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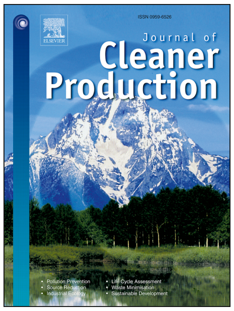

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Environmental impacts of pig production systems using European local breeds: the contribution of carbon sequestration and emissions from grazing

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ABSTRACT: Environmental assessment of pig production systems using local breeds remains poorly documented in the literature. So far, studies did not account for specificities of outdoor rearing which is quite common in such systems. The present study aimed at evaluating the environmental impacts of pig production systems using local breeds in Europe, while accounting for emissions associated to consumption of grass and mitigation of impacts through soil-C sequestration. Environmental impacts were estimated for 48 farms using local pig breeds: 25 in France (Gascon breed), eight in Italy (Mora Romagnola breed) and 15 in Slovenia (Krškopolje breed). Assessment was performed with and without accounting for pasture-intake emissions and potential soil-C sequestration. The data were obtained from on-farm surveys. Systems with Gascon pigs had the lowest impacts per kg of live weight for global warming and cumulative energy demand, due to lower impacts of feeds. Acidification potential was higher for Krškopolje pigs due to high dietary crude protein content and high AP of feeds, while eutrophication potential was higher for Gascon pigs due to higher phosphorus content of feeds (28% higher than the mean of the other farms). When impacts were expressed per ha of land use, pig production in Gascon farms had the lowest impacts due to more available area per pig, except for eutrophication. Low contribution of soil-C sequestration to climate change mitigation was observed (4.7% on average). However, it may have a substantial contribution for the most extensive pig systems using large land surfaces. Emissions resulting from grazing had a rather low contribution to Global Warming Potential (4%) and Eutrophication (3%), but a substantial one to Acidification impact (9% on average).

In the frame of our study, the contribution of emissions related to grazing is moderate because commercial feed supply for outdoor pigs was higher than in extensive systems studied in literature. This study highlighted that main hotspots include feed composition and supply and the origin of feed ingredients. It also suggests that future assessments of extensive pig systems relying on pig foraging on grasslands or rangelands should account for soil-C sequestration and emissions associated to grazing and foraging.

Keywords: autochthonous breeds, hotspots, life cycle assessment, pig

1. Introduction

Modern livestock production is considered one of the main contributors to anthropogenic-related environmental impacts (Steinfeld *et al.*, 2010). Among animal products, pig systems contribute to various impacts like climate change, eutrophication, acidification, and energy demand. Studies first estimated the environmental impacts linked to pig production (Basset-Mens et al. 2007; Dourmad et al. 2014; Noya et al., 2017). Then a large amount of literature was dedicated to the investigation of various mitigation strategies, such as the reduction of the crude protein content of feeds (Garcia-Launay et al., 2014), the substitution of soyben meal with locally grown sources of protein (van Zanten et al., 2018), the formulation of feeds with both enconomic and environmental objectives (MacKenzie et al. 2016; Garcia-Launay et al., 2018), the application of precision feeding (Andretta et al., 2018). Few authors focused their research on the comparison of conventional systems with alternative systems including organic or outdoor rearing systems (Basset-Mens and van der Werf, 2005; Halberg et al., 2010; Dourmad et al., 2014; Wiedeman et al., 2016). However, their studies focused either on organic systems with modern highly selected breeds or on indoor rearing systems on deep-litter.

Pig production systems relying on autochtonous (local) pig breeds gained interest for the society in the past 20 years due to positive perception of the society for their contribution to the preservation of biotic diversity and to the production of high-quality products, often dry-cured, with local and traditionnal forms of husbandry (Čandek-Potokar et al., 2019a; Muñoz et al., 2018). The breeds that belong to these systems are usually characterized by high fat deposition potential and low sow productivity (Čandek-Potokar et al., 2019b). Breeding and feeding practices and housing are highly variable in these systems, ranging from indoor on slatted-floor to outdoor housing for all physiological stages. Some of these local breeds and the associated systems are particularly untapped. Regarding environmental issue, only Dourmad et al. (2014) and Espagnol and Demartini (2014) estimated the impacts associated with traditionnal pig production systems relying on local pig breeds. Espagnol and Demartini (2014) highlighted strong variability of environmental impacts between farms in Corsican traditional production according to the feeding strategy. Such results support the use of individual farm data to investigate the practices which reduce environmental impacts of these systems (Rudolph et al., 2018).

Life Cycle Assessment (LCA), which is a highly recognized methodology (ISO 2006) for the assessment of environmental impacts of agricultural products, was extensively used in the above-mentioned literature. When focusing on either organic or traditional systems, studies were limited to the evaluation of average environmental impacts, and to the identification of hotspots. So far, these studies relied on methodologies developed for conventional systems. Meier et al. (2015) already underlined the lacking methodologies and models to properly assess the environmental impacts of organic systems, whatever the considered product. For some European traditional systems using local pig breeds, one of the specifities is outdoor rearing with consumption of natural resources (grass, acorns, chestnuts,…). Consequently, nutrient excretion in these systems do not only result from the difference between commercial feed consumption and body retention. Moreover, these systems also contribute to the maintenance of agro-ecosystems which are carbon sinks. Although remaining controversial (Garnett et al., 2017), some studies included the mitigation potential of soil-C sequestration (Nguyen et al. 2012; Salvador et al. 2017) in grass-based ruminant production. Neither Dourmad et al. (2014) nor Espagnol and Demartini (2014) accounted for nutrient excretion consecutive to natural resources intake or soil-C sequestration. Rudolph et al. (2018) compared environmental impacts in three husbandry systems for organic pig production (indoor, outdoor, partly outdoor) but did not include these processes in the perimeter of their LCAs.

