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# Accepted Manuscript

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

Alessandra Nardina Trícia Rigo Monteiro, Aurélie Wilfart, Valerio Joe Utzeri, Nina Batorek Lukač, Urška Tomažin, Leonardo Nanni Costa, Marjeta Čandek-Potokar, Luca Fontanesi, Florence Garcia-Launay

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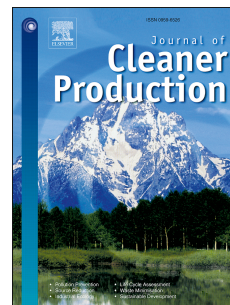
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1 **Environmental impacts of pig production systems using European local breeds: the**  
2 **contribution of carbon sequestration and emissions from grazing**

3  
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14  
15 **ABSTRACT:** Environmental assessment of pig production systems using local breeds  
16 remains poorly documented in the literature. So far, studies did not account for specificities of  
17 outdoor rearing which is quite common in such systems. The present study aimed at  
18 evaluating the environmental impacts of pig production systems using local breeds in Europe,  
19 while accounting for emissions associated to consumption of grass and mitigation of impacts  
20 through soil-C sequestration. Environmental impacts were estimated for 48 farms using local  
21 pig breeds: 25 in France (Gascon breed), eight in Italy (Mora Romagnola breed) and 15 in  
22 Slovenia (Krškopolje breed). Assessment was performed with and without accounting for  
23 pasture-intake emissions and potential soil-C sequestration. The data were obtained from on-  
24 farm surveys. Systems with Gascon pigs had the lowest impacts per kg of live weight for  
25 global warming and cumulative energy demand, due to lower impacts of feeds. Acidification  
26 potential was higher for Krškopolje pigs due to high dietary crude protein content and high  
27 AP of feeds, while eutrophication potential was higher for Gascon pigs due to higher  
28 phosphorus content of feeds (28% higher than the mean of the other farms). When impacts  
29 were expressed per ha of land use, pig production in Gascon farms had the lowest impacts due  
30 to more available area per pig, except for eutrophication. Low contribution of soil-C  
31 sequestration to climate change mitigation was observed (4.7% on average). However, it may  
32 have a substantial contribution for the most extensive pig systems using large land surfaces.  
33 Emissions resulting from grazing had a rather low contribution to Global Warming Potential  
34 (4%) and Eutrophication (3%), but a substantial one to Acidification impact (9% on average).

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

41

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

43

## 44 1. Introduction

45 Modern livestock production is considered one of the main contributors to  
46 anthropogenic-related environmental impacts (Steinfeld *et al.*, 2010). Among animal  
47 products, pig systems contribute to various impacts like climate change, eutrophication,  
48 acidification, and energy demand. Studies first estimated the environmental impacts linked to  
49 pig production (Basset-Mens *et al.* 2007; Dourmad *et al.* 2014; Noya *et al.*, 2017). Then a  
50 large amount of literature was dedicated to the investigation of various mitigation strategies,  
51 such as the reduction of the crude protein content of feeds (Garcia-Launay *et al.*, 2014), the  
52 substitution of soybean meal with locally grown sources of protein (van Zanten *et al.*, 2018),  
53 the formulation of feeds with both economic and environmental objectives (MacKenzie *et al.*  
54 2016; Garcia-Launay *et al.*, 2018), the application of precision feeding (Andretta *et al.*, 2018).  
55 Few authors focused their research on the comparison of conventional systems with  
56 alternative systems including organic or outdoor rearing systems (Basset-Mens and van der  
57 Werf, 2005; Halberg *et al.*, 2010; Dourmad *et al.*, 2014; Wiedeman *et al.*, 2016). However,  
58 their studies focused either on organic systems with modern highly selected breeds or on  
59 indoor rearing systems on deep-litter.

60 Pig production systems relying on autochthonous (local) pig breeds gained interest for  
61 the society in the past 20 years due to positive perception of the society for their contribution  
62 to the preservation of biotic diversity and to the production of high-quality products, often  
63 dry-cured, with local and traditional forms of husbandry (Čandek-Potokar *et al.*, 2019a;  
64 Muñoz *et al.*, 2018). The breeds that belong to these systems are usually characterized by high  
65 fat deposition potential and low sow productivity (Čandek-Potokar *et al.*, 2019b). Breeding  
66 and feeding practices and housing are highly variable in these systems, ranging from indoor  
67 on slatted-floor to outdoor housing for all physiological stages. Some of these local breeds

68 and the associated systems are particularly untapped. Regarding environmental issue, only  
69 Dourmad et al. (2014) and Espagnol and Demartini (2014) estimated the impacts associated  
70 with traditional pig production systems relying on local pig breeds. Espagnol and Demartini  
71 (2014) highlighted strong variability of environmental impacts between farms in Corsican  
72 traditional production according to the feeding strategy. Such results support the use of  
73 individual farm data to investigate the practices which reduce environmental impacts of these  
74 systems (Rudolph et al., 2018).

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

94 Therefore, in the framework of the H2020 TREASURE project (Čandek-Potokar et al.,  
95 2019a), our ambition was to produce knowledge on the environmental impacts of untapped  
96 traditional pig production systems using local breeds in Europe while addressing the below  
97 mentioned issues:

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

102

## 103 **2. Materials and methods**

### 104 **2.1. Datasets**

105 Environmental impacts of pig production chains based on European local pig breeds  
106 were estimated for 48 farms: 25 farms raised the Gascon breed in the Noir de Bigorre  
107 production chain in France (FR; these farms representing 42% of all farms in the production  
108 chain), eight farms raised Mora Romagnola pigs in Italy (IT; 26% of farms raising this breed)  
109 and 15 farms raised the Krškopolje breed in Slovenia (SI; 12% of farms raising this breed).  
110 The farms were classified as farrow-to-feeder (4 in FR, 1 in IT and 7 in SI), feeder-to-finish  
111 (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.  
112 Piglets enter in the feeder system with an average BW of 9.3, 11.2 and 12.4 kg in FR, SI and  
113 IT, respectively (Table 1). The assessment was based on responses to surveys obtained  
114 through interviews with farmers and/or their employees. The survey was based on questions  
115 already used within the Q-PorkChains project (Dourmad *et al.*, 2014) related to animal  
116 performance, feed chemical composition, animal housing, and manure management.

