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David Renaudeau, Jean-Yves Dourmad

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1 **Future consequences of climate change for EU pig production – A review**

2 D. Renaudeau <sup>a,†</sup>, J.Y. Dourmad <sup>a</sup>

3 <sup>a</sup>PEGASE, INRAE, Agrocampus-Ouest, 35590 Saint-Gilles, FR-35590, Saint-Gilles,  
4 France

5 <sup>†</sup> Corresponding author: David Renaudeau Email: E-mail: david.renaudeau@inrae.fr

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7

8 **Abstract**

9 Climate change is already a reality for livestock production. In contrast to the  
10 ruminants species little is known about the impacts and the vulnerability of pig UE  
11 sector to climate warming. This review deals with the potential and the already  
12 measurable effects of climate change in pig production. Based on evidences  
13 published in the literature, climate change may reduce UE pig productivity by  
14 indirectly reducing the availability of crops usually used in pig feeding, spreading the  
15 vector or pathogen to new locations and increasing the risk of exposure to cereals  
16 contaminated with mycotoxins; and directly mainly by inducing heat stress and  
17 increasing the animal's susceptibility to various diseases. Provision of realistic  
18 projections of possible impacts of future climate changes on EU pig sector is a  
19 prerequisite to evaluate its vulnerability and propose effective adaptation strategies.  
20 Simulation modeling approach is the most commonly used approach for exploring the  
21 effects of medium or long-term climate change/variability in pig production. One of  
22 the main challenge for this modelling approach is to account for both direct and  
23 indirect possible effects but also to uncertainties in parameter values that  
24 substantially increase the uncertainty estimates for model projections. The last part of  
25 the paper focus on the main issues that still need to be overcome for developing a  
26 decision support tools for simulating the direct and indirect effect of climate change in  
27 pig farms.

28 **Keywords**

29 Climate change; Heat stress; Feeding resources; Health; Modelling; Pigs.

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### 33 **Implication**

34 In the future, modeling approaches have to be developed to correctly evaluate the  
35 consequences of the future climate in EU pig sector. Considering the current state of  
36 modeling work, addressing of both direct and indirect effects of climate change in a  
37 same meta-model remains a major challenge for research. Future assessments of  
38 the degree of vulnerability of EU pig sector to climate change may also consider  
39 different socio-economic contexts for improving their reliability.

### 40 **Introduction**

41 Pig production is a major contributor to the agricultural economy in Europe (EU). In  
42 2018, the pig meat sector contributed 9% of total EU agricultural output and 35% of  
43 total EU meat output (source : <https://ec.europa.eu/eurostat/fr/>) The EU is the world's  
44 second biggest producer of pork after China and the biggest exporter of pork and  
45 pork products. In future, a major challenge facing the EU pig production sector will be  
46 to reduce its negative local and global impacts on the environment and satisfy animal  
47 welfare needs while at the same time maintaining the sector's profitability at a time of  
48 significant uncertainty as to the direct and indirect consequences of global warming.

49 Compared with ruminant species, monogastrics have received far less attention  
50 where the impacts of climate change are concerned (Escarcha et al., 2018; Mikovits  
51 et al., 2019). This is probably because ruminant animals are considered to be more  
52 vulnerable because they are immediately impacted by outdoor climatic conditions  
53 (whether directly or indirectly) whereas most monogastric animals reared in the mid-  
54 latitudes are housed in closed buildings where the temperature is, in theory well  
55 controlled. In the EU, housing for pigs is predominantly equipped with only  
56 mechanical ventilation systems, having no dedicated air treatment devices to provide

57 heat relief (Vitt et al., 2017). Because high ventilation rates alone are insufficient for  
58 the removal of sensible heat from animals during the summer months, indoor air  
59 temperatures frequently exceed the upper limit of the thermoneutral zone with  
60 detrimental effects on animal performance. This problem is exacerbated during  
61 summer heat waves and in animals at certain physiological stages such as lactating  
62 sows and finishing pigs.

63 This paper aims to review the available knowledge of climate change impacts on EU  
64 pig production and to identify the main issues that need to be overcome to improve  
65 assessment of quantitative evaluations of the vulnerability of pig farms to the  
66 consequences of global heating.

### 67 **Pig production in Europe**

68 The EU countries with the highest production of pig meat in 2020 were Germany (5.1  
69 million tons) and Spain (5.0 million tons), followed by France (2.2 million tons);  
70 together, these three countries account for more than half of the EU's total production  
71 (Source Eurostat). Since the nineties, growth in UE pig production has occurred  
72 mainly in Germany and Spain (Figure 1). This trend is expected to continue in 2021,  
73 driven by strong pork production in Spain. Pig farming in the EU is particularly  
74 concentrated in certain regions: Scandinavia (mainly Denmark), the central EU  
75 (mainly Germany, Poland, the Netherlands, and Belgium), the western EU (mainly  
76 France), and the southern EU (mainly Spain and Italy). In these EU countries, pigs  
77 produced in conventional intensive systems account for approximately 90% of total  
78 slaughter pigs (Bonneau et al., 2011).