Therefore, in the framework of the H2020 TREASURE project (Čandek-Potokar et al., 2019a), our ambition was to produce knowledge on the environmental impacts of untapped traditional pig production systems using local breeds in Europe while adressing the below mentioned issues:

- How including the specificities of these systems in the LCA methodology? i.e. accounting for nutrient excretion consecutive to the consumption of natural resources and for soil-C sequestration
- What are the hotspots for reduction of environmental impacts in these systems?

2. Materials and methods

2.1. Datasets

Environmental impacts of pig production chains based on European local pig breeds were estimated for 48 farms: 25 farms raised the Gascon breed in the Noir de Bigorre production chain in France (FR; these farms representing 42% of all farms in the production chain), eight farms raised Mora Romagnola pigs in Italy (IT; 26% of farms raising this breed) and 15 farms raised the Krškopolje breed in Slovenia (SI; 12% of farms raising this breed). The farms were classified as farrow-to-feeder (4 in FR, 1 in IT and 7 in SI), feeder-to-finish (10 in FR, 0 in IT and 4 in SI) and farrow-to-finish (11 in FR, 7 in IT and 4 in SI) farms. Piglets enter in the feeder system with an average BW of 9.3, 11.2 and 12.4 kg in FR, SL and IT, respectively (Table 1). The assessment was based on responses to surveys obtained through interviews with farmers and/or their employees. The survey was based on questions already used within the Q-PorkChains project (Dourmad *et al.*, 2014) related to animal performance, feed chemical composition, animal housing, and manure management.

2.2. Life cycle assessment: goal and scope definition

A cradle-to-farm-gate life cycle assessment (LCA) was conducted for each surveyed farm. The system boundaries were derived from Dourmad *et al.* (2014) and included the production of piglets (farrowing unit) as well as post-weaning and growing-finishing periods, land used to produce feed ingredients and raise pigs outdoors, production and transport of feed ingredients up to the feed factory, production of feeds on-farm and at the feed factory, and emissions from animals and manure storage (Figure 1). Functional units were 1 kg of live weight (LW) and 1 ha of land used (by crop production, buildings and pig production).

2.3. Life cycle inventory

Resource use and emissions associated with the production and delivery of inputs for crop production came from the ecoinvent database V3 (SimaPro LCA software 8.0, PRé Consultants, Amersfoort, The Netherlands). Energy use for lighting and heat lamps in farrowing units was calculated, but not the emissions and resources used to construct buildings or outdoor sheds. Veterinary and cleaning products were not included. For the feed ingredients that are coproducts (e.g. soybean meal, rapeseed meal, wheat bran, whey powder), resource use and emissions were economically allocated.

2.3.1. Production of feeds and feed ingredients

Feed composition was collected on farms from the labels on bags. The farmers provided information about the crude protein (CP) composition and total phosphorus (P) content of feed mixtures produced on-farm (Table 1). To further calculate nutrient contents of feeds produced on-farm, feed formulas and nutrient contents of feed ingredients provided in the INRA-AFZ feed tables (Sauvant *et al.*, 2004) were used.

Life cycle inventories (LCIs) of feed ingredients in France came from the EcoAlim dataset (Wilfart *et al.*, 2016), while LCIs for feed ingredients in Slovenia and Italy were adapted from it based on yields and fertilization rates in each country (Table A3; supplementary material). Additional processes were obtained from AgriFootPrint® database to include impacts of processing feed ingredients and to obtain a complete LCA of feed ingredients (Table A4; supplementary material). Feed ingredients that represented less than 0.5% of annual intake and that were absent from the EcoAlim dataset were not included in the LCI. Feed production at the feed factory was included in the LCIs of commercial feeds by assuming that it would occur in the same region as the pig production, and would require 41 kWh of electricity and 20.5 kWh of natural gas per t of feed produced, for grinding and pelleting (Garcia-Launay *et al.*, 2014). For on-farm feed production, grinding and mixing required 18 kWh of electricity per t of feed produced (Badouard and Roy, 2011).

2.3.2. Transport specifications

For grain, root and tuber crops, the mean distance from fields to farms (southwestern France, northern Italy and southeastern Slovenia) was calculated from survey data (100 km in FR, 93 km in IT and 10 km in SI). Products imported into all countries were assumed to be transported mainly by sea, followed by train and/or road (mean distance = 500 km).

2.3.3. Pig production

The performance of sows, post-weaning pigs and fattening pigs was obtained from surveys (Table 1). Nutrient (mainly N, P and potassium) excretion for each physiological stage was calculated as the difference between nutrient intake and retention. For growing animals, retention was calculated as the difference between body content at the beginning and at the end of a given period. For reproductive sows, the amounts retained in uterine contents during gestation and in the bodies of suckling piglets during lactation were also considered. Equations were adapted from the literature review of Rigolot *et al.* (2010a) to predict this retention, assuming a body lean tissue percentage at slaughter of 35% for Gascon breed (Sans *et al.*, 1996), 44 % for Krškopolje breed (Čandek-Potokar *et al.*, 2003; Furman *et al.*, 2010) and 39 % for Mora Romagnola breed (Fortina *et al.*, 2005).

