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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, SL 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 NH₃, N₂O, NO_x, and CH₄ 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, NH₃, N₂O, NO₃ and NO_x 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 NH₃ and N₂O 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_x, and from Nguyen *et al.* (2011) for NO₃. **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 NH₃, IPCC (2006) for N₂O, and Nemecek and Kägi (2007) for NO_x.

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 **(R² = 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 (CO₂)-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 CO₂-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 CO₂-eq.; 100-year horizon),
231 eutrophication potential (EP, g PO₄-eq.), acidification potential (AP, g SO₂-eq.), cumulative
232 energy demand (CED, MJ), and land occupation (LO, m²year) **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 CO₂-eq; mean GWP was highest in the IT and SI systems (9.35 and 7.16 kg CO₂-eq.,
 238 respectively) and lowest (5.07 kg CO₂-eq.) in the FR system. Mean AP was highest in the SI
 239 system (49.0 g SO₂-eq.), lowest in the FR and IT systems (32.6 and 32.9 g SO₂-eq.,
 240 respectively). Mean EP was highest in the FR system (46.9 g PO₄-eq.) and lowest in the SI
 241 and IT systems (39.5 and 35.5 g PO₄-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 m².year) and lowest in the IT system (7.55
 244 m².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 CO₂-eq., with the highest mean
 247 GWP (12411 kg CO₂-eq.) in the IT system and the lowest (4,679 kg CO₂-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).

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 CO₂-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 CO₂-eq/kg LW) and those obtained by Dourmad *et al.* (2014) for traditional pig
274 production (mean = 3.47 kg CO₂-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 CH₄ emissions (Rigolot *et al.*, 2010a). Since CH₄ is 25 times as potent as
279 CO₂ 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 NH₃, N₂O and NO_x 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 SO₂-eq.) was lower than values
291 calculated by Dourmad *et al.* (2014) (54 g SO₂-eq./kg LW) and Espagnol and Demartini
292 (2014) (39-52 g SO₂-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 PO₄-eq.), however, is
294 slightly higher than the mean EP calculated by Dourmad *et al.* (2014) (34 g PO₄-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 m²).

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 CO₂-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 CO₂-eq./ha) and Dourmad *et al.* (2014) for a traditional system (3,672
320 kg CO₂-eq./ha). Conversely, mean AP in the present study (39,836 g SO₂-eq./ha) lay close to
321 that predicted by Basset-Mens and van der Werf (2005) of 36,000 SO₂-eq., although the EP
322 (42,518 g PO₄-eq./ha) and CED (34,685 MJ-eq./ha) in the present study were higher than
323 those they predicted (29,300 g PO₄-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 m²/pig) in the FR system, which was even
329 lower than that in the *Label Rouge* quality label system (2.6 m² 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 CO₂ 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 CO₂-eq. per kg LW in organic pig production. Similarly, in the present study this
337 decrease ranged from 0.24-0.59 kg CO₂-eq. per kg LW in the FR system (highest effect) to
338 0.12-0.28 kg CO₂-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 **11m².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 CH₄ 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 CH₄ 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 CH₄ 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

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- 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 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

676 ¹For 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
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

681

682

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 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 ² year	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

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

689 ² For each farm, the impact was calculated as: [10,000 m² (1 ha) * Impact per kg of LW] / LO
 690 per kg of LW (m²year). 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 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

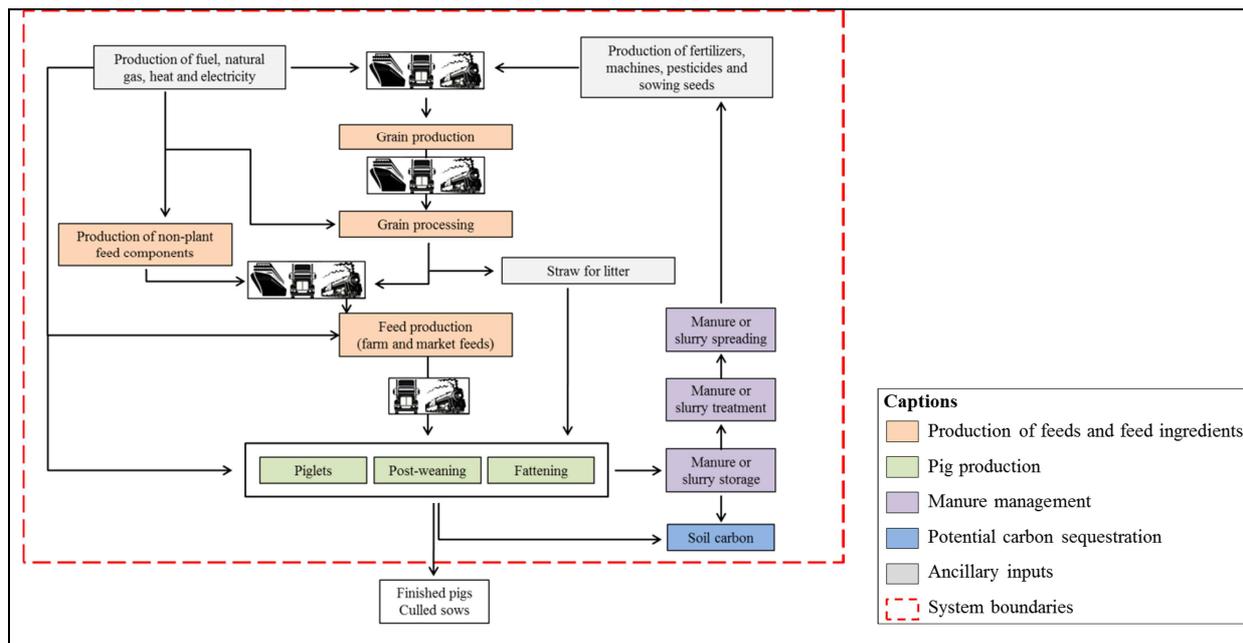
696 s.d., standard deviation; GWP, global warming potential; AP, acidification potential; EP,
 697 eutrophication potential.

698 ¹ For farrow-to-finish and feeder-to-finish farms.

699 ² This scenario considers grass intake with high (High_D) and low (High_L) digestibility
 700 coefficients for CP and OM for pigs and the subsequent excretion of N and OM.

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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.

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