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Feeding the 45 Million:

Substituting soybean protein with insect protein within EU
poultry & egg production

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Abstract

A global population increasing both in number and in resource consumption per capita has resulted in food, livestock feed and energy crop demands that are increasingly difficult to meet on rapidly degrading soils within a diminishing available area of arable land. With further expansion of agricultural land infeasible and yield increases through further intensification insufficient to meet the scale of predicted crop demand, the use of insects as an animal feed has gained traction as a method of not only reducing competition for arable land, but also some of the detrimental environmental consequences of livestock and conventional feed production. However, while recent years have seen an explosion of academic studies investigating aspects of the use of insects as a livestock feed, there has been very little work investigating the potential ramifications of insect production and use at a scale on par with existing livestock feed products. With soybean one of the most popular livestock feed components, the EU one of the largest soy importers in the world and chickens the largest consumer of compound livestock feed, this study substitutes soybean meal-based protein utilised within EU poultry and egg production with protein from three insect species - each proven to be a viable dietary substitute for soybean protein - at ratios of up to 100%. The results of this study indicate that the protein currently provided to EU poultry & egg production through soybean meal could be entirely replaced with insect-based meal using less than 1% of the land currently used for protein production. This would represent the saving of over 4.6 Mha of soybean crop or fertile arable land that could potentially be made available for alternative uses. Further, this study finds the redundant soybean crop able to meet the complete annual calorific requirements of up to 45 million people, with further potential benefits of large-scale insect production including significant quantities of biofertiliser and biodiesel, as well as the possible aiding of the implementation of carbon-sequestering and soil-retaining alternative farming methods. With the use of waste side-stream substrates during insect production key to potential land-use reductions, sourcing sufficient amounts of appropriate waste side-streams without compromising alternative waste uses is likely to be a major obstacle to a large-scale substitution, despite EU regulations and public opinion increasingly accepting of the use of insects as a livestock feed. Other problems such as significant energy usage and technological barriers are largely considered to be a result of the burgeoning nature of the industry, though the poikilothermic nature of insects implies possible limitations to insect production in colder climates. This study concludes that substitution of soybean meal-based protein with insect-based protein has the potential to positively impact a variety of upcoming global issues such as diminishing arable lands, increasing resource consumption and increasing crop demand, with a lack of published academic data regarding large-scale insect production providing exciting future research opportunities.

Keywords: Insects, Insect Production, Livestock Feed, Entomophagy, Land Use, Futures Research, Food Security, Energy Security, Black Soldier Fly, Mealworm, House Cricket, Sustainable Development

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1 Introduction

A multitude of complex, interconnected, global-scale problems are currently converging. With global population predicted to exceed 9 billion before 2050 (FAO, 2018), it is becoming increasingly difficult to foresee how demand for critical food, energy and water resources can be met in the context of diminishing natural resource availability, environmental degradation and climate change. Compounding this, the continuing urbanisation, industrialisation and socioeconomic progress of developing countries is expected to fuel the greenhouse gas emissions and land use changes that exacerbate existing environmental challenges through further climate and ecosystem impacts (Al-mulali et al., 2012, Grimm et al., 2008, McKinney, 2002, Wu et al., 2016), reinforced by the exponential nature of the global economic system (Lenzen et al., 2012).

One of the most significant impacts of these socioeconomic changes has been the growth of the global middle class, as rising incomes erode the disparity in animal product consumption patterns between developing and developed countries (Wheary, 2009). Annual consumption of animal products in developing countries more than doubled between 1973 and 1998 to 25kg per capita (Delgado, 2003), and by 2030 annual consumption is expected have further increased by over 100kg per capita, matching that seen in developed countries (Robinson and Pozzi, 2011). The equalising of global lifestyles has served to highlight the detrimental environmental impacts of animal products; if we consider planetary boundaries for example (Rockström et al., 2009), animal production severely impacts land-system change, greenhouse gas emissions, freshwater use, biodiversity loss and the nitrogen and phosphorous cycle through fertiliser use. The livestock sector alone accounts for 14.5% of global greenhouse gas emissions (Gerber et al., 2013) and 70% of all available agricultural land (Steinfeld et al., 2006), with beef water footprints exceeding 20 times that of the equivalent cereal production (Mekonnen and Hoekstra, 2012) and biodiversity losses through pasture expansion (Chaudhary et al., 2016).

This period of unprecedented animal product demand has been termed the 'livestock revolution' (Delgado et al., 1999), with the production of animal feed arguably the most detrimental consequence. Not only does the feed supply chain account for 33% of total livestock emissions (FAO, 2016), but one third of available arable land is now dedicated solely to the production of animal feed crops such as soy, wheat and corn (Steinfeld et al., 2006). This is further exacerbated by an increasing global demand for biofuel, which is anticipated to increase significantly as part of climate-change mitigation efforts and provide further competition for valuable arable land (Valentine et al., 2012). In fact, despite an anticipated 43% increase in cereal production by 2050, the majority of these cereals will not be consumed directly by humans. Of the increase in maize production, for example, 60% will be used to feed animals, with a further 23% used as biofuel (Alexandratos and Bruinsma, 2012). In addition, the unrelenting demand for crop products is thought to directly prevent the adoption of less-harmful conservation agriculture (CA) practices (Zikeli and Gruber, 2017). The competition between these vital demands has garnered significant interest as part of the water-energy-food nexus (Smajgl et al., 2016).

The ability to meet these converging demands on finite arable land is of vital importance. Historically, meeting additional crop demand for food, feed and fuel has entailed either the intensification or expansion of arable land. The 'Green Revolution' of the late 1960s onwards saw drastic yield improvements of between 150-200% through the development of intensive farming methods such as high-yielding crop varieties, the use of high-input inorganic fertilisers & pesticides, intensive irrigation and industrial-scale mono-cropping systems (Bernard and Lux, 2016). The use of these farming methods is widely considered

responsible for the reduction of global hunger during this period (IFPRI, 2002, Djurfeldt et al., 2005, Pingali, 2012), but has come at an environmental cost. Intensive farming practices have resulted in major environmental problems including but not limited to: a loss of biodiversity, diminished soil quality, soil salinisation, soil compaction, direct and indirect pesticide hazards, increased disease incidents and as a heavy reliance on fossil fuels (Reddy, 2016). Though intensification has prevented agricultural expansion (Havlik et al., 2014, Reddy, 2016), intensive farming practices have been responsible for the loss of one third of global fertile land in just fifty years (Cameron et al., 2015). Furthermore, though many suggest that yield increases through various methods of efficiency savings and intensification present the most promising pathway towards the meeting of future crop demand (e.g. De Schutter, 2014, Sentelhas et al., 2015, Mottet et al., 2017) current yield increase trends predict that supply will fall far short of the anticipated 2050 crop demand (Ray et al., 2013).

Given then that further intensification is a problematic and likely insufficient method of attempting to meet increasing crop demand, conversion of the estimated 1.4bn ha of potential arable land available in the long-term (Alexandratos and Bruinsma, 2012) and/or the 65 Mha of potential arable land readily accessible in the short term (Sentelhas et al., 2015) would appear to provide an easy solution. However, agriculture already sprawls across 38% of the terrestrial surface of the earth (Kernebeek et al., 2016), with over 5 billion hectares of land currently utilised for agricultural purposes (FAOSTAT 2017). Some 70% of grassland, 50% of savannah, 45% of temperate deciduous forest and 27% of tropical forest biome has already been converted to agriculture (Foley et al., 2011), and the vast majority of the 65 Mha of easily accessible land is only available at the expense of ecosystems of increasingly vital importance (Sentelhas et al., 2015). Compounding this already challenging situation, climate change is predicted to severely impact biodiversity, soil fertility and fresh water availability, while desertification further reduces the amount of viable agricultural land (Steinfeld et al., 2006). Foley et al. (2011) argues that the prevention of agricultural expansion represents the single most important factor in creating sustainable food production systems, and although livestock feed is not always of sufficient quality for direct human consumption (Wu et al., 2014) it nevertheless presents a huge land-use competition for increasingly valuable fertile land.

With the continuation of conventional livestock and agricultural production trends infeasible, the utilisation of insects as a six-legged livestock both for human food and animal feed has been placed firmly on the global agenda by the Food and Agriculture Organisation of the United Nations (FAO) in recent years (Huis et al., 2013). The environmental impacts of insect production compare favourably with poultry, pig and beef production (de Vries and de Boer, 2010), with studies investigating the potential inclusion of a variety of insect species into both human and animal diets finding favourably both in terms of nutritional viability and environmental impact, with high feed conversion ratios, favourable protein and amino acid contents, low water demands, low technology and input requirements, an ability to be reared on waste products and – most pertinently – low space requirements all highlighted as major potential benefits (see reviews by Sánchez-Muros et al., 2014, Moon and Lee, 2015, Huis and Oonincx, 2017). Even so, while studies investigating the suitability of insects as a livestock feed have greatly increased in recent years as interest in the field has expanded, academic research regarding their viability and environmental impacts at large-scale production remains sparse. The widely-utilised mealworm, for example, could boast only a single Life Cycle Analysis (LCA) courtesy of Oonincx and De Boer (2012) until this year with a further publication by Thévenot et al. (2018).

While cattle production is well known to have the greatest environmental impacts of all livestock species (de Vries and de Boer, 2010), global ruminant production (a category including sheep, goats, deer and other mammals as well as cattle) accounted for just 20% of compound (i.e. industrially-produced fodder blends) feed (IFIF, 2017), with cattle diets instead consisting of grasses, legumes and agricultural bi-products (Jayanegara et al., 2017). Conversely, despite being considered the most environmentally-friendly of all commonly-produced livestock (Józefiak et al., 2016), in terms of feed requirements it is chickens that dominates compound feed production consuming 45 % of the 117 MT global feed production (IFIF, 2017). Further, it is this feed production – principally maize and soybean – that accounts for 57% of total poultry meat and egg production greenhouse gas emissions, with additional emissions related to the expansion of soybean crops alone estimated to be 21.1% and 12.7% respectively (Gerber et al., 2013). Indeed, soybeans are one of the most widespread vegetable-based animal feeds, with 334 MT produced globally in 2016 alone for use as a protein supplement (IFIF, 2017). The European Union (EU) is extremely reliant on imported vegetable proteins, collectively the largest soybean meal and second-largest soybean oilseed importers in the world (Kroes and Kuepper, 2015). The EU therefore represents a significant proportion of global demand for soybean, so the behaviour of the EU with regards to chicken feed has far-reaching environmental consequences for soybean-exporting nations.

