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

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

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

## 1. Introduction

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

The poultry industry (meat-producing chickens, egg laying hens, turkeys etc.) collectively consumes the most soybeans of any livestock sector in Europe (van Gelder et al., 2008). This protein requirement is set to increase further as the demand for chicken meat, in particular, continues to grow (Alexandratos and Bruinsma, 2012; FAO, 2016). In addition, the inclusion of valuable conventional protein sources of animal origin in livestock feed are either limited (e.g. fishmeal) or banned (e.g. meat and bone meal) in the EU (Brookes, 2001; European Commission, 2001), whilst growing soybeans in Europe is non-competitive with imports due to relatively low yields and a long growing season (van Krimpen et al., 2013). Thus, the poultry industry is presented with the challenge of providing an adequate and more sustainable supply of protein to feed meat-producing chickens in Europe.

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

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

Thus, the overall aim of our study was to assess the environmental implications of incorporating novel ingredients into the feeding strategy of future chicken meat production systems. The novel ingredient inventory was modelled in feeding scenarios, based on the nutritional requirements of future meat-producing chicken lines which were predicted in a previous study (Tallentire et al., 2018). Whilst the environmental impacts of some of these novel ingredients have been assessed in the past (e.g. Aitken et al., 2014; de Boer et al., 2014; Jorquera et al., 2010; Oonincx and de Boer, 2012), this is the first time the environmental burdens of all seven ingredients have been calculated systematically by applying a common methodology and reported in contrast to the use of imported soybeans as the main protein source in chicken feed. A sensitivity analysis developed in previous studies was also employed here to identify any substantial uncertainty in our projections (Mackenzie et al., 2015; Tallentire et al., 2017). This is the first study to demonstrate and compare the potential environmental trade-offs of incorporating novel ingredients into chicken meat production systems, whilst also accounting for the requirements of future genetic lines and their implications.

## 2. Methods

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

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

The model inputs included: a detailed inventory of feed production (section 2.2.), the total feed intake and body composition of future chicken lines, their nutritional requirements and the nutrient content of all ingredients included within the feed formulation calculation. The model structure can be summarised as follows: all diets were formulated for a fixed set of minimum nutritional requirements for the different growth phases modelled, i.e. the starter, grower and finisher phases. Two meat-producing lines were considered. Since the nutritional requirement of each line was met in every diet formulated, it was presumed that bird growth rate per kg of feed consumed was unaffected between different diets. The methodology for calculating the nutritional requirements of these two future meat-producing chicken lines is discussed below (section 2.3). Maximum and minimum limits constrained the inclusion of each ingredient in each diet to ensure that issues of palatability, inhibition of digestibility or variability in specific ingredients did not adversely affect bird performance i.e. growth rate or carcass composition. The methodology also assumed meat quality would not be adversely affected. Although some of the novel ingredients have been shown to have a positive effect on bird health (Bovera et al., 2016; Pulz and Gross, 2004; Qureshi et al., 1996) and performance (Shanmugapriya and Saravana Babu, 2014), this was not included within the scope of this study. Environmental burden values were assigned to each ingredient, conventional and novel, in order to determine the environmental implications of formulating each diet for future chicken meat production. Finally, the environmentally important nutrients excreted by the bird were calculated based on mass balance.