### 79 **Predicted evolution of climate in the EU**

80 The climate crisis will lead to a rise in the average overall temperature in the EU.  
81 Projections from the EURO-CORDEX initiative (<https://cordex.org>) suggest that  
82 temperatures across the EU land mass will continue to increase throughout this  
83 century at a higher rate than the global world average. Inland temperatures in some  
84 EU regions are projected to experience an additional increase of 1.4 to 4.2 °C under  
85 the RCP4.5 scenario and by 2.7 to 6.2 °C under the RCP8.5 scenario (for the period  
86 2071-2100 as compared to 1971-2000) (Jacob et al., 2014). These authors project  
87 the highest level of warming to be across north-eastern Europe and Scandinavia in  
88 winter and southern Europe in summer. Projected extreme weather events such as  
89 summer heat waves are expected to have the greatest impacts in the area of  
90 livestock production. In the literature, several indices have been used to characterize  
91 heat waves, all of which are based on a certain period of consecutive days (3 to 5  
92 days) of excessively warm weather conditions (i.e., average ambient temperature >  
93 summer 90-95<sup>th</sup> percentile). Historical analysis provides numerous examples of  
94 extreme heat events that inflicted serious damage on livestock production. In France,  
95 the frequency and the intensity of summer heat waves have dramatically increased in  
96 the period 1947 – 2019, with more than the half of heat waves occurring since 2000  
97 (Figure 2). This trend seems set to continue in the near future, with all climate  
98 scenarios showing a doubling of the number of heat waves from 2021 to 2050  
99 (Soubeyroux et al., 2016). For the EU, future projections for heat waves were  
100 recently obtained from a set of 14 regional climate models under the RCP8.5 future  
101 emission scenario (Cardell et al., 2020). These authors predict general increases in  
102 the frequency, duration and amplitude of heat waves (i.e., the accumulated heat  
103 stress exceedance for all days under warm conditions in a given period; expressed in  
104 degrees-day) in all the major production basins for pigs (Figure 3). The South

105 Eastern EU will experience a strong increase of the number of warm days (+26%),  
106 with heat wave amplitudes of up to 194°C day during the summer period by 2071-  
107 2095.

## 108 **Consequences of climate change for pig production**

### 109 *Heat stress effects*

110 Pigs are homeothermic animals that have to maintain a relatively constant body core  
111 temperature over a wide range of climatic conditions. Heat stress results from an  
112 accumulation of energy in the body brought about by an imbalance between total  
113 heat production and heat loss. In the thermoneutral zone of temperature, heat  
114 production (HP) is classically divided in 3 components: (i) fasting HP, (ii) HP related  
115 to physical activity and (iii) HP related to feed intake and its digestive and metabolic  
116 utilization (known as the thermic effect of feed). For 60 kg BW growing pigs, these  
117 three components represent about 60, 15 and 25% of the total HP, respectively (Le  
118 Bellego et al., 1999). Fasting HP is a function of the chemical composition of the  
119 animal (involving the relative weights of metabolically active body compartments such  
120 as viscera and lean (van Milgen et al., 1998). The thermic effect of feed is mainly  
121 determined by feeding characteristics (feeding level and nutrient composition) and by  
122 animal related factors such as the animal's ability to deposit lean tissue (Noblet et al.,  
123 1999). The higher HP in leaner animals probably accounts for the fact that genetic  
124 selection aimed at increasing the amount and efficiency of lean growth in pigs also  
125 produces animals with higher sensitivity to HS (Nienaber et al., 1997; Renaudeau et  
126 al., 2011). Heat can be lost from the body by two physical processes: sensible and  
127 latent heat loss. Sensible heat can be gained or lost by conduction, convection and  
128 radiation depending on the temperature gradient between the body surface of the  
129 animal and its surroundings. In pigs, latent heat is lost mainly through the evaporation

130 of moisture from the respiratory tract that occurs while panting as pigs have few  
131 active sweat glands (Renaudeau et al., 2006). This limited ability to lose heat by  
132 evaporation explains why pigs are very vulnerable to high temperatures, especially  
133 when, as in most conventional housing systems, the animals cannot access to a  
134 wallow or a watering device.

135 Thermal HS can be classified in two major categories: “acute HS” and “chronic HS”.  
136 Chronic HS designates a high ambient temperature over a long period of time (days  
137 to weeks) which may in theory allow partial or total acclimatization to the  
138 environment. There are numerous physiological consequences of chronic HS and  
139 these have been extensively reviewed in the past (Baumgard and Rhoads, 2013).  
140 Above the upper limit of the thermoneutral zone, core body temperature begins to  
141 increase as a result of the animal’s inability to adequately dissipate the excess heat  
142 load. The concomitant decline in feed consumption is considered to be the main  
143 adaptation mechanism to limit metabolic HP. This limited nutrient intake results in  
144 reduced production performance, health and well-being if the adverse conditions  
145 persist (Nienaber et al., 1999). In lactating sows, reduced milk production as a direct  
146 effect of HS has also been documented in the literature (Messias de Bragança et al.,  
147 1998; Vilas Boas Ribeiro et al., 2018). The temperature threshold at which  
148 performance starts to decrease depends on the animal’s particular characteristics  
149 (genotype, physiological stage) but it is also determined by factors relating to the  
150 conditions in which the animal is raised (feed management, housing conditions and  
151 climatic factors other than ambient temperature) (Renaudeau et al., 2012). The  
152 metabolic and physiological adjustments that occur in the course of acclimatization to  
153 chronic HS may have long-term consequences for animal performance. For instance,  
154 it is now well established that chronic HS during the gestation period may change the



155 ability of the resultant offspring to express their genetic potential (Johnson and  
156 Baumgard, 2018). In particular, prenatal heat stress alters the distribution of energy  
157 between lean and fat deposition, resulting in fatter carcasses at slaughter (Johnson  
158 et al., 2015; Serviento et al., 2020).