117

### 118 **2.2. Life cycle assessment: goal and scope definition**

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

126

### 127 **2.3. Life cycle inventory**

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

### 135 2.3.1. *Production of feeds and feed ingredients*

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

141 Life cycle inventories (LCIs) of feed ingredients in France came from the EcoAlim  
142 dataset (Wilfart *et al.*, 2016), while LCIs for feed ingredients in Slovenia and Italy were  
143 adapted from it based on yields and fertilization rates in each country (Table A3;  
144 supplementary material). Additional processes were obtained from AgriFootPrint® database  
145 to include impacts of processing feed ingredients and to obtain a complete LCA of feed  
146 ingredients (Table A4; supplementary material). Feed ingredients that represented less than  
147 0.5% of annual intake and that were absent from the EcoAlim dataset were not included in the  
148 LCI. Feed production at the feed factory was included in the LCIs of commercial feeds by  
149 assuming that it would occur in the same region as the pig production, and would require 41  
150 kWh of electricity and 20.5 kWh of natural gas per t of feed produced, for grinding and  
151 pelleting (Garcia-Launay *et al.*, 2014). For on-farm feed production, grinding and mixing  
152 required 18 kWh of electricity per t of feed produced (Badouard and Roy, 2011).

### 153 2.3.2. *Transport specifications*

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

### 158 2.3.3. *Pig production*

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

169 For feeder-to-finish farms, we included the impacts related to piglet production by  
170 incorporating an average life cycle inventory (LCI) constructed from farrow-to-feeder farms  
171 surveyed in each system. Farrow-to-feeder farms have two outputs (culled sows/year and  
172 weaners/sow/year). The LCI incorporated the average kg of culled sows produced/piglet/year.  
173

## 174 **2.4. Life cycle impact assessment**

### 175 **2.4.1. Emissions from pig production**

176 Emissions to the air were estimated separately for NH<sub>3</sub>, N<sub>2</sub>O, NO<sub>x</sub>, and CH<sub>4</sub> for sows,  
177 post-weaning piglets, fattening pigs, feed production, animal housing and manure  
178 management using SAS software (SAS Inst. Inc., Cary, NC, USA). Housing condition was  
179 accounted to calculate the gaseous emissions (Table 2). For the periods in which the animals  
180 were kept outdoors, NH<sub>3</sub>, N<sub>2</sub>O, NO<sub>3</sub> and NO<sub>x</sub> emissions were calculated based on emission  
181 factors provided by Basset-Mens *et al.* (2007). For the periods during which the animals were  
182 kept indoors, gaseous N emissions were calculated for housing and storage and field  
183 application of solid manure using the step-by-step procedure recommended by EMEP/EEA  
184 (2016). Emission factors for NH<sub>3</sub> and N<sub>2</sub>O came from Rigolot *et al.* (2010b) and Basset-Mens  
185 *et al.* (2007), for housing and storage of solid manure, respectively, from Dämmgen and  
186 Hutchings (2008) for NO<sub>x</sub>, and from Nguyen *et al.* (2011) for NO<sub>3</sub>. Solid manure composting  
187 on the farms that did so was also considered using emission factors provided by Paillat *et al.*  
188 (2005). Emissions following field application of solid manure were calculated according to  
189 EMEP/EEA (2016) for NH<sub>3</sub>, IPCC (2006) for N<sub>2</sub>O, and Nemecek and Kägi (2007) for NO<sub>x</sub>.

### 190 **2.4.2. Emissions from grazing**

191 Mean grass intake was estimated as a function of concentrate intake (per kg LW)  
192 according to previous studies (Jensen and Anderse, 2002; Gustafson and Stern, 2003; Santos e  
193 Silva *et al.*, 2004; Bikker and Binnendijk, 2012). Grass intake (kg dry matter (DM)/kg  
194 LW/day) for pigs was estimated as  $0.02558 - 0.83335 \times \text{concentrate intake (kg DM/kg LW/day)}$   
195 ( $R^2 = 0.95$ ; Table A6 and Figure A1; supplementary material). For sows, grass  
196 intake (kg DM/kg LW/day) did not vary greatly as a function of concentrate intake (Rivera  
197 Ferre *et al.*, 2001); therefore, a mean value of 4.49 g DM/kg LW/day (Rivera Ferre *et al.*,  
198 2001) was used. The equations were applied to each animal category on each farm.

199 The mean botanical composition of pastures was estimated based on expert knowledge  
200 in each country, and the nutrient composition was obtained from INRA (2010)  
201 (Supplementary material). Due to the lack of information on the nutrient digestibility of pig  
202 forage, mean digestibility coefficients of Sauviant *et al.* (2004) for dehydrated grass were

203 used: CP digestibility of 46% and 59%, and organic matter (OM) digestibility of 43% and  
204 51%, for pigs and sows, respectively. To consider potential uncertainty in these coefficients, a  
205 range around each mean was defined based on previous studies (Lindberg and Andersson,  
206 1998; van der Peet-Schwering *et al.*, 2006; van Krimpen *et al.*, 2013), expressed as grass with  
207 high digestibility (+25% of the mean) or with low digestibility (-50% of the mean). Therefore,  
208 for emissions from grazing we obtained two different scenarios: grass intake of forages with  
209 high (HighD) and low (HighL) digestibility coefficient for CP and OM for pigs.

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

#### 212 2.4.3. Potential carbon sequestration

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

218 The low potential scenario was based on Dollé *et al.* (2009), from measurements of  
219 soil C summarized by Arrouays *et al.* (2002). Since all three countries are part of continental  
220 Europe and have a temperate climate, the same mean sequestration rate of permanent pasture  
221 was applied to all farms: 730 kg of carbon dioxide (CO<sub>2</sub>)-eq./ha/year (Nguyen *et al.*, 2012).  
222 The high potential scenario was based on the Food Climate Research Network report (Garnett  
223 *et al.*, 2017): 1,800 kg of CO<sub>2</sub>-eq./ha/year.

#### 224 2.4.4. Impact categories

225 The analysis was based on the CML 2001 (baseline) method V3.02 as implemented in  
226 SimaPro software V8.03 and added the following categories: land occupation from CML  
227 2001 (all categories) V2.04 and total cumulative energy demand V1.8 (non-renewable fossil +  
228 nuclear). The CML method was chosen because it was used in most pig LCA studies in the  
229 literature, which allows for comparison of our results to previous results. Thus, potential  
230 impacts of pig production on global warming potential (GWP, kg CO<sub>2</sub>-eq.; 100-year horizon),  
231 eutrophication potential (EP, g PO<sub>4</sub>-eq.), acidification potential (AP, g SO<sub>2</sub>-eq.), cumulative  
232 energy demand (CED, MJ), and land occupation (LO, m<sup>2</sup>/year) were assessed.