### *2.2. Model inventory and system boundary.*

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

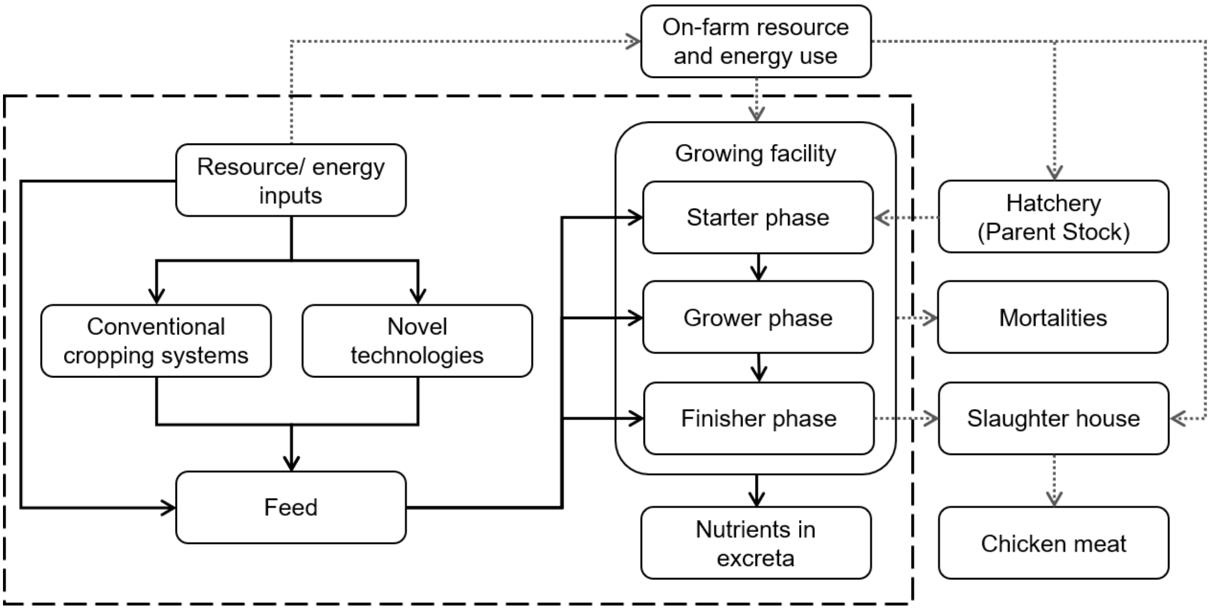

Figure 1: The structure and main components of the chicken meat production systems as considered by the Life Cycle Assessment (LCA) model in this study; the inputs that were considered (solid line arrows), the inputs that were not considered (dotted line arrows) and the system boundary (dashed line)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

### *2.3. Future bird nutritional requirements.*

The nutritional specifications were based on two breeding scenarios that were presented in Tallentire et al. (2018) via horizon scanning which result in: 1) a fast-growing line based on the apparent maximum feed efficiency that could be achieved through further artificial selection and 2) a reduced growth rate for high welfare line (Table 1). For the two scenarios, total energy requirement was quantified based on predictions of the biological limits of digestive efficiency, protein and lipid growth and the metabolic rate of heat production (Tallentire et al., 2018). The difference in the traits between these future meat-producing lines and current commercial meat-producing chickens is low (Aviagen, 2014a, 2016; Fancher, 2014), thus it is reasonable to expect these lines will be achieved before the novel technologies outlined in this study come into wide scale operation. Since there is no evidence that the efficiency of protein utilization has changed as a result of selective breeding, the protein requirements of the meat-producing chicken lines were calculated based on the current baselines for feed intake, feed protein content and body composition (Aviagen, 2014b, 2016). In this way the protein utilization efficiency equates to the protein retained in the body (kg) divided by the protein intake (kg) of one bird. The requirements of the future lines could therefore be calculated as follows: first the change in energy requirement, and therefore the feed intake, was calculated whilst keeping the feed energy content unchanged from current requirements. Then, the nutrient requirements of the new birds were estimated based on the changes in feed intake and in bird requirements, (the change of nutrient requirement was assumed to be proportional to the change of protein requirement). The new diets could then be constructed to meet these requirements (Appendix B, Table B.3 and B.4).