With fertile arable land diminishing and increasingly occupied by crops intended as livestock feed, it is important to explore alternative livestock feed possibilities that could help to alleviate the coming issues and conflicts. As yet, there has been no attempt to calculate the potential impact of a large-scale substitution of conventional feed components with insect-based feed components. **Therefore, this study will substitute soybean-based protein used in EU poultry and egg production with several promising insect-based proteins, investigating the land use, greenhouse gas (GHG) emissions and energy consumption at current insect production levels.** Through these substitutions, the potential benefits, opportunities and challenges of the scaling-up of insect production may be better understood.

2 Background

2.1 Soybean production, processing and use as a livestock feed

Soybean is the world's most abundant oilseed, and production is likely only to increase as demand for food, feed and oil is bolstered by population growth (Orf, 2008). Globally, 6% of soybeans grown are consumed directly by humans as food in the form of tofu, soy-milk, other substitute foodstuffs or edamame beans, with the remaining 94% of soybeans crushed to produce soybean meal and soybean oil (Oliveira and Schneider, 2016). As a result of the crushing process, 18.5% of the whole soybean oilseed is extracted as oil, 79.6% as soybean meal and the remainder is a waste product (Goldsmith, 2008). 98% of soybean meal is used as a protein supplement within industrially-produced compound livestock feeds (Oliveira and Schneider, 2016). Livestock feed composition is dominated by the requirement to provide sufficient energy and protein. In the diets of poultry in particular, energy requirements are ordinarily met using cereals such as corn, wheat and barley, with soybean meal or fish meal supplementation used to provide the bulk of the protein requirements (Khan et al., 2016). Soybeans are unique amongst plants in that they boast a protein quality and amino acid profile of equal quality to that of meat (Hartman et al., 2011). Combined with the fact that they are easily digested by many animal species (Sánchez-Muros et al., 2014), soybean is an extremely efficient livestock protein supplement (Hartman et al., 2011). In addition, soybean products are easy to transport cost-effectively across vast distances (Westhoek et al., 2011), making them an attractive export product.

2.2 EU soybean product import 2016/17

The EU has become excessively reliant on the import of plant-based protein supplements. A 2011 EU parliamentary motion revealed the depth of concern felt at the lack of domestically produced plant-based proteins, calling for greater research and development in achieving the goal of greater protein self-sufficiency (Häusling, 2011). Dependency on the import of plant-based proteins such as soybean for use in animal feed exceeds 70 percent (Verbeke et al., 2015), with diversification of European protein supply therefore considered an important goal (de Visser et al., 2014).

Table 1. EU soybean product import 2016/17 (Oilworld 2017)

<i>Country of Origin</i>	<i>Import (1000T)</i>				
	Soybean Oilseed	Soybean Meal	Soybean Oil	Total	% of Total
<i>Brazil</i>	5353	7096	-	12449	36
<i>Argentina</i>	154	10137	-	10291	30
<i>USA</i>	4940	222	-	5162	15
<i>Paraguay</i>	1382	1112	34	2528	7
<i>Canada</i>	1022	47	-	1069	3
<i>Other Countries*</i>	1447	1313	257	3017	9
Total	14298	19927	291	34516	100

*Soybean Oilseed: Serbia/Montenegro, Kazakhstan, Russia, Moldova, Togo, Burkina Faso, Ukraine, Nigeria, Uruguay, China, India, Turkey, Others.

* Soybean Meal: Serbia/Montenegro, Kazakhstan, Russia, Ukraine, Nigeria, Bolivia, Uruguay, China, India, Others.

* Soybean Oil: Serbia/Montenegro, Russia, Moldova, Ukraine, Norway, Belarus, Others.

This reliance reflected in the trade figures for soybean in particular. Between September 2016 and October 2017, the EU imported 34.5 MT of soybean products. Soybean meal represented the largest share of imported soybean products, followed by whole soybean oilseed at and finally soybean oil. During 2016/17, Brazil, Argentina, the USA, Paraguay and Canada represented over 90% of total soybean product imports to the EU by mass (Table 1). Less than 7% of total soybean products consumed during 2016/17 were sourced from within the EU (Table 2).

Table 2. EU soybean product availability 2016/17 (Oilworld 2017)

<i>Soy Product</i>	<i>1000T</i>					
	Domestic Production	Import	Oilseed Crushed	Results of Crushing	Exports	Available for use within EU
<i>Oilseed</i>	2454	14298	14575	-	220	1957
<i>Meal</i>	-	19927	-	11435	296	31066
<i>Oil</i>	-	291	-	2714	862	2143
Total	2454	34516	14575	14149	1378	35166

As seen previously, the majority of soybean oilseeds are crushed to produce soybean meal and soybean oil. This is reflected in the total soybean product availability within the EU. Data in Table 2 shows that 87% of available oilseeds are crushed into soybean meal and soybean oil (Oilseed Crushed)/(Domestic Production + Imported Oilseed)). Soybean meal accounts for 88% of all soybean products available for use within the EU, almost all of which is used as livestock feed.

2.3 Environmental impact of soybean production on exporting nations

The environmental consequences of soybean production are severe. Conventional agricultural practices result in the release of huge amounts of carbon from soils (McCarl et al., 2007), with the exposure of topsoil to drying and oxidation through tillage resulting in rapid soil degradation and erosion (Piccolo, 2012). In addition, they are also associated with eutrophication, acidification, biodiversity loss and fossil fuel reliance (FAO, 2016). Soil erosion is especially severe for soybean production as is herbicide use (Pimentel et al., 2009), while legume production in general is considered the second heaviest disruptor of the nitrogen cycle with an estimated 20 MT/year converted from the atmosphere (Rockström et al., 2009). Despite conservation agricultural practices such as no-till, residue retention and alternative crop rotations having been found to vastly improve soil and water quality while preventing soil erosion (Palm et al., 2014) and suggestions that it can reduce nitrogen requirements (Islam, 2016), these methods remain a minority – though increasingly popular – practice in nations exporting soybean to the EU (FAO, 2015).

Furthermore, there are specific environmental impacts related to EU soybean exporting nations, not least those located in South America. Brazil and Argentina are presently the two largest exporters of soybean products to the EU, together accounting for over 60% of imported soybean products (*Table 1*). A very strong correlation between the expansion of soybean production and deforestation exists in Argentina (Gasparri et al., 2013) with the value of soybean as a cash crop incentivising the conversion of rotational cropping into permanent soybean production (Phélinas and Choumert, 2017), intensifying the environmental impacts of soybean production in addition to destructive soybean expansion. Brazil meanwhile is the second-largest producer and exporter of soybean in the world (FAO, 2018), with the area of land dedicated to soybean production nearly doubling over the last two decades (FAO, 2018). It is also the world's largest producer and exporter of cattle (FAO, 2018), with the pasture expansion over the same period occurring almost entirely within the Amazon (Bowman et al., 2012). Post-2000 studies of the Brazilian Amazon have largely attributed deforestation and vegetation loss to conversion to pasture rather than conversion to arable land (Brown et al., 2005, Morton et al., 2006, Barona et al., 2010, Nepstad et al., 2014). However, though the ostensible cause of deforestation is the expansion of pasture by cattle ranchers, this expansion is necessitated by the conversion of existing pasture to allow for the production of the more lucrative soybean crop (Fearnside, 2001, Nogueira et al., 2018). As such, the relieving of soybean-related production pressures is vital to reducing deforestation rates in the region.

The subsequent environmental impacts of this soy/cattle-led deforestation are devastating. It is thought that 18.3% of carbon stock has been lost to the clearing in the Brazilian Amazon alone, with enormous implications for global carbon sequestration. Pasture now represents some 70% of agricultural land in Brazil (FAO, 2018), much of which is a result of Amazonian conversion. Simulations indicate that the continued deforestation of the Brazilian Amazon could have potentially catastrophic results locally, with sharp declines in dry season rainfall, higher temperatures and an increase in the frequency and severity of El Niño-type droughts (McAlpine et al., 2009). While there is evidence to suggest that recent years have seen Brazilian deforestation drastically reduced through regulation and favourable economic conditions (Nepstad et al., 2014, Nepstad et al., 2009), it is likely that deforestation is simply shifting into areas such as Peru and Bolivia (Kalamandeen et al., 2018). Plus, the mining industry continues to drive deforestation in the Amazon entirely separate from expansion for pasture or arable land (Sonter et al., 2017), meaning that the reduction of any preventable deforestation – e.g. through reducing soybean demand as a livestock feed – is increasingly important.

2.4 The viability of insects as livestock feed compared to human foodstuff

With such severe direct environmental consequences, it would appear beneficial for a swift reduction in EU animal product consumption to occur. To this end, insects have been suggested as a useful alternative protein source to meat (Huis et al., 2013). However, the likelihood of widespread dietary changes occurring remains unknown. Entomophagy (the practice of eating insects) is commonly undertaken by a third of the world population, with 80% of countries partaking in the consumption of over 2000 different insect species (Miglietta et al., 2015). Therefore, the Western world represents a global minority in this regard, with the idea of entomophagy yet to receive popular support the Western world (Hussein et al., 2017) despite the direct correlation between the consumption of animal products and often devastating environmental impacts being increasingly well-publicised (Hallström et al., 2015). Given the complexity of factors that underlie the adoption of dietary changes (Tilman and Clark, 2014) – compounded by the candidly-termed ‘disgust factor’ by the FAO (Huis et al., 2013) – it appears unlikely that an overwhelming paradigm-shift in Western food culture will occur in the near future.

While the perception of insects within the Western world appears to present a significant obstacle to their direct consumption as part of a human diet, public opinion has been found to be largely in support of insect-fed animal products - especially for those animals for whom insects are considered part of their natural diet, such as pigs and poultry (Verbeke et al., 2015). Furthermore, there is increasing evidence that insects are able provide similar protein, amino acid and digestibility profiles as conventional livestock feed. One of the largest studies to date - over 200 insect species - found that many insects display excellent nutritional values for energy, protein, amino acids, and monounsaturated fatty acids and/or polyunsaturated fatty acids, as well as several micronutrients including copper, iron, magnesium, manganese, phosphorous, selenium, zinc, riboflavin, pantothenic acid, biotin, and folic acid (Rumpold and Schluter, 2013). Furthermore, insect digestibility in animals has been found to be at least equal to conventional livestock feeds (e.g. De Marco et al., 2015, Miech et al., 2017, Schiavone et al., 2017). As such, the introduction of insect-based animal feeds as an alternative to conventional plant-based livestock feeds may enable the swift assuaging of many negative environmental impacts of animal product consumption and production while circumventing the social challenges obstructing the adoption of entomophagy.

