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1 Can novel ingredients replace soybeans and reduce the environmental 2 burdens of European livestock systems in the future?

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9 **Abstract.** Much of the protein in the diets of European livestock is sourced from imported
10 soybeans produced in the Americas. This protein deficit in livestock production presents a
11 risk to social, economic and environmental progress in Europe. In this study the impact of
12 incorporating novel ingredients into future chicken diet formulations to serve as European
13 sourced alternatives to imported soybeans was investigated. The novel ingredients
14 considered were: microalgae, macroalgae, duckweed, yeast protein concentrate, bacterial
15 protein meal, leaf protein concentrate and insects. Using horizon scanning and a modelling
16 approach, the nutritional requirements of two potential meat-producing chicken lines were
17 simulated. The two chicken lines were a fast-growing line based on the apparent maximum
18 feed efficiency that could be achieved through further artificial selection, and a reduced
19 growth rate for high welfare line. Diets were formulated to include the novel ingredients,
20 whilst meeting the nutritional requirements of the birds. The effects of diet composition on
21 indicators of environmental burdens, associated with feed production for the poultry industry,
22 were then assessed. We found that soybean products can be completely replaced by novel
23 feed ingredients, whilst reducing the greenhouse gas emissions and arable land
24 requirements for feed provision relative to conventional diets formulated for both chicken
25 lines. Switching from conventional diets to diets which incorporate novel ingredients was
26 also shown to mitigate the increased environmental burdens associated with moving towards
27 higher welfare livestock systems. Incorporation of novel ingredients in diet formulations
28 offers a viable option for providing sustainable and nutritionally balanced livestock feed in the
29 future and thus provides huge potential for facilitating bespoke feeding strategies and
30 specific management choices for mitigating environmental impacts of chicken systems.

31 Key words: Alternative ingredients; Livestock; Feed formulation; Chicken diets;
32 Environmental impact

33 1. Introduction

34 Europe's reliance on imported protein, particularly soybeans, to feed livestock is inconsistent
35 with sustainability objectives (de Boer et al., 2014; de Visser et al., 2014; Kebreab et al.,
36 2016; Leinonen et al., 2012).

37 The poultry industry (meat-producing chickens, egg laying hens, turkeys etc.) collectively
38 consumes the most soybeans of any livestock sector in Europe (van Gelder et al., 2008).
39 This protein requirement is set to increase further as the demand for chicken meat, in

40 particular, continues to grow (Alexandratos and Bruinsma, 2012; FAO, 2016). In addition, the
41 inclusion of valuable conventional protein sources of animal origin in livestock feed are either
42 limited (e.g. fishmeal) or banned (e.g. meat and bone meal) in the EU (Brookes, 2001;
43 European Commission, 2001), whilst growing soybeans in Europe is non-competitive with
44 imports due to relatively low yields and a long growing season (van Krimpen et al., 2013).
45 Thus, the poultry industry is presented with the challenge of providing an adequate and more
46 sustainable supply of protein to feed meat-producing chickens in Europe.

47 In seeking a long-term solution to this protein deficit, the following second or third generation
48 protein sources have been identified for future application in poultry diets: microalgae,
49 macroalgae, duckweed, yeast protein concentrate (YPC), bacterial protein meal (BPM), leaf
50 protein concentrate (LPC) and insect meal. All these novel ingredients are characterized by
51 their potential to be cultivated in Europe and their low agricultural land use (ALU)
52 requirement; each of the novel technologies that produce them is in a different phase of
53 development. The novel ingredients were included individually (at a fixed inclusion level) and
54 combined into mixtures of ingredients in alternative diet formulations.

55 The nutrient requirements of two future meat-producing chicken lines that are likely to arise
56 from breeding strategies with different objectives were considered: a fast-growing and slow-
57 growing line. The “fast-growing line” would be the result of the current, globally predominant
58 selection strategy which is based on the continuation of artificial selection for increased
59 energy efficiency. The performance and therefore the energy and nutritional intake of the
60 fast-growing birds can be calculated based on evidence of current genetic trends and
61 apparent biological limits in their underlying biology (Tallentire et al., 2016; Tallentire et al.,
62 2018). The “slow-growing line” would have a reduced growth rate according to higher
63 welfare standards (Tallentire et al., 2018), representing a market shift in response to growing
64 societal concerns about animal welfare (Clark et al., 2016; Clark et al., 2017; Efsa Panel on
65 Animal Health and Welfare, 2010).

66 Thus, the overall aim of our study was to assess the environmental implications of
67 incorporating novel ingredients into the feeding strategy of future chicken meat production
68 systems. The novel ingredient inventory was modelled in feeding scenarios, based on the
69 nutritional requirements of future meat-producing chicken lines which were predicted in a
70 previous study (Tallentire et al., 2018). Whilst the environmental impacts of some of these
71 novel ingredients have been assessed in the past (e.g. Aitken et al., 2014; de Boer et al.,
72 2014; Jorquera et al., 2010; Oonincx and de Boer, 2012), this is the first time the
73 environmental burdens of all seven ingredients have been calculated systematically by
74 applying a common methodology and reported in contrast to the use of imported soybeans

75 as the main protein source in chicken feed. A sensitivity analysis developed in previous
76 studies was also employed here to identify any substantial uncertainty in our projections
77 (Mackenzie et al., 2015; Tallentire et al., 2017). This is the first study to demonstrate and
78 compare the potential environmental trade-offs of incorporating novel ingredients into
79 chicken meat production systems, whilst also accounting for the requirements of
80 future genetic lines and their implications.