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

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

### *2.4. Diet formulation rules.*

The novel ingredients were selected based on five criteria: 1) The ingredient could potentially serve as an alternative to imported soybeans in livestock diets. 2) The incorporation of the ingredient into chicken diets was not common practice already. 3) The maximum inclusion limit of the novel ingredient, its digestible amino acid profile and metabolizable energy content were available in the literature. 4) Production in Europe is a realistic option for the future. 5) Enough data was available to compile an inventory of relevant energy and material inputs and environmental releases related to the novel ingredient. Seven novel ingredients were identified for inclusion within the scope of this study: microalgae, macroalgae, duckweed, YPC, BPM, LPC and insect meal. For each of these ingredients a production inventory (Appendix A, Fig. A.1 – A.7 and Tables A.1 – A.7) and nutritional profile (Appendix B, Table B.1) was compiled.

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

Inclusion limits of conventional ingredients were based on input data from literature, national inventory reports, databases and expert advice (Tallentire et al., 2017). The maximum inclusion of each novel ingredient in the grower-finisher phases was determined from assessing literature, in which the effects of inclusion rates on bird performance were measured (Appendix B, Table B.2); the maximum inclusion in the starter phases was 50% of this value as a conservative estimate (Leinonen et al., 2013). For the three ingredients sourced from aquatic based systems, microalgae (venkataraman et al., 1994), macroalgae (Ventura et al., 1994) and duckweed (Haustein et al., 2009), a consistent maximum inclusion limit of 18% was modelled. Maximum YPC inclusion rates are particularly variable due to issues with its nutritional characterization; an inclusion of 20% was determined to be feasible without negatively affecting bird performance (Scholey et al., 2016; Scholey et al., 2014). BPM has been shown at 10% inclusion with no negative effect on chicken growth performance (Schøyen et al., 2007; Skrede et al., 2003; Whittemore et al., 1978). It is expected that LPC should have very similar properties to other plant protein and replace soymeal completely in the grower-finisher phases at a maximum inclusion level of 40% (Ameenuddin et al., 1983). Insect meal had a maximum inclusion of 30% (Bovera et al., 2016); although beneficial to the immune system, chitin can limit digestibility beyond this inclusion level. It should be kept in mind that insect meal would not be allowed to be incorporated into poultry diets under current EU law, however the regulation has recently been relaxed so that insects can be utilised in aquaculture systems (European Commission, 2017; Józefiak and Engberg, 2015) and its incorporation into other livestock feeds continues to be championed in scientific literature (Marberg et al., 2017).

### 2.5. Environmental burden assessment.

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

Over 70% of the GHG associated with chicken meat production can be attributed to feed provision (Leinonen et al., 2012). In this study the GHG was measured in $CO_2$ equivalent ($CO_2$ eq.) with a 100-year timescale in accordance with the IPCC (2006) emissions factors. The ALU was calculated based on the total land occupation and the total area of land which was transformed for the functional unit (Guinée et al., 2002). Calculation of the GHG emissions and ALU followed the ReCiPe methodology (Goedkoop et al., 2008). Notably, soybeans and soymeal carry a high GHG footprint due to associated deforestation; the $CO_2$ eq. released due to land transformation, such as for soybean production, was included according to the PAS2050:2012-1 methodology (BSI, 2012).

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

### 2.6. Analysis

In total 24 diets were formulated, with 12 for each future meat-producing chicken line. The results were analysed by comparing the environmental burdens caused by each alternative diet scenario with those of the Conventional diet from the corresponding line using the mean values produced by the model. An uncertainty analysis was also conducted using parallel Monte Carlo simulations. For each alternative diet scenario, the model was simulated 1000 times to calculate the environmental burdens of the alternative diet as compared with those of the Conventional diet from the corresponding line. Input parameters were randomly assigned a value along their defined distribution in each simulation; parallel simulations were used to account for shared uncertainty between the two diet scenarios (Mackenzie et al., 2015; Tallentire et al., 2017). The output of the uncertainty analysis was the probability that the environmental burdens of each diet were larger or smaller than the Conventional diet for each impact category. A table of the parameters included in the uncertainty analysis and their assigned distributions can be found in Appendix C (Table C.1).

