chains (MacLeod et al., 2013) predicted that GWP values for Western European systems were somewhere above 6 kg CO_2 eq. kg^{-1} CW, which is higher than that found in the current study and in most of the studies compiled by McAuliffe et al. (2017). As noted by McAuliffe et al. (2017), this discrepancy is largely attributable to the fact that MacLeod et al. (2013) fully included land use change (LUC) from soybean cultivation. However, the proportions of soya meal and corn gluten in the typical Norwegian concentrate feeds for sows and weaners are low, 5% and 9% (Table 4), respectively. For the concentrate feed for finishers neither soya nor corn gluten are added. Depending on calculation method, the LUC effects range from 0.564 to 5.272 kg CO_2 eq. kg^{-1} DM for soya and from 0 to 0.221 kg CO_2 eq. kg^{-1} DM for corn gluten (Mogensen et al., 2018), and taking into account the proportions of carcasses from sows and finishers, the inclusion of LUC effects in the GHG emissions estimates of pork carcasses results in a range from 2.38 to 2.68 kg CO_2 eq. kg^{-1} CW; *i.e.* 1.3 to 14% increase. There is an ongoing effort to further reduce, or even completely remove, soya meal from pig feed in Norway. This, in addition to the continuous improvement in Western European pig production systems, suggests that pork can be a valuable source of protein supply in sustainable food production. With the basis of the estimated GHG intensity of 2.35 kg CO_2 eq. kg^{-1} pork CW and an edible share of 0.87, the intensity will be 2.70 kg CO_2 eq. kg^{-1} pork meat without bones. Assuming 0.6 kg CO_2 eq. kg^{-1} for slaughter, rendering, meat processing per kg, the estimate will be 3.30 kg CO_2 eq. per kg pork meat, and with 19 g protein per kg pork meat this will result in 1.74 kg CO_2 eq. per 100 g protein. Compared to a range of food products, including vegetarian, presented by Oort and Andrew (2016), this is clearly in the lower part of GHG emission intensities per kg protein. Particularly, this is important for areas with a humid and cold climate with limited possibilities for growing high quality protein crops (*e.g.* Norway: Abrahamsen et al., 2019), making it possible also under such climatic conditions to contribute to reduce the pressure on the world's vulnerable natural areas by using local resources, as recommended by Mollier et al. (2017). Further, a lasting increase in the proportion of by-products used in feed for pigs contributes to maintain and perhaps increase the already high proportion of the global livestock's feed intake that consists of feed materials which are not currently edible for humans (Mottet et al., 2017). Animal welfare is part of agricultural sustainability, and Norway has a legislation for keeping of pigs that is stricter in terms of animal welfare than most other countries in the world (Norwegian Ministry of Agriculture and Food, 2004). The purpose of the legislation is to create the conditions for good health and well-being in pigs, and to ensure that the animals' natural needs are taken care of. Norway, as the only country in the world, has a requirement that male pigs have to be castrated by a veterinarian using local anaesthetics and long-acting painkillers. Tail docking has been banned in Norway for decades. Pigs at all ages must always have access to sufficient types of fibre rich material. There is a requirement tight floor with sawdust or similar material for sleeping areas. From year 2000 on, sows are to be loose housed during the entire gestation period; fixation, where the sows cannot turn, is not legal. Further it is specified that sows have to be loose in the farrowing pen, together with their piglets. Weaning of piglets is at an average age of 33 days and is not permitted before 28 days. In addition to this, the required space for pigs is 25% larger in Norway compared with the EU countries (EC Directive, 2008).

As in the current investigation (Table 12), Reckmann and Krieter (2015) identified FCR as the characteristic that most affected the GHG emissions per kg pork. The FCR used by the latter was 2.87 kg feed per kg LW for the finishing stage, with variation from 2.68 to 3.06 kg feed per kg LW. For the Flemish pig population of Devers et al. (2012), the FCR was 2.97 kg feed per kg LW. For a merged weaner and finishing stage, weaning to slaughter, McAuliffe et al. (2017) reported a FCR of 2.49 kg feed per kg LW for average herds, and 2.27 kg feed per kg LW for 10% best herds. Corresponding values for FCR in our study were 2.23 kg feed per kg LW for the period from weaning to slaughter and 2.41 kg feed per kg LW for the finisher period from 30 to 120 kg LW. These relatively higher feed efficiencies contribute to lower GHG emissions per kg pork. The relatively lower FCRs might be due to the fact that feed cost is high in Norway, such that farmers and the national breeding organisation have aimed at increasing feed efficiency in pig production for 60 years (Martinsen et al., 2016). It is noteworthy that the average FCR in the dataset from the 653 farms from 2019 in the current work is 16% better than the FCR reported for the Western European systems by MacLeod et al. (2013).

As the second most impacting production characteristic that affected the GHG emissions per kg pork, Reckmann and Krieter (2015) identified the number of live piglets per litter. The relative importance of the number of live piglets per litter corresponds with our results (Table 12). The average number of live piglets per litter in our study ranged from 13.2 in 2014 to 14.5 in 2019 (Table 5), which is close to that is reported in the comparable studies. In the study of McAuliffe et al. (2017), the number of liveborn piglets per litter was 13, and Reckmann and Krieter (2015) reported 13.7, with variation of the 10–90% quantiles from 11.1 to 16.3. A high number of weaned piglets per sows implies that the feed consumption of the sow is distributed to many offspring, thus meaning that piglet mortality will impact total feed efficiency. By comparing with recent pig production data from six countries in Europe, Norwegian pig production with 27.1 finishers per sow per year would have been ranked between 4th and 5th position of finishers produced per sow per year in the InterPig 2018 ranking (Hoste, 2020). The highest number was 32.1 finishers per sow per year in Denmark, and the lowest such number was 25.1 in Spain. However, regarding the total feed consumption for the system from farrow-to-finish divided by the total LW production of finishers, the total FCR of 2.65 kg feed per kg LW in 2019 in our study suggested that only one of the seventeen countries compared in InterPIG 2018 (Hoste, 2020) had better total feed efficiency than Norway.

