Insect-based protein feed: from fork to farm¹

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Abstract

Numerous studies show that insects are efficient in converting organic waste into proteins and fats, which makes them an interesting alternative source of feed. Moreover, since around one-third of global food produced for human consumption is lost or wasted, the production of insect-based meals from food waste is considered a sustainable alternative to other protein sources. This paper introduces a quantitative framework able to analyse the economic implications of developing a large-scale insect-based meal industry worldwide, which would require important regulatory changes. Our calculations, based on findings from the literature, suggest that almost 1.4 billion tonnes of food, that could potentially be used as insect feed, went to waste at the world level in 2018, a figure that is projected to rise to 2 billion tonnes by 2030. Results show that the use of food waste for insect meal and oil production would have important downward price impacts on meals and oils (fish- and plant-based), reducing feed costs and stimulating global aquaculture and livestock production, reducing total land use for agriculture production and lead to a lower dependence on protein imports.

Keywords: insect-based meals, protein feed markets, aquaculture, protein self-sufficiency, partial equilibrium model

1. Introduction

The United Nations (UN) estimates that the global population will increase by 2 billion persons in the next 30 years, adding further pressure on natural resources to meet the growing demand for food (UN, 2019). Given the constrained availability of resources and changing climate, food security can only be achieved by deploying more sustainable and efficient production systems (IPCC, 2019). One important contribution to attaining this goal is to increase the efficiency of the entire food supply chain 'from farm to fork', which includes reducing the amount of food waste. The UN in its 12th Sustainable Development Goal (SDG) highlights this: 'Ensure sustainable consumption and production patterns' (UN, 2015). Specifically, SDG target 12.3 refers to food waste. Target 12.5 refers to waste in general and to recycling.²

These goals are also reflected in the European Green Deal (EC, 2019, 2020) and its Farm to Fork Strategy (F2F), in which the transition towards a sustainable food chain is a key objective. The F2F envisions a circular bio-based economy with bio-refineries creating new jobs and contributing to a lower climate footprint of the farming sector through the production of bio-fertilisers, protein feeds, bioenergy and bio-chemicals. It also mentions that the Commission will examine EU rules to reduce the dependency of the livestock sector on imported soybeans by fostering additional production of domestically grown plant protein as well as alternative feed materials including insects and by-products such as fish waste (EC, 2020: 10).³ In this context, the insect farming industry could play an important role in closing the loop 'from fork to farm', by transforming food losses and waste into an additional supply of protein feed for livestock and aquaculture. This would

¹ The opinions expressed and arguments employed herein are those of the authors and do not necessarily reflect the official views of the European Commission.

² Target 12.3: 'By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses.' Target 12.5: 'By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.'

³ See also EC (2018).

imply reintroducing nutrients back into the food chain, substantially reducing waste through recycling.

The insect farming industry is already present in Europe today producing more than 5,000 tonnes of insect protein for pet foods and aquaculture feed on by-products from the agri-food industry (IPIFF, 2019). The industry is expanding with increasing investments in new industrial size insect farms. Moreover, there is a strong demand for 'green' policies and several regulatory agencies around the world are evaluating the potential for insect production on an industrial scale. There are several publicly funded research projects looking into the issue as well (Kupferschmidt, 2015). Given the potential contribution insect farming could have in reaching the SDG of reducing food waste, this paper analyses how a large expansion of this industry will affect global agricultural markets and the greenhouse gas (GHG) emissions associated with agricultural production.

Specifically, we analyse three scenarios using the OECD-FAO Aglink-Cosimo model of the global agricultural markets and the FAO FISH Model. In the first scenario, all available global food waste is converted into insect protein meal (ITM) and insect oil (ITL), and utilised in the agricultural and aquaculture sectors. The second scenario is more moderate since only 50% of the total food waste is recycled, with the resulting protein being fed to both livestock and aquaculture production activities, as in the previous scenario. Last, but not least, a third scenario contemplates a more restrictive situation where ITM is only utilised in the aquaculture sector requiring 21% of the total available food waste to be recycled.

After this introductory section, the paper first gives an overview of the insect farming industry and the current regulatory environment. It then provides a calculation of the globally available food waste, followed by a description of the analytical framework and the scenarios considered in the analysis. Finally, the main results are discussed and some limitations of the study highlighted.

2. Insects, closing the loop from farm to fork

The main reason why insects are an interesting source of food and feed is that they are able to connect the agricultural supply chains and improve the circularity of the bio-economy. Around one-third of all food produced for human consumption is lost or wasted globally according to the Food and Agricultural Organization of the United Nations (FAO, 2011). While this estimate is subject to considerable uncertainty, there is no doubt that large quantities of food go to waste every year and only few options are available for reutilisation. One option, which has received considerable interest recently, is to recycle

wasted food through insect bioconversion into protein feed used in the livestock and aquaculture sectors (Barbi *et al.*, 2020; Dicke, 2018; Dobermann *et al.*, 2017; Ganda *et al.*, 2019; Govorushko, 2019; St-Hilaire *et al.*, 2007; Stamer, 2015; Tao and Li, 2018).