81 **2. Methods**

82 *2.1. Goal, scope and model structure.*

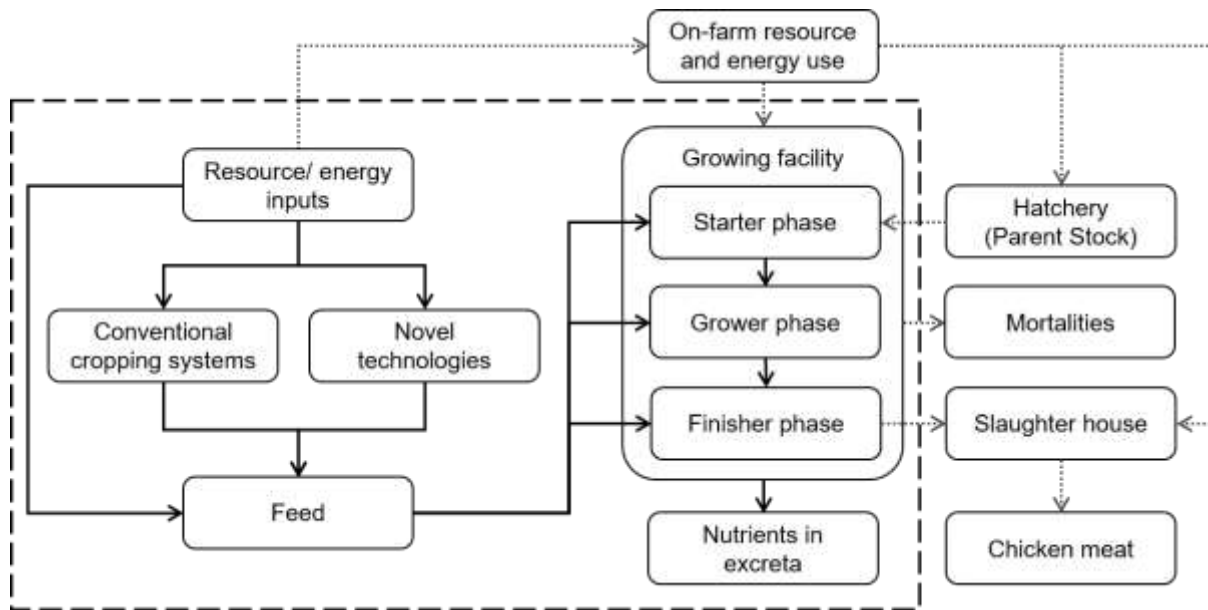
83 The goal of this study was to assess the environmental implications of replacing soybeans
84 with novel ingredients in chicken feed formulations. From this analysis the most sustainable
85 technologies were identified for use in livestock production; this information is crucial for
86 nutritionists, livestock producers, breeders, policy makers and potential investors. The scope
87 of the study was to propose potential diets, which incorporated novel protein sources, for
88 future chicken meat production systems in Europe based on analysis of trends in recent
89 genetic change and the apparent physical limits of the biological processes (Tallentire et al.,
90 2018), i.e. energy (feed) intake, digestion, metabolic heat production and chemical energy
91 partitioning. To achieve this a life cycle assessment (LCA) methodology with an integrated
92 diet formulation tool, which was developed in a previous study, was used (Tallentire et al.,
93 2017). The functional unit of this study was one bird grown to a live weight of 2.2kg, the
94 average slaughter weight of meat-producing chickens in the UK (Defra, 2014), raised in a
95 standard European indoor system i.e. climate-controlled (e.g. fan-ventilated), artificially lit
96 buildings.

97 The model inputs included: a detailed inventory of feed production (section 2.2.), the total
98 feed intake and body composition of future chicken lines, their nutritional requirements and
99 the nutrient content of all ingredients included within the feed formulation calculation. The
100 model structure can be summarised as follows: all diets were formulated for a fixed set of
101 minimum nutritional requirements for the different growth phases modelled, i.e. the starter,
102 grower and finisher phases. Two meat-producing lines were considered. Since the nutritional
103 requirement of each line was met in every diet formulated, it was presumed that bird growth
104 rate per kg of feed consumed was unaffected between different diets. The methodology for
105 calculating the nutritional requirements of these two future meat-producing chicken lines is
106 discussed below (section 2.3). Maximum and minimum limits constrained the inclusion of
107 each ingredient in each diet to ensure that issues of palatability, inhibition of digestibility or
108 variability in specific ingredients did not adversely affect bird performance i.e. growth rate or
109 carcass composition. The methodology also assumed meat quality would not be adversely

110 affected. Although some of the novel ingredients have been shown to have a positive effect
111 on bird health (Bovera et al., 2016; Pulz and Gross, 2004; Qureshi et al., 1996) and
112 performance (Shanmugapriya and Saravana Babu, 2014), this was not included within the
113 scope of this study. Environmental burden values were assigned to each ingredient,
114 conventional and novel, in order to determine the environmental implications of formulating
115 each diet for future chicken meat production. Finally, the environmentally important nutrients
116 excreted by the bird were calculated based on mass balance.

117 2.2. *Model inventory and system boundary.*

118 An inventory of conventional feed ingredients was compiled and used to build system
119 processes in Simapro based mainly on the Agri-footprint database (Blonk Agri Footprint,
120 2015a, b; Durlinger et al., 2014; Vellinga et al., 2013) and previous studies (Tallentire et al.,
121 2018; 2017). Inventory data for the processes involved in the production of a few minor
122 ingredients were adapted from the Ecoinvent database, e.g. limestone (Swiss Centre for Life
123 Cycle Inventories, 2007). An inventory was compiled for the novel ingredients using peer-
124 reviewed sources and industry supplied primary data (Appendix A). All upstream system
125 processes associated with the feed production were included within the boundary of the LCA
126 analysis. All resource and energy inputs to fertilizer, herbicide and pesticide production and
127 the various processing requirements of the ingredients (harvesting, separation, grinding and
128 drying) were included in the analysis. The direct and indirect emissions that arise as a result
129 of these system processes, including any land transformation associated with production,
130 were all accounted for within the boundaries of the model (Blonk Agri Footprint, 2015a, b;
131 Defra, 2015; FAOSTAT, 2015; Vellinga et al., 2013). The production of conventional
132 ingredients was based on current practices (i.e. Conventional cropping systems), whilst
133 novel ingredient production was based on potential upscaled processing scenarios based on
134 novel technologies (Appendix A). It was expected that the housing conditions were
135 maintained in such a way as to provide each chicken line with the optimum growing
136 conditions for its genotype. However, with the exception of the feed, the resource and
137 energy inputs to the birds' growing facility and beyond the farmgate were not included within
138 the boundary of this study (Fig. 1). Finally, since the functional unit was only one bird raised
139 to a live weight of 2.2kg, the effects of bird mortality were not considered within the boundary
140 of the model.



141

142 Figure 1: The structure and main components of the chicken meat production systems as
 143 considered by the Life Cycle Assessment (LCA) model in this study; the inputs that were
 144 considered (solid line arrows), the inputs that were not considered (dotted line arrows) and
 145 the system boundary (dashed line) are clearly illustrated.