### *2.7. Sensitivity*

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

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

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

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

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

## 3. Results

### *3.1. Environmental burdens of diets*

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

Table 2: The environmental burdens of soymeal and each novel ingredient included in this study as alternative protein sources. The Greenhouse gas (GHG) emissions and agricultural land use (ALU) associated with the production of 1 kg of each ingredient are presented. The 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 |

The environmental burdens of producing the total feed required by a chicken, of a fast-growing line and raised to a live weight of 2.2kg on a conventional diet formulation, were 4.96 kg $CO_2$ eqv., 8.84 $m^2$, 0.045 kg and 0.011 kg for GHG, ALU, N and P respectively. The environmental burdens of producing the total feed required by a chicken, of a slow-growing line and raised to a live weight of 2.2kg on a conventional diet formulation, were 5.90 kg $CO_2$ eqv., 11.2 $m^2$, 0.068 kg and 0.016 kg for GHG, ALU, N and P respectively (Appendix D, Fig. D.1 – D.4). The percentage inclusion of each ingredient in each diet formulated for this study is presented in Appendix B (Table B.5 and B.6). The trend in the environmental burdens shown between diet formulations was similar for both meat-producing chicken lines that were considered (Fig. 2 and 3). Slow-growing birds have a lower protein requirement for protein per kg of feed than birds of the fast-growing line (Appendix B, Table B.3 and B.4), hence the slow-growing birds' diets consistently contained less soybeans and soybean derivatives (where incorporated) to meet the bird growth requirements. Thus, per kg of feed, diets formulated for slower growers had a lower GHG and ALU, than the diets formulated with the same objectives for the fast-growing line. Despite this, rearing a slow-growing bird resulted in an increase of every environmental burden considered in this study compared to rearing a fast-growing bird to the same live weight, for every diet formulation (Fig. 2). This was due to the increase in the total feed required by the slow-growing line to reach slaughter weight (4.39 kg) compared to the fast-growing line (3.49 kg) (Tallentire et al., 2018).

For every alternative diet formulated with a fixed inclusion of one novel ingredient, at least two burdens were reduced compared to the Conventional diets (Fig. 2). With the exception of the Insect meal diets, the total P in the excreta was the environmental burden that was least affected in each diet with a fixed inclusion of one novel ingredient, when compared to the Conventional diets. The Insect meal diets were also the only diets to reduce three burdens compared to the Conventional diets. With the exception of the Macroalgae diet, the total N excretion was the environmental burden most affected in each diet with a fixed inclusion of one novel ingredient, compared to the Conventional diets. The total N excretion was increased in every diet with a fixed inclusion of one novel ingredient compared to the conventional diets, but the increase was greater in the fast-growing line (Fig. 2a) than in the slow-growing line (Fig. 2b). ALU was the only environmental burden to be reduced in every diet with a fixed inclusion of one novel ingredient, compared to the Conventional diet.