Insects have the ability to convert organic waste into proteins and fat at a high conversion rate (Van Broekhoven *et al.*, 2015). The protein and part of the fat can be utilised directly in the feed industry and the rest of the fat has further uses in the biofuel and other processing industries (Fowles and Nansen, 2020; Li *et al.*, 2011; Manzano-Agugliaro *et al.*, 2012; Wang *et al.*, 2017; Zheng *et al.*, 2012). However, in most countries, there is a regulation in place, which prevents large-scale production of insects for food and feed use (Lähteenmäki-Uutela and Grmelová, 2016; Lotta, 2019; Pinotti *et al.*, 2019).

The use of food waste as animal feed has been a common practice for centuries. However, the practice of feeding food waste to animals has declined rapidly since the 1980s when there were several disease outbreaks linked to animal feed, including foot-and-mouth and transmissible spongiform encephalopathy. In an attempt to prevent the spread of such diseases, many governments around the world have passed regulations that restrict the use of food waste in animal feed. In the EU, for example, a ban of mammalian processed animal protein (PAP) fed to cattle, sheep and goats was introduced in 1994. The ban was expanded in January 2001 with the feeding of all processed animal proteins to all farmed animals being prohibited, with certain limited exceptions.⁴ This is to ensure that there is no cross-contamination between feed containing PAP intended for non-ruminants and feed intended for ruminants. In 2015 the European Food Safety Authority (EFSA) published a scientific opinion discussing the risks associated with insect based feed (EFSA Scientific Committee, 2015). Based on this opinion ITM were approved for use in aquaculture feed within the EU in 2017.⁵

Insects produced in the EU for food, feed or other purposes are considered 'farmed animals' and are therefore covered by the rules restricting the types of feed they may be given. Consequently, farmed insects may only feed on materials of vegetable origins, with some exceptions on milk, eggs and other products of animal origins. Moreover, EU regulation requires producers to keep their animals in good health and this applies to insect producers as well. Invertebrates,

⁴ Regulation EC No. 999/2001 (EC, 2001).

⁵ Commission Regulation (EU) 2017/893 (EC, 2017).

including insects, are exempted from regulation in the area of animal welfare though (IPIFF, 2020).

Many insect species can be used for protein production, including the larvae of the black soldier fly (BSF) (*Hermetia illucens*), the common housefly (*Musca domestica*), the yellow mealworm (*Tenebrio molitor*) as well as blue bottle (*Calliphora vomitoria*) and blow flies (*Chrysomya* spp.). Among those, the most promising in terms of food-waste recycling is the BSF (Oonincx *et al.*, 2015; Veldkamp and Bosch, 2015). The BSF is neither a pest nor a disease vector and its larvae are omnivorous and very robust against diseases (Nguyen *et al.*, 2015; Purschke *et al.*, 2017). Originating from the southern states of USA, BSF now occurs worldwide in all tropical, warm and moderate climate zones due to the shipping from continent to continent. Fully-grown larvae produce a biomass that contains 40–45% protein with an advantageous amino acid composition and up to 35% fat in dry matter, which makes it suitable as a feed supplement for various animals (Barragan-Fonseca *et al.*, 2017; Schiavone *et al.*, 2017). Meal from BSF larvae have a protein content that is similar to defatted soybean meal but the fat content is well above the fat content of fish meal (FM). Because the fatty acid profile of BSF meal is suboptimal for feed purposes, the oil must be extracted from the biomass before it is processed. It has been shown that extracted insect oil meets most of the requirements set by the international standard EN 14214 for biodiesel (Nguyen *et al.*, 2018). ITL processed into biodiesel is therefore potentially an important by-product from protein feed based on the BSF larvae.

In addition to regulatory and production issues affecting supply, the arrival of an insect feed industry depends on demand factors. The main question is whether insect meal can be introduced in the feed diet of the different animals without affecting the feed conversion, the taste and the quality of the products. Different studies support the fact that insect meals will be easier to introduce in the diet of aquaculture species, followed by poultry, and in particular, laying hens (Belghit *et al.*, 2018; Gariglio *et al.*, 2019; Heuel *et al.*, 2019; Iaconisi *et al.*, 2017; Magalhães *et al.*, 2017; Makkar *et al.*, 2014; Maurer *et al.*, 2016; Sealey *et al.*, 2011; Veldkamp *et al.*, 2012).