### 233 3. Results

#### 234 3.1. Environmental impacts of pig production

235 Environmental impacts of the systems per kg of pig LW produced per year are  
236 presented in Table 3. Systems had large differences in impacts. Overall mean GWP was 7.19  
237 kg CO<sub>2</sub>-eq; mean GWP was highest in the IT and SI systems (9.35 and 7.16 kg CO<sub>2</sub>-eq.,  
238 respectively) and lowest (5.07 kg CO<sub>2</sub>-eq.) in the FR system. Mean AP was highest in the SI  
239 system (49.0 g SO<sub>2</sub>-eq.), lowest in the FR and IT systems (32.6 and 32.9 g SO<sub>2</sub>-eq.,  
240 respectively). Mean EP was highest in the FR system (46.9 g PO<sub>4</sub>-eq.) and lowest in the SI  
241 and IT systems (39.5 and 35.5 g PO<sub>4</sub>-eq., respectively). Mean CED was 32% and 8% higher  
242 in the SI system than in those the FR and IT systems, respectively (Table 3). Mean LO was  
243 highest in the FR and SI systems (11.0 and 10.9 m<sup>2</sup>.year) and lowest in the IT system (7.55  
244 m<sup>2</sup>.year).

245 When expressed per ha of land used, the IT system had the highest impacts in almost  
246 all categories (Table 3). Overall mean GWP was 8,070 kg CO<sub>2</sub>-eq., with the highest mean  
247 GWP (12411 kg CO<sub>2</sub>-eq.) in the IT system and the lowest (4,679 kg CO<sub>2</sub>-eq.) in the FR  
248 system. Mean AP in the SI system was 33% and 4% higher than in the FR and IT systems,  
249 respectively (Table 3). Mean CED was 49% and 20% higher in the IT system than those in  
250 the FR and SI systems, respectively (Table 3). The overall mean amount of LW produced per  
251 ha land used (Table 3) was 1,151 kg/ha, with the highest mean amount in the IT system  
252 (1,336 kg/ha) and the lowest in the FR system (944 kg/ha).

253

#### 254 3.2. Effect of carbon sequestration and emissions resulting from grazing

255 When considering only potential C sequestration of the soil, GWP decreased in all  
256 systems, especially in FR. Mean GWP in the FR, SI and IT systems decreased by 5%, 2% and  
257 1%, respectively, in the low potential sequestration scenario. In the high potential  
258 sequestration scenario, mean GWP in the FR, SI and IT systems decreased by 12%, 5% and  
259 3%, respectively (Table 4), with the IT system having the highest mean GWP.

260 Conversely, when considering emissions resulting from grass intake and subsequent N  
261 and OM excretions by the animals, mean GWP in the FR, SI and IT systems increased by 5%,  
262 2% and 4%, respectively, for grass with low digestibility, and 5%, 2% and 4%, respectively,  
263 for grass with high digestibility (Table 4). Mean AP in the FR, SI and IT systems increased by  
264 12%, 6% and 18%, respectively, for grass with low digestibility and 7%, 3% and 10%,  
265 respectively, for grass with high digestibility (Table 4). Mean EP in the FR, SI and IT systems

266 increased by 3%, 2% and 5%, respectively, for grass with low digestibility and 1%, 1% and  
267 3%, respectively, for grass with high digestibility (Table 4).

268

## 269 4. Discussion

### 270 4.1. Environmental impacts of pig production

271 GWP estimated in the present study (5.07-9.35 kg CO<sub>2</sub>-eq/kg LW) were higher than  
272 those estimated by Espagnol and Demartini (2014) for outdoor pig production in Corsica  
273 (3.03-4.09 kg CO<sub>2</sub>-eq/kg LW) and those obtained by Dourmad *et al.* (2014) for traditional pig  
274 production (mean = 3.47 kg CO<sub>2</sub>-eq/kg LW). Fattening pigs in the present study were  
275 slaughtered at a mean weight of 170 kg, whereas slaughter weights ranged from 110-140 kg  
276 in previous studies. Additionally, the longer fattening period in the present study (mean age at  
277 slaughter of 415 days) induced higher enteric fermentation and OM excreted per pig, both of  
278 which contribute to CH<sub>4</sub> emissions (Rigolot *et al.*, 2010a). Since CH<sub>4</sub> is 25 times as potent as  
279 CO<sub>2</sub> in trapping heat in the atmosphere (Guinée *et al.*, 2002), higher GWP of local pig breeds  
280 was expected. Additionally, the higher feed supply required for local breeds increased the  
281 impact. As previously reported for traditional systems, feed production and intake can  
282 represent 65-75% of GWP (Dourmad *et al.*, 2014).

283 The higher AP of the SI system was due to the high NH<sub>3</sub>, N<sub>2</sub>O and NO<sub>x</sub> emissions  
284 from sows and fattening pigs in four farms, due to the higher CP content of its feeds resulting  
285 in higher N excretion and due to higher AP impacts of feeds in SI system. These four farms  
286 are the reason why there is a much higher standard deviation in AP values for SI system in  
287 comparison with the FR and IT systems (Table 3). The same trend was predicted for dietary P  
288 and EP. For all animal categories, the FR system had the highest P content in feeds, which  
289 resulted in greater P excretion than those in the other systems.

290 The range of AP for FR and IT systems (32.6-32.9 g SO<sub>2</sub>-eq.) was lower than values  
291 calculated by Dourmad *et al.* (2014) (54 g SO<sub>2</sub>-eq./kg LW) and Espagnol and Demartini  
292 (2014) (39-52 g SO<sub>2</sub>-eq.). This difference could be due to the higher CP in the diets in the  
293 previous studies. The range of EP in the present study (35.5-46.9 g PO<sub>4</sub>-eq.), however, is  
294 slightly higher than the mean EP calculated by Dourmad *et al.* (2014) (34 g PO<sub>4</sub>-eq./kg LW)  
295 for traditional pig production.

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

299 75% of CED, meaning that the impact of feed and the feed supply are the main drivers of  
300 CED impact. IT system feeds had high CED because soybean meal was included in almost all  
301 of its diets. The LCI assumed that soybean was imported mainly from Brazil, since Europe is  
302 the world's second largest importer of soybeans (USDA, 2017). Indeed, the high impact of  
303 soybean meal on CED is associated to both deforestation and high transportation demand  
304 (both road and across the ocean). Previous research showed that reducing the content of  
305 Brazilian soybean meal in diets could reduce CED, regardless of the pig production context  
306 considered in the LCA (Kebreab *et al.*, 2016; Monteiro *et al.*, 2016).