146 *2.3. Future bird nutritional requirements.*

147 The nutritional specifications were based on two breeding scenarios that were presented in
 148 Tallentire et al. (2018) via horizon scanning which result in: 1) a fast-growing line based on
 149 the apparent maximum feed efficiency that could be achieved through further artificial
 150 selection and 2) a reduced growth rate for high welfare line (Table 1). For the two scenarios,
 151 total energy requirement was quantified based on predictions of the biological limits of
 152 digestive efficiency, protein and lipid growth and the metabolic rate of heat production
 153 (Tallentire et al., 2018). The difference in the traits between these future meat-producing
 154 lines and current commercial meat-producing chickens is low (Aviagen, 2014a, 2016;
 155 Fancher, 2014), thus it is reasonable to expect these lines will be achieved before the novel
 156 technologies outlined in this study come into wide scale operation. Since there is no
 157 evidence that the efficiency of protein utilization has changed as a result of selective
 158 breeding, the protein requirements of the meat-producing chicken lines were calculated
 159 based on the current baselines for feed intake, feed protein content and body composition
 160 (Aviagen, 2014b, 2016). In this way the protein utilization efficiency equates to the protein
 161 retained in the body (kg) divided by the protein intake (kg) of one bird. The requirements of
 162 the future lines could therefore be calculated as follows: first the change in energy
 163 requirement, and therefore the feed intake, was calculated whilst keeping the feed energy
 164 content unchanged from current requirements. Then, the nutrient requirements of the new

165 birds were estimated based on the changes in feed intake and in bird requirements, (the
 166 change of nutrient requirement was assumed to be proportional to the change of protein
 167 requirement). The new diets could then be constructed to meet these requirements
 168 (Appendix B, Table B.3 and B.4).

169 Table 1: Characteristics of birds at a live weight of 2.2kg at slaughter for two potential future
 170 lines. The fast-growing line assumes that the current trends in chicken genetic selection
 171 continue, whereas the slow-growing line results from societal pressures to reduce the growth
 172 rate, giving higher priority to animal welfare.

	Fast-growing line	Slow-growing line
Growth rate (g day ⁻¹)	65.3	38.6
Age at slaughter (days)	33	57
Total Metabolizable energy intake (MJ)	42.0	58.3
Total protein content of body (%)	20.6	20.6

173 Diets were formulated for three growth phases for the fast-growing line (i.e. the starter,
 174 grower and finisher phases). For the slow-growing line, the grower and finisher phases were
 175 each split into two to account for the extended lifespan and slower growth rate of the birds;
 176 hence the diets of the slow-growing line were formulated for five growth phases (Appendix
 177 B). Since the fast-growing line was selected for increased growth rate, it follows that an
 178 increased proportion of its life would be spent in the starter phase (days 0 - 10) and a
 179 reduced period of time in the finisher phase. Hence, the bird required a substantially
 180 increased protein intake in the starter phase (266.6 g kg⁻¹), in order to achieve this higher
 181 growth rate, than the slow-growing bird (225.0 g kg⁻¹). Therefore, the average energy and
 182 crude protein content requirement of the feed for the fast-growing birds was 13.1 MJ kg⁻¹
 183 and 205.4 g kg⁻¹ respectively. The average energy and crude protein content requirement of
 184 the feed for the slow-growing birds was 13.3 MJ kg⁻¹ and 187.7 g kg⁻¹ respectively.

185 2.4. Diet formulation rules.

186 The novel ingredients were selected based on five criteria: 1) The ingredient could
 187 potentially serve as an alternative to imported soybeans in livestock diets. 2) The
 188 incorporation of the ingredient into chicken diets was not common practice already. 3) The
 189 maximum inclusion limit of the novel ingredient, its digestible amino acid profile and
 190 metabolizable energy content were available in the literature. 4) Production in Europe is a
 191 realistic option for the future. 5) Enough data was available to compile an inventory of
 192 relevant energy and material inputs and environmental releases related to the novel
 193 ingredient. Seven novel ingredients were identified for inclusion within the scope of this
 194 study: microalgae, macroalgae, duckweed, YPC, BPM, LPC and insect meal. For each of

195 these ingredients a production inventory (Appendix A, Fig. A.1 – A.7 and Tables A.1 – A.7)
196 and nutritional profile (Appendix B, Table B.1) was compiled.

197 For each meat-producing chicken line a “Conventional diet” was formulated; both these diets
198 were formulated for least cost, using only ingredients currently used in the UK as a case
199 study for western European systems (Tallentire et al., 2017); both diets included soymeal.
200 For each line, a further 11 “alternative diets” were formulated. 7 of these alternative diets
201 each incorporated one novel ingredient fixed at its potential maximum inclusion rate; these
202 alternative diets were formulated to match the nutritional requirements of the birds using
203 linear programming for least cost. The prices of the conventional ingredients were obtained
204 from commodity price indexes for animal feeds (Defra, 2016; Tallentire et al., 2017). Since
205 their inclusion values were fixed in these diets, the prices of the novel ingredients were not
206 relevant to the diet formulation procedure. Each of the remaining 4 diets for each line was
207 formulated to reduce a specific environmental burden (section 2.5). When formulating these
208 diets any of the 7 novel ingredients, as well as any of the conventional ingredients, were able
209 to be incorporated within their corresponding inclusion limits in order to optimise the diet to
210 minimise a specific environmental burden. Therefore 12 diets were formulated for each line
211 and 24 diets were formulated in this study in total.