3. From food waste to insect-based protein meal

Estimating the amount of food that goes to waste every year along the food chain at the global or regional level is not an easy task and only a few studies attempt to do it (Caldeira *et al.*, 2019; FAO, 2011, 2019). Amongst them, the most comprehensive reference in the literature is FAO (2011). This study considers seven geographical areas and seven agricultural and fish products that are wasted or lost throughout five stages of the food chain: agricultural

production; post-harvest handling and storage; processing; distribution; consumption.⁶

Since in our ex-ante analysis we consider market developments until 2030, food loss percentages in FAO (2011) have been extrapolated based on the positive relationship between per capita GDP and food waste in the consumption stage of the food chain. Conversely, in the processing and packaging as well as in the distribution stages of the chain, there is a negative relationship between food waste and per capita income has been used as the basis for extrapolation. Only in the agricultural production and post-harvest stages no correlation is assumed between food waste and per capita income, so that the same estimates are used in all years.

The food waste available for insect feeding is assumed to come from the production, processing, distribution and consumption of root, tubers, fruits and vegetable, pulses, eggs, meat, fish, sugar, cereals and dairy products. In the technical annex, a detailed description of the approach used to calculate the amount of food waste available for insect production in each stage of the supply chain is provided. It involves an assessment of the amounts available of each commodity in each of the stages after accounting for by-products. The general formula used to calculate the waste available for insect production is as follows:

$$\begin{aligned} Waste_{i,r} = & QP_{i,r} \times \frac{SHR_{L,i,r}}{1 - SHR_{L,i,r}} \\ & + QC_{i,r} \times (SHR_{3,i,r} + (1 - SHR_{3,i,r}) \times SHR_{4,i,r} \\ & + (1 - SHR_{3,i,r}) \times (1 - SHR_{4,i,r}) \times SHR_{5,i,r}) - BPFeed_{i,r} \end{aligned}$$

where *i* and *r* are the commodity and country indices, respectively. $QP_{i,r}$ denotes production, $QC_{i,r}$ consumption, $SHR_{s,i,r}$ is the waste share in the different stages and $BPFeed_{i,r}$ denotes by-product feed (see paragraph below).

To calculate the amount of fruits and vegetables (FV) waste available for insect feed, for example, we start with $QP_{FV,r}$ and subtract the loss occurring in stage 1 (agricultural production) due to mechanical damage or spillage during harvest operations. Losses occurring in stage 2 (post-harvest handling and storage) are not included since degradation

⁶ The report distinguishes between food loss and food waste. The former refers to losses occurring in the parts of the supply chain that leads to food for human consumption, i.e. the production, post-harvest and processing stages. Food waste, on the other hand, refers to losses occurring in the final stages of the supply chain, i.e. in connection with distribution and consumption (Parfitt *et al.*, 2010). In the present paper, the term food waste refers to losses occurring in all stages of the food chain. The food waste percentages in FAO (2011) do not include sugar beets and eggs, so for these commodities we supplement with food loss percentages calculated from Table 1 in Caldeira *et al.* (2019).

during handling, storage and transport from the farm would probably leave the product in a sufficiently good state to be directly used as feed. Waste occurring in stages 3 to 5 (processing, distribution and consumption) is calculated using the total consumption of FV, which includes waste. Finally, some by-products already being used as animal feed (for example distillers grains with solubles (DDGS), molasses, meat and bone meal, etc.) are deducted from the total amount of waste available for insect production.

In order to calculate the amount of insect meal that can be produced from food waste information on the feed conversion ratio (FCR) is needed. Salomone *et al.* (2017) report that with one tonne of food waste 29.6 kg of dry larvae with 42% protein and 35% crude fat could be produced. The protein content is similar to defatted soybean meal (48%) but the fat content is well above the fat content of FM (around 14%). Since insect meal is considered to be a good replacement of FM and oilseed meal used in aquaculture and in the first feeding phase of poultry and pigs, we assume that the extra fat (i.e. from 35 to 14%) will be extracted and used in the biodiesel industry rather than in the feed system. With this extraction the percentage of protein will increase to 53% which is much closer to the typical percentage of protein in FM.

The numbers reported by Salomone *et al.* (2017) corresponds to an FCR of 33.8 on a dry weight (DW) basis or 12.7 on a wet weight (WW) basis (assuming a water content of 62.3%). This is in line with other estimates found in the literature. Danieli *et al.* (2019), for example, report WW FCRs of 13.1–19.2, depending on the diet given to the BSFs. There are, however, also examples in the literature of much lower FCRs, implying a higher feed efficiency (e.g. Banks *et al.*, 2014). The choice of FCR has a large effect on the scenario results and we therefore stick to a fairly conservative estimate of the FCR estimated by Salomone *et al.* (2017), which is used universally across all countries and commodities found in this analysis.