From a regulatory perspective, the European Union recently introduced EU/2015/2283 on novel foods, hugely expanding the definition of novel foods and simplifying and hastening approval and authorisation of alternative foods for sale on the European market for human consumption – including insects. However, animal feed is regulated separately from human foodstuffs, and though animal feed regulations were recently amended to lift restrictions on insect-derived protein use in animal feeds, the use of insect proteins was legalised only in aquaculture production, with use in poultry and pig production remaining prohibited (*Figure 1*).

EU legal opportunities for the use of insect PAPS in animal feed

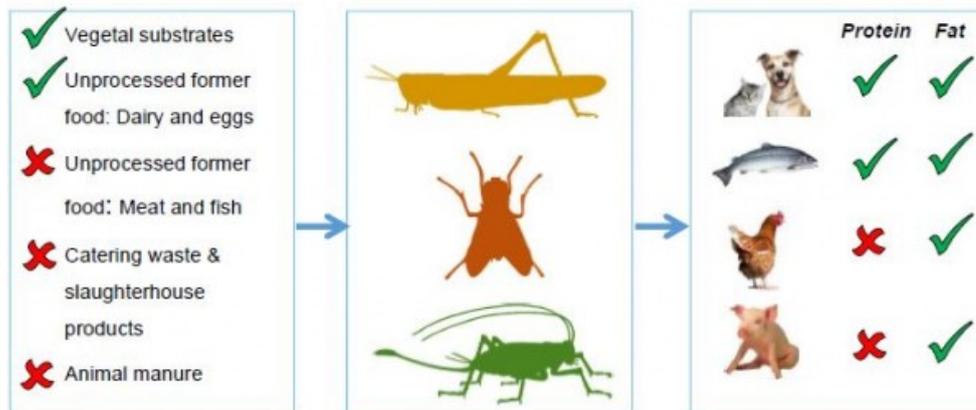


Figure 1. EU regulation on the use of insect PAPS (Processed Animal Protein) in livestock feed (IPFF, 2018)

In addition, even insects fed to aquaculture animals may only be reared on ‘feed-grade’ materials, potentially limiting their environmental impact mitigation. Evidence suggests that the inherent safety risks involved in the production and consumption of insects are no greater than those inherent to other livestock in terms of bacterial, viral, fungal or parasitic transmissions (Committee, 2015), and can be largely avoided using existing preventive measures (Belluco et al., 2013). Though some concerns have been raised – such as with the cadmium content of *Acheta domesticus* (Charlton et al., 2015) - the momentum that the edible insect concept continues to generate and their recent acceptance into novel food legislation would suggest a trend towards wider regulatory acceptance.

2.5 The necessity of livestock production

Despite this study focussing on the alleviation of problems associated with livestock production and consumption, they are raised in a firmly European perspective. Within developing countries livestock are often more than simply a dietary choice; as well as invaluable calories and protein in areas where arable land is often unproductive, they provide many other important services to some of the most resource-poor on the planet such as traction, manure, regular income and risk management (Havlik et al., 2014). Furthermore, livestock are able to graze on infertile pasture land unsuitable for crop production, improving diets, economic conditions and food security in some of the most vulnerable world regions (Foley et al., 2011). Globally, current agricultural land is thought to be most efficiently utilised when ~12% protein is derived from animal sources; were all protein derived from plant-based sources, it is highly improbable that global protein requirements could be met (Kernebeek et al., 2016). Thus, while excessive animal product consumption should be curtailed, and damaging production processes avoided, it is important to recognise the significant benefits that modest animal production provides at both local and global scales.

3 Methodology

3.1 Theoretical framework and limitations

This study falls under the category of futures research inasmuch as it is an interdisciplinary study of possible futures changes; the benefit is less in the accuracy of the forecast – although of course it will endeavour to ensure scientific reliability to as great a degree as is possible – but in the potential ability to open minds to consider new possibilities and anticipate new opportunities (Giaoutzi and Sapio, 2013). It does not present an exercise in backcasting, as while potential futures will be considered, it does not intend to provide a pathway to a chosen ‘desirable’ scenario (Vergragt and Quist, 2011). Scenario development has become a key research tool in assisting stakeholders and decision-makers to think creatively about plausible futures, and see the potential in new ideas (Bengston et al., 2012). In asking the question ‘what *could* happen’, it is possible to affect both policy and behaviour both in the short and long term (Vergragt and Quist, 2011).

Importantly, this paper does not present an LCA of any product, instead utilising existing LCAs to provide the most reliable insect production data possible. While this study focuses on the potential land use benefits from large-scale insect production, land use savings are often offset by problems in other production areas when substituting soybean meal with alternative products (Watson et al., 2017). As such, this study will extract the land utilisation of the insect production area and soybean meal-related land use from insect feed (if any), the GHG emissions and the energy use of each insect species for comparison with soybean meal. However, the dearth of available insect LCAs means that there are unavoidable differences between LCA methodologies that affect their respective outcomes, and subsequently impact the results of this study. These differences in are both explained in 3.3.3 and their impact considered as part of the results discussion.

3.2 Calculating the land use of soybean meal utilised in EU poultry and egg production

To find the land use of soybean meal utilised as poultry feed within the EU, several calculations are needed. First, the total amount of soybean meal fed to EU livestock is found (*Table 3*), before the amount of this soybean meal used in poultry and egg production is calculated (*Table 4*). The land used by this soybean meal production is then calculated (*Table 5*), before the amount of protein provided by this soybean meal is found (*Table 6*) so that the amount of protein required for substitution with insect meal is known. This section will explain these calculations in greater detail.

3.2.1 EU soybean meal utilised as livestock feed 2016/17

Table 3. EU soybean meal supply for livestock feed 2016/17 (Oilworld, 2017)

Country of Origin	(1000T)			(%)
	Oilseed Crush Result (Meal)	Imported Soybean Meal	Total Imported Soybean Meal	Total EU Soybean Meal Supply
Brazil	3733	6954	10587	34.6
Argentina	105	9934	10039	33.3
USA	3353	218	3570	11.3
Paraguay	896	1090	1985	6.6
Canada	662	46	708	2.3
Other Countries	982	1287	2269	7.4
Total	9630	19528	29158	95.4

(Imported Soybean Oilseed * 0.87 * 79.6 * 0.98) = Oilseed Crush Results (Meal)
Oilseed Crush Results (Meal) + (Imported Soybean Meal * 0.98) = Total Imported Soybean Meal
(Total Soybean Meal Available for Use Within EU * 0.98)/(Total Imported Soybean Meal) 100 = % EU Soybean Meal Supply

Applying the 87% proportion of oilseeds crushed as per Table 2, the 79.6% soybean meal that results from the crushing process and the 98% of meal that is used as livestock feed to only imported soybean oilseeds as per Table 2 provides the amount of crushed imported soybean oilseeds used as livestock feed (Table 3). Adding the amount of imported soybean meal (at 98% to reflect use for livestock feed) results in total amount of imported soybean oilseed and soybean meal used as EU livestock feed. By comparing this amount to the total available soybean meal in Table 2 (at 98%) a reliance on imported soybean of over 95% is evident in the supply of EU soybean meal for livestock feed, with Brazil and Argentina alone supplying almost 70% (Table 3).

3.2.2 EU soybean meal used as poultry feed

As has been lamented by previous authors wishing to investigate the use of soybean in animal feed at a European scale (e.g. Van Gelder et al., 2008, Kroes and Kuepper, 2015), no official data or estimations exist as to the proportion of soybean (and other feed products) within animal feed across the EU. As such, this must be calculated manually. Taking cues from three existing studies, notably Van Gelder et al. (2008), Hoste (2014) and Kroes and Kuepper (2015), this study utilises the soybean proportion within the diets of livestock in the Netherlands as representative of soybean meal utilisation in the wider European area. The departure for this study is simply that it is attempting to isolate soybean meal used within poultry and egg production.

Table 4. Soybean meal requirement of EU poultry and egg production 2016/17 (FEFAC 2017; Hoste 2014)

<i>Product</i>	EU Total Production (1000T)	Soybean Meal Required (g/kg)	Total Soybean Meal Required (1000T)	% EU Soybean Meal Used in Poultry & Egg Production
<i>Poultry (Slaughter Wt.)</i>	14810	578.00	8560.18	27.55
<i>Eggs</i>	7700	305.00	2348.50	7.56
Total	22510	-	10908.68	35.83

EU Total Production * (Soybean Meal Required / 1000) = Total Soybean Meal Required
 (Total Soybean Meal Required)/(Total Soybean Available for Use Within EU * 0.98) 100 = % Available
 Soybean Meal Livestock Feed

Representing the best figures available at present, (Hoste, 2014) calculated a soybean meal requirement of 578g/kg poultry meat (slaughter weight), and 305g/kg eggs between 2011-2013. Thus, the production of poultry and eggs within the EU requires over 35% of available soybean meal, totalling 10.91 MT (Table 4).

3.2.3 Soybean land-use of EU poultry and egg production

Adjusting the soybean meal supplied by each exporting nation by the 35.83% as per Table 4 provides the proportion of imported soybean meal used as feed for poultry or egg production. Multiplying by 0.796 provides the equivalent soybean oilseed mass, and by then applying the 2016 soybean yields for each country as per the (FAO, 2018) the total land required to produce soybean meal in poultry and egg production across the EU can be found (Table 5).