159 Acute HS designates a short period of abnormal ambient temperature as is observed  
160 during summer heat waves. The short-term effects of acute HS (i.e., during exposure  
161 to elevated temperature) are already well described in the literature. During the first  
162 24-48 h exposure to HS, primary responses observed in pigs include a drop in feed  
163 intake and a sharp rise in heat loss via the cardiovascular adjustments that are made  
164 to increase peripheral vasodilation at the expense of the delivery of blood to the  
165 splenic tissues (Collin et al., 2001; Renaudeau et al., 2010). In contrast, the  
166 consequences of such thermoregulatory responses for an animal's ability to recover  
167 once a summer heat wave is over have been studied only recently (Mayorga et al.,  
168 2018). The reduction in nutrient and oxygen supplies alters the intestinal morphology,  
169 leading to a possible impairment of nutrient absorption and inflammatory stress for at  
170 least the 3-6 d period following acute HS (Abuajamieh et al., 2018). The absence of  
171 compensatory feed intake observed during the recovery period could thus be  
172 associated with the HS impacts on the gastrointestinal tract mentioned above and  
173 could lead to retarded growth with possible economic consequences (Renaudeau,  
174 2020).

#### 175 *Availability and quality of feed resources*

176 In 2019, feed production for the pig sector represented about 30% of total animal  
177 compound feed produced in EU (FEFAC, 2020). Feed materials used in compound  
178 feeds are obtained from a wide variety of primary sources of EU origin (cereals,  
179 oilseeds, rapeseed and sunflower meals, coproducts) and from other ingredients

180 particularly rich in protein (soybean meals) that must be imported from third countries  
181 (USA, Brazil, Argentina) (FEFAC, 2020). Where feed resources are concerned, the  
182 potential impacts of global warming on the pig industry would probably be brought  
183 about mainly by cumulative changes in yields and feed-food competition levels, but  
184 also to a lesser extent by reductions in the quality of raw materials for pig feed.

185 At a global scale, the various predictive models infer for the main part that climate  
186 change will continue to reduce the production of major crops. By the end of the  
187 century, without considering CO<sub>2</sub> fertilization, effective adaptation and genetic  
188 improvement, each degree-Celsius increase in the global mean temperature is  
189 predicted to reduce global yields of wheat by 6.0% and maize by 7.4% with wide  
190 variations according to geographical area (Zhao et al., 2017). In that study, the  
191 models showed a slight non-significant negative effect on soybean yield (-3.1%/°C).  
192 However, climate-driven impacts on crop production are shown to be variable both  
193 across crop types and geographically for individual crops. In France, cereal yields are  
194 also predicted to decline due to climate change under a wide range of climate models  
195 and emissions scenarios. However, due to the positive effect of climate change in  
196 some areas and the increased demand for cereals, some authors predict an increase  
197 in arable land used for crop production in France at the expense of permanent  
198 pasture or forest (De Cara et al., 2014; Lungarska and Chakir, 2018). Under the most  
199 rapid warming scenario (RCP8.5) and keeping growing areas constant, a 16%  
200 decline in winter wheat yield, a 20% decline in winter barley yield, and a 42% decline  
201 in spring barley yield are predicted by the end of the century (Gammans et al., 2017).  
202 In all studies, the simulations have difficulty in accurately accounting for uncertainties  
203 still to be documented, such as water availability for irrigation, changes in phenology  
204 and cropping calendars, the effects of increased CO<sub>2</sub> concentrations on plant growth,

205 along with the potential impacts of pests, diseases and weeds and the increased  
206 frequency of extreme events (Tubiello et al., 2007). Extreme weather, especially, may  
207 increase the risks of multiple simultaneous crop failures within regions or globally. In  
208 2018, the drought experienced in the Northern, Central and Eastern EU led to  
209 massive losses in crop yields which were only partially compensated by higher yields  
210 in the Southern EU as the result of favorable spring rainfall conditions (Beillouin et al.,  
211 2020). These extreme climatic episodes of 2018 were also associated with above-  
212 normal temperatures in North America and the Caspian Sea regions resulting in a  
213 deficit in global crop production and causing cereal prices to spike. More generally,  
214 growing evidence indicates that climate change will adversely influence agricultural  
215 crop yields and cause greater year-on-year variability. The increased variability of the  
216 climate and the occurrence of more frequent extreme climatic events is expected to  
217 lead to additional price increases for the most important agricultural crops – wheat,  
218 maize, and soybeans – that are used for livestock feeding (Nelson et al., 2009). A  
219 simulation study has suggested that ,under the predicted impacts of climate change,  
220 world crop price levels will increase twofold and world crop price volatility will  
221 increase fivefold between 2000 and 2080 (Tran et al., 2012). This increase in crop  
222 prices would be driven by the combined effects of the direct and indirect impacts of  
223 climate change on production yields but also by population and income growth and  
224 demand for biofuels (Nelson et al., 2009). Despite steady progress in increasing feed  
225 efficiency through a combination of improvements in feed management and genetic  
226 selection, feeding will continue to be the biggest cost factor in pig production in the  
227 future. By contrast, as reviewed by Rozegrant et al. (1999), the prices of food-feed  
228 crops are likely to increase at faster rates than the prices of pig meat from now to

229 2050. As a consequence, the predicted rising costs of crops is likely to be one of the  
230 main threats of climate change for pig producers.