For feeder-to-finish farms, we included the impacts related to piglet production by incorporating an average life cycle inventory (LCI) constructed from farrow-to-feeder farms surveyed in each system. Farrow-to-feeder farms have two outputs (culled sows/year and weaners/sow/year). The LCI incorporated the average kg of culled sows produced/piglet/year.

2.4. Life cycle impact assessment

2.4.1. Emissions from pig production

Emissions to the air were estimated separately for NH_3, N_2O, $NO_{x,}$ and CH_4 for sows, post-weaning piglets, fattening pigs, feed production, animal housing and manure management using SAS software (SAS Inst. Inc., Cary, NC, USA). Housing condition was accounted to calculate the gaseous emissions (Table 2). For the periods in which the animals were kept outdoors, NH_3, N_2O, NO_3 and NO_x emissions were calculated based on emission factors provided by Basset-Mens *et al.* (2007). For the periods during which the animals were kept indoors, gaseous N emissions were calculated for housing and storage and field application of solid manure using the step-by-step procedure recommended by EMEP/EEA (2016). Emission factors for NH_3 and N_2O came from Rigolot *et al.* (2010b) and Basset-Mens *et al.* (2007), for housing and storage of solid manure, respectively, from Dämmgen and Hutchings (2008) for NO_x, and from Nguyen *et al.* (2011) for NO_3. Solid manure composting on the farms that did so was also considered using emission factors provided by Paillat *et al.* (2005). Emissions following field application of solid manure were calculated according to EMEP/EEA (2016) for NH_3, IPCC (2006) for N_2O, and Nemecek and Kägi (2007) for NO_x.

2.4.2. Emissions from grazing

Mean grass intake was estimated as a function of concentrate intake (per kg LW) according to previous studies (Jensen and Anderse, 2002; Gustafson and Stern, 2003; Santos e Silva *et al.*, 2004; Bikker and Binnendjk, 2012). Grass intake (kg dry matter (DM)/kg LW/day) for pigs was estimated as 0.02558 – 0.83335 × concentrate intake (kg DM/kg LW/day) ($R^2 = 0.95$; Table A6 and Figure A1; supplementary material). For sows, grass intake (kg DM/kg LW/day) did not vary greatly as a function of concentrate intake (Rivera Ferre *et al.*, 2001); therefore, a mean value of 4.49 g DM/kg LW/day (Rivera Ferre *et al.*, 2001) was used. The equations were applied to each animal category on each farm.

The mean botanical composition of pastures was estimated based on expert knowledge in each country, and the nutrient composition was obtained from INRA (2010) (Supplementary material). Due to the lack of information on the nutrient digestibility of pig forage, mean digestibility coefficients of Sauvant *et al.* (2004) for dehydrated grass were used: CP digestibility of 46% and 59%, and organic matter (OM) digestibility of 43% and 51%, for pigs and sows, respectively. To consider potential uncertainty in these coefficients, a range around each mean was defined based on previous studies (Lindberg and Andersson, 1998; van der Peet-Schwering *et al.*, 2006; van Krimpen *et al.*, 2013), expressed as grass with high digestibility (+25% of the mean) or with low digestibility (-50% of the mean). Therefore, for emissions from grazing we obtained two different scenarios: grass intake of forages with high (HighD) and low (HighL) digestibility coefficient for CP and OM for pigs.

Consumption of acorns by finishing pigs' was not considered due to its low contribution to CP, crude fiber and crude fat intake (Rodríguez-Estévez *et al.*, 2012).

2.4.3. Potential carbon sequestration

Potential C sequestration was estimated for pastures but not for forests, because most studies indicate higher organic C content in pasture soils than in forest soils (Wei *et al.*, 2012). Thus, two methods were used to estimate C sequestration of permanent pastures, because estimates of the latter have high uncertainty and few reference values are available, giving scenarios of "low potential" and "high potential" of C sequestration.

The low potential scenario was based on Dollé *et al.* (2009), from measurements of soil C summarized by Arrouays *et al.* (2002). Since all three countries are part of continental Europe and have a temperate climate, the same mean sequestration rate of permanent pasture was applied to all farms: 730 kg of carbon dioxide (CO_2)-eq./ha/year (Nguyen *et al.*, 2012). The high potential scenario was based on the Food Climate Research Network report (Garnett *et al.*, 2017): 1,800 kg of CO_2-eq./ha/year.

2.4.4. Impact categories

The analysis was based on the CML 2001 (baseline) method V3.02 as implemented in SimaPro software V8.03 and added the following categories: land occupation from CML 2001 (all categories) V2.04 and total cumulative energy demand V1.8 (non-renewable fossil + nuclear). The CML method was chosen because it was used in most pig LCA studies in the literature, which allows for comparison of our results to previous results. Thus, potential impacts of pig production on global warming potential (GWP, kg CO_2-eq.; 100-year horizon), eutrophication potential (EP, g PO_4-eq.), acidification potential (AP, g SO_2-eq.), cumulative energy demand (CED, MJ), and land occupation (LO, m^2year) were assessed.