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

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

317 Mean GWP per ha of land used predicted in the present study (8,070 kg CO<sub>2</sub>-eq./ha)  
318 was higher than those predicted by Basset-Mens and van der Werf (2005) for the *Label Rouge*  
319 quality label (5,510 kg CO<sub>2</sub>-eq./ha) and Dourmad *et al.* (2014) for a traditional system (3,672  
320 kg CO<sub>2</sub>-eq./ha). Conversely, mean AP in the present study (39,836 g SO<sub>2</sub>-eq./ha) lay close to  
321 that predicted by Basset-Mens and van der Werf (2005) of 36,000 SO<sub>2</sub>-eq., although the EP  
322 (42,518 g PO<sub>4</sub>-eq./ha) and CED (34,685 MJ-eq./ha) in the present study were higher than  
323 those they predicted (29,300 g PO<sub>4</sub>-eq. and 28,503 MJ per ha, respectively).

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

330

#### 331 **4.2. Effect of carbon sequestration and emissions resulting from grazing**

332 The decrease in GWP per kg LW among the systems when C sequestration in pasture  
333 was included was a result of removing CO<sub>2</sub> from the atmosphere and incorporating it into the  
334 terrestrial pool via plants growing in the soil (Garnett *et al.*, 2017). Similar results were  
335 reported by Halberg *et al.* (2010), who found that C sequestration decreased GWP by 0.40-  
336 0.60 kg CO<sub>2</sub>-eq. per kg LW in organic pig production. Similarly, in the present study this  
337 decrease ranged from 0.24-0.59 kg CO<sub>2</sub>-eq. per kg LW in the FR system (highest effect) to  
338 0.12-0.28 kg CO<sub>2</sub>-eq. per kg LW in the IT system (lowest effect), indicating that C  
339 sequestration has more effect in extensive systems with low stocking density, and can vary  
340 greatly according to the factor used (high or low potential C sequestration). Accounting for  
341 soil carbon sequestration in LCA of animal production systems is controversial (Garnett *et al.*,  
342 2017) and mainly applied in grass-based cattle systems (Stanley *et al.*, 2018). Moreover, for  
343 temperate grassland, values reported in literature range from 200 kg C/ha/year (Nguyen *et al.*,  
344 2012) up to 3590 C/ha/year (Stanley *et al.*, 2018) obtained for rotational grazing systems. In  
345 this study, conservative hypotheses have been used with 200 and 490 kg C/ha/year for low  
346 and high soil carbon sequestrations scenario, respectively. So, the low contribution of soil  
347 carbon sequestration to climate change mitigation can be explained by such hypotheses.  
348 Better knowledge of soil carbon sequestration by temperate grassland would improve the  
349 quality of assessment of animal production systems relying on grazing and foraging. This is  
350 particularly important for systems using large surfaces. In our study, the system with highest  
351 proportion of outdoor rearing (French system) is characterized by land occupation impact of  
352 11m<sup>2</sup>.year per kg BW which is much higher than values obtained in conventional systems but  
353 still much lower than land occupation impact per kg BW for grass-based cattle systems  
354 (Stanley *et al.*, 2018). However, some European extensive systems use much larger areas as  
355 reported by Gaspar *et al.* (2007) for Iberian pigs in dehesa (maximum stocking rate of 1 pig  
356 per ha).

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

361 When emissions from grazing were considered, GWP, AP and EP increased in all  
362 systems, with larger increases in the IT system. As previously mentioned, grass intake was  
363 calculated as a function of feed intake; thus, farms with the lowest feed supply (such as IT)  
364 would have the highest grass intake and, consequently, more emissions because of it. From

365 results obtained in Tables 3 and 4, contribution of emissions related to grazing to GWP, AP  
366 and EP impacts were calculated. For all systems and scenarios of grass digestibility,  
367 contribution ranged from 2.1% to 4.7% for GWP, 1.1% to 5.3% for EP, and 3.0% to 17.5%  
368 for AP. Therefore, the contribution was rather low for GWP and EP, but substantial for AP  
369 impact. This resulted from the application of emission factors for outdoor pigs from Basset-  
370 Mens et al. (2007) but it is noteworthy that very few information on these emission factors is  
371 available in the literature. Contribution of emissions related to grazing is not negligible but  
372 quite uncertain because of lack of knowledge. In the frame of our study, the contribution of  
373 emissions related to grazing is moderate because in the systems considered commercial feed  
374 supply for outdoor pigs is higher than in extensive systems studied in literature. Indeed, in FR,  
375 SI and IT systems investigated, the average commercial feed supply ranged from 620 to 908  
376 kg/fattening pig/year on average whereas Espagnol and Demartini (2014) reported for the  
377 most extensive Corsican pig systems a commercial feed supply lower than 200 kg/fattening  
378 pig/year. Therefore, for extensive systems, particularly when comparing systems with various  
379 levels of feed supply, accounting for the emissions associated to grazing is relevant.  
380 Moreover, when evaluating practices aiming at mitigating environmental impacts through the  
381 utilization of natural resources, this is important to include all the consequences of these  
382 different practices into the assessment (when pigs ingest and utilize grass and/or acorns they  
383 need less concentrate per kg weight gain). Ignoring the emissions resulting from grazing pigs  
384 may lead to wrong conclusions on different systems or strategies.

385 The lower AP and EP potentials when considering grass with high digestibility, than  
386 when considering grass with low digestibility, were due to pigs' slightly lower N excretion,  
387 resulting in lower N emissions. Conversely, grass with high digestibility increased the GWP.  
388 This was influenced by the amount of CH<sub>4</sub> produced via enteric fermentation, which varies  
389 according to the amount of digestible fiber ingested (Rigolot *et al.*, 2010a): the more  
390 digestible fiber ingested, the higher the CH<sub>4</sub> emissions. This seems to indicate that grass with  
391 high digestibility in outdoor pig production could reduce AP and EP of this system; however,  
392 it increases CH<sub>4</sub> emissions, which increases GWP at the farm gate.

393 Estimating C sequestration is challenging, given the large variation in its estimates  
394 among publications according to the chosen method. This highlights the need for additional  
395 studies to describe this potential more adequately, especially in agricultural soils. Even though  
396 we considered effects of C sequestration and emissions from grazing in the present study,  
397 there is a lack of references on these topics, and determining their parameters is highly  
398 complex. We used two extreme values of potential C sequestration but did not consider soil

399 tillage/land management practices, climate variability, cultivation techniques, vegetation type,  
400 or N content of the soil. These factors may influence the conversion of OM into stable below-  
401 ground C, i.e. potential C sequestration (Garnett *et al.*, 2017).