With these assumptions, our calculations suggest that almost 1.4 billion tonnes of food, that could potentially be used as insect feed, were wasted at the world level in 2018. This could increase to 2 billion tonnes by 2030 with waste originating from: fruit and vegetables 63%, cereals 20%, other crops 5%, meat and dairy 7% and fish 5%. The large share of fruits and vegetables in total food waste is partly due to the large amounts produced together with a high waste percentage due to the perishability of the product, and partly a result of our assumptions regarding the economic feasibility of recuperating the wasted fruit and vegetables at the production level.

In the EU, about 129 million tonnes of food waste will be available, in principle, for insect meal production in 2030, according to our calculations. If this was used as insect

feed, the EU would be able to produce around 3 million tonnes of insect meal and 0.8 million tonnes of insect oil by 2030 (Figure 1 and 2), which is in line with the reported estimates by IPIFF (2019).

4. Analytical framework

The model and the baseline

The analysis in this paper is based on the Aglink-Cosimo model and the associated OECD-FAO Agricultural Outlook database⁷. Aglink-Cosimo is a recursive-dynamic multi-commodity model of global agriculture and includes projections of agricultural markets until 2030 (Araujo Enciso *et al.*, 2015; OECD, 2015), what we refer to as the medium-term outlook (MTO) or ‘baseline’.

For this analysis, we modified the standard version of Aglink-Cosimo to include the FV sector and an ITM and ITL industry producing high protein feed from BSF larvae in all countries. Insect farming is assumed to be entirely based on food waste, with a large proportion coming from FV and FV by-products.⁸ This includes the amounts of wasted material in each part of the supply chain for each of the agricultural commodities. The amount of food waste feed to the BSF larvae is exogenously phased in over the baseline period using a homogenous feed conversion ratio across all countries (Salomone *et al.*, 2017). The amount of insect-based meals (ITM) and insect-based oils (ITL) produced are simply added to the aggregated vegetable protein meal (PM) and the vegetable oils (VL) production already present in the Aglink-Cosimo model. This modelling approach implies that insect meals and oils are perfect substitutes of vegetable meals and oil. In the present Aglink-Cosimo model, market-clearing prices for vegetable meals and oils are endogenously determined. As the amount of waste fed to the BSF larvae is phased in, market mechanisms (i.e. supply, demand and the equilibrium condition) reduce the price of vegetable meals and oil. In our modelling approach, it is assumed that insect meals and oil are price takers, with their prices being equal to the market-clearing price of vegetable meals and oil.

This assumption is of course linked to the fact that we are exogenously (outside of the model) deciding the level of production through how much waste is utilised by the insect farming industry. To change this assumption would require us to estimate an ITM production function requiring own price elasticities as well as cross price elasticities with regard to the price of soya meal, rape meal, sunflower meal, fish meal, etc. combined with waste price elasticities and possibly

⁷ www.agri-outlook.org.

⁸ More detailed explanations are presented in the technical annex; Supplementary Material S1.

Figure 1. Food waste by commodity group, 2010-2030.

elasticities linked to size of animal production. Then the question of market clearing prices of waste and own prices would have to be specified. This is beyond the scope of this paper given the global coverage of the Aglink-Cosimo model. Instead we span a range of waste utilised in the BSF larva farming industry in three scenarios to highlight the impact this could have on agricultural and aquaculture markets.

Additional to Aglink-Cosimo, the fisheries and seafood sectors are covered by the FISH model, a model developed and maintained by the FAO (OECD/FAO, 2020). This model is used to produce a global fisheries outlook and contributes on a yearly basis to the OECD-FAO agricultural outlook with a chapter on fisheries for which it formally interacts with the Aglink-Cosimo model for consistency purposes (e.g. alignment of short to medium-term macroeconomic developments). On the supply side, the FISH model

distinguishes between fish from capture fisheries and aquaculture. Fish commodities are used for food consumption, feed processing (meals and oils) and bait. FM demand responds to the size of the aquaculture sector and prices of the different protein meals. For this paper, the Aglink-Cosimo and the FISH models were used simultaneously.

The FISH model suffers from three main limitations. First, the model assumes that countries for which the fishmeal production is based on controlled capture (i.e. fish quotas), production does not react to prices and only to the El Niño-Southern Oscillation (ENSO) cycle. Second, the model only has a single representative aquaculture price per country used for all the individual aquaculture species. Third, the model has a limited ability to capture the effect of the 'fishmeal trap' (i.e. lower availability of fishmeal due to the strict controls on capture fisheries and the rapid growth

Figure 2. Global insect meal and insect oil production in the three scenarios.

in aquaculture production creating a premium price for fish meal compared to oilseed meals) on the FM to oilseed meal price ratio. Since ITM might be more appropriate than oilseed meal in the feed ration of many aquaculture species, part of this price gap between FM and oilseed meal could be eliminated with the market expansion of ITM⁹.