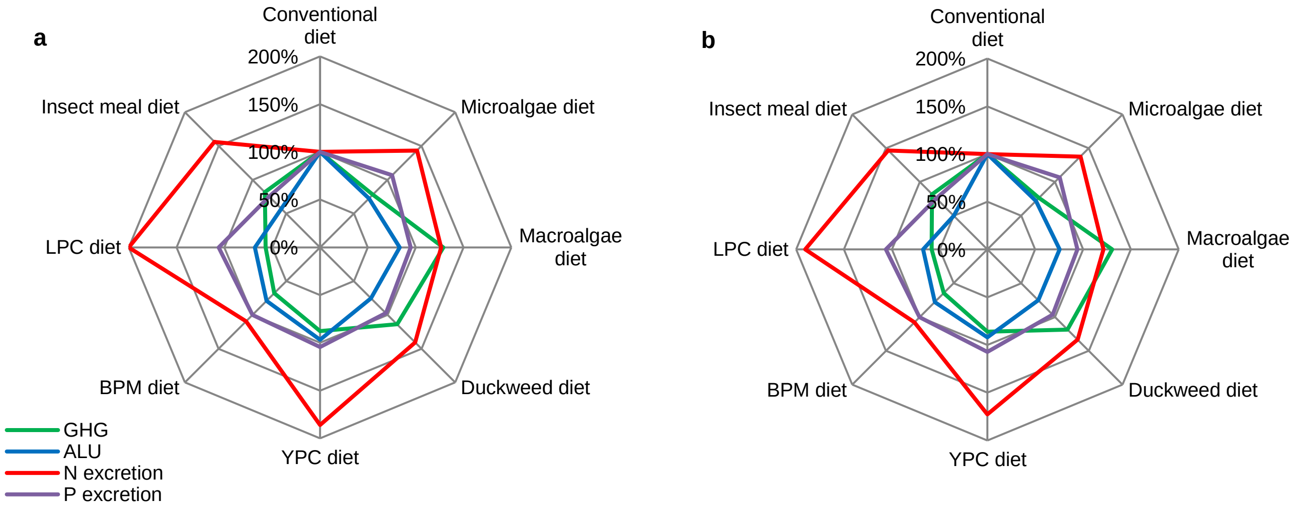

Figure 2: The environmental burdens of the Microalgae, Macroalgae, Duckweed, Yeast protein concentrate (YPC), Bacterial protein meal (BPM), Leaf protein concentrate (LPC) and Insect meal diets are represented as a percentage of the Conventional diets (also displayed). The environmental burdens shown in the spider charts are greenhouse gas (GHG; $CO_2$ eq.), agricultural land use (ALU; $m^2$), nitrogen excretion (N; kg) and phosphorus excretion (P; kg). The burdens of producing the total feed required by chicken, of a fast-growing line (**a**) and a slow-growing line (**b**), to reach a 2.2kg live weight are presented.