Table 5. Soybean land use in exporting countries for EU poultry feed 2016/17 (Oilworld 2017; FAOSTAT 2018)

<i>Country of Origin</i>	1000T	Equivalent Soybean Oilseed	T/ha	1000ha
	Meal Used for Poultry & Egg Production	Equivalent Soybean Oilseed	Soybean Yield	Land Required for Soybean used in Poultry & Egg Production
<i>Brazil</i>	3793	4766	3.0	1581
<i>Argentina</i>	3597	4519	2.9	1556
<i>Paraguay</i>	711	894	2.7	329
<i>USA</i>	1279	1607	3.5	459
<i>Canada</i>	254	319	2.7	120
<i>Other Countries</i>	813	1021	1.8	572
Total	10448	13125	-	4617

Total Imported Soybean Meal * 0.3583 = Meal Used for Poultry & Egg Production
 Meal Used for Poultry & Egg Production / 0.796 = Equivalent Soybean Oilseed
 Equivalent Soybean Oilseed / Soybean Yield = Land Required for Soybean Used in Poultry & Egg Production

3.2.4 EU crude protein provided by soybean meal in poultry feed

To find the quantity of protein required for substitution with insect meal, it is necessary to calculate the amount of protein that soybean meal provides EU poultry and egg production. The EU has itself estimated the protein content of imported soybean meal at 45.5% (AGRI, 2017). Imported soybean meal therefore supplied a total of 4.6 MT crude protein for egg and poultry meat production during 2016/17. Furthermore, by combining the crude protein and land use calculations, we can estimate the protein yield of individual exporter countries, with an average protein yield of 1.03 Tonnes/Hectare evident across all soybean exporting nations (Table 6).

Table 6. EU imported soybean meal protein content & yield (Oilworld 2017)

<i>Country of Origin</i>	<i>1000T</i>		<i>1000ha</i>	<i>T/ha</i>
	Meal Used for Poultry & Egg Feed Production	Total Crude Protein	Land Used for Soybean Production	Soybean Meal Protein Yield
<i>Brazil</i>	3793	1726	1581	1.09
<i>Argentina</i>	3597	1637	1556	1.05
<i>Paraguay</i>	711	324	329	0.98
<i>USA</i>	1279	582	459	1.27
<i>Canada</i>	254	115	120	0.96
<i>Other Countries</i>	813	370	572	0.65
Total	10448	4754	4617	1.03

(Meal Used for Poultry & Egg Production * 0.455) = Total Crude Protein

Total Crude Protein / Land Used for Soybean Production = Soybean Meal Protein Yield

3.2.5 Future soybean productivity improvements

Though this study is focussed on the substitution of soybean meal-based protein with insect-based protein, a fair representation of the substitution of soybean meal also necessitates the consideration of potential land-use reductions through the increased productivity, as this is generally believed to be the most likely method of meeting additional crop demand in the future (Gregory and George, 2011). The calculation:

Equivalent Soybean Oilseed Production / Soybean Yield

enables a basic consideration of the impact of soybean productivity, and thus the potential that greater future soybean productivity may have on land use in comparison to insect production.

3.3 Calculating the land use of insect production

3.3.1 Species selection

Insects are often collected manually in the wild on an ad-hoc basis for subsistence purposes (Huis et al., 2013). Not only does this provide obvious benefits in areas where food is a scarce resource (Moreki et al., 2012), but it can have other positive effects such as the control of pest species (Vogel, 2010) - though the uncontrolled collection of wild insects does present an extinction risk (Banjo et al., 2006). For the purposes of this study however, the main characteristic of wild collection is that it is an implausible method of acquiring insects on the scale necessary for any substantial substitution in animal feeds. Furthermore, it is vital that species chosen for production are native to the local area to minimise the risk of introducing a potentially invasive species (Jansson and Berggren, 2015). The FAO have identified a number of insect species considered to have the greatest potential for eventual large-scale industrial production – the black soldier fly, the common housefly, the yellow mealworm, the lesser mealworm, the silkworm, and several species of cricket (Huis et al., 2013). An ever-increasing amount of literature exists on the utilisation of these insects as feed for use in aquaculture, for poultry and for pigs (e.g. Kenis et al., 2014, Miglietta et al., 2015, Newton et al., 1977), with species such as the black soldier fly already industrially produced (AgriProtein, 2016). As such, the species selected for use in this study 1) are within the group considered to be potentially suitable for industrial production by the FAO 2) have empirical evidence of use as a substitute for soybean meal in chicken feed and 3) exist to some extent on the European continent.

Diptera: Black Soldier Fly Larvae (*Hermetia illucens*)

Thought to originate in South America, the Black soldier fly *Hermetia illucens* is now found throughout tropical and subtropical areas of the world. The most northernmost record in Europe was recently updated to Czechia, having previously been recorded in Northern France, Switzerland, Southern Germany and the Balkan Peninsula (Roháček and Hora, 2013). *Hermetia illucens* feed only in the larval stage of development, surviving adulthood solely on the fat stores accumulated through this period; with no mouth pieces, they have no interest in human habitation or food and as such are not considered a pest species (Newton et al., 2005). In fact, the pest species *Musca domestica* (the house fly) is disinclined from ovipositing in the same areas as *Hermetia illucens* (Bradley and Sheppard, 1984). The larvae of the black soldier fly are well researched with regards to their nutritional competition and suitability to food and feed applications. The digestibility of *Hermetia illucens*. L in chickens has been found to be similar to soybean meal, with similar nutritional values and protein content in excess of 40% (e.g. DeMarco et al 2015; Leiber et al 2017). One study found it possible to completely substitute soybean meal with black soldier fly larvae in poultry feed whilst maintaining a growth rate 96% of the control group, while consuming less feed (Hale, 1973). More modern studies have focussed more on utilising black soldier fly larvae meal in combination with soybean meal in poultry diets rather than complete replacement (e.g. Oluokun, 2000, De Marco et al., 2015, Leiber et al., 2017), while no negative impacts on egg production or chicken health were detected at a 24% replacement with soybean cake in laying hens (Maurer et al., 2016)

Coleoptera: Mealworm Beetle Larvae (*Tenebrio molitor*)

Indigenous to Europe and now at a worldwide distribution (Tran et al., 2018), the larvae of the beetle *Tenebrio molitor* are very well researched in terms of their applicability to food and feed purposes, with crude protein levels found to match or exceed that of soybean meal and adequate levels of amino acids to be a viable food and feed ingredient (Bovera et al., 2015, Zhao et al., 2016). In terms of their applicability as poultry feed, digestibility has been found to be equal to soybean meal in broilers (Józefiak 2014), while several studies

have confirmed feasibility in terms of growth efficiency and nutrition at various levels of substitution. Ramos-Elorduy et al. (2002) were able to substitute 10% of soybean meal with yellow mealworm larvae without a loss in weight gain. More recently, Biasato et al. (2018) found that mealworm larvae substituted at 25-45% rates with soybean meal positively impacted body weight and feed intake, with some negative impacts on feed efficiency and intestinal morphology. Bovera et al. (2015) were able to completely substitute a baseline poultry feed containing 44.6% soybean meal with yellow mealworm larvae, with no impact on weight gain at slaughter age and with a greater feed conversion ratio - although supplementation of the methionine and lysine amino acids were required for normal growth, as is also the case with soybean meal.

Orthoptera: House Cricket (*Acheta domesticus*)

Crickets are widely used as laboratory animals and reared for exotic animals (Józefiak et al., 2016), and represent one of only a few species that have a long history of being farmed at scale (Hanboonsong et al., 2013). *Acheta domesticus* are commonly found in Europe (Ghouri, 1961), but while the species offers similar nutritional benefits to other insect species, it also boasts one of the highest crude protein contents of all edible insects. Proximate analysis of *Acheta domesticus* has often found dry matter crude protein contents in excess of 70% (Rumpold and Schluter, 2013, Barroso et al., 2014, Oonincx, 2015), and a defatted protein content approaching 80% (Sipponen 2018). Furthermore, there have been a number of feeding trials performed on broiler chickens utilising cricket meal as a direct substitute for soybean meal. Wang et al. (2005) was able to entirely replace fishmeal (10% of control diet) and 32% of soybean meal (22.5% of control diet) with field cricket meal (albeit of the similar family *Gryllus*) with no negative impact on broiler growth. DeFoliart et al. (1982) and Finke et al. (1985) both found results in favour of substituting soybean meal with Mormon cricket meal (*Anabrus simplex*). Finally, Nakagaki et al. (1987) fed *Acheta domesticus* to poultry as a soybean meal substitute with no negative impact on broiler growth rate.

3.3.2 Selected insect species composition summary

As is evident in *Table 7*, the selected insect species have key nutritional values very similar to that of conventional soybean meal, especially regarding protein content. The main exception to the compositional similarities is the far greater moisture content of insect species in comparison to soybean meal.

Table 7. Composition of selected insect species in comparison to a representative soybean meal

	Dry Matter (%)	Energy (KJ)*	Crude protein (g)*	Fat (g)*	Crude Fibre (g)*	References
Soybean (meal, defatted)	87.5 ^a	1864 ^a	47.5 ^a	1.9 ^a	10.6 ^a	^a (Baker et al., 2011)
<i>Hermetia illucens</i>. L	37.7 ^b	2380 ^c	48 ^b	35 ^b	7 ^d	^b (Salomone et al., 2017) ^c (DeMarco 2015) ^d (Newton et al., 1977)
<i>Acheta domesticus</i>	32.2 ^e	1905 ^f	47.1 ^e	25.8 ^e	5.5 ^e	^e (Ayieko et al., 2016) ^f (Rumpold and Schluter, 2013)
<i>Tenebrio molitor</i>. L	38.1 ^g	2440 ^c	51.9 ^h	21.6 ^h	7.2 ^h	^g (Finke, 2002) ^h (Bovera et al., 2015) ^c (DeMarco 2015)

* values are /100g DM

3.3.3 *Insect production data selection*

There are very few LCAs of insect production, and the lack of publications severely hampers the ability to acquire directly comparable data with identical methodologies. Ideally, soybean meal would be substituted with insect meal – i.e. dried insect that is milled to form a grain, for easy substitution with soybean meal in compound chicken feed. However, with so few insect LCAs available that include the meal production phase it was not possible to do so. As such, the selected LCA studies represent the best available sources for the aims of this study, with unavoidable differences between studies explained below.

Acheta domesticus – whole cricket production, Thailand (Halloran et al., 2017)

The cricket facility produces whole adult crickets for human consumption, and as such no processing – either drying or meal production – is accounted for in the results. Both a current and an optimised future cricket-rearing scenario were offered, with the optimised scenario considered fairer for comparison given to the burgeoning state of insect production. Insects were reared on a mixture of grains and oilseed that included 28% soybean meal. Despite *Acheta domesticus* production being disrupted in Europe by the cricket paralysis virus (AdDNV) and the subsequent switching of some farmers to species in the similar genus *Gryllus* (Eilenberg et al., 2015), the study by Halloran et al. (2017) remains the only published LCA for cricket production and is thus considered as applicable nonetheless.