Scenarios

We construct three counterfactual scenarios to the baseline, denoted Scen1, Scen2 and Scen3, in order to analyse the additional supply of protein feed and the oil by-product produced from insects fed on food waste. The scenarios differ with respect to the availability of food waste to feed

the insect farming sector (supply side) and the possibility to feed non-ruminant livestock and aquaculture species (regulatory side). Table 1 summarises these differences.

Scen1 is the most extreme of these scenarios in the sense that there are no restrictions on the use of ITM as feed in any of the livestock sectors. In addition, we assume that the ITM input costs (i.e. cost of recycling waste) are low enough and the revenue obtained from sales of by-product from ITM production makes ITM so competitive to other protein meals that it is profitable to use the entire amount of available food waste to produce ITM. In Scen2, it is assumed that turning food waste into feed for insects shows an upward marginal cost curve with a steeper slope than in Scen1 and therefore only 50% of the total amount of available food waste used for ITM production can be competitive. There are no restrictions, however, on the use of ITM feed in the livestock sector in this scenario. Finally,

⁹ See the section of the fishmeal trap in the technical annex; Supplementary Material S1.

Table 1. Comparison of the three scenarios.

	Scen1	Scen2	Scen3
Share of food waste used to produce insects	100%	50%	21%
Demand for insect meal	all livestock sectors	all livestock sectors	only aquaculture

in Scen3 it is assumed that insect meal is only allowed to be fed to aquatic animals and as a result the size of this new industry is determined by the demand coming from aquaculture. For that reason, in this scenario the demand for oilseed meal coming from aquaculture is replaced by ITM, which is assumed to be a better adapted feed ingredient for aquaculture species. Compared to the two supply scenarios (Scen1, Scen2) where we utilise 100 and 50% of total food waste, respectively, the demand scenario (Scen3) requires the insect farming industry to recycle only 21% of global food waste to meet aquaculture feed demand.

Scen1 represents the upper limit of the potential market impacts associated with the use of ITM feed produced from food waste. It is not meant as a realistic scenario but rather as a reference point for the other two scenarios that are less extreme in their assumptions. On a weight basis, the amount of ITM produced in this scenario represents around 6% of protein meal consumption and 9% of the vegetable oil used in the production of biodiesel in the EU. At the global level, if all available food waste was recycled by insects, 46.5 million tonnes of insect meal could be produced in 2030, corresponding to 11% of the total protein meal consumption in the baseline (without insect meal) (Figure 2). ITL production would reach 12.3 million tonnes, which is equivalent to 5% of the global vegetable oil production and 41% of the vegetable oil used for biodiesel production.

In all scenarios, the changes considered are relative to the medium-term baseline. The additional ITM and ITL production is introduced over a seven years period, with equal step in the first 6 years, reaching respectively 100 and 50% use of food waste by the year 2025 in the first two supply-driven scenarios. Finally, in all scenarios, the assumption is made that part of the price gap between FM and OM is eliminated and that the percentages of food waste feed to insects is homogenous across all countries in the model.

5. Results

The main impacts of an expansion of the insect farming sector on the global agricultural and fish markets are summarised in Table 2-5. Scenario results are presented

for year 2030 and compared to the medium-term baseline projections. In general, impacts are largest in Scen1, followed by Scen2 and Scen3.

Oilseed markets are heavily affected, since the price of vegetable PM competes with ITM in the feed market and VL compete with ITL in the biodiesel market. On the global level, production of traditional vegetable PM (excluding ITM), falls by around 5 and 1% in Scen1 and Scen3, respectively, and the price falls by almost a third in Scen1 and by 9% in Scen3. Soybean and other oilseed prices fall by 20 and 16%, respectively, in Scen1 and by 5 and 4%, respectively, in Scen3. Vegetable oil prices fall by 15 and 3%, respectively, in the two scenarios and the pass-through rate to the price of biodiesel is around 50%. This implies that biodiesel price declines by 6.9 and 1.3%, respectively, in the two scenarios

The decline in the price of oilseeds through substitution provokes a shift in land use in favour of cereals and pasture (Table 4), dragging grain prices down. This leads to a modest increase in the forest area and a decrease in the agricultural area. The lower prices will in turn exert a downwards pressure on yields (i.e. lower intensity), so that the net effect on grain production is not clear a priori. Table 2 shows that, in practice, maize production decreases slightly whereas production of other coarse grains increases. Wheat and rice production is not affected. Lower feed prices are passed on to the animal product markets through lower feed cost and higher supply. The size of the shift depends on the amount of high-protein feed in the feed ration of the different livestock. The pasture and fodder area reacts positively to ruminant production incentives and negatively to crop production incentives. In each of the three scenarios, the latter effect dominates the former so the net result is an increase in the pasture and fodder area.