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

411

#### 412 **4.3. Hotspots for improvement**

413 For animal performance, farms with high feed supply or poor FCR generally tended to  
414 have the highest impacts per kg LW, because environmental impacts depend greatly on feed  
415 intake and were expressed per kg LW. The feed supply seems high, given that pigs were  
416 raised outdoors (in FR) with access to grazing and consumed acorns and/or chestnuts in  
417 autumn period. Hodgkinson *et al.* (2017) observed that wild boar and domestic pigs obtained  
418 20% and 7%, respectively, of their total daily intake of dietary energy from grazing. This  
419 seems to indicate that outdoor pigs could also obtain a considerable portion of nutritional  
420 requirements from grazing, which reduces the need for a high feed supply, given their lower  
421 amino acid requirements. For digestible lysine (from 40 to 100 kg of BW), for example, it was  
422 demonstrated that European local breeds have an average requirement between 5.2 and 12.8  
423 g/d (Brossard *et al.*, 2019), much lower than the 14.8 and 16.9 g/d reported for genetically  
424 improved pig breeds (NRC, 2012). This can be explained by the low potential for protein  
425 deposition of local pig breeds (Barea *et al.*, 2007). After a certain LW, extra nutrient and  
426 energy intake is deposited into non-lean carcass tissue (de Greef and Verstegen, 1993, van  
427 Milgen and Noblet, 2003), which suggests that local breeds did not use the extra CP and L-  
428 lysine for protein deposition. It was recently demonstrated that in European local breeds, only  
429 a small proportion of total body energy retention is dedicated to protein deposition (between  
430 0.97 and 2.77 MJ/d); the greatest proportion (between 9.22 and 16.88 MJ/d) is in the form of  
431 lipids (Brossard *et al.*, 2019). However, as in some situations and for some impact categories  
432 such as GWP, the reduction on dietary CP does not reduce the impact (Monteiro *et al.*, 2016),

433 it could be explored the use of co-products. The use of meat meal in pig diets increased the  
434 dietary CP compared to a control feed based on maize and soybean meal (147 vs. 133g CP/kg,  
435 respectively), and consequently increase AC and EP by 7% and 10%, respectively  
436 (Mackenzie *et al.*, 2016). However, it decreased simultaneously by 2% the GWP per kg of pig  
437 carcass.

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

445

## 446 5. Conclusions

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

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

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

467

468

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480

**481 References**

482

- 483 Arrouays D, Balesdent J, Germon JC, Jayet PA, Soussana JF and Stengel P 2002.  
484 Contribution à la lutte contre l'effet de serre. Stocker du carbone dans les sols  
485 agricoles de France?. In Expertise scientifique collective. INRA report, p. 332.
- 486 Andretta, I., Hauschild, L., Kipper, M., Pires, P., & Pomar, C. (2018). Environmental impacts  
487 of precision feeding programs applied in pig production. *Animal*, 12(9), 1990-1998.  
488 doi:10.1017/S1751731117003159
- 489 Badouard B and Roy H 2011. Bien calculer le coût de fabrication à la ferme des aliments pour  
490 porcs. In *Septembre - Octobre 2011 - n° 1* (Ed. T Porc), p. 3.
- 491 Barea R, Nieto R and Aguilera JF 2007. Effects of the dietary protein content and the feeding  
492 level on protein and energy metabolism in Iberian pigs growing from 50 to 100 kg  
493 body weight. *Animal: an international journal of animal bioscience* 1, 357-365.
- 494 Basset-Mens C and van der Werf HMG 2005. Scenario-based environmental assessment of  
495 farming systems: the case of pig production in France. *Agriculture, Ecosystems &*  
496 *Environment* 105, 127-144.
- 497 Basset-Mens C, van der Werf HMG, Robin P, Morvan T, Hassouna M, Paillat JM and Vertès  
498 F 2007. Methods and data for the environmental inventory of contrasting pig  
499 production systems. *Journal of Cleaner Production* 15, 1395-1405.

- 500 Bikker P and Binnendijk GP 2012. Grass silage in diets for organic growing finishing pigs. In  
501 Rapport 603 Wageningen UR Livestock Research, Lelystad, The Netherlands.
- 502 Brossard L, Nieto R, Charneca R, Araujo JP, Puhliese C, Radović Č, Čandek-Potokar M  
503 2019. Modelling Nutritional Requirements of Growing Pigs from Local Breeds Using  
504 InraPorc. *Animals* 9(4), 169.
- 505 Čandek-Potokar, M., Batorek Lukač, N., Tomažin, U., Škrlep, M., Nieto, R., 2019a.  
506 Introductory Chapter: Concept and Ambition of Project TREASURE. In: Nieto, M.Č.-  
507 P.a.R. (Ed.), *European Local pig breeds - diversity and performance*. IntechOpen,  
508 DOI: 10.5772/intechopen.84246.
- 509 Čandek-Potokar, M., Batorek Lukač, N., Tomažin, U., Škrlep, M., Nieto, R., 2019b.  
510 Analytical review of productive performance of local pig breeds. In: Nieto, M.Č.-  
511 P.a.R. (Ed.), *European Local pig breeds - diversity and performance*. IntechOpen, .
- 512 Čandek-Potokar M, Žlender B, Kramar Z, Šegula B, Fazarinic G and Uršič M 2003.  
513 Evaluation of Slovene local pig breed Krškopolje for carcass and meat quality. *Czech*  
514 *Journal of Animal Science* 48, 8.
- 515 Dämmgen U and Hutchings NJ 2008. Emissions of gaseous nitrogen species from manure  
516 management—A new approach *Environmental Pollution* 154, 9.
- 517 de Greef KH and Verstegen MWA 1993. Partitioning of protein and lipid deposition in the  
518 body of growing pigs. *Livestock Production Science* 35, 317-328.
- 519 Dollé JB, Gac A and Le Gall A 2009. L’empreinte carbone du lait et de la viande. *Rencontres*  
520 *autour des Recherches sur les Ruminants* 16, 3.
- 521 Dourmad JY, Ryschawy J, Trousson T, Bonneau M, Gonzalez J, Houwers HW, Hviid M,  
522 Zimmer C, Nguyen TL and Morgensen L 2014. Evaluating environmental impacts of  
523 contrasting pig farming systems with life cycle assessment. *Animal: an international*  
524 *journal of animal bioscience* 8, 2027-2037.
- 525 EMEP/EEA 2016. EMEP/EEA air pollutant emission inventory guidebook 2016: Technical  
526 guidance to prepare national emission inventories. In EEA Report No 21/2016, p. 28.  
527 European Environmental Agency, Copenhagen, Denmark.
- 528 Espagnol S and Demartini J 2014. Environmental impacts of extensive outdoor pig production  
529 systems in Corsica In 9th International Conference on Life Cycle Assessment in the  
530 Agri-Food Sector, Vashon, WA, USA, pp. 364-371.
- 531 Fortina R, Barbera S, Lussiana C, Mimosi A, Tassone S, Rossi A and Zanardi E 2005.  
532 Performances and meat quality of two Italian pig breeds fed diets for commercial  
533 hybrids. *Meat Science* 71, 713-718.