Hermetia illucens – dried larvae production, Italy (Salomone et al., 2017)

The production of *Hermetia illucens* takes place at a pilot bioconversion facility in Italy, where the larvae consume organic food waste and convert it into bio-fertiliser. As the flies are raised on food waste, no land is considered as required for the production of their feed. It was also assumed for the purposes of annual yields that the facility ran at full potential capacity for the entire year. No meal production occurred at the bioconversion plant, so the results include only the drying phase of production. While other sources are available that detail production to an extent, some lack industrial scale (Sheppard et al., 2002, Newton et al., 2005), while others lack specific production data (Józefiak et al., 2016). Just three peer-reviewed life cycle analysis exist for this species in Smetana et al. (2016) Roffeis et al. (2017) and Salomone et al. (2017), with Salomone et al. (2017) more relevant for the purposes of this study.

Tenebrio molitor – dried larvae meal production, France (Thévenot et al., 2018)

Mealworm production data gathered by Thévenot et al. (2018) is based upon a commercial production facility in France, and is the only study where both the drying and meal production phases were included. The mealworms were raised on a mixture of grains and oilseed, although the soybean meal content was an unspecified proportion of 24.5% ‘meals’. As such, for the purposes of this study it is assumed that the entirety of ‘meals’ is soybean. The LCA carried out by Oonincx and De Boer (2012) is widely cited and was until recently the only published mealworm LCA, but as a farm-to-gate study it did not account for the drying or meal production phases, making the LCA by Thévenot et al. (2018) more appropriate for use here.

3.3.4 Insect production land use

It is essential to account for the agricultural land use of any soybean meal utilised in the production of the selected insect species to obtain an accurate substitution. To this end, *Hermetia illucens. L* is considered to require no bespoke land for feed production as it is fed solely with food waste. As such, the land use figures extracted from Salomone et al. (2017) represent only insect production and processing land use. For *Tenebrio molitor*, Thévenot et al. (2018) reported a total land use of 6.35 m²/kg mealworm meal protein produced, with 13% of land use required for insect & meal production and the remaining 87% of land use attributed to feed production. As it was assumed that soy accounted for the entire 24.5% proportion of ‘meals’ in mealworm diets, *Tenebrio molitor. L* Insect Production = 6.35*0.13, and Soy Production = 6.35*0.87* 0.245. *Acheta domesticus* land use required further calculations as per the data and formulae in Table S1.

Table 8. Insect production land use data

	<i>m²/kg crude protein (DM)</i>			References
	Insect Production	Soy Production	Total	
<i>Hermetia illucens. L</i>	0.05	N/A	0.05	(Salomone et al., 2017)
<i>Acheta domesticus</i>	0.11	11.40	11.51	(Halloran et al., 2017)
<i>Tenebrio molitor. L</i>	0.83	1.35	2.18	(Thévenot et al., 2018)
<i>Soybean</i>	N/A	9.71	9.71	Table 6

3.4 Calculating greenhouse gas emissions

While insect GHG emissions are extracted directly from the selected studies under their respective, varied production conditions, the difficulties in estimating GHG emissions from soybean production are well documented. As explained by Castanheira and Freire (2013) in their review of existing soybean-related LCA studies, reported emissions are heavily dependent on local land-use changes and production methods and as such, the results of an emissions study should be considered relevant only for the specific production and environmental circumstances of the study area. Therefore, presenting as accurate data as is possible requires data aggregated both by region and production method.

FAO data regarding soybean emissions is extracted from the LEAP database (LEAP, 2018a) and aggregated data by country, region and tillage method – either conventional or no-till (NT). NT is usually part of a wider alternative agricultural methodology called Conservation Agriculture (CA), usually involving no-tillage as well as alternative crop rotation, manure and residue management strategies (Grignani et al., 2012). For this study it was considered that the use of CA represents the major contributing factor in terms of production emission differentiation ¹.

¹ Although the use of irrigation (rather than rainfall) in soybean production has a significant impact on emissions, this factor was discounted given the very small proportion of irrigated soybean and general crops in the major exporting nations.

CA adoption varies globally (Kassam et al., 2015), so to obtain the proportion of land each country under CA, data is adapted from the most recent FAO estimations (FAO, 2015) and then combined with the total arable land for the same period for each major exporting nations (AQUASTAT, 2018). For ‘other countries’, the emissions for the three next largest exporters (India, Ukraine and Uruguay) are averaged, and because most countries who utilise CA to any significant extent are already major exporters (LEAP, 2018b) it is assumed that soybean production under ‘other countries’ is carried out entirely under conventional tillage. This provides the regionalised eq. CO² emissions (production emissions + LUC emissions²) for soybean production.

Finally, because the FAO emissions data utilises a FU of 1kg DM soybean, these figures are adjusted using a crude protein content of 40.8% (Dalgaard et al., 2008) to produce an FU of 1kg protein, enabling comparison on a crude protein basis with insect proteins. It does not include possible emissions from the meal production phase of soybean. Data tables and calculations for soybean GHG emissions are available in the appendix (S2).

3.5 Calculating energy use

Energy use /kg crude protein is extracted as reported for mealworms and black soldier flies from Thévenot et al. (2018) and Salomone et al. (2017) respectively. For cricket energy usage, the formula (*Annual Energy Use*)/(*Annual Insect Production* * *DM* * *CP*) using data from Halloran et al. (2017) was used to obtain a FU of 1kg protein. Energy use for soybean meal production was extracted from Thévenot et al. (2018).

² LUC has an enormous impact on soy production emissions, and its inclusion has been shown as vital by many authors e.g. (Cederberg et al, 2007) (Esteves et al, 2016)

4 Results

4.1 Land use comparison – soybean-based protein substitution with insect-based protein

Substitution of soy protein with insect protein within EU poultry and egg production potentially reduces the land used for feed production by up to 4.6 Mha - an area of land greater than that of the Netherlands, Switzerland or Estonia. This is achieved at a 100% substitution with protein from *Hermetia illucens*. L, utilising just 24 000 ha or less than 1% of land currently used to produce soy-based protein. In fact, all insect species were able to entirely substitute soy protein while utilising less than 8.5% of the current feed production area (Figure 2).

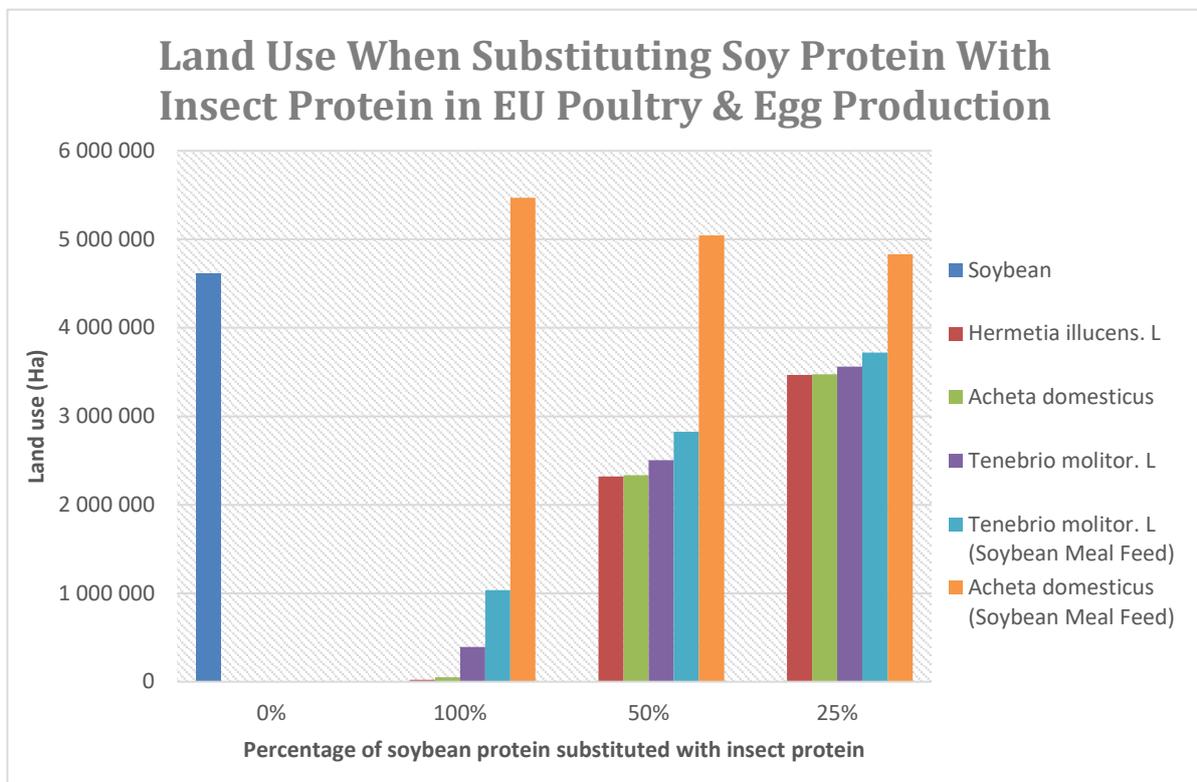


Figure 2. Land use for EU poultry feed at different rates of soy protein substitution with insects

The use of soybean meal in insect production has a clear influence on land use. The amount of soybean meal required to produce *Acheta Domesticus* protein at a 100% protein substitution rate is significantly greater than current total soybean requirements. The more modest soybean meal requirements of *Tenebrio Molitor* production results in a land use far less pronounced than *Acheta Domesticus*. Production of mealworm fed with soybean meal still shows a significant land saving, utilising only 22.44% of current soybean meal land use at a 100% substitution rate. Even at a protein substitution rate of just 25%, *Tenebrio molitor. L* fed using soybean meal reduces land use by 900,000 ha – an area roughly the size of the island of Cyprus.