3. Results

3.1. Environmental impacts of pig production

Environmental impacts of the systems per kg of pig LW produced per year are presented in Table 3. Systems had large differences in impacts. Overall mean GWP was 7.19 kg CO_2-eq; mean GWP was highest in the IT and SI systems (9.35 and 7.16 kg CO_2-eq., respectively) and lowest (5.07 kg CO_2-eq.) in the FR system. Mean AP was highest in the SI system (49.0 g SO_2-eq.), lowest in the FR and IT systems (32.6 and 32.9 g SO_2-eq., respectively). Mean EP was highest in the FR system (46.9 g PO_4-eq.) and lowest in the SI and IT systems (39.5 and 35.5 g PO_4-eq., respectively). Mean CED was 32% and 8% higher in the SI system than in those the FR and IT systems, respectively (Table 3). Mean LO was highest in the FR and SI systems (11.0 and 10.9 m^2.year) and lowest in the IT system (7.55 m^2year).

When expressed per ha of land used, the IT system had the highest impacts in almost all categories (Table 3). Overall mean GWP was 8,070 kg CO_2-eq., with the highest mean GWP (12411 kg CO_2-eq.) in the IT system and the lowest (4,679 kg CO_2-eq.) in the FR system. Mean AP in the SI system was 33% and 4% higher than in the FR and IT systems, respectively (Table 3). Mean CED was 49% and 20% higher in the IT system than those in the FR and SI systems, respectively (Table 3). The overall mean amount of LW produced per ha land used (Table 3) was 1,151 kg/ha, with the highest mean amount in the IT system (1,336 kg/ha) and the lowest in the FR system (944 kg/ha).

3.2.Effect of carbon sequestration and emissions resulting from grazing

When considering only potential C sequestration of the soil, GWP decreased in all systems, especially in FR. Mean GWP in the FR, SI and IT systems decreased by 5%, 2% and 1%, respectively, in the low potential sequestration scenario. In the high potential sequestration scenario, mean GWP in the FR, SI and IT systems decreased by 12%, 5% and 3%, respectively (Table 4), with the IT system having the highest mean GWP.

Conversely, when considering emissions resulting from grass intake and subsequent N and OM excretions by the animals, mean GWP in the FR, SI and IT systems increased by 5%, 2% and 4%, respectively, for grass with low digestibility, and 5%, 2% and 4%, respectively, for grass with high digestibility (Table 4). Mean AP in the FR, SI and IT systems increased by 12%, 6% and 18%, respectively, for grass with low digestibility and 7%, 3% and 10%, respectively, for grass with high digestibility (Table 4). Mean EP in the FR, SI and IT systems increased by 3%, 2% and 5%, respectively, for grass with low digestibility and 1%, 1% and 3%, respectively, for grass with high digestibility (Table 4).

4. Discussion

4.1. Environmental impacts of pig production

GWP estimated in the present study (5.07-9.35 kg CO_2-eq/kg LW) were higher than those estimated by Espagnol and Demartini (2014) for outdoor pig production in Corsica (3.03-4.09 kg CO2-eq/kg LW) and those obtained by Dourmad *et al.* (2014) for traditional pig production (mean = 3.47 kg CO_2-eq/kg LW). Fattening pigs in the present study were slaughtered at a mean weight of 170 kg, whereas slaughter weights ranged from 110-140 kg in previous studies. Additionally, the longer fattening period in the present study (mean age at slaughter of 415 days) induced higher enteric fermentation and OM excreted per pig, both of which contribute to CH_4 emissions (Rigolot *et al.*, 2010a). Since CH_4 is 25 times as potent as CO_2 in trapping heat in the atmosphere (Guinée *et al.*, 2002), higher GWP of local pig breeds was expected. Additionally, the higher feed supply required for local breeds increased the impact. As previously reported for traditional systems, feed production and intake can represent 65-75% of GWP (Dourmad *et al.*, 2014).

The higher AP of the SI system was due to the high NH_3, N_2O and NO_x emissions from sows and fattening pigs in four farms, due to the higher CP content of its feeds resulting in higher N excretion and due to higher AP impacts of feeds in SI system. These four farms are the reason why there is a much higher standard deviation in AP values for SI system in comparison with the FR and IT systems (Table 3). The same trend was predicted for dietary P and EP. For all animal categories, the FR system had the highest P content in feeds, which resulted in greater P excretion than those in the other systems.

The range of AP for FR and IT systems (32.6-32.9 g SO_2-eq.) was lower than values calculated by Dourmad *et al.* (2014) (54 g SO_2-eq./kg LW) and Espagnol and Demartini (2014) (39-52 g SO_2-eq.). This difference could be due to the higher CP in the diets in the previous studies. The range of EP in the present study (35.5-46.9 g PO_4-eq.), however, is slightly higher than the mean EP calculated by Dourmad *et al.* (2014) (34 g PO_4-eq./kg LW) for traditional pig production.

The higher CED predicted in the IT and SI systems than in the FR system was due to the high CED of feeds in the IT system and the high feed supply in some farms from SI system. According to Garcia-Launay *et al.* (2014), feed production accounts for more than

75% of CED, meaning that the impact of feed and the feed supply are the main drivers of CED impact. IT system feeds had high CED because soybean meal was included in almost all of its diets. The LCI assumed that soybean was imported mainly from Brazil, since Europe is the world’s second largest importer of soybeans (USDA, 2017). Indeed, the high impact of soybean meal on CED is associated to both deforestation and high transportation demand (both road and across the ocean). Previous research showed that reducing the content of Brazilian soybean meal in diets could reduce CED, regardless of the pig production context considered in the LCA (Kebreab *et al.*, 2016; Monteiro *et al.*, 2016).