231 The potential impacts of climate change on the composition of crops is now  
232 beginning to be well documented in the literature. From a meta-analysis, a systematic  
233 reduction in minerals and protein concentrations in response to elevated CO<sub>2</sub> has  
234 been reported, especially for C3 crops (Taub et al., 2008). For wheat, barley, and  
235 rice, the reduction in grain protein ranged from 10% to 15% when grown at elevated  
236 (540-958 ppm) CO<sub>2</sub>. For soybean and legumes more generally, the reduction in  
237 protein content is projected to be much smaller (1 to 2%). In addition to the reduced  
238 crude protein content, possible changes in amino acid composition may occur in  
239 cereal crops (DaMatta et al., 2010). Finally, high temperatures, especially if coupled  
240 with drought, are often associated with the production of secondary compounds  
241 (tannins, phenols, and other anti-nutritional factors) that protect plants against abiotic  
242 stresses and can result in lower feed digestibility for monogastric animals. Due to  
243 their high consumption of cereals and their limited ability to transform mycotoxins into  
244 less toxic products (Ji et al., 2016), pigs are the animal species most severely  
245 affected by mycotoxins. Climate represents the key factor in driving fungal community  
246 structure and mycotoxin contamination levels pre- and post-harvest (Magan et al.,  
247 2011). Climate change related effects that bring forward wheat flowering and full  
248 maturation by 1–2 weeks in north western EU could increase deoxynivalenol (DON)  
249 contamination by up to a factor of three, with an estimated mean DON concentration  
250 in this future scenario that exceeds the EC limit of 1250 µg/kg (Van der Fels-Klerx et  
251 al., 2013). A model designed to predict future aflatoxin contamination in cereal grown  
252 in Europe has shown that a +2°C climate scenario would result in a significant  
253 increase in contamination in all corn growing areas, whereas the predicted impact on

254 contamination in wheat would be negligible (Battilani et al., 2016). These possible  
255 changes in patterns of mycotoxin occurrence in feed crops as the result of climate  
256 change have to be taken into consideration in order to assess the impact of climate  
257 heating in the pig sector and are a matter of concern that may call for anticipatory  
258 measures to be taken.

## 259 *Health*

260 Infectious diseases are among the primary constraints on pig production, and the  
261 globalization of the pig industry has contributed to the emergence and spread of  
262 pathogens, driven in part by the frequent movement of pigs, feed, and pork products  
263 at local, national, and international scales (VanderWaal and Deen, 2018). Despite the  
264 importance of disease prevention for animal health and the stability and productivity  
265 of the global pig industry, there have been few projections of the development of  
266 swine pathogens under future climate change scenarios in Europe. It is assumed that  
267 a heating climate would affect pig health, either directly by causing death or  
268 modifying the ability to cope with pathogenic agent exposure, or indirectly by  
269 increasing the risk of exposure to sanitary threats. Variations in climatic factors  
270 influence the survival and development of pathogens, and affect the spatial  
271 distribution of vector-borne diseases (Lacetera, 2018).

272 Direct impacts include temperature related illness and death, and morbidity of  
273 livestock under severe heat stress (Gaughan et al., 2009). In the past 2 decades, the  
274 increased frequency and severity of heat waves has resulted in many deaths of  
275 livestock across the world. In 2003, Europe experienced thousands of heat-related  
276 deaths in pigs in the course of a summer heat wave where the average temperature  
277 was 3.5°C above normal during a 2-wk period. In pigs, the risk of an increased  
278 mortality rate is particularly high for heavy finishing pigs and lactating sows and their

279 litters. For example, a higher incidence of sow mortality during the summer months  
280 has been reported, especially in the 2-4 days after farrowing (Chagnon et al., 1991).  
281 When the temperature in the farrowing unit exceeds 22°C at parturition, the risk of  
282 stillbirth increases due to the prolonged duration of farrowing and the associated risk  
283 of hypoxia for piglets (Vanderhaeghe et al., 2010). In addition, a higher risk of pig  
284 death has also been reported during transport and lairage at the slaughter house in  
285 the hot season (Vitali et al., 2014). Based on our knowledge of humans and rodents,  
286 it has been suggested that the etiology of heat stroke is related to multi-organ system  
287 failure (Leon and Helwig, 2010). The primary cardiovascular response to heat  
288 exposure is an increase in skin blood flow promoting heat loss to the environment.  
289 Increased skin blood flow is accompanied by a fall in splanchnic blood flow as a  
290 compensatory mechanism to maintain blood pressure. As observed in reproductive  
291 sows, this rapid change in blood flow distribution would explain a large proportion of  
292 deaths due to cardiac failure (D'Allaire et al., 1996). Moreover, a reduction in  
293 splanchnic blood flow can result in an ischemia likely to produce nitrosative and  
294 oxidative stress that causes intercellular junctions in the gut to become “leaky”  
295 (Lambert et al., 2002; Pearce et al., 2012). Bacteria and bacterial products that are  
296 normally contained in the gut lumen are then able to freely cross the tight junction  
297 protein barrier and enter systemic circulation (Pearce et al., 2013). In addition to local  
298 gut inflammation, a systemic inflammatory response to endotoxin leakage appears to  
299 be an important element of heat stroke syndrome (Leon and Helwig, 2010). As well  
300 as reducing intestinal integrity, acute HS has been shown to induce morphological  
301 damage in the gastro-intestinal tract (GIT) (Pearce et al., 2012; Johnson et al., 2016)  
302 with possible transitory effects on nutrient digestion and absorption. This damage in

303 the GIT would explain why pigs are unable to increase their voluntary feed intake on  
304 the days following the end of a heat wave (Renaudeau, 2020).