In each scenario, the grain area increases and in the case of other coarse grains it increases more than production, implying a decline in yield. For soybeans and other oilseeds, on the other hand, the area decreases but production decreases even more, which also implies declining yields. In fact, as shown in Table 5 all crop yields decrease in the EU, USA and Brazil. This is the case in other countries as well, such as Canada, China, and Russia.

Ruminants consume small amounts of high-protein feed, so the price of beef and sheep meat is less affected than pork, poultry and several aquaculture species that have a large share of high-protein feed in their feed ration. In the case of salmonid and marine fish, oil is also an important ingredient of the feed ration. Since the introduction of ITM leads to a sharp decrease in the price of high-protein feed and oil, the largest supply shift comes from salmonid, marine fish and shrimp (Table 3).

Table 2. World market impacts in 2030. Percentage difference between scenario and baseline values.

	Scen1		Scen2		Scen3	
	Price	Production	Price	Production	Price	Production
Meat						
Sheep	-5.6	0.7	-3.1	0.4	-1.9	0.0
Beef and veal	-7.5	0.6	-4.0	0.3	-2.2	0.1
Pork	-10.5	0.8	-5.8	0.4	-3.2	0.2
Poultry	-10.6	1.3	-5.8	0.7	-3.1	0.3
Dairy						
Cheese	-5.8	-0.2	-3.1	-0.1	-1.6	-0.1
Skim milk powder	-1.5	-1.0	-0.9	-0.5	-0.5	-0.3
Whole milk powder	-4.7	0.5	-2.5	0.2	-1.3	0.1
Butter	-7.9	0.5	-4.2	0.3	-2.1	0.2
Grains and oilseeds						
Wheat	-8.6	0.0	-4.8	0.0	-2.5	0.0
Maize	-8.9	-0.2	-4.9	-0.1	-2.6	-0.1
Other coarse grains	-12.5	0.3	-6.9	0.2	-3.6	0.1
Rice	-1.8	0.0	-1.1	0.0	-0.6	0.0
Soybean	-19.9	-6.0	-10.7	-3.2	-5.3	-1.5
Other oilseeds	-15.8	-3.5	-8.3	-1.8	-3.8	-0.8
Biofuels						
Biodiesel	-6.9	0.7	-3.4	0.4	-1.3	0.1
Ethanol	-3.2	0.2	-1.7	0.1	-0.9	0.1
Other processed products						
Protein meal	-30.4	5.0	-17.2	2.4	-9.0	0.8
Protein meal excl. insect meal		-6.1		-3.2		-1.5
Vegetable oil	-14.7	1.4	-7.2	0.6	-2.7	0.2
Vegetable oil excl. insect oil		-3.7		-1.9		-0.9
Sugar	-4.4	0.2	-2.4	0.1	-1.3	0.0

Table 3. World fish market impacts in 2030. Percentage difference between scenario and baseline values. Note: For all the aquatic species of this table, the price change represents total aquaculture.

	Scen1		Scen2		Scen3	
	Price	Production	Price	Production	Price	Production
Fish from aquaculture	-7.9	0.3	-4.4	0.3	-2.7	0.3
Fish from capture	-4.9	-0.3	-2.8	-0.2	-1.8	-0.1
Fish total	-6.8	0.0	-3.9	0.1	-2.5	0.1
Fish oil	-6.3	-1.5	-1.8	-1.0	1.6	-0.7
Fish meal	-40.6	-1.3	-28.2	-0.8	-20.3	-0.3
Other freshwater & diadromous fish	-7.9	1.1	-4.4	0.8	-2.7	0.3
Tilapia	-7.9	0.6	-4.4	0.5	-2.7	0.3
Mollusc	-7.9	-3.3	-4.4	-1.9	-2.7	-1.3
Shrimp	-7.9	5.7	-4.4	4.0	-2.7	3.9
Carp	-7.9	-0.7	-4.4	-0.3	-2.7	-0.2
Salmonid	-7.9	7.1	-4.4	4.2	-2.7	3.0
Marine fish	-7.9	6.6	-4.4	3.9	-2.7	2.3
Other aquaculture species	-7.9	-3.2	-4.4	-1.8	-2.7	-1.1

Table 4. Global land use impacts in 2030. Difference between scenario and baseline values in percent and in 1000 ha.

	Scen1		Scen2		Scen3	
	perc.	1000 ha	perc.	1000 ha	perc.	1000 ha
Forest	0.05	2,076.5	0.03	1,066.5	0.01	514.6
Total agricultural area	-0.04	-2,076.5	-0.02	-1,066.5	-0.01	-514.6
of which changes in						
Pasture and fodder	0.15	4,852.8	0.07	2,414.2	0.03	1,143.5
Oilseeds	-3.57	-7,602.6	-1.87	-3,991.6	-0.86	-1,839.3
Cereals	0.52	2,822.6	0.28	1,497.0	0.12	676.9
Other crops	-0.28	-2,149.4	-0.13	-986.1	-0.07	-495.7

Table 5. Yield impacts in 2030. Percentage difference between scenario and baseline values.