- 534 Furman, M., Malovrh, Š., Levart, A., Kovač, M., 2010. Fatty acid composition of meat and  
535 adipose tissue from Krškopolje pigs and commercial fatteners in Slovenia. *Archiv*  
536 *Tierzucht* 53, 12.
- 537 Garcia-Launay F, van der Werf HMG, Nguyen TTH, Le Tutour L and Dourmad J-Y 2014.  
538 Evaluation of the environmental implications of the incorporation of feed-use amino  
539 acids in pig production using life cycle assessment. *Livestock Science* 161, 17.
- 540 Garcia-Launay, F., Dusart, L., Espagnol, S., Laisse-Redoux, S., Gaudré, D., Méda, B.,  
541 Wilfart, A. 2018. Multiobjective formulation is an effective method to reduce  
542 environmental impacts of livestock feeds. *British Journal of Nutrition*, 120(11), 1298-  
543 1309
- 544 Garnett T, Godde C, Muller A, Rööös E, Smith P, de Boer I, zu Ermgassen E, Herrero M, van  
545 Middelaar C, Schader C and van Zanten H 2017. Grazed and confused? In (Ed. FCR  
546 Network), p. 127. Environmental Change Institute, University of Oxford, Oxford,  
547 United Kingdom.
- 548 Gaspar, P., Mesias, F.J., Escribano, M., de Ledesma, A.R., Pulido, F., 2007. Economic and  
549 management characterization of dehesa farms: implications for their sustainability.  
550 *Agroforestry Systems* 71, 151-162.
- 551 Guinée JB, Gorée M, Heijungs R, Huppes G, Kleijn R, Koning Ad, Oers LV, Sleeswijk AW,  
552 Suh S and de Haes HAU 2002. Handbook on life cycle assessment: Operational guide  
553 to the ISO standards. Kluwer Academic Publishers, Leiden, The Netherlands.
- 554 Gustafson GM and Stern S 2003. Two strategies for meeting energy demands of growing pigs  
555 at pasture. *Livestock Production Science* 80, 167-174.
- 556 Halberg N, Hermansen JE, Kristensen IS, Eriksen J, Tvedegaard N and Petersen BM 2010.  
557 Impact of organic pig production systems on CO<sub>2</sub> emission, C sequestration and  
558 nitrate pollution. *Agronomy for Sustainable Development* 30, 721-731.
- 559 Hodgkinson S, Polanco C, Aceiton L and Lopez I 2017. Pasture intake and grazing behaviour  
560 of growing European wild boar (*Sus scrofa* L.) and domestic pigs (*Sus scrofa*  
561 *domesticus*, Landrace×Large White) in a semi-extensive production system. *The*  
562 *Journal of Agricultural Science* 155, 9.
- 563 INRA 2010. Alimentation des bovins, ovins et caprins. Besoins des animaux - Valeurs des  
564 aliments. Quae.
- 565 IPCC 2006. Emissions from livestock and manure management. In IPCC Guidelines for  
566 National Greenhouse Gas Inventories, p. 87.

- 567 ISO, 2006. Environmental Management - Life Cycle Assessment - Principles and Framework.  
568 EN ISO 14040
- 569 Jensen HF and Anderse BH 2002. Grovfoder til økologiske slagtesvin. In Husdyrbrug nr. 27 •  
570 2002 Ministeriet for Fødevarer, Landbrug og Fiskeri, Danmark.
- 571 Kebreab E, Liedke A, Caro D, Deimling S, Binder M and Finkbeiner M 2016. Environmental  
572 impact of using specialty feed ingredients in swine and poultry production: A life  
573 cycle assessment<sup>1</sup>. Journal of Animal Science 94, 2664-2681.
- 574 Lindberg JE and Andersson C 1998. The nutritive value of barley-based diets with forage  
575 meal inclusion for growing pigs based on total tract digestibility and nitrogen  
576 utilization. Livestock Production Science 56, 43-52.
- 577 Mackenzie SG, Leinonen I, Ferguson N, Kyriazakis I 2016. Can the environmental impact of  
578 pig systems be reduced by utilising co-products as feed? Journal of Cleaner  
579 Production 56, 12-22.
- 580 Meier, M.S., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., Stolze, M., 2015.  
581 Environmental impacts of organic and conventional agricultural products – Are the  
582 differences captured by life cycle assessment? Journal of Environmental Management  
583 149, 193-208.
- 584 Monteiro ANTR, Garcia-Launay F, Brossard L, Wilfart A and Dourmad JY 2016. Effect of  
585 feeding strategy on environmental impacts of pig fattening in different contexts of  
586 production: evaluation through life cycle assessment<sup>1</sup>. Journal of Animal Science 94,  
587 4832-4847.
- 588 Muñoz, M., Bozzi, R., García, F., Núñez, Y., Geraci, C., Crovetto, A., García-Casco, J., Alves,  
589 E., Škrlep, M., Charneca, R., Martins, J.M., Quintanilla, R., Tibau, J., Kušec, G.,  
590 Djurkin-Kušec, I., Mercat, M.J., Riquet, J., Estellé, J., Zimmer, C., Razmaite, V.,  
591 Araujo, J.P., Radović, Č., Savić, R., Karolyi, D., Gallo, M., Čandek-Potokar, M.,  
592 Fontanesi, L., Fernández, A.I., Óvilo, C., 2018. Diversity across major and candidate  
593 genes in European local pig breeds. Plos One 13, e0207475.
- 594 Nemecek T and Kägi T 2007. Life cycle inventories of Swiss and European agricultural  
595 production systems. In Ecoinvent V2.0 Rep. No. 15a Swiss Centre for Life Cycle  
596 Inventories, Zurich, Switzerland.
- 597 Nguyen TTH, van der Werf HMG, Eugène M, Veysset P, Devun J, Chesneau G and Doreau  
598 M 2012. Effects of type of ration and allocation methods on the environmental  
599 impacts of beef-production systems. Livestock Science 145, 239-251.