305 A further theory to explain a possible link between high temperatures and health  
306 problems is that stressors such as HS may impair components of the immune  
307 system, thus enhancing an animal's vulnerability to disease (Gaughan et al., 2009).  
308 In ruminants, it has been suggested that heat stress would disrupt the immune  
309 function by changing the balance between cell-mediated immunity and humoral  
310 immunity (Bagath et al., 2019). This disruption in immune response seems to occur  
311 independently of feeding levels and is generally explained by the activation of the  
312 HPA axis and an increase in peripheral levels of glucocorticoids that then suppresses  
313 the synthesis and release of cytokines (Salak-Johnson and McGlone, 2007). For  
314 pigs, the data on the interactions between heat stress and the immune function are  
315 conflicting. Morrow-Tesch et al. (1994) showed that immunosuppression under heat  
316 stress conditions (28 d at 33°C) depends on social status in group-housed growing  
317 pigs. Immune suppression was also observed in pigs that endured chronic HS  
318 lasting 21 d (Xiang-hong et al., 2011). However, it has also been reported that pigs  
319 previously exposed to a 7-d HS displayed improved capacity to limit the  
320 physiological problems caused by repeated administrations of LPS (Campos et al.,  
321 2019). Whatever the nature of the stressors, specific and non-specific physiological  
322 and cellular adaptation responses were elicited in the animals. In other words, it was  
323 suggested that non-specific mechanisms to counteract the effects of acute HS had  
324 also helped the animals to cope with an inflammatory problem.

325 Under HS conditions, factors related to feeding conditions can influence a pig's  
326 health status. For instance, the reduced voluntary feed intake that occurs under heat

327 stress conditions reduces levels of the energy, protein, minerals, vitamins and trace  
328 elements that can help the pig to cope with health challenges.

329 Global warming can affect animal health by increasing the frequency of exposure to  
330 existing or emerging diseases by creating conditions conducive to the development  
331 vectors and their host reservoirs, and to the survival of pathogenic agents. Although  
332 the potential problems associated with climate change are now becoming widely  
333 recognized, quantitative data on the distribution and numbers of many vector species  
334 within the EU are not available and the influence of climate change on the distribution  
335 of these vectors remains highly uncertain (Gale et al., 2010). In pigs, a number of  
336 reports indicate seasonal changes in disease occurrence. However, the results of  
337 these studies are conflicting. Through the abattoir monitoring of pig carcasses, Lee et  
338 al. (2020) showed that the prevalence of respiratory problems increased during  
339 summer and fell in winter. A higher Salmonella seroprevalence was found in pigs  
340 exposed to housing temperatures over 26°C than in those kept at thermoneutral  
341 temperatures (Hautekiet et al., 2008). In contrast, a study of the influenza herd-level  
342 prevalence in Midwestern pig farms showed a seasonal pattern of higher levels of  
343 influenza in the winter and spring months (Chamba Pardo et al., 2017).

344 Pigs are very sensitive to mycotoxins due to their high consumption of cereals. As  
345 stated above, climate change has the potential to increase the risks that  
346 mycotoxigenic fungi pose to feed safety for pigs. Even though the major mycotoxins  
347 (aflatoxins, trichothecenes, fumonisins, zearalenone) have different toxic effects, all  
348 target the immune system (Pierron et al., 2016). The toxic effects of mycotoxin  
349 include increased susceptibility to and severity of infectious diseases, but can also  
350 impair vaccination efficacy, so that risk of disease increases even in appropriately  
351 vaccinated flocks (Pierron et al., 2016).



352 **Methodological issues for evaluating the vulnerability of pig production to**  
353 **climate change**

354 Pig production systems will need to adapt as the climate continues to change.  
355 Adaptation strategies for coping with climatic disruptions of pig production are well  
356 documented. For example, the adoption of generic management and technological  
357 adaptation measures have been found to be effective in reducing the impact of  
358 chronic heat stress in pigs (Renaudeau et al., 2012; Cottrell et al., 2015; Mayorga et  
359 al., 2019). However, such adaptation strategies take little or no account of specific  
360 climate change impacts. Thus, the production of realistic projections of the possible  
361 impacts of future climate changes on the EU pig sector is a prerequisite for the  
362 evaluation of its vulnerabilities and the proposal of effective adaptation strategies.  
363 This goal sets scientists the challenge of having to take account in our simulations of  
364 all the impacts of climate change, both direct (climatic conditions) and indirect  
365 (availability of feed resources, health pressures), but also of the socio-economic  
366 context in which changes to the pig sector will occur.