212 Inclusion limits of conventional ingredients were based on input data from literature, national
213 inventory reports, databases and expert advice (Tallentire et al., 2017). The maximum
214 inclusion of each novel ingredient in the grower-finisher phases was determined from
215 assessing literature, in which the effects of inclusion rates on bird performance were
216 measured (Appendix B, Table B.2); the maximum inclusion in the starter phases was 50% of
217 this value as a conservative estimate (Leinonen et al., 2013). For the three ingredients
218 sourced from aquatic based systems, microalgae (venkataraman et al., 1994), macroalgae
219 (Ventura et al., 1994) and duckweed (Haustein et al., 2009), a consistent maximum inclusion
220 limit of 18% was modelled. Maximum YPC inclusion rates are particularly variable due to
221 issues with its nutritional characterization; an inclusion of 20% was determined to be feasible
222 without negatively affecting bird performance (Scholey et al., 2016; Scholey et al., 2014).
223 BPM has been shown at 10% inclusion with no negative effect on chicken growth
224 performance (Schøyen et al., 2007; Skrede et al., 2003; Whittemore et al., 1978). It is
225 expected that LPC should have very similar properties to other plant protein and replace
226 soymeal completely in the grower-finisher phases at a maximum inclusion level of 40%
227 (Ameenuddin et al., 1983). Insect meal had a maximum inclusion of 30% (Bovera et al.,
228 2016); although beneficial to the immune system, chitin can limit digestibility beyond this
229 inclusion level. It should be kept in mind that insect meal would not be allowed to be
230 incorporated into poultry diets under current EU law, however the regulation has recently

231 been relaxed so that insects can be utilised in aquaculture systems (European Commission,
232 2017; Józefiak and Engberg, 2015) and its incorporation into other livestock feeds continues
233 to be championed in scientific literature (Marberg et al., 2017).

234 2.5. *Environmental burden assessment.*

235 The Simapro software was used to conduct LCA calculations. Due to the novelty of some of
236 the ingredient production processes assessed for the purpose of this study, the differences
237 in the potential environmental burdens of each diet were limited to the most relevant feed-
238 related environmental indicators, as in Tallentire et al. (2018). As such, the environmental
239 parameters used to compare the environmental impact potential of each potential diet
240 formulation was represented by the greenhouse gas (GHG) emissions, the agricultural land
241 use (ALU) and the total nitrogen (N) and phosphorus (P) that would be excreted.

242 Over 70% of the GHG associated with chicken meat production can be attributed to feed
243 provision (Leinonen et al., 2012). In this study the GHG was measured in CO₂ equivalent
244 (CO₂ eq.) with a 100-year timescale in accordance with the IPCC (2006) emissions factors.
245 The ALU was calculated based on the total land occupation and the total area of land which
246 was transformed for the functional unit (Guinée et al., 2002). Calculation of the GHG
247 emissions and ALU followed the ReCiPe methodology (Goedkoop et al., 2008). Notably,
248 soybeans and soymeal carry a high GHG footprint due to associated deforestation; the CO₂
249 eq. released due to land transformation, such as for soybean production, was included
250 according to the PAS2050:2012-1 methodology (BSI, 2012).

251 Whilst the GHG and ALU burdens were restricted to the direct result of feed provision, the
252 quantities of the environmentally important nutrients (N and P) were calculated based on
253 what ends up in bird excreta. To calculate these, a mass balance principle was applied; the
254 nutrients retained in the animals' body were subtracted from the total N and P supplied by
255 their diet, where the total nitrogen content of the protein in the body was assumed to be
256 16%. These nutrients are associated with acidification and localised eutrophication, whilst N
257 is responsible for the ammonia emissions at housing, manure storage and field spreading.
258 On the other hand, these nutrients can be used in the place of synthetic fertilizers, this is
259 especially important in organic farming where manure is a major source of nutrients
260 (Leinonen et al., 2012).

261 2.6. *Analysis*

262 In total 24 diets were formulated, with 12 for each future meat-producing chicken line. The
263 results were analysed by comparing the environmental burdens caused by each alternative
264 diet scenario with those of the Conventional diet from the corresponding line using the mean

265 values produced by the model. An uncertainty analysis was also conducted using parallel
266 Monte Carlo simulations. For each alternative diet scenario, the model was simulated 1000
267 times to calculate the environmental burdens of the alternative diet as compared with those
268 of the Conventional diet from the corresponding line. Input parameters were randomly
269 assigned a value along their defined distribution in each simulation; parallel simulations were
270 used to account for shared uncertainty between the two diet scenarios (Mackenzie et al.,
271 2015; Tallentire et al., 2017). The output of the uncertainty analysis was the probability that
272 the environmental burdens of each diet were larger or smaller than the Conventional diet for
273 each impact category. A table of the parameters included in the uncertainty analysis and
274 their assigned distributions can be found in Appendix C (Table C.1).

275 2.7. Sensitivity

276 Since this model contained only linear relationships, a local sensitivity analysis was suitable
277 for identifying the inputs to which the environmental burdens were most sensitive (Tallentire
278 et al., 2017). This was carried out on the assumptions of the model in three important areas
279 in recognition of both their importance to the results of this study and the unavoidable
280 uncertainty in the assumptions made. These were: 1) the efficiency of the manufacturing
281 process for the novel ingredients; 2) the coproduct allocation methodology used to calculate
282 the environmental burdens of producing these novel ingredients; and 3) the maximum levels
283 to which these ingredients could be included in poultry diets without negatively affecting bird
284 performance.

285 To test the sensitivity of process efficiency in producing the novel ingredients, the yield of
286 each novel ingredient was depressed and increased. Whilst upscaling these system
287 processes is likely to increase the efficiency of their production in the future, this is not a
288 certainty and other considerations (e.g. quality control) can change the incentives which
289 drive process changes. For some novel ingredients there was large variation in the process
290 yields since they are in their development phase; we expect the coefficients of variation in
291 the yields to range from 15% for insect meal to 50% for the more variable LPC produced
292 from alfalfa (Lamb et al., 2003) (Appendix C, Table C.1). The coefficients of variation for the
293 other novel ingredients were estimated to be 33% for microalgae and for duckweed, and
294 20% for macroalgae and YPC (Feedipedia, 2017; Philippsen et al., 2014; Wen, 2014); we
295 did not find yield data to determine the coefficient of variation of BPM production therefore it
296 was presumed to be at the top of the range (50%).

297 Where system separation was not possible in our model, coproduct allocation within the
298 supply chain was conducted using economic allocation (Mackenzie et al., 2016b) using
299 commodity prices available on e-commerce sites and recent alternative fuel price data

300 (European Biomass Association, 2017) (Appendix A, Tables A.1, A.2, A.4 and A.6). A
301 sensitivity analysis of this economic allocation strategy was carried out whereby the value of
302 the novel ingredients produced with coproducts was altered so that their value was equitable
303 with soymeal per kg of lysine. This methodology was chosen to represent a scenario where
304 the novel ingredients would be produced and utilised on a scale that makes them
305 competitors of soymeal as a protein source in the animal feed market. Such a scenario
306 would likely drive price increases for these products and thus alter calculations made when
307 using economic allocation.