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

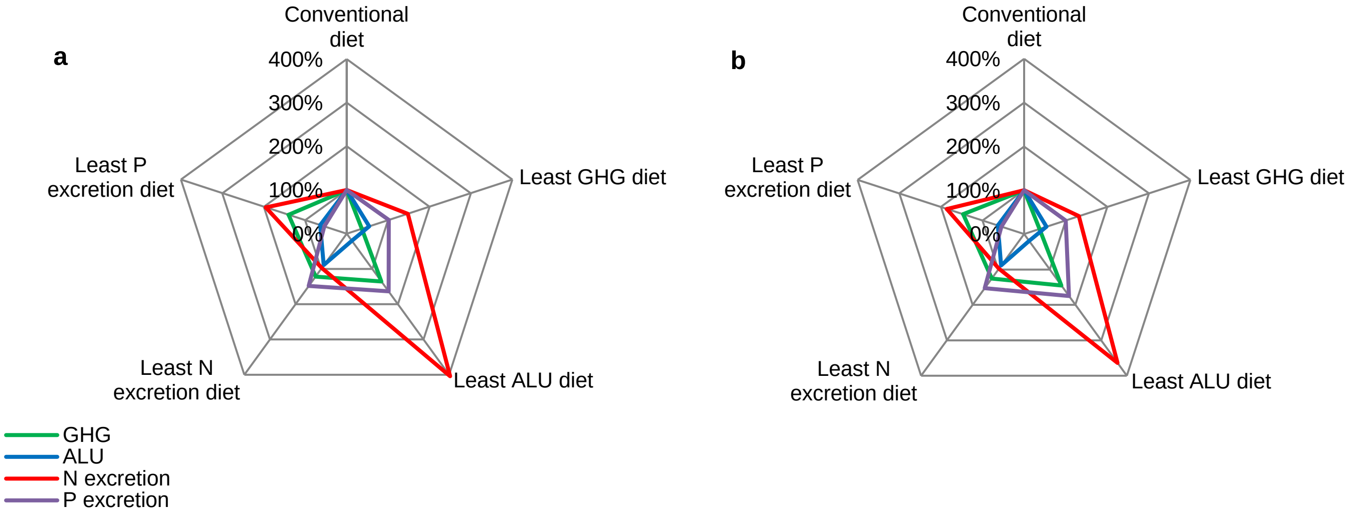

Figure 3: The environmental burdens of the Least Greenhouse gas (GHG), Least Agricultural land use (ALU), Least N excretion and Least P excretion diets represented as a percentage of the Conventional diets (also displayed). The environmental burdens shown in the spider charts are greenhouse gas (GHG; $CO_2$ eq.), agricultural land use (ALU; $m^2$), nitrogen excretion (N; kg) and phosphorus excretion (P; kg). The burdens of producing the total feed required by chicken, of the fast-growing line (**a**) and the slow-growing line (**b**), to reach a 2.2kg live weight are presented.

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

The outputs of the uncertainty analysis are provided in full in the Appendix C (Table C.2). The uncertainty analysis showed only two cases of uncertainty in the results when comparing the environmental burdens of the alternative diets to the Conventional diet (i.e. the alternative diets had a greater or lower value than the Conventional diet for any one environmental burden in <95% of the parallel simulations). These were the Insect meal diet and the Least ALU diet, the commonality between these diets was that both incorporated insect meal. For all results the alternative diets had a consistently greater or consistently lower impact than the Conventional diet in >90% of the parallel simulations.

### *3.2. Sensitivity analysis*

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

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

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

## 4. Discussion

Europe faces increased pressure for feed protein supplies from a global population which is growing annually in size and appetite for animal products, especially in developing nations (van Krimpen et al., 2013). Low self-sufficiency of protein supply for the increasing production of chicken meat exposes Europe to food security risks, which may be related to market factors such as trade distortions, global price volatility and ingredient scarcity. Furthermore, feed provision represents the poultry industry's biggest environmental hotspot (Leinonen et al., 2012; Tallentire et al., 2017), exacerbated by the inclusion of imported soybeans from South America where they are grown in vast monocultures on land obtained via deforestation (de Visser et al., 2014; Kebreab et al., 2016; Leinonen et al., 2012; van der Werf et al., 2009). Meanwhile, the chicken meat industry is facing increasing pressure to improve animal welfare by reducing growth rates (Compassion in World Farming, 2017; Efsa Panel on Animal Health and Welfare, 2010; Jansen, 2014; RSPCA, 2015), which leads to increased feed intake (Tallentire et al., 2018). Tackling these future challenges, whilst still meeting the demands of stakeholders and society in general, will continue to be a key objective of the poultry industry (The Poultry Site, 2014). It is therefore highly relevant to investigate novel ingredients as an alternative protein source to imported soybeans for feeding future meat-producing chicken lines, in European livestock systems.

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

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

In order to meet bird nutritional requirements whilst minimising a specific objective, some of the diets formulated using this model incorporated conventional ingredients that were not present in the Conventional diet formulation (Appendix B, Table B.5 and B.6). For instance, barley, and to a lesser extent sunflower meal, was incorporated into the Insect meal diets. Including these ingredients ensured that the dietary threonine and arginine levels reached at least their minimum requirements, since these amino acids are low in insect meal relative to soymeal, for the least cost. Due to their low crude protein content, oats were only incorporated in the Least N excretion diets. The utilization of conventional yet less commonly used ingredients to meet bird nutritional requirements, alongside potential novel ingredients, highlights the advantages of performing a holistic approach to diet formulation such as what was carried out in this study. More generally, incorporating additional ingredients provides a market for a diversity of crops which in turn diversifies farming systems and leads to positive, indirect effects on soil quality, as well as insect and bird biodiversity.

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

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

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

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

## 5. Conclusion

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

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## Competing financial interests

There are no conflicts of interest.

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