The FR system had the highest LO among systems due to the high LO of its feeds and because its fattening pigs and most of its gestating sows were raised outdoors (Table 2 and Table A4; supplementary material). According to Dourmad *et al.* (2014), outdoor fattening of pigs contributes almost 50% of the LO per kg LW. Even though pigs are raised outdoors in some farms of the SI and IT systems, the Protected Designation of Origin label in the FR system ensures a minimum area of pasture for each pig (500 m^2).

Having more area available for pigs in the FR system is one reason it had the lowest impacts per ha of land used (except EU). The same effect of the functional unit on results was reported by Basset-Mens and van der Werf (2005) and Dourmad *et al.* (2014) for traditional pig production, which uses land for grazing and has a low stocking density.

Mean GWP per ha of land used predicted in the present study (8,070 kg CO_2-eq./ha) was higher than those predicted by Basset-Mens and van der Werf (2005) for the *Label Rouge* quality label (5,510 kg CO_2-eq./ha) and Dourmad *et al.* (2014) for a traditional system (3,672 kg CO_2-eq./ha). Conversely, mean AP in the present study (39,836 g SO_2-eq./ha) lay close to that predicted by Basset-Mens and van der Werf (2005) of 36,000 SO_2-eq., although the EP (42,518 g PO_4-eq./ha) and CED (34,685 MJ-eq./ha) in the present study were higher than those they predicted (29,300 g PO_4-eq. and 28,503 MJ per ha, respectively).

Mean kg of pig LW produced per ha in the present study in the SI (1,173 kg LW/ha) and IT (1,336 kg LW/ha) systems were similar to those predicted by Basset-Mens and van der Werf (2005) (1,592 kg LW/ha) and Dourmad *et al.* (2014) (1,229 kg LW/ha). The mean of the FR system (944.4 kg LW/ha), however, was much lower than those previously predicted. This result agreed with the low stocking density (> 500 m^2/pig) in the FR system, which was even lower than that in the *Label Rouge* quality label system (2.6 m^2 per pig) (Halberg *et al.*, 2005).

4.2. Effect of carbon sequestration and emissions resulting from grazing

The decrease in GWP per kg LW among the systems when C sequestration in pasture was included was a result of removing CO_2 from the atmosphere and incorporating it into the terrestrial pool via plants growing in the soil (Garnett *et al.*, 2017). Similar results were reported by Halberg *et al.* (2010), who found that C sequestration decreased GWP by 0.40-0.60 kg CO_2-eq. per kg LW in organic pig production. Similarly, in the present study this decrease ranged from 0.24-0.59 kg CO_2-eq. per kg LW in the FR system (highest effect) to 0.12-0.28 kg CO_2-eq. per kg LW in the IT system (lowest effect), indicating that C sequestration has more effect in extensive systems with low stocking density, and can vary greatly according to the factor used (high or low potential C sequestration). Accounting for soil carbon sequestration in LCA of animal production systems is controversial (Garnett *et al.*, 2017) and mainly applied in grass-based cattle systems (Stanley *et al.*, 2018). Moreover, for temperate grassland, values reported in literature range from 200 kg C/ha/year (Nguyen *et al.*, 2012) up to 3590 C/ha/year (Stanley *et al.*, 2018) obtained for rotational grazing systems. In this study, conservative hypotheses have been used with 200 and 490 kg C/ha/year for low and high soil carbon sequestrations scenario, respectively. So, the low contribution of soil carbon sequestration to climate change mitigation can be explained by such hypotheses. Better knowledge of soil carbon sequestration by temperate grassland would improve the quality of assessment of animal production systems relying on grazing and foraging. This is particularly important for systems using large surfaces. In our study, the system with highest proportion of outdoor rearing (French system) is characterized by land occupation impact of 11m².year per kg BW which is much higher than values obtained in conventional systems but still much lower than land occupation impact per kg BW for grass-based cattle systems (Stanley *et al.*, 2018). However, some European extensive systems use much larger areas as reported by Gaspar *et al*. (2007) for Iberian pigs in dehesa (maximum stocking rate of 1 pig per ha).

Therefore, when considering pig production systems with low land occupation related to grazing and foraging, contribution of soil carbon sequestration can be considered negligible. However, when assessing extensive pig production systems this contribution has to be accounted for, even more when comparing indoor and outdoor systems.

When emissions from grazing were considered, GWP, AP and EP increased in all systems, with larger increases in the IT system. As previously mentioned, grass intake was calculated as a function of feed intake; thus, farms with the lowest feed supply (such as IT) would have the highest grass intake and, consequently, more emissions because of it. From results obtained in Tables 3 and 4, contribution of emissions related to grazing to GWP, AP and EP impacts were calculated. For all systems and scenarios of grass digestibility, contribution ranged from 2.1% to 4.7% for GWP, 1.1% to 5.3% for EP, and 3.0% to 17.5% for AP. Therefore, the contribution was rather low for GWP and EP, but substantial for AP impact. This resulted from the application of emission factors for outdoor pigs from Basset-Mens et al. (2007) but it is noteworthy that very few information on these emission factors is available in the literature. Contribution of emissions related to grazing is not negligible but quite uncertain because of lack of knowledge. In the frame of our study, the contribution of emissions related to grazing is moderate because in the systems considered commercial feed supply for outdoor pigs is higher than in extensive systems studied in literature. Indeed, in FR, SI and IT systems investigated, the average commercial feed supply ranged from 620 to 908 kg/fattening pig/year on average whereas Espagnol and Demartini (2014) reported for the most extensive Corsican pig systems a commercial feed supply lower than 200 kg/fattening pig/year. Therefore, for extensive systems, particularly when comparing systems with various levels of feed supply, accounting for the emissions associated to grazing is relevant. Moreover, when evaluating practices aiming at mitigating environmental impacts through the utilization of natural resources, this is important to include all the consequences of these different practices into the assessment (when pigs ingest and utilize grass and/or acorns they need less concentrate per kg weight gain). Ignoring the emissions resulting from grazing pigs may lead to wrong conclusions on different systems or strategies.