308 Finally, in order to account for discrepancies in the maximum inclusion levels shown in
309 literature (Gijzen and Khondker, 1997; Hoving et al., 2012; Mwale and Gwaze, 2013;
310 Olorunfemi, 2006; Rusoff et al., 1980), the maximum inclusion limit of each novel ingredient
311 was reduced by 15%. The effects on the environmental burdens of each diet associated with
312 each assumption are shown in Appendix C where at least one burden was affected (Tables
313 C.3 - C.5).

314 **3. Results**

315 *3.1. Environmental burdens of diets*

316 Of all the novel ingredients included in the study, insect meal had the highest GHG
317 emissions associated with its production; this was caused by the requirement for a suitable
318 ambient temperature for insect growth and development (47%), insect feed provision (13%)
319 and other energy inputs to the rearing and processing of the mealworms into insect meal.
320 Micro- and macroalgae had the second and third highest GHG emissions respectively (Table
321 2), due to considerable process energy input requirements e.g. drying. LPC was the novel
322 ingredient with lowest GHG emissions, although it also had the greatest ALU due to the
323 cultivation of alfalfa from which it is sourced, followed by YPC and insect meal. The ALU of
324 the YPC could be almost entirely attributed to the cultivation of wheat, whilst 94% of the ALU
325 of the insect meal was attributed to insect feed procurement. Unsurprisingly, the aquatic
326 novel ingredients (i.e. microalgae, macroalgae and duckweed) had the lowest ALU. The
327 GHG and ALU burdens of the conventional ingredients considered in this study are
328 presented in Appendix A (Table A.8). The novel ingredients with the highest crude protein
329 content and crude protein to amino acid ratio, e.g. YPC, resulted in the highest N in the
330 excreta. Similarly, ingredients which had the highest total P content and had the lowest
331 available P to total P ratio, resulted in the highest P in the excreta. Macroalgae was the
332 novel ingredient with lowest total P content, whilst insect meal had the highest available P to
333 total P ratio.

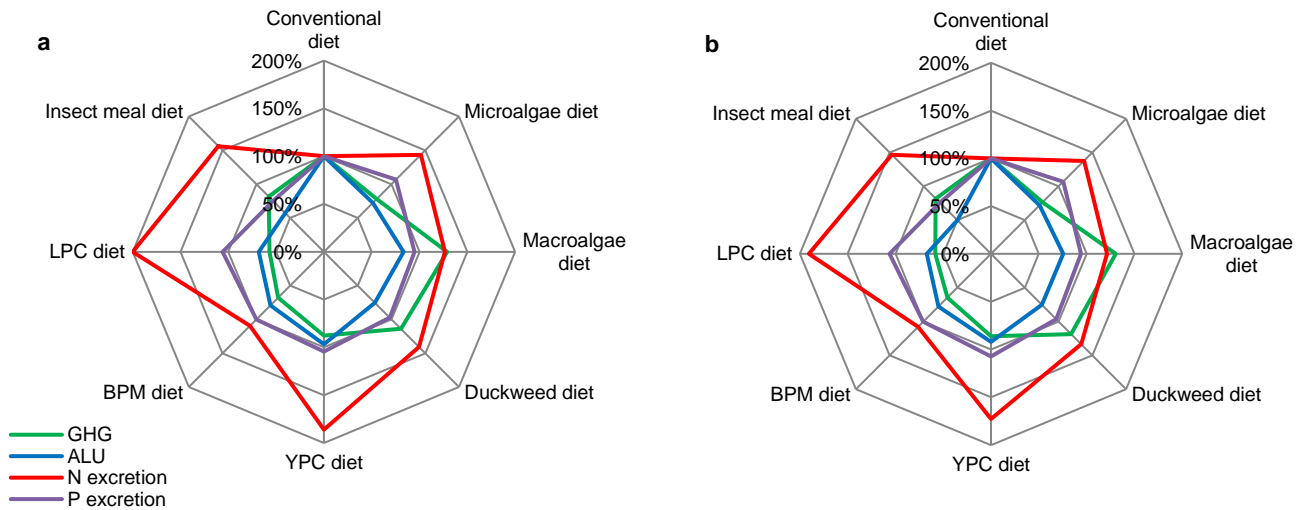
334 Table 2: The environmental burdens of soymeal and each novel ingredient included in this
 335 study as alternative protein sources. The Greenhouse gas (GHG) emissions and agricultural
 336 land use (ALU) associated with the production of 1 kg of each ingredient are presented. The
 337 Nitrogen (N) and Phosphorus (P) content of the ingredients are also shown.

Ingredient	GHG (CO ₂ eqv.; kg kg ⁻¹)	ALU (m ² kg ⁻¹)	Total N content (kg kg ⁻¹)	Total P content (kg kg ⁻¹)
Soymeal	3.05	3.11	0.075	0.006
Microalgae	2.31	0.034	0.093	0.014
Macroalgae	2.10	0.021	0.037	0.002
Duckweed	1.03	0.004	0.048	0.004
Yeast protein concentrate	1.08	1.26	0.108	0.013
Bacterial protein meal	1.49	0.026	0.117	0.015
Leaf protein concentrate	0.611	1.98	0.093	0.005
Insect meal	2.91	1.06	0.084	0.008

338 The environmental burdens of producing the total feed required by a chicken, of a fast-
 339 growing line and raised to a live weight of 2.2kg on a conventional diet formulation, were
 340 4.96 kg CO₂ eqv., 8.84 m², 0.045 kg and 0.011 kg for GHG, ALU, N and P respectively. The
 341 environmental burdens of producing the total feed required by a chicken, of a slow-growing
 342 line and raised to a live weight of 2.2kg on a conventional diet formulation, were 5.90 kg CO₂
 343 eqv., 11.2 m², 0.068 kg and 0.016 kg for GHG, ALU, N and P respectively (Appendix D, Fig.
 344 D.1 – D.4). The percentage inclusion of each ingredient in each diet formulated for this study
 345 is presented in Appendix B (Table B.5 and B.6). The trend in the environmental burdens
 346 shown between diet formulations was similar for both meat-producing chicken lines that
 347 were considered (Fig. 2 and 3). Slow-growing birds have a lower protein requirement for
 348 protein per kg of feed than birds of the fast-growing line (Appendix B, Table B.3 and B.4),
 349 hence the slow-growing birds' diets consistently contained less soybeans and soybean
 350 derivatives (where incorporated) to meet the bird growth requirements. Thus, per kg of feed,
 351 diets formulated for slower growers had a lower GHG and ALU, than the diets formulated
 352 with the same objectives for the fast-growing line. Despite this, rearing a slow-growing bird
 353 resulted in an increase of every environmental burden considered in this study compared to
 354 rearing a fast-growing bird to the same live weight, for every diet formulation (Fig. 2). This
 355 was due to the increase in the total feed required by the slow-growing line to reach slaughter
 356 weight (4.39 kg) compared to the fast-growing line (3.49 kg) (Tallentire et al., 2018).