367 First, the direct impacts of future climate change in pig production can be estimated  
368 by using predictive computer models based on existing knowledge concerning the  
369 “dose-response” relationships between climatic conditions and animal performance.  
370 However, the purpose of these models is to show what would occur under different  
371 climate scenarios rather than to predict what exactly is going to happen. For the  
372 predictions of future climate, climatologists are now able to offer a satisfactory model  
373 of the climatic consequences of future greenhouse gas emission. These large-scale  
374 global climate models can be downscaled to make climate predictions at finer  
375 temporal and spatial scales in order to explore the potential effects of climate change  
376 on livestock production. By linking these climate scenarios with animal performance

377 models, we can estimate the impacts of future climate on pig farm performance.  
378 Animal modelling requires the inclusion of a corpus of mechanistic and/or empirical  
379 mathematical equations to represent the complexity of animal/farm responses to the  
380 various environmental changes that result from climate change. To incorporate the  
381 specific effects of heat stress on pigs, mechanistic equations (where mathematical  
382 equations are used to describe the mechanisms that underlie statistical relationships)  
383 have been used to produce heat balance models to predict the effects of heat stress  
384 on pig feed intake, heat production and growth (Turnpenny et al., 2000; Fialho et al.,  
385 2004). However, to date, since we do not have sufficient knowledge of some of the  
386 parameters of the heat balance model, the accuracy levels of such models in  
387 predicting heat loss and change in feed intake are very low. An alternative has been  
388 to use empirical equations (based on statistical relationships between variables) to  
389 predict the effects of heat stress on voluntary feed intake in pigs. These equations  
390 are generally easier to handle than mechanistic equations because they can be quite  
391 simply derived by fitting statistical functions to experimental data published in the  
392 literature or directly collected on commercial farms (Renaudeau et al., 2011;  
393 Dourmad et al., 2015; Fragomeni et al., 2016). Equations of the latter type have  
394 recently been introduced to a model by being coupled with bioclimatic and growth  
395 sub-models to simulate the effects of raised temperatures on growing-finishing pig  
396 performance and carcass composition (Brossard et al., 2019). In this model, pig  
397 performance is predicted from changes in voluntary feed intake related to climatic  
398 conditions but it does not take account of the direct effects of higher temperatures on  
399 pig metabolism and health. More generally, if we are to improve the accuracy of our  
400 simulations and/or implement a model that can inform us on the effects of climate  
401 change on the pig sector, further work needs to be done to quantify the effects of

402 high ambient temperatures on reproductive performance (farrowing rate, litter size,  
403 etc.. ), on the heat-related mortality and morbidity risks for those key physiological  
404 stages with high susceptibility to overheating (e.g., reproductive sows, finishing pigs),  
405 on the direct effects of extreme temperatures on health, and on the trans-  
406 generational effects of *in-utero* heat stress on growth and reproductive performance.  
407 In addition, in light of the growing future impacts of summer heat waves,  
408 complementary studies need to be conducted to evaluate the short and long term  
409 effects of such extreme heat events on pig performance (Renaudeau, 2020).

410 As described in this review, the potential impacts of climate change on the pig sector  
411 are not limited to the effects of high ambient temperature on animal performance.  
412 Given that feed costs comprise around 60-70% of the total costs of production,  
413 efforts to maintain or to reduce feed costs must continue to be a major concern if the  
414 pig industry is to remain competitive. Future rises in the predicted costs of primary  
415 cereal crops associated with feed/food competition and climate-induced reductions in  
416 production yields will represent a threat for the pig sector as cereal grains (wheat,  
417 corn, barley) are the principal sources of energy in EU pig diets. In addition, growing  
418 societal and environmental concerns in the EU about imported soybean meal from  
419 Latin America are likely to result in improved import standards requiring certified  
420 sustainable soy and(or) the development of protein self-sufficiency within the EU  
421 which carries the potential risk of increasing protein costs for the EU pig industry  
422 (Boerema et al., 2016). Finally, it is anticipated that bioenergy demands will create  
423 competition for land and water resources and exacerbate the existing competition for  
424 land caused by increased demand for feed resources (Thornton, 2010). As a  
425 consequence, it can be assumed that increasing feed costs would probably have a  
426 much greater impact on pig farm profitability than the direct effects of heat stress.

427 This suggests that in simulating the impacts of climate change on the pig sector we  
428 must consider various scenarios to provide reliable projections of feed costs.

429 As previously stated, the potential effects of climate change on pig health are  
430 significant, ranging from direct effects such as heat related mortality or morbidity, to  
431 indirect effects such as those associated with ecological changes and the spread of  
432 certain pathogens and vectors, or the increased risk of mycotoxin contamination. In  
433 order to assess the impacts of climate change on pig production, one future  
434 challenge will be to include the risk of animal disease in our simulations. This is made  
435 harder by the fact that, according to a comprehensive survey including contributions  
436 from many researchers across Europe, modelling livestock health and pathogens in  
437 the context of climate is a very complex matter (Özkan et al., 2016). For example, not  
438 only does it require more effective modelling of the spread of pathogens and vectors  
439 under climate change, it is also dependent on an improvement in our understanding  
440 of the complex relationships between the environment, hosts and pathogens.

441 During the 1980s, the technical performance of pig farms showed great improvement  
442 thanks to a concomitant improvement of animal management and an intense  
443 selection drive for highly prolific sows and fast growing, lean animals with a high feed  
444 efficiency. According to the French National Pig Management database, between  
445 1980 and 2015, the per annum number of pigs marketed per present sow, growth  
446 rates and gain:feed ratios from 30 to 115 kg that were recorded on farrow to finish  
447 commercial farms increased from 15.1 to 22.9 pigs/year, 595 to 815 g/d, and 0.28 to  
448 0.39 kg/kg respectively. It can be expected that these technical performance will  
449 continue to increase in future, unless the evolution would be disrupted due to a  
450 higher priority given to animal welfare. As a consequence, it is very likely that animals  
451 raised on commercial farms in 2050 or 2100 will differ considerably from current

452 animals, making them even more vulnerable to future heat stress, especially if no  
453 heat tolerance traits are incorporated into the genetic selection criteria for pigs. This  
454 suggests that the analysis on which simulations of the impact of our future climate  
455 are based must take account of continued improvements to pig genetic potential.