The lower AP and EP potentials when considering grass with high digestibility, than when considering grass with low digestibility, were due to pigs' slightly lower N excretion, resulting in lower N emissions. Conversely, grass with high digestibility increased the GWP. This was influenced by the amount of CH_4 produced via enteric fermentation, which varies according to the amount of digestible fiber ingested (Rigolot *et al.*, 2010a): the more digestible fiber ingested, the higher the CH_4 emissions. This seems to indicate that grass with high digestibility in outdoor pig production could reduce AP and EP of this system; however, it increases CH_4 emissions, which increases GWP at the farm gate.

Estimating C sequestration is challenging, given the large variation in its estimates among publications according to the chosen method. This highlights the need for additional studies to describe this potential more adequately, especially in agricultural soils. Even though we considered effects of C sequestration and emissions from grazing in the present study, there is a lack of references on these topics, and determining their parameters is highly complex. We used two extreme values of potential C sequestration but did not consider soil tillage/land management practices, climate variability, cultivation techniques, vegetation type, or N content of the soil. These factors may influence the conversion of OM into stable below-ground C, i.e. potential C sequestration (Garnett *et al.*, 2017).

Another methodological concern is the digestibility of grass for pigs. Since GWP, AP and EP varied according to the digestibility of grass, determining the digestibility of grass for pigs more accurately is critical to quantify the emissions caused by grazing, mainly for pig production in outdoor or organic systems. Although grass is a common ingredient in organic pig production, its digestibility varies greatly among studies, grass species and grass stages. Few studies on this topic exist, which makes it difficult to accurately estimate grass digestibility for pigs. More accurate estimates of grass digestibility and C sequestration could reduce uncertainties associated with LCA of outdoor pig production and provide more precise estimates of environmental impact.

4.3. Hotspots for improvement

For animal performance, farms with high feed supply or poor FCR generally tended to have the highest impacts per kg LW, because environmental impacts depend greatly on feed intake and were expressed per kg LW. The feed supply seems high, given that pigs were raised outdoors (in FR) with access to grazing and consumed acorns and/or chestnuts in autumn period. Hodgkinson *et al.* (2017) observed that wild boar and domestic pigs obtained 20% and 7%, respectively, of their total daily intake of dietary energy from grazing. This seems to indicate that outdoor pigs could also obtain a considerable portion of nutritional requirements from grazing, which reduces the need for a high feed supply, given their lower amino acid requirements. For digestible lysine (from 40 to 100 kg of BW), for example, it was demonstrated that European local breeds have an average requirement between 5.2 and 12.8 g/d (Brossard *et al.*, 2019), much lower than the 14.8 and 16.9 g/d reported for genetically improved pig breeds (NRC, 2012). This can be explained by the low potential for protein deposition of local pig breeds (Barea *et al.,* 2007). After a certain LW, extra nutrient and energy intake is deposited into non-lean carcass tissue (de Greef and Verstegen, 1993, van Milgen and Noblet, 2003), which suggests that local breeds did not use the extra CP and L-lysine for protein deposition. It was recently demonstrated that in European local breeds, only a small proportion of total body energy retention is dedicated to protein deposition (between 0.97 and 2.77 MJ/d); the greatest proportion (between 9.22 and 16.88 MJ/d) is in the form of lipids (Brossard *et al.*, 2019). However, as in some situations and for some impact categories such as GWP, the reduction on dietary CP does not reduce the impact (Monteiro *et al.*, 2016), it could be explored the use of co-products. The use of meat meal in pig diets increased the dietary CP compared to a control feed based on maize and soybean meal (147 vs. 133g CP/kg, respectively), and consequently increase AC and EP by 7% and 10%, respectively (Mackenzie *et al.*, 2016). However, it decreased simultaneously by 2% the GWP per kg of pig carcass.

Other options have been investigated in literature to reduce environmental impacts such as the replacement of imported feedstuffs by locally produced or local natural resources. Indeed, van Zanten *et al.* (2018) showed that the replacement of imported protein sources such as soybean for locally produced rapeseed meal can decrease the impact of pig production in 14% on land occupation, and in 3% on GWP. Espagnol and Demartini (2014) demonstrated that using natural feed resources (acorns and chestnuts) in extensive systems may reduce environmental impacts per kg LW.

5. Conclusions

This study provides one of the first life cycle assessment of traditional pig production systems using local breeds in Europe. The impacts per kilogram of live weight in the systems investigated in this study were in the upper limit of the range of values reported in literature for pig production. To our knowledge, it addresses for the first time the effect of emissions associated to the consumption of natural resources available on grasslands on the level of the environmental impacts. It is also one of the only articles accounting for soil carbon sequestration in the assessment of pig production systems with outdoor rearing.