357 For every alternative diet formulated with a fixed inclusion of one novel ingredient, at least
 358 two burdens were reduced compared to the Conventional diets (Fig. 2). With the exception
 359 of the Insect meal diets, the total P in the excreta was the environmental burden that was
 360 least affected in each diet with a fixed inclusion of one novel ingredient, when compared to
 361 the Conventional diets. The Insect meal diets were also the only diets to reduce three

362 burdens compared to the Conventional diets. With the exception of the Macroalgae diet, the
 363 total N excretion was the environmental burden most affected in each diet with a fixed
 364 inclusion of one novel ingredient, compared to the Conventional diets. The total N excretion
 365 was increased in every diet with a fixed inclusion of one novel ingredient compared to the
 366 conventional diets, but the increase was greater in the fast-growing line (Fig. 2a) than in the
 367 slow-growing line (Fig. 2b). ALU was the only environmental burden to be reduced in every
 368 diet with a fixed inclusion of one novel ingredient, compared to the Conventional diet.

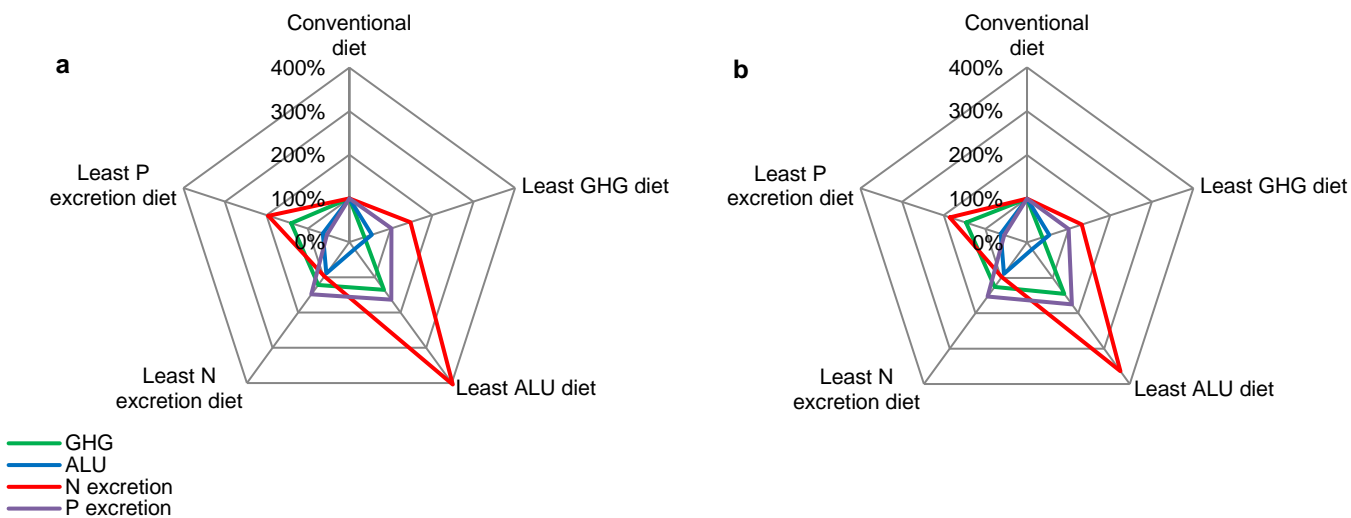


369

370 Figure 2: The environmental burdens of the Microalgae, Macroalgae, Duckweed, Yeast
 371 protein concentrate (YPC), Bacterial protein meal (BPM), Leaf protein concentrate (LPC)
 372 and Insect meal diets are represented as a percentage of the Conventional diets (also
 373 displayed). The environmental burdens shown in the spider charts are greenhouse gas
 374 (GHG; CO₂ eq.), agricultural land use (ALU; m²), nitrogen excretion (N; kg) and phosphorus
 375 excretion (P; kg). The burdens of producing the total feed required by chicken, of a fast-
 376 growing line (a) and a slow-growing line (b), to reach a 2.2kg live weight are presented.

377 The lowest value for each environmental burden was axiomatically achieved by the
 378 alternative diet formulated to reduce that burden specifically (Appendix B, Table B.5 and
 379 B.6). For instance, in the Least GHG and Least ALU diets this was achieved by reducing the
 380 inclusion of soybeans and soybean derivatives to zero; this protein was replaced by
 381 incorporating the novel ingredients. The Least ALU diet was the only formulation that
 382 resulted in the increase in three burdens compared to the Conventional diets (Fig 2). With
 383 the exception of the Least N excretion diets, the total N in the excreta was the environmental
 384 burden most affected by minimising a specific environmental burden, compared to the
 385 Conventional diets. Only the Least N excretion diets reduced the N excretion compared the
 386 Conventional diets; this was also the only formulation that included soybean derived
 387 ingredients at a higher level than in the Conventional diets. Again, ALU was the only

388 environmental burden to be reduced in every diet formulated to reduce specific
 389 environmental burdens, compared to the Conventional diets.



390

391 Figure 3: The environmental burdens of the Least Greenhouse gas (GHG), Least
 392 Agricultural land use (ALU), Least N excretion and Least P excretion diets represented as a
 393 percentage of the Conventional diets (also displayed). The environmental burdens shown in
 394 the spider charts are greenhouse gas (GHG; CO₂ eq.), agricultural land use (ALU; m²),
 395 nitrogen excretion (N; kg) and phosphorus excretion (P; kg). The burdens of producing the
 396 total feed required by chicken, of the fast-growing line (a) and the slow-growing line (b), to
 397 reach a 2.2kg live weight are presented.