456 Finally, modelling studies to evaluate the impacts of climate on the EU pig sector will  
457 also have to take into consideration the full range of uncertainties in the socio-  
458 economic environment, such as future demand for pig meat, the evolution of EU  
459 policy to promote greener and more sustainable pig production and changes to EU  
460 regulations concerning animal welfare.

461

## 462 **Conclusions**

463 In the absence of any effective adaptation options, the EU pig sector will be  
464 vulnerable to climate change through reduced animal performance and higher  
465 production costs. The impacts will result from a combination of direct effects of heat  
466 stress on pig performance and health status and indirect effects on the availability of  
467 affordable feed resources and sanitary pressures due to changes in the spread of  
468 pathogens and vectors. Future modeling approaches must be developed that can  
469 correctly quantify the consequences of future climate change for the EU pig sector.  
470 This step is necessary to provide farmers with the basis for an informed perception of  
471 climate risks and to propose effective adaptation strategies. Given the current  
472 development level of modelling techniques, the successful combination of both direct  
473 and indirect effects of climate change in the same meta-model remains a major  
474 challenge for research. Future assessments of the degree of vulnerability of the EU

475 pig sector to climate change could improve their reliability by taking into account a  
476 variety of possible socio-economic contexts.

477

478

479 **References**

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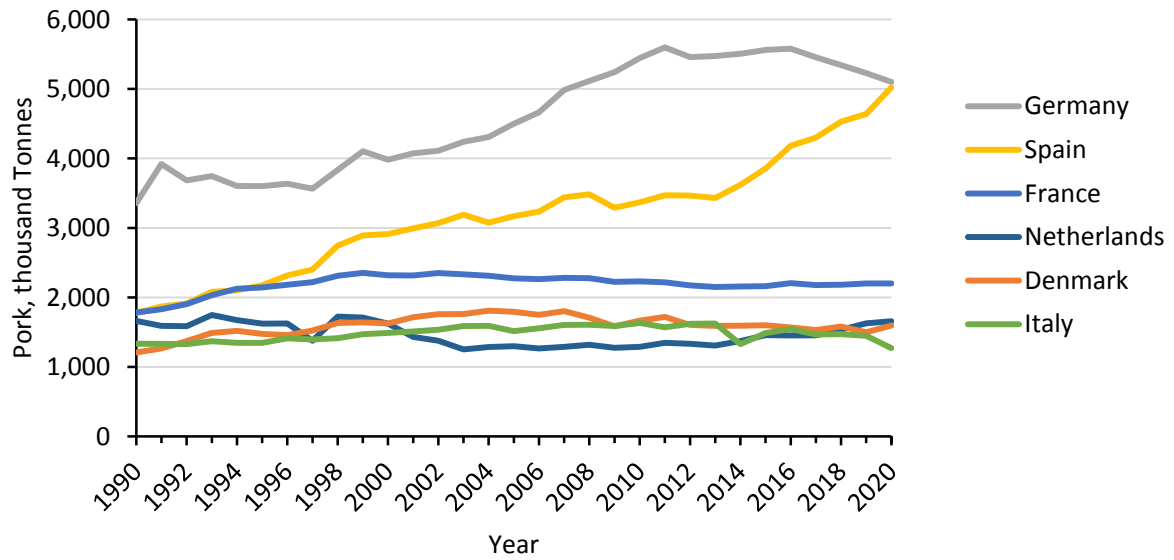
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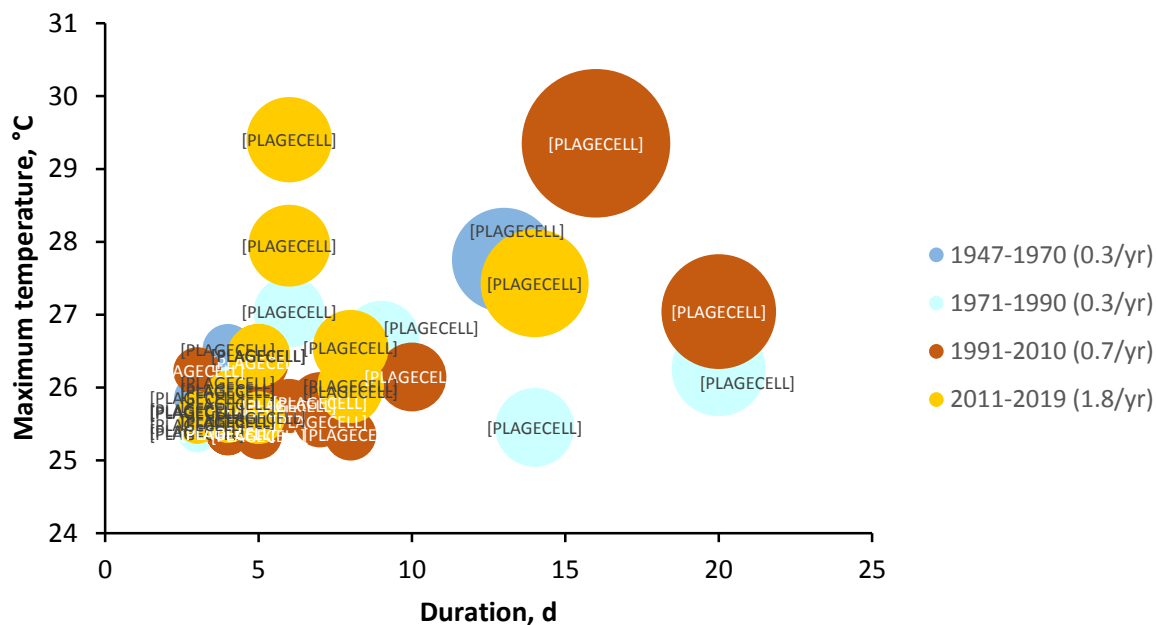