4.2 Greenhouse gas emissions and energy use comparison – soybean protein substitution with insect protein

Extrapolating /kg crude protein results for energy consumption and GHG emissions to 100% substitution rates demonstrates the consequences of large-scale production in a less abstract perspective (Figure 3). Using figures from the World Energy Council, at a 100% substitution with soy-based protein the energy consumption of *Tenebrio Molitor* production is equivalent to the annual energy consumption of 79 million European Union households (WEC, 2016a). By comparison, the total current energy consumed in the production of soybean meal for EU poultry and egg production is the equivalent of 1.5 million EU households (WEC, 2016a). *Acheta domesticus* production uses the equivalent annual energy consumption of only 1.2 million EU households, with *Hermetia illucens* energy use the equivalent of 5.4 million households (WEC, 2016a).

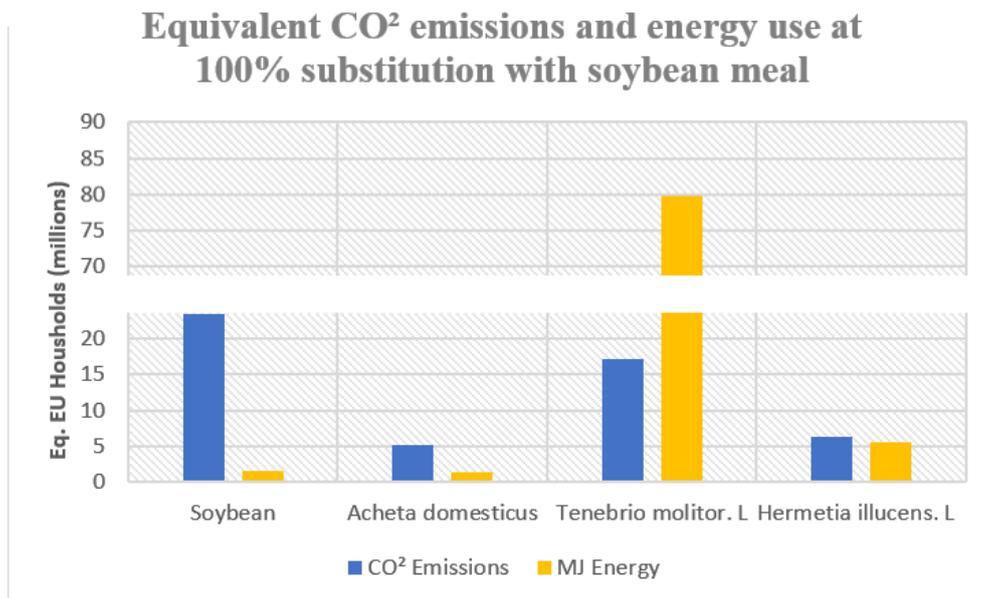


Figure 3. Equivalent EU household CO² emissions and energy use at 100% substitution

Current soybean production emissions meanwhile are the equivalent of the annual emissions of roughly 23 million EU households, while production of the insect species with the lowest GHG emissions – *Acheta domesticus* – emits the equivalent of less than 5 million EU households (WEC, 2016b). *Tenebrio molitor* has relative high emissions in addition to exceptionally high energy consumption, with emissions equivalent to 16.7 million EU households, while *Hermetia illucens* production emits the equivalent CO² emissions of 6 million EU households (WEC, 2016b).

4.3 Land use comparison – future soybean yield improvements

There is a huge difference in productivity between soybean exporters to the EU (*Figure 4*). Were US soybean productivity levels matched across all of the soybean meal used in EU poultry & egg production, total land use would be reduced by 860,000 ha. While Brazil, Argentina, Paraguay and Canada all boast similar soybean productivity level, ‘other countries’ (represented by India, Ukraine and Uruguay as the three next-largest soybean exporters, as per section 3.4) have significantly lower soybean productivity levels. At this productivity level, EU poultry & egg production would utilise 56% more land than the 4.61 Mha of land currently required. Low-volume exporters therefore represent the least-efficient soybean producers.

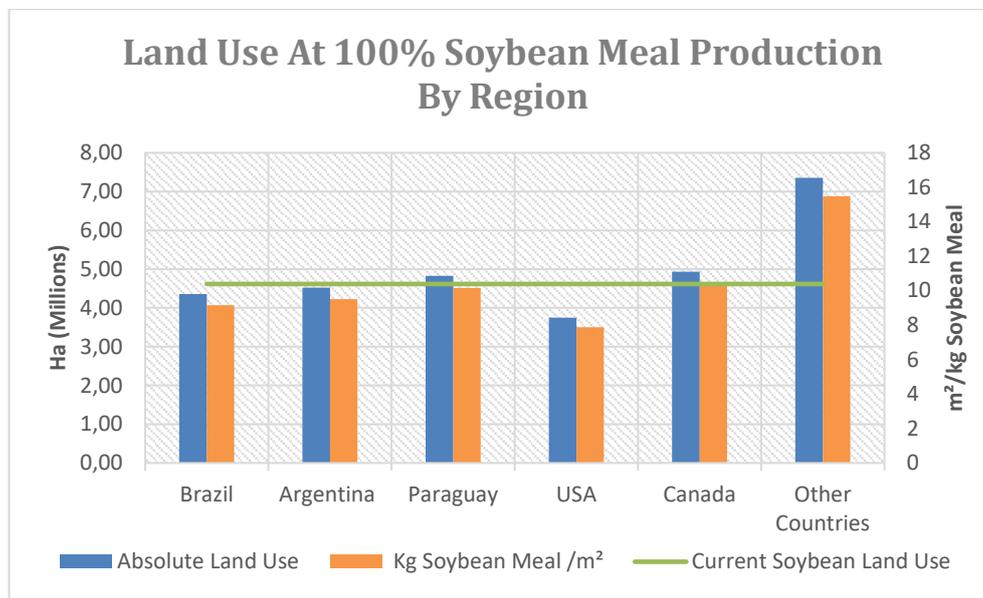


Figure 4. Land use at 100% soybean meal production by region

5 Discussion

5.1 Land-use implications of a large-scale insect protein substitution

This study has found that insect-sourced protein has the potential to significantly reduce current land used to provide soy-based protein in EU poultry & egg production. In the best-case scenario, this could save over 4.6 Mha of land – an area greater than the size of the Netherlands, Estonia or Switzerland (*Figure 2*). Not are the potential land savings enormous, but are likely underestimates as many studies utilise far greater soybean meal contents in poultry diets than our source data from Hoste (2014) (e.g. studies by Ramos-Elorduy et al., 2002, Van Gelder et al., 2008, Serrano et al., 2013, Alhotan et al., 2014, Bovera et al., 2015), which would result in even greater land requirements for soybean meal production. While an improvement in soybean productivity to US levels would use 860,000 ha less land, this would still do little else to mitigate the other major environmental impacts of soybean production. In addition, a greater amount of land would be saved through substitution with 25% of any soybean-free insect proteins (*Figure 3*). As such, the next question to ask is exactly what the reduced land-use associated with the introduction of insect-based protein could mean in real terms.

5.1.1 Feeding the world?

Inspired by the work of (Cassidy et al., 2013), one potential utilisation of any arable land no longer required as livestock feed would be the redirection of the soybean crop from animal feed to human consumption. 13.12 MT soybean oilseed equivalents (TS) were imported in 2016/17 (*Table 5*) for use in EU poultry & egg production, with one tonne of soybean (SC) producing 3430000.40 calories (Cassidy et al., 2013). At a calorie requirement of 2700 per day, $((TS * SC)/2700)/365$ demonstrates that the redirected soybean crop could feed over 45 million people for an entire year, in the event of a 100% substitution of soy protein with *Hermetia illucens*. *L* protein. This is important not only in the context of future global population growth, but also the potential for an immediate impact on the estimated 789.1m people currently undernourished worldwide. To this end, the soybean crop used for feed in EU poultry and egg production alone could provide an additional 1200 calories daily to over 100m people - all with no further agricultural intensification or expansion necessary.

5.1.2 Fuelling the world?

While crop competition undoubtedly impacts global hunger (Godfray et al., 2010), Holt-Giménez et al. (2012) laments that enough food already exists to feed 10 million people but goes to waste, and world hunger therefore represents the prioritisation of livestock and automobiles over people. However, soybean meal is by definition the by-product of soybean oil extraction; diverting soybeans to human consumption and preventing the production of soybean meal would therefore directly prevent soybean oil extraction. Because biodiesel derived from soybean oil is an important biofuel (Hill et al., 2006, Pimentel et al., 2009), this could conceivably encourage biofuel production to move elsewhere and thus negate the land savings of any insect protein substitution.

However, most insect species yield a significant amount of oil (Manzano-Agugliaro et al., 2012), with mealworm, black soldier fly larvae and house cricket containing 36%, 26%

and 17% oil respectively (Makkar et al., 2014). This is clearly comparable to the 18.62% soybean oil resulting from the 2016/17 EU oilseed crush (Section 2.2). While the nature of our source data does not allow for an accurate comparison of soybean oil yields with insect oil yields, an estimate can nevertheless be made. Given that Salomone et al. (2017) reported a BSF meal protein content of 42%, if oil represents 26% of BSF meal composition, multiplying our BSF protein yield (~200 tonnes/ha) by 0.565 results in the relative oil yield - 113 tonnes/ha. In comparison, our study results suggest a soybean oil yield of 0.59 tonnes/ha.

These oil yields are not only greater than those of soybean, but the quality of oil extracted from mealworm larvae and black soldier fly larvae has been found to be of equal quality to that of existing biofuels (Li et al., 2011, Zheng et al., 2012, Zheng et al., 2013, Leong et al., 2016). As such, while the loss of soybean meal production would prevent the production of potential biodiesel and threaten the displacement of biodiesel production to other areas, it is plausible that this could be directly replaced – and possibly surpassed - by insect-based biodiesels utilising a fraction of the land.

5.1.3 *Mitigating the world?*

While the results in *Figure 3* suggest that some insect production circumstances could result in higher emission and energy costs in comparison to soybean production, both Thévenot et al. (2018) and Oonincx and De Boer (2012) point out that these impacts can potentially be reduced through a variety of strategies and new technologies. Fertile land on the other hand is ultimately finite. In fact, the use of insect-based protein could help to mitigate overall emissions, despite possible emission increases at the production stage in comparison to soybean.

Feed production is not a zero-sum game. As proponents of land-sharing (as opposed to land-sparing) have argued in relation to biodiversity (Tscharrntke et al., 2012), agricultural production is not an absolute negative influence on the environment. While land-sparing actions such as reforestation may improve carbon sequestration prospects on land no longer required for soybean production (Pan et al., 2011), it is highly improbable such land would simply be abandoned for reforestation. Instead, reduced soybean demand may alleviate the pressure on farmers to increase yields (Zikeli and Gruber, 2017), allowing for the introduction of CA practices that vastly reduce the environmental impacts of agricultural production while maintaining land productivity.