398 For both meat-producing chicken lines, each alternative diet formulation generated similar
 399 percentage changes for every environmental burden compared to the corresponding
 400 Conventional diet (Fig. 2 and 3). When compared to the Conventional diet formulated for the
 401 fast-growing line, some environmental burdens of the alternative diets formulated for slow-
 402 growers were similar or reduced. For instance, the Least GHG diet formulated for the slow-
 403 growing line reduced the GHG and the ALU by 55% and 32% respectively and increased the
 404 N and P in the excreta by 99% and 29% respectively, when compared to the Conventional
 405 diet formulated for and fed to the fast-growing line. In another example, the Insect meal diet
 406 formulated for the slow-growing line reduced the GHG and the ALU and P in the excreta by
 407 3.1%, 37% and 17% respectively, and increased the N in the excreta by 108%, when
 408 compared to the Conventional diet formulated for and fed to the fast-growing line.

409 The outputs of the uncertainty analysis are provided in full in the Appendix C (Table C.2).
 410 The uncertainty analysis showed only two cases of uncertainty in the results when
 411 comparing the environmental burdens of the alternative diets to the Conventional diet (i.e.
 412 the alternative diets had a greater or lower value than the Conventional diet for any one
 413 environmental burden in <95% of the parallel simulations). These were the Insect meal diet

414 and the Least ALU diet, the commonality between these diets was that both incorporated
415 insect meal. For all results the alternative diets had a consistently greater or consistently
416 lower impact than the Conventional diet in >90% of the parallel simulations.

417 3.2. *Sensitivity analysis*

418 The model was sensitive (i.e. change in at least one burden was $\geq \pm 5\%$ the mean in at least
419 one diet) to the coefficient of variation in the yield of microalgae, BPM, LPC and insect meal
420 (Appendix C, Table C.3). The N and P excretion was only affected where the change in
421 production yield led to an alternative diet formulation, e.g. when the LPC was reduced in the
422 Least GHG diet. The N and P excretion was however not sensitive to the variation in the
423 production yield (change $< \pm 5\%$ the mean).

424 The GHG and ALU burdens of microalgae, macroalgae and LPC were sensitive to changing
425 the economic allocation data that was applied to the base model (Appendix C, Table C.4),
426 hence the diets which incorporated these ingredients showed high sensitivity to this
427 assumption, namely the Microalgae, Macroalgae, LPC, Least GHG, Least ALU and Least P
428 excretion diets. The fast-growing line's Least ALU diet was the only diet where the
429 formulation was altered and the changes were small: the inclusion of wheat, monocalcium
430 phosphate, duckweed and LPC were all reduced whilst YPC was increased by 0.99% of the
431 total feed.

432 Finally, changing the maximum inclusion of each novel ingredient axiomatically affected the
433 diet formulation of the Microalgae, Macroalgae, Duckweed, YPC, BPM, LPC and Insect meal
434 diets. Lowering the maximum inclusion of some of the novel ingredients also affected the
435 formulations of the diets that minimised GHG, ALU and P excretion (Appendix C, Table C.5),
436 however not the Least N excretion diets, since no novel ingredients were incorporated into
437 these diets.

438 4. Discussion

439 Europe faces increased pressure for feed protein supplies from a global population which is
440 growing annually in size and appetite for animal products, especially in developing nations
441 (van Krimpen et al., 2013). Low self-sufficiency of protein supply for the increasing
442 production of chicken meat exposes Europe to food security risks, which may be related to
443 market factors such as trade distortions, global price volatility and ingredient scarcity.
444 Furthermore, feed provision represents the poultry industry's biggest environmental hotspot
445 (Leinonen et al., 2012; Tallentire et al., 2017), exacerbated by the inclusion of imported
446 soybeans from South America where they are grown in vast monocultures on land obtained

447 via deforestation (de Visser et al., 2014; Kebreab et al., 2016; Leinonen et al., 2012; van der
448 Werf et al., 2009). Meanwhile, the chicken meat industry is facing increasing pressure to
449 improve animal welfare by reducing growth rates (Compassion in World Farming, 2017; Efsa
450 Panel on Animal Health and Welfare, 2010; Jansen, 2014; RSPCA, 2015), which leads to
451 increased feed intake (Tallentire et al., 2018). Tackling these future challenges, whilst still
452 meeting the demands of stakeholders and society in general, will continue to be a key
453 objective of the poultry industry (The Poultry Site, 2014). It is therefore highly relevant to
454 investigate novel ingredients as an alternative protein source to imported soybeans for
455 feeding future meat-producing chicken lines, in European livestock systems.

456 The Microalgae, YPC, BPM, LPC and Insect meal diets all had lower associated GHG
457 emissions than the Conventional diets, whilst incorporating macroalgae and duckweed into
458 the diets resulted in greater GHG emissions than the Conventional diets. Macroalgae and
459 duckweed have low energy contents relative to conventional protein and energy sources
460 (e.g. soymeal and wheat respectively), hence the energy deficit caused by the incorporation
461 of these ingredients was largely counteracted by the increased incorporation of oil and maize
462 gluten meal which increased the GHG burden of the diets. Insect meal replaced the most
463 soybeans and soybean derivatives. This is due, in part, to its high maximum inclusion limit,
464 but also due to its high energy content relative to (for example) BPM, which was the next
465 best novel ingredient at replacing the need for soybeans and soybean derivatives. The
466 Insect meal diet, therefore, had the lowest oil inclusion of all the alternative diets. Despite
467 this, the BPM diet had a lower GHG burden due to BPM having the lowest associated GHG
468 emission of all the novel ingredients included in this study.

469 Since the arable land in developed countries has declined in recent decades and this trend
470 is expected to continue into the future, reducing the ALU burden of European livestock
471 production is important in maximising the global carrying capacity (Alexandratos and
472 Bruinsma, 2012). Every diet that included novel ingredients formulated in this study had an
473 overall lower ALU burden than the Conventional diet corresponding to the requirements of
474 each meat-producing chicken line. This is because the cultivation of the novel ingredients
475 was intrinsically associated with low arable land requirements, especially the aquatic novel
476 ingredients and BPM. LPC, YPC and insect meal all had a higher ALU burden due to the
477 requirement of arable land to produce the feedstock used in these system processes, but all
478 these novel ingredients had a lower ALU burden than soybeans and their derivatives.