- 600 Nguyen TLT, Hermansen JE, and Mogensen L 2011. Environmental assessment of Danish  
601 pork. Faculty of Agricultural Sciences Internal Report. Faculty of Agricultural  
602 Sciences, Aarhus, Denmark.
- 603 Noya, I., Villanueva-Rey, P., González-García, S., Fernandez, M.D., Rodriguez, M.R.,  
604 Moreira, M.T., Life Cycle Assessment of pig production: A case study in Galicia.  
605 Journal of Cleaner Production 142, 4327-4338.
- 606 NRC 2012. Nutrient requirements of swine. National Research Council. 424 pp.
- 607 Paillat J-M, Robin P, Hassouna M and Leterme P 2005. Predicting ammonia and carbon  
608 dioxide emissions from carbon and nitrogen biodegradability during animal waste  
609 composting. Atmospheric Environment 39, 6833-6842.
- 610 Rigolot C, Espagnol S, Pomar C and Dourmad JY 2010a. Modelling of manure production by  
611 pigs and NH<sub>3</sub>, N<sub>2</sub>O and CH<sub>4</sub> emissions. Part I: animal excretion and enteric CH<sub>4</sub>,  
612 effect of feeding and performance. Animal: an international journal of animal  
613 bioscience 4, 1401-1412.
- 614 Rigolot C, Espagnol S, Robin P, Hassouna M, Beline F, Paillat JM and Dourmad JY 2010b.  
615 Modelling of manure production by pigs and NH<sub>3</sub>, N<sub>2</sub>O and CH<sub>4</sub> emissions. Part II:  
616 effect of animal housing, manure storage and treatment practices. Animal: an  
617 international journal of animal bioscience 4, 1413-1424.
- 618 Rivera Ferre MG, Edwards SA, Mayes RW, Riddoch I and Hovell FDD 2001. The effect of  
619 season and level of concentrate on the voluntary intake and digestibility of herbage by  
620 outdoor sows. Animal Science 72, 501-510.
- 621 Rodríguez-Estévez V, Sánchez-Rodríguez M, Arce C, García AR, Perea JM and Gómez-  
622 Castro AG 2012. Consumption of Acorns by Finishing Iberian Pigs and Their  
623 Function in the Conservation of the Dehesa Agroecosystem. In Agroforestry for  
624 Biodiversity and Ecosystem Services – Science and Practice (ed. M Kaonga)  
625 Departamento de Producción Animal, Facultad de Veterinaria, University of Cordoba,  
626 Cordoba, Spain.
- 627 Rudolph, G., Hortenhuber, S., Bochicchio, D., Butler, G., Brandhofer, R., Dippel, S.,  
628 Dourmad, J.Y., Edwards, S., Fruh, B., Meier, M., Prunier, A., Winckler, C., Zollitsch,  
629 W., Leeb, C., 2018. Effect of Three Husbandry Systems on Environmental Impact of  
630 Organic Pigs. Sustainability 10, 3796.
- 631 Salvador, S., Corazzin, M., Romanzin, A., Bovolenta, S., 2017. Greenhouse gas balance of  
632 mountain dairy farms as affected by grassland carbon sequestration. Journal of  
633 Environmental Management 196, 644-650.

- 634 Sans P, Gandemer G, Sanudo C, Métro B, Sierra I and Darré R 1996. Growth performances  
635 and carcass, meat and adipose tissue quality of gascon pigs reared in outdoor  
636 conditions. *Journées de la Recherche Porcine*, 5.
- 637 Santos e Silva JP, Enes MA, Figueiredo FO, Pires da Costa JS and Abreu JM 2004. Grass  
638 utilization in growing finishing bísaro pigs (85-107 kg). performance and carcass  
639 composition. In *III Symposium International sur le Porc Méditerranéen*, Tarbes,  
640 France.
- 641 Sauvant D, Perez J-M and Tran G 2004. *Tables INRA-AFZ de composition et de valeur*  
642 *nutritive des matières premières destinées aux animaux d'élevage: 2ème édition.*  
643 *Versailles, France.*
- 644 Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S., Hamm, M.W., 2018. Impacts of  
645 soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA  
646 beef finishing systems. *Agr. Syst.* 162, 249-258.
- 647 Steinfeld, H., Mooney, H.A., Schneider, F., Neville, L.E., 2010. *Livestock in a Changing*  
648 *Landscape: Drivers, Consequences, and Responses.* . Island Press, London.
- 649 USDA 2017. *EU-28 Oilseeds and Products Annual.* In *Global Agricultural Information*  
650 *Network* (Ed. UFA Service) United States Department of Agriculture, Vienna.
- 651 van der Peet-Schwering CMC, van Krimpen MM, Kemme P, Binnendijk GP, van Diepen  
652 JTM, Jongbloed AW and Henniphof-Schoonhoven C 2006. Alternative protein crops  
653 in diets of organically housed weanling pigs. In *PraktijkRapport Varkens* 47, p. 29.  
654 Wageningen UR, Lelystad, The Netherlands.
- 655 van Krimpen MM, Bikker P, van der Meer IM, van der Peet-Schwering CMC and Vereijken  
656 JM 2013. Cultivation, processing and nutritional aspects for pigs and poultry of  
657 European protein sources as alternatives for imported soybean products. In (Ed. WUL  
658 Research), p. 63. Wageningen UR Livestock Research, Lelystad.
- 659 van Milgen J and Noblet J 2003. Partitioning of energy intake to heat, protein, and fat in  
660 growing pigs. *Journal of Animal Science* 81, E86-E93.
- 661 van Zanten HHE, Bikker P, Meerburg BG, de Boer IJM 2018. Attributional versus  
662 consequential life cycle assessment and feed optimization: alternative protein sources  
663 in pig diets. *International Journal of Life Cycle Assessment* 23, 1-11.
- 664 Wei J, Cheng J, Li W and Liu W 2012. Comparing the Effect of Naturally Restored Forest  
665 and Grassland on Carbon Sequestration and Its Vertical Distribution in the Chinese  
666 Loess Plateau. *PLoS ONE* 7, e40123.

- 667 Wiedemann, S.G., McGahan, E.J., Murphy, C.M., 2016. Environmental impacts and resource  
668 use from Australian pork production assessed using life-cycle assessment. 1.  
669 Greenhouse gas emissions. *Anim Prod Sci* 56, 1418-1431.
- 670 Wilfart A, Espagnol S, Dauguet S, Tailleur A, Gac A and Garcia-Launay F 2016. ECOALIM:  
671 A Dataset of Environmental Impacts of Feed Ingredients Used in French Animal  
672 Production. *PLoS ONE* 11, e0167343.
- 673

674 **Table 1.** Performance of sows, post-weaning pigs and fattening pigs, and the average diet  
 675 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 <sup>1</sup>	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
<b>Estimated grass intake (kg/sow/year)</b>	<b>173</b>	<b>23.3</b>	<b>160</b>	<b>56.6</b>	<b>23.3</b>	<b>6.39</b>
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
<b>Estimated grass intake (kg/piglet/year)</b>	<b>0.00</b>	<b>0.00</b>	<b>11.5</b>	<b>0.00</b>	<b>3.37</b>	<b>1.41</b>
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

676 <sup>1</sup>For farms with sows.