	Scen1			Scen2			Scen3		
	Brazil	EU	USA	Brazil	EU	USA	Brazil	EU	USA
Barley		-0.60	-1.72		-0.32	-0.92		-0.16	-0.47
Maize	-0.70	-0.42	-0.41	-0.38	-0.23	-0.22	-0.19	-0.12	-0.11
Wheat	-2.99	-0.43	-0.17	-1.63	-0.23	-0.09	-0.83	-0.12	-0.05
Rice	-0.47	-0.15	-0.03	-0.26	-0.09	-0.02	-0.13	-0.05	-0.01
Soybean	-2.57	-1.15	-0.90	-1.32	-0.59	-0.46	-0.63	-0.28	-0.22
Rapeseed		-1.15			-0.58			-0.25	
Sunflower seed		-0.77			-0.39			-0.17	
Sugarbeet		-0.13	-0.64		-0.07	-0.34		-0.04	-0.18
Sugarcane	-0.51		-0.63	-0.27		-0.34	-0.14		-0.18
Roots and tubers	-0.45	-0.17	-0.08	-0.23	-0.09	-0.04	-0.12	-0.04	-0.02
Pulses	-2.05	-1.80	-1.81	-1.09	-0.96	-0.96	-0.56	-0.50	-0.50
Cotton	-0.17	-0.14	-0.03	-0.09	-0.08	-0.02	-0.04	-0.04	-0.01

Dairy prices are also affected, which is partly caused by a fall in the feed demand for skimmed milk powder (a high-protein feed), which lowers the price of non-fat solids and, in turn, the price of other dairy products (Table 2). Moreover, the increase in milk supply caused by lower feed costs exerts further pressure on prices.

FM is a high-protein feed consumed by non-ruminants and by various aquaculture species. Depending on the scenario, ITM will replace other high-protein meals used in feed, but in the aquaculture sector specifically, it will replace FM in feed rations of aquaculture species where the content of FM is above the minimum required amount. This is mostly the case in aquaculture of the developed economies of Europe, North America, Oceania and Japan. Thailand shrimp and tilapia and Malaysia shrimp are the only three exceptions. However since fishmeal is mostly produced from controlled capture production and from waste, the addition of ITM only results in a modest decline of FM

production in each of the scenarios. The inelastic supply of FM also means that the introduction of ITM as a novel source of feed proteins has a large effect on the price of FM. It reduces the demand for FM, thereby lowering the price of FM, e.g. by 28% in scen2 (Table 3).

In the demand driven scenario (Scen3) the amount of waste used for insect meal production hovers around 21% in all the years. Given the assumption that the same percentages of waste are used in all countries of the model, creates a situation where production of insect meal can be smaller or greater than demand depending on the amount of waste and aquaculture production. For that reason, a complete balance sheet of the insect meal sector had to be included in the model for the production of this scenario. There are more net exporters than net importers of ITM. In the camp of the net importers Vietnam, India, Indonesia, LDCs of Asia, Egypt, Norway and Chile are the main one. The main exporters are European Union, USA, China and Africa (excluding Egypt).

More generally, the differential impacts on prices and production in different countries affects the trade flows (Table 6). African and European imports of meat increase. Oilseed imports decrease in all regions except for Europe and protein meal imports (incl. ITM) increase everywhere except in Oceania and North America.

Food security implications

Food security is a multifaceted concept involving stable physical availability, physical and economic access and utilisation of food. There are consequently many indicators related to the different dimension of food security. In the following, we focus on food expenditure, as well as calorie consumption in developing countries.

Figure 3 illustrates the distribution of per capita food expenditure impacts across countries in different income groups for the three scenarios. All countries experience lower food prices and the largest impacts occur in Scen1, implying a positive impact on food security. However, there is no relationship between the income status of the country and the food price impact. The median impact in the three scenarios is -2.1, -1.1 and -0.6%, respectively. As the upper panel shows, lower expenditure on animal products contributes less than proportionally to the total change in

each of the income groups. The lower food prices in the scenarios lead to a modest changes in per capita calorie and protein consumption, with most countries experiencing a small increase in intake (less than 1% compared to the baseline).¹⁰

Carbon footprint

The impact of GHG emissions from agriculture in the scenarios depends on the global crop and livestock production and land use changes caused by the introduction of this novel source of feed proteins.¹¹ In addition, the impact on total agricultural GHG emissions depends on the emissions of the insects themselves during the production process. As it turns out, GHG emission estimates from BSF farming vary largely between studies in the bioconversion literature. For BSFs, Parodi *et al.* (2020) report an emission coefficient of 17±8.6 g carbon dioxide equivalents (CO₂-eq) per kg of dry larvae. This estimate is, reportedly, twice as large as the one in Ermolaev *et al.* (2019), half as large as

¹⁰ The nutrition impact calculations are based on the FAOSTAT Food Balance Sheets.