479 In order to meet bird nutritional requirements whilst minimising a specific objective, some of
480 the diets formulated using this model incorporated conventional ingredients that were not
481 present in the Conventional diet formulation (Appendix B, Table B.5 and B.6). For instance,

482 barley, and to a lesser extent sunflower meal, was incorporated into the Insect meal diets.
483 Including these ingredients ensured that the dietary threonine and arginine levels reached at
484 least their minimum requirements, since these amino acids are low in insect meal relative to
485 soymeal, for the least cost. Due to their low crude protein content, oats were only
486 incorporated in the Least N excretion diets. The utilization of conventional yet less commonly
487 used ingredients to meet bird nutritional requirements, alongside potential novel ingredients,
488 highlights the advantages of performing a holistic approach to diet formulation such as what
489 was carried out in this study. More generally, incorporating additional ingredients provides a
490 market for a diversity of crops which in turn diversifies farming systems and leads to positive,
491 indirect effects on soil quality, as well as insect and bird biodiversity.

492 No alternative diet formulated using the model presented in this study reduced all four
493 environmental burdens simultaneously, when compared to the Conventional diets. GHG
494 emissions are often prioritised when it comes to quantifying environmental burdens in
495 literature, corporate social responsibility reports, policy or voluntary carbon labelling
496 schemes (Garnett, 2009; Tan et al., 2014). However, targeting an individual environmental
497 burden can have huge implications on other types of environmental impact caused by a
498 production system in a phenomenon often referred to as “pollution swapping” (Stevens and
499 Quinton, 2009). For instance, minimising ALU resulted in the greatest nutrient excretions
500 (Fig. 3); this is because of the high inclusion of novel ingredients which resulted in the
501 oversupply of important nutrients in the diets. Formulating diets to reduce certain
502 environmental burdens within specified economic and environmental constraints has been
503 shown in previous studies (Castrodeza et al., 2005; Dubeau et al., 2011; Mackenzie et al.,
504 2016a; Moraes and Fadel, 2013; Pomar et al., 2007; Tallentire et al., 2017), and can be
505 applied in the future when incorporating novel ingredients such as the ones discussed here.
506 This methodology could therefore allow nutritionists to integrate environmental objectives
507 into system specific diet formulation. For instance, to reduce the GHG and ALU burdens of
508 systems where manure can be managed sustainably, or to limit the excretion of N in nitrate
509 vulnerable zones. In some cases the novel ingredients themselves show huge potential for
510 mitigating the negative impacts of these future chicken diets, such as by integrating
511 duckweed ponds at the end of the livestock systems as a manure management option, thus
512 contributing towards a circular economy (Cheng et al., 2002; Krishna and Polprasert, 2008;
513 Xu and Shen, 2011). This gives nutritionists and livestock producers the option to integrate
514 environmental objectives into diet formulation, facilitating bespoke feeding strategies and
515 management choices specific to individual systems.

516 Whilst the total environmental burdens of feeding the birds each diet were greater for the
517 slower-growing line than they were for the fast-growing line, in some cases the incorporation
518 of novel ingredients led to the slow-growing line having at least some environmental burdens
519 that were lower than those of the fast-growing line fed on a Conventional diet formulation.
520 Incorporating microalgae, BPM, LPC and insect meal all reduced at least two environmental
521 burdens of the slow-growing birds, compared to fast-growers reared on the Conventional
522 diet. This shows that the environmental burdens of feed associated with transitioning
523 towards a slow-growing, high welfare chicken production system can be partially mitigated
524 through carefully considered nutritional and manure management.

525 The sensitivity analysis revealed that the GHG and ALU were sensitive to the coefficient of
526 variation in the yield of microalgae, BPM, LPC and insect meal. Further research into the
527 production efficiency of these ingredients would strengthen the model. Sensitivity was shown
528 to variation in the economic allocation input data, however only one diet formulation was
529 changed by altering the economic value of the coproducts; this revealed that our allocation
530 method was sufficiently robust to allow the tool to generate diet formulations for specific
531 sustainability objectives. At least one environmental burden was sensitive to reducing the
532 maximum inclusion level of macroalgae, duckweed, LPC and insect meal in most diets
533 where incorporation of these ingredients were fixed at that inclusion level. In addition,
534 reducing the maximum inclusion level of microalgae, macroalgae, BPM, LPC and insect
535 meal all affected the formulation of at least one diet designed to reduce an environmental
536 burden. This demonstrates the importance of, where possible, not constraining the diet
537 formulation process with overly conservative maximum inclusion limits, as to maximise the
538 potential sustainability of the industry (Mackenzie et al., 2016a).

539 Whilst the use of imported soybeans in European livestock feed is unsustainable, thus far
540 only a few studies have addressed the implications of using alternative proteins for system
541 level environmental impacts (e.g. de Boer et al., 2014; Leinonen et al., 2013; Van Zanten et
542 al., 2015). This is the first study to investigate the potential of several novel ingredients
543 simultaneously to reduce the total required soybeans in future chicken diets, by combining
544 linear programming feed formulation and a LCA methodology with horizon scanning. By
545 applying this to two potential future meat-producing chicken lines, it enables nutritionists,
546 livestock producers, breeders and policy makers to integrate environmental objectives into
547 future feeding and breeding strategies. Comparing the environmental implications of each
548 novel ingredient in this way is an important step when considering which novel technologies
549 could produce the most sustainable outcomes.

550 **5. Conclusion**

551 We have presented a holistic diet formulation methodology which accounts for both
552 environmental burdens and future livestock requirements. Novel ingredients were
553 incorporated into these diets, which display enormous potential for use as alternatives to
554 soybeans in meat-producing chicken diets in the future. However, the technologies being
555 developed to produce these novel ingredients are still in their infancy; much work is required
556 to viably upscale these system processes so that production is efficient and competitive with
557 imported soybeans. Additional research is still required in the characterization of these
558 ingredients and their effects on specific livestock before they can become viable feed
559 alternatives. In some cases, their incorporation into the diets face technical challenges and
560 legislative barriers e.g. the inclusion of insects in EU poultry diets. Nevertheless, we have
561 shown that increased environmental burdens associated with increasing animal welfare may
562 be mitigated through carefully integrated nutrition and manure management systems. Most
563 importantly in terms of Europe's future food security, we have shown how imported
564 soybeans can be replaced in chicken diets. Such work is crucial in efforts to improve the
565 sustainability of livestock systems moving forward.

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570 **Competing financial interests**

571 There are no conflicts of interest.

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