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752 **Figure 1** Evolution of pork production in the top six pork producing countries in the EU from 1990 to  
753 2020 (source: own illustration based on the Eurostat database).

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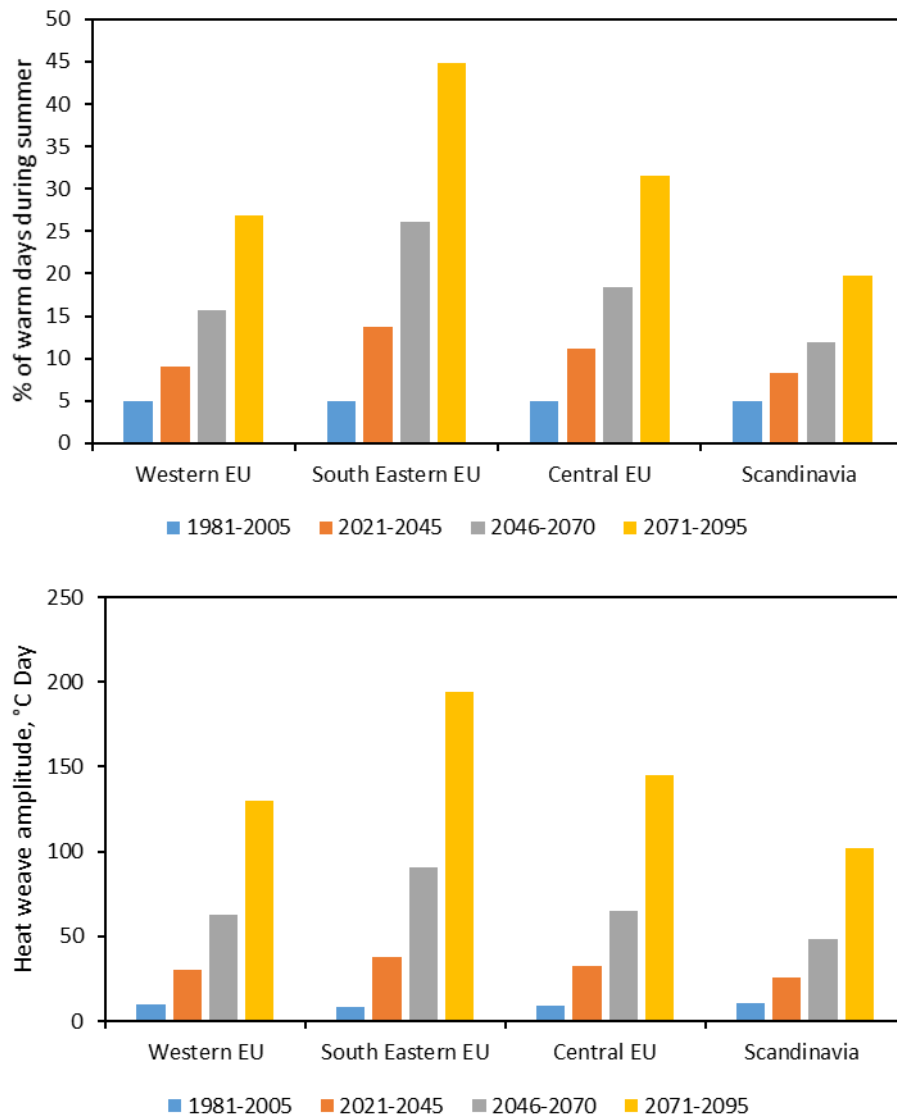


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757 **Figure 2** Heat waves recorded in France from 1947 to 2019. Each circle gives information on duration  
 758 (x axis), maximum temperature (y axis) and global intensity (bubble size). Global intensity is an  
 759 indicator of the severity of a heat wave. Data were provided by Météo France (J.M. Soubeyrou,  
 760 personal communication). Details on the methodology used to characterize heat waves were  
 761 provided by Ouzeau et al. (2016).

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765 **Figure 3** Multi-model amplitudes of regional summer heat waves (°C days) and percentage of warm  
 766 summer days for the 4 EU regions comprising the main pig production basin, showing historic data  
 767 for recent period (1981-2005) and projections for short term (2021-2045), medium term (2046-2070)  
 768 and long term (2071-2095). Western EU = France, Southeastern EU = Spain, Scandinavia = Denmark,  
 769 and Central EU = Belgium, Germany, Netherlands, and Poland. Adapted from Cardell et al (2020).