This study supports the following recommendations. Soil carbon sequestration should be accounted for when assessing pig systems with large foraging area dedicated to pigs. Emissions associated to grazing should be included in the perimeter of the assessment when natural resources have a significant contribution to the coverage of nutritional requirements. Both these recommendations should be particularly applied when comparing contrasted systems (e.g. indoor feed-based *vs*. outdoor natural resources-based).

The findings of this study have two practical applications. Environmental impacts of these systems may be mitigated by reducing feed amino acids and crude protein contents of feeds in accordance with the low nutritional requirements of local breeds. Better knowledge on nutrients contents and digestibility of fresh grass and acorns in pigs is needed for better management of these systems, and more precise assessment of the emission associated to their consumption. Further investigation should improve the estimation of the potential of soil carbon sequestration to mitigate climate change impact of these systems.

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Table 1. Performance of sows, post-weaning pigs and fattening pigs, and the average diet composition among the local pig production systems studied.

	France		Slovenia		Italy	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
Number of farms						
Farrow-to-feeder	4		7		1	
Feeder-to-finish	10		4		0	
Farrow-to-finish	11		4		7	
Number of sows/farm[1]	30	11.4	10	5.8	17	16.7
Number of fattening pigs/farm	252	119.7	81	51.9	267	275.8
Sows						
Weaned/year, number	13.1	2.97	12.6	3.56	12.9	2.09
Weaning weight, kg	9.3	1.80	11.2	2.40	12.4	1.47
Age at weaning, days	36.3	4.29	51.9	8.84	43.1	11.9
Feed supply, kg/sow/year	1,262	119.2	1,637	269.7	1,120	108.8
Feed composition						
CP, g/kg	128	13.3	116	19.0	147	16.3
Total P, g/kg	4.7	0.78	3.4	1.31	3.6	0.13
Estimated grass intake (kg/sow/year)	173	23.3	160	56.6	23.3	6.39
Post-weaning						
Final BW, kg	40	11.4	29	1.3	30	0.0
Days in weaner system	87	25.7	65	28.1	66	7.8
Mortality rate, %	4.7	2.82	1.3	0.25	20	11.4
FCR, kg/kg	2.49	0.761	3.47	0.849	3.02	0.853
Feed composition						
CP, g/kg	160	22.3	144	43.7	141	10.7
Total P, g/kg	5.3	0.97	3.4	1.52	3.7	0.37
Estimated grass intake (kg/piglet/year)	0.00	0.00	11.5	0.00	3.37	1.41
Fattening pigs						
Slaughter LW, kg	174	5.7	164	14.6	167	6.1
Age at slaughter, days	415	17.4	404	62.0	451	9.4
Mortality rate, %	1.4	0.66	6.0	1.00	7.0	4.00
FCR, kg/kg	6.04	0.784	4.66	1.660	4.99	0.010

Feed composition						
CP, g/kg	126	13.3	142	24.5	158	7.1
Total P, g/kg	4.9	1.12	3.1	1.39	4.2	0.58
Estimated grass intake (kg/pig/year)	147	104	185	123	591	122

[1] For farms with sows.

s.d., standard deviation; CP, dietary crude protein; P, total phosphorus content; LW, body weight; FCR, feed-conversion ratio.

679 **Table 2.** Frequency (%) of housing conditions on farms studied in each local pig production 680 system.

	France	Slovenia	Italy
Gestating sows			
Housing			
Indoor	0.0	37.5	54.5
Outdoor	93.3	12.5	18.2
Indoor with outdoor access	6.7	50.0	27.3
Floor (when indoors)			
Slatted or concrete floor	0.0	42.9	33.3
Deep litter	100	57.1	66.7
Lactating sows			
Housing			
Indoor	86.7	100	90.9
Outdoor	6.7	0.0	9.1
Indoor with outdoor access	6.7	0.0	0.0
Floor (when indoors)			
Slatted or concrete floor	7.2	100	40.0
Deep litter	85.7	0.0	60.0
Concrete and deep litter	7.2	0.0	0.0
Weaner pigs			
Housing			
Indoor	100	57.1	78.6
Outdoor	0.0	14.3	7.1
Indoor with outdoor access	0.0	28.6	14.3
Floor (when indoors)			
Slatted or concrete floor	0.0	100	42.9
Deep litter	100	0.0	57.1
Fattening pigs			
Housing			
Indoor	0.0	71.4	58.3
Outdoor	100	28.6	16.7
Indoor with outdoor access	0.0	0.0	25.0

Floor (when indoors)			
Slatted or concrete floor	0.0	60.0	50.0
Deep litter	0.0	40.0	50.0

Table 3. Potential environmental impacts per kg of live weight (LW) and per ha of land used in each local pig production system

	France		Slovenia		Italy	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
Number of farms[1]	21		9		7	
Per kg LW						
GWP, kg CO_2-eq.	5.07	0.791	6.94	2.53	9.35	3.92
AP, g SO_2-eq.	32.6	4.21	47.3	21.1	32.9	2.73
EP, g PO_4-eq.	46.9	7.49	37.9	15.7	35.5	6.17
CED, MJ	24.7	4.12	35.6	13.0	33.7	4.49
LO, m^2year	11.0	1.88	10.4	5.03	7.55	0.713
Per ha of land used[2]						
GWP, kg CO_2-eq.	4,679	573.3	7,119.9	1,851.3	12,441	5,142.0
AP, g SO_2-eq.	30,276	4,329.2	45,519	8,560.0	43,714	2,243.2
EP, g PO_4-eq.	43,055	3,245.6	37,442	6,186.0	47,058	7,544.8
CED, MJ	22,830	3,259.0	36,174	10,194	45,052	7,920.4
kg of LW produced	944.4	208.0	1,183	606.5	1,336	133.7

s.d., standard deviation; LW, live weight; GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; CED, cumulative energy demand; LO, land occupation.