This could be especially valuable in terms of carbon sequestration. Despite some authors questioning CA sequestration potential (Palm et al., 2014, Powlson et al., 2016), other studies have suggested that CA practices could have an enormous impact on soybean production emissions. Bernacchi et al. (2005) calculated that the introduction of no-till agriculture across the whole of US corn & soybean production could transform it from a carbon source to a carbon sink, able to sequester 21.7 Mt carbon annually - more than double the emissions of black soldier fly production at 100% substitution with soybean meal. In South America, Sá et al. (2017) have suggested a potential for additional carbon mitigation of up to 8.24 Gt (1 Gt=1000 Mt) between 2016-2050 in the event of the adoption of multiple carbon-mitigation strategies including no-till agriculture and forestation – more than a quarter of annual global emissions. Carbon sequestration at this scale would render additional emissions related to insect production insignificant in comparison.

5.1.4 Fertilising the world?

The disruption of the nitrogen and phosphorous cycles through fixation for fertiliser production is considered by Rockström et al. (2009) to be of an importance almost equal to its own planetary boundary. Fertiliser produced from damaging nitrogen-fixing then contributes significantly to livestock-sector Nitrous Oxide (N₂O) emissions (Rojas-Downing et al., 2017), and with the IPCC estimating the warming potential of N₂O to be 310 times that of s (Stocker et al., 2013) fertiliser-related emissions are particularly damaging.

Insect production can help to alleviate this reliance on nitrogen-fixation (though interestingly soybean actually requires no nitrogen fertilisation due to a symbiotic relationship with the bacteria *Bradyrhizobium japonicum* (Orf, 2008)), as food waste has been found to be of equal quality to commercial fertilizer post-digestion by black soldier fly larvae (Choi et al., 2009) and mealworm larvae (Wang et al., 2017), and assumed to be of equal quality by house crickets (Halloran et al., 2017). The black soldier fly bioconversion plant utilised by Salomone et al. (2017) reported a biofertilizer output of one third of the food waste input, and given that the biofertilizer is a necessary output of insect production with food waste, it would represent a significant amount of essentially free alternative fertiliser.

5.2 Potential obstacles to a large-scale insect meal substitution

Though it is impossible to speculate as to the specific outcome for land-use at a local scale, these would represent four outcomes that, crucially, are not mutually exclusive. Livestock feed, human food, biofuel and biofertiliser could all be produced with no additional land requirement, while increasing the viability of alternative farming methods that could sequester a significant amount of carbon and reduce environmental impacts. For this to become a realistic proposition however, the results imply a number of obstructions to overcome.

5.2.1 Land-use benefits dependent on the use of alternative insect feed sources

Though the results show that the substitution of soybean protein with insect-based protein results in vastly-decreased land requirement, they also show that the inclusion of soybean meal within the diets of insect species has a significant impact on land use, markedly increasing the amount of land needed per kg crude protein production. The soybean meal-free *Hermetia illucens* production boasts by far the lowest land use, though when soybean-related land uses are removed from *Acheta domesticus* and *Tenebrio molitor* production both land requirements are reduced to a similar level as the black soldier fly (Figure 1). Of course, the removal of soybean meal from *Acheta domesticus* and *Tenebrio molitor* production is entirely theoretical; unlike black soldier fly larvae, as yet no large-scale studies exist for these two species using anything other than commercial, grain-based feeds.

The lack of large-scale studies is not an indication of infeasibility, but simply a reflection of the burgeoning interest in the use of insects as food and feed. In fact, all of the insect species used in this study have been raised successfully from waste products and side streams at experimental scales. Though doubt has been cast by some authors as to the viability of the use of waste side streams in raising crickets at a commercial scale (Lundy and Parrella, 2015), others have found positive rearing results for crickets (Miech et al.,

2016), mealworms (Ramos-Elorduy et al., 2002, van Broekhoven et al., 2015), black soldier flies (Leong et al., 2016, Moula et al., 2017, Surendra et al., 2016) and house flies (Čičková et al., 2015). This use of waste side streams as insect feed is key to the extremely low land use evident in *Figure 2*, with this study finding the greatest land-use reductions associated with waste-based insect production that avoids the use of conventional feeds such as soy.

5.2.2 Potentially prohibitive quantities of alternative feed required

The use of waste sides-streams is key to maximising the potential benefits of insect production. Therefore, the obtaining of sufficient quantities of such feeds is essential to the viability of large-scale insect production.

Food waste is the most common alternative food source used in the production of the insect species investigated in this paper (e.g. Ramos-Elorduy et al., 2002, Oonincx et al., 2015, van Zanten et al., 2015, Surendra et al., 2016, Mondello et al., 2017), and is also used in current industrial insect production facilities such as Enterra (Enterra, 2018) in Canada and AgriProtein (AgriProtein, 2016) in South Africa. However, in Europe the use of food waste as an insect feed is currently prohibited in many circumstances under the ‘feed-grade’ materials requirement detailed in section 2.4. Furthermore, if we take the total amount of food waste required for the complete substitution of soybean meal protein with *Hermetia illucens*. *L* meal protein as per production data in Salomone et al. (2017), over 332 Mt of food waste would be required annually to enable complete substitution. In comparison only 88 million tonnes of EU food waste is produced annually (Stenmarck et al., 2016), suggesting that the sheer amount of waste required to feed insects could in itself be prohibitive. Though the EU have moved to encourage the use of food waste as fish and pet feed, the amount made available is a comparatively insignificant at 3.5 million tonnes (IFIF, 2017).

Despite the obtaining of the necessary amount of food waste for large-scale production appearing to be some way off, it is important to note that existing feed companies such as AgriProtein (AgriProtein, 2016) claim to be able to produce 50 tonnes of larvae per day from 250 tonnes of organic food waste, suggesting a productive efficiency far exceeding that reported in Halloran et al. (2017) and thus greatly reduced food waste requirements. Plus, with an estimated 1.3bn tonnes of food waste generated worldwide only from food intended for human consumption (Kojima and Ishikawa, 2013), there remains a significant volume of waste that could potentially be utilised for insect production.

In addition, while food waste is currently the most popular alternative substrate to conventional feeds, the insect species in this study have been raised on a wide variety of other waste side-streams such as manure (Sheppard et al., 2002, Newton et al., 2005, Čičková et al., 2015, Lundy and Parrella, 2015, Hussein et al., 2017), sewage sludge (Leong et al., 2016) and agricultural by-products (van Broekhoven et al., 2015, Miech et al., 2016), to varying degrees of success. *Tenebrio molitor*. *L* are even able to feed on polystyrene and convert it to usable organic matter (Yang et al., 2015). Thus, there are many waste side-streams aside from food waste that insect production could potentially exploit.

5.2.3 Excessive energy consumption

In terms of energy use, it is generally considered that all products with a low dry matter content (e.g. lucerne, leaves, aquatic proteins) are less sustainable from an energy

consumption perspective due to the high energy costs incurred during the drying stage (van Krimpen et al., 2016). Indeed, ability to delay soybean harvest is until a specific moisture content is achieved is an inherent advantage of soybean production from an energy use perspective (Johnson et al., 2008). Moisture contents up to 250% greater than that of soybean meal are evident in our selected species' composition (Table 7), and it is clear from Figure 3 that insect production is generally energy intensive in comparison to soybean production.

It is possible that the lack of either drying or processing in the production of *Acheta domesticus* contributed significantly to its low energy requirement, both of which occurred in the energy-intensive *Tenebrio molitor. L* production. However, another reason for this energy consumption disparity may be that as poikilotherms, insects do not regulate their internal body temperature and as such expend far less energy than animals who need to maintain a core temperature. While this allows insects to convert feed to biomass far more efficiently than ordinary livestock and is therefore one of the great advantages of insect production (see reviews by Huis and Oonincx, 2017, Moon and Lee, 2015, Sánchez-Muros et al., 2014), it also means that it is necessary to maintain suitable ambient temperatures for optimal production, increasing energy use (Oonincx and De Boer, 2012).

The ideal rearing temperature the three insect species used in this study is considered to be around 30°C (Clifford and Woodring, 1990, Harnden and Tomberlin, 2016, Kim et al., 2016), closely matching the average ambient temperature of the region of Thailand where the low-energy *Acheta domesticus* production takes place (Climate-Data, 2018). Conversely, temperatures drop to 12°C in the region of Italy where the more energy-intensive *Hermetia illucens. L* production takes place (Yr, 2018b), and as low as 2°C (Yr, 2018b) in the region of France where *Tenebrio molitor. L* are produced (Yr, 2018a) with the highest energy consumption (Figure 3). This suggests a geographic correlation between climate and energy consumption, potentially resulting in far more energy-intensive insect production in colder climates in Northern Europe - at least while mass production techniques are refined (Oonincx and De Boer, 2012).

5.2.4 Lack of available data

The lack of applicable large-scale insect production data in itself inhibits the scaling-up of insect production, a lack of data increases uncertainties.

Insect production methods can vary greatly depending on factors such as purpose and audience (Feng et al., 2018), something distinctly reflected in this study. For example, *Acheta domesticus* production took place at a low-tech facility in a developing country, rearing whole crickets intended for direct human consumption. Conversely, *Hermetia illucens. L* and *Tenebrio molitor. L* were both produced in more high-tech facilities in Europe, with neither product intended for human consumption. Purpose concretely impacted output units, with the crickets intended for human consumption kept whole, with black soldier fly larvae dried as a by-product of biofertiliser production and mealworms dried and ground to create meal for sale as pet food or research. It is possible that the lack of a meal processing stage in the production of black soldier fly larvae gives the process misleading efficiency, considering that 3.8kg dried mealworms were required to produce 1kg mealworm meal in Thévenot et al. (2018). In addition, variations of up to 25% have been reported for *Acheta domesticus* DM content (32.2, (Ayieko et al., 2016), 30.2 (Finke, 2002) & (Williams et al., 2016), 29.2 (Yi et al., 2013) and 24.1% (Oonincx, 2015)) which would in turn have a significant impact on the amount of insects required for protein substitution and thus directly impact land use conclusions. In addition, Halloran et al.