677 s.d., standard deviation; CP, dietary crude protein; P, total phosphorus content; LW, body

678 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
<b>Gestating sows</b>			
<b>Housing</b>			
Indoor	0.0	37.5	54.5
Outdoor	93.3	12.5	18.2
Indoor with outdoor access	6.7	50.0	27.3
<b>Floor (when indoors)</b>			
Slatted or concrete floor	0.0	42.9	33.3
Deep litter	100	57.1	66.7
<b>Lactating sows</b>			
<b>Housing</b>			
Indoor	86.7	100	90.9
Outdoor	6.7	0.0	9.1
Indoor with outdoor access	6.7	0.0	0.0
<b>Floor (when indoors)</b>			
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
<b>Weaner pigs</b>			
<b>Housing</b>			
Indoor	100	57.1	78.6
Outdoor	0.0	14.3	7.1
Indoor with outdoor access	0.0	28.6	14.3
<b>Floor (when indoors)</b>			
Slatted or concrete floor	0.0	100	42.9
Deep litter	100	0.0	57.1
<b>Fattening pigs</b>			
<b>Housing</b>			
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

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

	France		Slovenia		Italy	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
Number of farms <sup>1</sup>	21		9		7	
Per kg LW						
GWP, kg CO <sub>2</sub> -eq.	5.07	0.791	6.94	2.53	9.35	3.92
AP, g SO <sub>2</sub> -eq.	32.6	4.21	47.3	21.1	32.9	2.73
EP, g PO <sub>4</sub> -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 <sup>2</sup> year	11.0	1.88	10.4	5.03	7.55	0.713
Per ha of land used <sup>2</sup>						
GWP, kg CO <sub>2</sub> -eq.	4,679	573.3	7,119.9	1,851.3	12,441	5,142.0
AP, g SO <sub>2</sub> -eq.	30,276	4,329.2	45,519	8,560.0	43,714	2,243.2
EP, g PO <sub>4</sub> -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

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

688 <sup>1</sup> For farrow-to-finish and feeder-to-finish farms.

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

692

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

	France		Slovenia		Italy	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
Number of farms <sup>1</sup>	21		9		7	
GWP, kg CO <sub>2</sub> -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 <sub>D</sub> ) <sup>2</sup>	5.32	0.734	7.09	2.474	9.73	3.663
Low digestibility of grass (Low <sub>D</sub> )	5.31	0.718	7.09	2.472	9.73	3.661
AP, g SO <sub>2</sub> -eq.						
High digestibility of grass (High <sub>D</sub> )	35.0	3.58	48.8	20.4	36.7	4.77
Low digestibility of grass (Low <sub>D</sub> )	36.9	3.59	50.1	20.0	39.9	8.50
EP, g PO <sub>4</sub> -eq.						
High digestibility of grass (High <sub>D</sub> )	47.6	7.28	38.3	15.6	36.6	7.29
Low digestibility of grass (Low <sub>D</sub> )	48.2	7.07	38.7	15.6	37.5	8.28

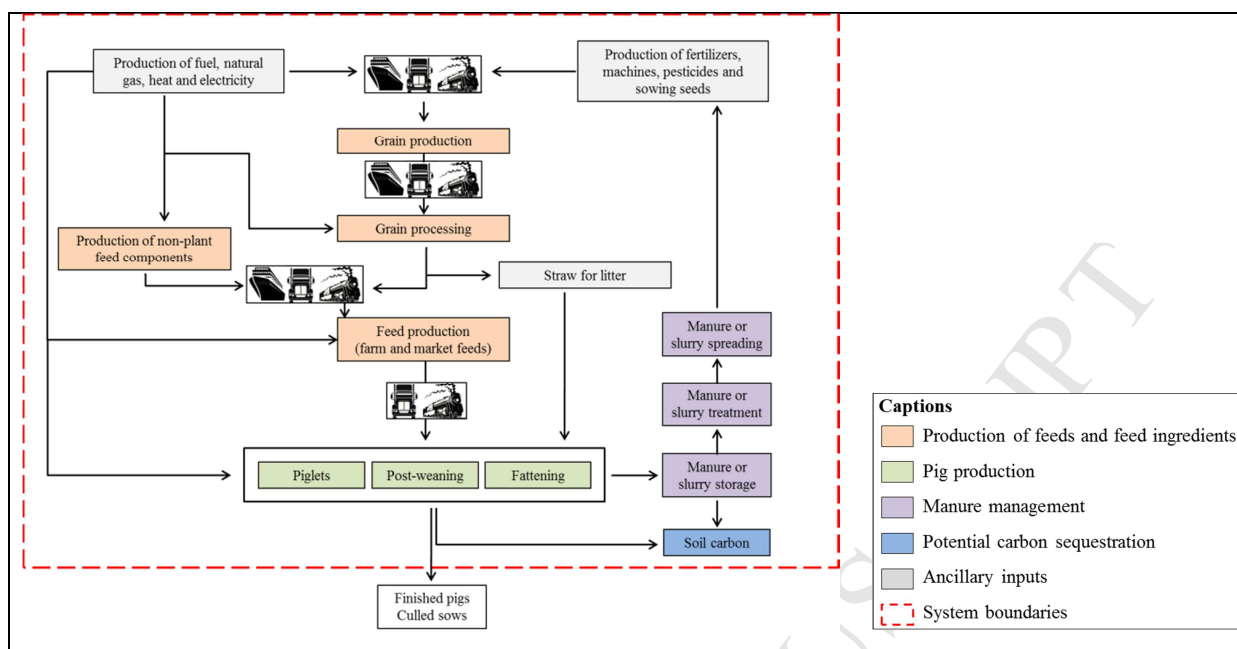
696 s.d., standard deviation; GWP, global warming potential; AP, acidification potential; EP,  
 697 eutrophication potential.

698 <sup>1</sup> For farrow-to-finish and feeder-to-finish farms.

699 <sup>2</sup> This scenario considers grass intake with high (High<sub>D</sub>) and low (High<sub>L</sub>) digestibility  
 700 coefficients for CP and OM for pigs and the subsequent excretion of N and OM.

701

702



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

705

**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<sub>2</sub> emissions by sequestering carbon.
- Feed composition, supply and feedstuffs origin are hotspots for improvement.