The progress in the number of weaned piglets per sow per year with a total of 15% increase over five years (Table 5), is mainly the result of three factors: (1) using a new Yorkshire-breed in the hybrid sow, (2) genetic gain from the breeding programme and (3) general increased professionalism regarding management and feeding. A hybrid sow is normally a cross of two maternal breeds, and Landrace and Yorkshire are commonly used. In Norway, Norsvin Landrace have been bred for 60 years and used as a dam breed for the last 30. In the period from 2014 to 2019, a Nordic Yorkshire-breed in the hybrid sow has been replaced by the more fertile Topigs Norsvin Z-line Yorkshire dam breed (Lopes et al., 2017), which together with Norsvin Landrace form the new TN70 sow (Schild et al., 2020).

The grouping in lowest, medium, and best performing thirds of herds is based on profitability (Table 8). However, about 81% of the GHG emissions per kg CW comes from feed production, and on Norwegian pig farms about 75% of the variable costs comes from the feed (Flaten et al., 2005). Pigs are bred with the aim of obtaining the highest possible profit for the entire value chain, but even if the breeding goal had been to minimize the GHG emissions per kg pork produced, the direction of selection would probably have been similar (Knap, 2012; Shirali et al., 2012).

Ensuring healthy livestock is highlighted as important for minimizing GHG emissions from food production systems (Özkan et al., 2015). Norwegian pig farms are small, based on family farm units, and the pig production has higher health and higher requirements for animal welfare than in most other European countries (Falk and Hofshagen, 2020). While differences in health status contribute to the differences in

GHG emission intensities among the low, medium, and high productivity groups, the impact of health status on such intensities is most marked for farms following the SPF health regime (Table 9). The main difference between SPF and the conventional health regime is the absence of the bacteria APP in SPF herds. The largest effect is for the piglet and finisher age categories, with better FCR, ADG and lower mortality. Farms with SPF health status require better farm hygiene and biosecurity practices. Our understanding is that for the overwhelming majority of SPF farms, the motivation for joining this health regime was that the herd was affected by methicillin-resistant *Staphylococcus aureus* (MSRA) or other diseases. This indicates that the effect of SPF can be attributed to the health regime and not the farmer's skilfulness *per se*. Further effects of the SPF regime can be achieved if the genetic lag at herd level is avoided. Norwegian pig farms are too small to achieve efficient selection of hybrid sows at herd level, and as most SPF herds raise their own young gilts, the genetic lag is significant. A strategy for minimizing genetic lag is to obtain replacement gilts from a professional supplier, and when this approach is followed at the herd level, an even stronger reduction in GHG emissions per kg CW could be achieved.

There is a difference in growth efficiency between entire males and castrated males. Today, boars are often castrated to ensure meat quality without boar taint, which is caused by the substances androstenone and skatole. However, boar production is increasing globally, and methods are being developed to detect excessive levels of boar taint in individuals at the slaughter line. If carcasses with boar taint could be excluded there, the production of entire males would have had a strong positive impact on feed efficiency and thereby reduce the GHG emissions intensities (Table 9). Entire males grow faster, have better feed utilization and have a higher lean meat percentage compared to other categories (Xue et al., 1997; Pauly et al., 2009; Lundström et al., 2009; Quiniou et al., 2010). In addition to the boar taint, the challenges associated with boars are that the product quality may be poorer than in other categories and that the animals may have more male behavior towards other pen mates. However, for the GHG emissions intensities and for resource utilization in general, intact male production is highly favourable (Table 9).

The IPCC methodology used in the current work reflected the variation in production characteristics in the Ingris data on the estimated GHG emissions intensities. Thus, the algorithms used can form the base of a farm-level model for estimating GHG emissions from pig production units. Further, the results suggest that the GHG emissions estimated by 'HolosNorPork' on Ingris data can provide a reliable method for upscaling the contribution of GHG emissions from pig production to the agricultural sector at a national level, based on the number of animals registered at slaughter in Norway (Table 11). Of the changes investigated in the sensitivity analysis (Table 13), the expected increase in GWP for CH_4 is the one that will have the largest direct impact on estimated GHG emissions attributable to the agricultural sector, whereas the suggested measure of indoor storage of all manure would have only a minor impact. For the GHG emission intensities, the expected increase in the use of by-products for feed will reduce the emissions considerably. This measure will have an indirect effect on the estimate of the emissions from the agricultural sector as it will lower the need for growing feed crops. If the lower crust formation of pig manure was not taken into account, this would have increased both the estimated GHG emission intensities and the estimated emissions from the agricultural sector. The other changes investigated in this study would have only minor impacts.

In conclusion, the model 'HolosNorPork' presented in this study was able to estimate the effects on net GHG emissions intensity from pork production on the basis of key production characteristics from pig production units. The estimated GHG emission intensities of pork from finishers and sows, and from live weaners were found to have decreased throughout the investigated time period, and these trends are expected to continue as the effects of introduced measures were estimated to be profound. The investigated introduced measures for lowering the GWP of pork production include the continuing improvement in pig genetics, introduction of the SPF health regime, the finishing of boars and the use of by-products in feeds. This on-going progress in genetics and management in pig production systems will contribute to the strengthening of pork produced in Norway as a sustainable source for human protein supply.

Declaration of Competing Interest

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

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