(2017) specifies colour and size as of particular interest for human consumption, yet cosmetic appearance is not relevant for either of the other production systems.

How these species' production would perform under a different purpose is unknown. Directly comparable insect production studies at an industrial-scale and for the purpose of meal production would help to strengthen the case for insect protein use, enable targeted research and provide clearer pathways to its wider implementation.

5.2.5 System complexity & maturity

The potential real-world benefits of the substitution of soybean protein with insect protein such as a greater food supply, biodiesel production, fertiliser production and carbon mitigation are interrelated; the inherent conflicts between resources required for optimum insect production and competing uses suggest that insect protein substitution could only occur within a complex, global system.

These conflicts come in a variety of guises both in terms of supply & demand and consumer behaviour. For example, despite food waste representing the most common alternative insect feed, food and agricultural waste is also necessary for the production of biofuel, energy and biomaterials (Giroto et al., 2015) – something that could be difficult if the volume of food waste required for insect production that has been calculated is accurate. Waste and overconsumption - the two most significant global food system losses (Alexander et al., 2017) – are responsible for the supply of food waste, but are driven by consumer behaviour. Perversely, this could mean that the more efficiently food is produced, distributed and consumed, the less food waste is available and thus the less viable insect production actually becomes. Further, the use of crop residues in the production of insects (e.g. Lundy and Parrella, 2015, Miech et al., 2016, Wang et al., 2017) directly conflicts with CA implementation, as CA requires that crop residues are retained to prevent soil degradation (Grignani et al., 2012, Palm et al., 2014). This is compounded by the fact that farmers are reluctant to adopt CA systems regardless of environmental benefits simply due to increased weed pressures and the prospect of yield reductions in cash crops (Zikeli and Gruber, 2017). As such, while insect production may alleviate yield pressures and encourage farmers to adopt CA practices, it could also provide additional competition for crop residues central to the effectiveness of CA. Modelling by Rööös et al. (2017) reinforces the idea that the reduction of negative agricultural impacts requires action not only on supply, but equally on demand and waste; the compound benefits of action on all three fronts far exceeded action on just one facet of agricultural production and consumption.

Such conflicts are not criticisms of or insurmountable obstacles to the substitution of soybean protein with insect-based protein, but simply a reflection of a relatively burgeoning idea that is only now beginning to gain significant traction. Soybean production in comparison is a mature system developed over many decades, with US soybean yields more than doubling between 1961 and 2016. The impact of this can be seen in our results, where the high-tech, high-volume soybean exporters to the EU boast yields approaching double those of exports sourced from low-volume, low-tech countries (*Figure 4*). This is a factor highlighted by Čičková et al. (2015); the apparent efficiency of commercial insect production facilities such as AgriProtein suggests that technological progress may be further than available LCA studies indicate.

Ultimately, this study implies that an interconnected, global system would be required to cope with the conflicting demands of waste side-stream-based insect production, and time required for the system itself to mature. As such, there is an urgent need for further studies

investigating the relationship between these potential conflicts with regards to large-scale insect production.

6 Conclusion

The convergence of an increasing population, greater resource demand for dwindling natural resources, increasing anthropomorphic environmental impacts and climate change necessitates the urgent exploration of consumptive, productive and cultural changes that could help to alleviate these pressures. To this end, this paper investigated the land use impact of the substitution of soybean protein with insect-based protein in EU poultry and egg production.

The results of this study indicate potential land-use savings of over 4.6 Mha – an area of land greater than that of the Netherlands, Estonia or Switzerland. The production and expansion of soybean severely impacts vital ecosystems in South America where the majority of EU soybean meal is sourced, so these land-use savings are very significant on a global scale. Land use reductions associated with the use of insect protein were found to vary by species and feed composition, with land-use increasing sharply when soybean meal was included in the diets of *Tenebrio molitor. L* and *Acheta domesticus*. The greatest land-use savings were associated with the rearing of insects on waste-side streams – specifically *Hermetia illucens. L* reared on food waste – though a lack of large-scale insect production LCAs for our selected insect species meant this was the only insect species where a specialised food waste-based rearing process was utilised.

In the event of a complete substitution of soybean meal with *Hermetia illucens. L*, the soybean crop no longer required for EU poultry and egg production could meet the complete calorific requirements of 45 million people, for an entire year. Alternatively, this soybean could provide 1200 calories per day to 100,000 million people annually. In addition to potentially alleviating global hunger, the production of insect species for livestock feed could result in several by-products such as oil and biofertilizer, enabling the substitution of biodiesel currently sourced from soybean meal processing while also reducing the reliance on damaging nitrogen fixation necessary for commercial fertiliser production. While the GHG emissions and energy use of some insect species production were found to be considerable, mitigation strategies are available for both GHG emissions and energy use, whereas arable land is a finite – and dwindling – resource. In fact, reduced demand for soybean could in itself assist GHG mitigation, as it may ease the introduction of CA practices that have been widely suggested to have significant carbon sequestration potential in soybean production. These potential benefits are not mutually exclusive, with no further agricultural intensification or expansion necessary.

However, the expansion of insect production to a scale where complete substitution with soybean meal is possible presents several major issues. With food waste representing the common insect substrate, it is apparent that an enormous amount of food waste would be required at the insect yields reported, a far larger amount in fact than the total volume of EU food waste currently produced annually. Though other waste side-streams such as manure, agricultural wastes and even polystyrene have been shown as viable substrates, they are yet to be expanded to an industrial scale. The drying and heating requirements of insect production are likely to be of concern in colder European climates, with significantly increased energy usage and thus GHG emissions, though future carbon-free energy sources may negate these concerns. In addition, though EU regulations are moving towards the acceptance of insects as both human food and animal feed, the use of insect meals in the production of terrestrial livestock remains prohibited at the present time.

While this study presented a comparison, interpretation and extrapolation of existing insect production analysis to a large scale, it is important to recognise that this is done largely for ease of conceptualisation of the scale of potential land-use, GHG emissions and

energy use changes. It is intended only as a starting point for alternative insect production methods able to exploit waste or underused resources on a more local scale – for example, the utilisation of permanent meadows as insect feed, the introduction of a sewage sludge/insect production method, or small-scale local production on alternative waste sources. Large-scale, centralised insect production may or may not end up being a preferable – or even feasible – method of achieving the vast environmental benefits that have been suggested in this paper.

This study was limited by the lack of available commercial-scale insect production studies. Press releases from commercial-scale insect production ventures suggest far greater insect yields are currently possible than the studies available for analysis in this paper, though with no data publicly available to evidence these claims they cannot be considered reliable. Despite the multitude of potential benefits to the substitution soybean protein with insect protein, there are many unknowns and knowledge gaps to overcome. Future research is urgently required as to the viability and impact of different waste side-streams on insect composition and yield, insect production techniques, the applicability of a wider variety of insect species into the diets of common livestock, and the nature of potential resource conflicts and their resolution as part of a larger system. Ultimately, the substitution of soybean protein with insect-based protein shows great potential for alleviating a multitude of current environmental issues and future conflicts, with control of waste usage at regional and global scale central to the ability of insect production to become viable at industrial scale.

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Appendix

S1. Cricket Production Data (Halloran 2017)

Annual Cricket Production (kg)	DM (%)	Crude Protein (%)	Production Area (m ²)	Annual Feed (kg)	Soybean Meal in Feed (%)
152056	26	63	2720	223522	28

$(Annual\ Insect\ Yield * DM * CP) / (Production\ Area) = Annual\ Protein\ Production$

$(Annual\ Feed * \% \text{ Soybean Meal in Feed }) / 0.796 / 2.77$ (Average of soybean yields from Table 5) = Land Use for Soybean Production

$(Production\ Area + Land\ Use\ for\ Soy\ Production) / (Annual\ Protein\ Production)$ = Total Land Use (m²/kg)

$(Production\ Area) / (Annual\ Protein\ Production)$ = Land Use Without Soybean Meal (m²/kg)

S2. Soybean GHG Emission Calculation

Table S2.1. Proportion of Arable Land Using Conventional Agriculture (AQUASTAT, 2018) (FAO, 2015)

Country	1000ha		%
	Total Arable Land	Land Under CA	Land Under CA
USA	155108	35613	22.96
Canada	46915	18313	39.03
Brazil	72607	31811	43.81
Argentina	39754	29101	73.20
Paraguay	4415	3000	67.95
Other Countries	n/a	n/a	n/a

Table S2.2 GHG Emissions from Soybean Production under CA and Conventional Agriculture (LEAP, 2018a)

Country	CO ₂ eq. /kg DM (Excl. LUC)	
	Conservation Agriculture	Conventional Agriculture
USA	0.96 (0.75)	1.38 (0.94)
Canada	1.2 (0.6)	2.17 (0.87)
Brazil	2.88 (0.55)	3.54 (0.63)
Argentina	3.83 (0.60)	4.76 (0.71)
Paraguay	No figure (0.49)	6.08 (0.57)
Other Countries	n/a	4.59

Table S2.3. GHG Emissions from Soybean Production in ‘Other Countries’ (LEAP, 2018a)

Country	CO ² eq. /kg
Ukraine	3.9124
India	3.9658
Uruguay	5.8919
	4.59

Table S3. Combined GHG Emissions from Soybean Production Under Conservation Agriculture and Conventional Agriculture

Country of Origin	Tonne	Tonne CO ² eq.			CO ² eq. /kg
	Eq. Soybean Import DM	Conservation Agriculture	Conventional Agriculture	Total Emissions	Crude Protein
Brazil	4146100	5231559	8246738	13478297	7.81
Argentina	3931404	11022334	5014709	16037043	9.80
Paraguay	777472	258864	1515006	1773870	5.48
USA	1398164	308179	1486458	1794637	3.08
Canada	277382	129930	366964	496894	4.30
Other Countries	888502	0	4078254	4078254	11.03
Total	11419025	16950866	20708128	37658994	7.92

Eq. Soybean Import DM = Eq. Soybean Import (Table 5) * 0.87

Conservation Agriculture Tonne CO² eq. = Eq. Soybean DM * % Land Under CA (Table S2) * Conservation Agriculture (Table S2)

Conventional Agriculture Tonne CO² eq. = Eq. Soybean DM * % Land Not Under CA (Table S2) * Conventional Agriculture (Table S2)

Crude Protein CO² eq. /kg = Total Emissions / Total Crude Protein (Table 6)