[1] For farrow-to-finish and feeder-to-finish farms.

[2] For each farm, the impact was calculated as: [10,000 m^2 (1 ha) * Impact per kg of LW] / LO per kg of LW (m^2year). LO per kg LW and LW produced per ha used include off-farm and on-farm LO.

Table 4. Potential environmental impacts expressed per kg of pig live weight produced in each local pig production system according to carbon (C) sequestration and grass digestibility scenarios

	France		Slovenia		Italy	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
Number of farms[1]	21		9		7	
GWP, kg CO$_2$-eq.						
Low potential C sequestration	4.83	0.790	6.79	2.481	9.23	3.921
High potential C sequestration	4.48	0.796	6.58	2.436	9.07	3.919
High digestibility of grass (High$_D$)[2]	5.32	0.734	7.09	2.474	9.73	3.663
Low digestibility of grass (Low$_D$)	5.31	0.718	7.09	2.472	9.73	3.661
AP, g SO$_2$-eq.						
High digestibility of grass (High$_D$)	35.0	3.58	48.8	20.4	36.7	4.77
Low digestibility of grass (Low$_D$)	36.9	3.59	50.1	20.0	39.9	8.50
EP, g PO$_4$-eq.						
High digestibility of grass (High$_D$)	47.6	7.28	38.3	15.6	36.6	7.29
Low digestibility of grass (Low$_D$)	48.2	7.07	38.7	15.6	37.5	8.28

s.d., standard deviation; GWP, global warming potential; AP, acidification potential; EP, eutrophication potential.

[1] For farrow-to-finish and feeder-to-finish farms.

[2] This scenario considers grass intake with high (High$_D$) and low (High$_L$) digestibility coefficients for CP and OM for pigs and the subsequent excretion of N and OM.

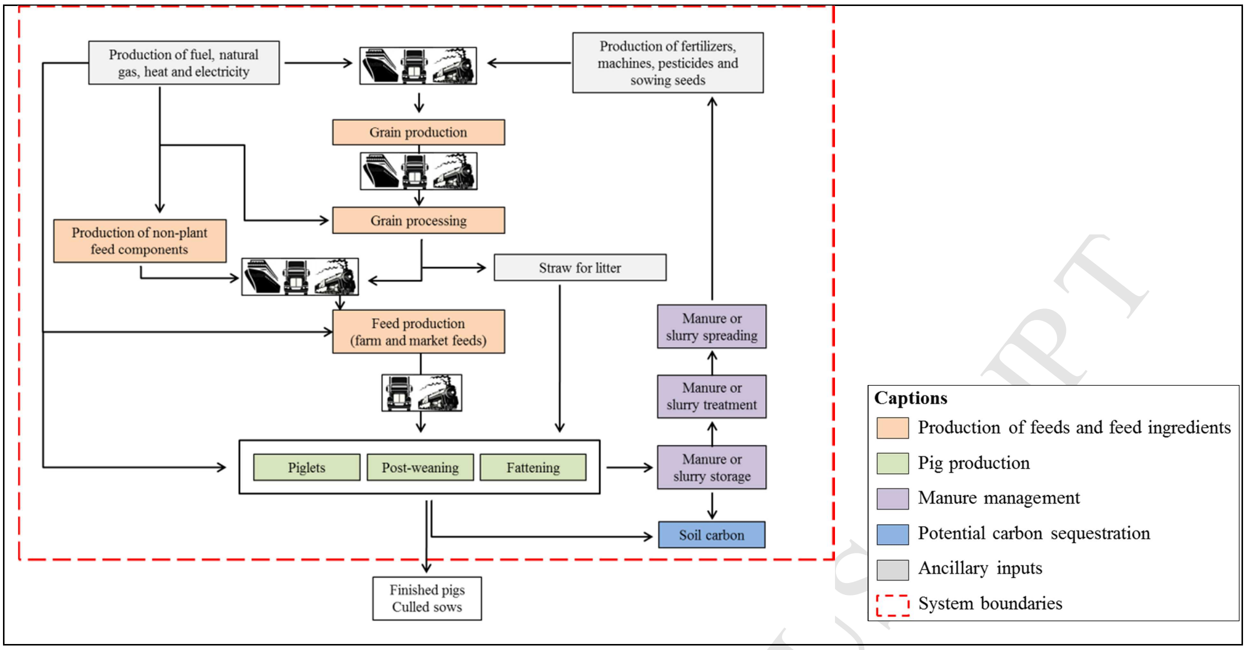

Figure 1. System boundaries for local pig breeds in France, Slovenia and Italy, with main processes used to produce crop inputs, crops, feed ingredients and feeds, and pig production.

Highlights

- Grazing emissions and potential carbon sequestration were estimated.
- Farms had great variability in environmental impacts.
- Systems relying the most directly on natural resources had the lowest impacts.
- Outdoor systems can reduce CO_2 emissions by sequestering carbon.
- Feed composition, supply and feedstuffs origin are hotspots for improvement.