¹¹ The GHG emission impact calculations for agricultural commodities other than insects are based on the GLOBIOM database.

Table 6. Import impacts in 2030 in Scen2. Percentage difference between scenario and baseline values.

	World	Africa	Asia Pacific	Europe	Latin America	North America	Oceania
Meat							
Sheep	-1.0	6.2	-2.4	1.5	2.2	0.1	0.2
Beef and veal	0.5	2.9	0.2	1.4	1.7	-1.0	-0.6
Pork	-1.0	1.9	-2.5	2.9	-0.5	-1.2	-1.7
Poultry	3.7	5.8	2.6	4.5	3.2	9.1	2.1
Dairy							
Cheese	-0.4	2.0	0.2	1.0	-4.3	-8.0	0.0
Skim milk powder	-0.3	-0.3	-0.3	0.4	-0.7	0.0	-0.1
Whole milk powder	0.1	0.1	0.4	0.7	-0.9	0.0	0.0
Butter	-0.7	0.2	-0.9	1.3	-6.1	-7.4	0.0
Grains and oilseeds							
Wheat	1.3	0.3	2.6	-1.2	0.5	-3.4	-2.8
Maize	0.4	0.8	0.3	-1.2	0.8	1.2	-10.8
Other coarse grains	0.0	4.7	0.8	0.0	-15.7	-11.4	3.0
Rice	0.4	0.0	1.6	-0.8	-2.3	-0.9	0.0
Soybean	-2.7	-1.5	-3.5	2.2	-1.9	-0.6	-6.4
Other oilseeds	-1.9	2.1	-2.7	2.5	-1.7	-9.0	-0.2
Biofuels							
Biodiesel	-1.4	0.0	8.7	-2.0	0.0	-1.0	14.4
Ethanol	0.4	0.0	2.3	-0.8	-1.5	0.4	1.0
Other processed products							
Protein meal	-3.5	-10.0	-5.7	-1.9	-4.8	21.6	2.9
Vegetable oil	-1.2	-0.7	-2.4	0.6	-1.2	7.1	-6.0
Sugar	0.3	0.3	0.4	0.2	-1.2	-0.5	0.5

Figure 3. Per capita food expenditure impact in 2030. Percentage difference between scenario and baseline values.

the one in Mertenat *et al.* (2019) and six times as large as the one in Pang *et al.* (2020). Nonetheless, even the largest of these emission coefficients are significantly lower than conventional livestock production. Specifically, in the model database, the 2020 EU GHG emission coefficients for beef, pork, poultry and sheep are 12.9, 2.0, 0.6 and 24.4 kg CO₂-eq per kg output, respectively.

We base our insect emission calculations on the estimates from Parodi *et al.* (2020) and do not include indirect GHG emissions in the calculations. The reason is that indirect emissions are not included in the emission coefficients for conventional livestock or crops. However, Mertenat *et al.* (2019) report that the inclusion of indirect emission related to electricity consumption in the production process increases the GHG emissions by a factor of 1.8. This, of course, is strongly influenced by type of energy used

i.e. whether it derives from renewables or conventional sources. However, direct insect GHG emissions are low in comparison to conventional livestock, so that it does not have a large effect on the results. For example, with these assumptions, the emissions from one kg of poultry produced in the EU in 2020 are almost 40 times higher than emissions from one kg of BSF larvae production.

Less intensive crop production, more forest and pasture area and lower sheep production contribute to lower GHG emissions from agriculture in each of the scenarios (Table 7). Although production of livestock increases, the additional emissions do not outweigh the reductions resulting from land use changes, so the net result is a small decrease in global agricultural GHG emissions over the outlook period 2020-2030.

Table 7. GHG emission impacts (CO₂ equivalents) by type and region. Cumulated difference between scenario and baseline values, million tonnes and percentage of baseline total, 2020-2030.

	Scen1			Scen2			Scen3		
	Total	AGRI	LULUCF ¹	Total	AGRI	LULUCF	Total	AGRI	LULUCF
World									
Difference	-466.50	169.30	-635.70	-231.60	93.20	-324.80	-132.00	25.60	-157.50
Percentage	-0.49	0.18	-0.67	-0.24	0.10	-0.34	-0.14	0.03	-0.17
Africa									
Difference	-54.30	-21.80	-32.50	-27.70	-10.90	-16.80	-38.40	-30.70	-7.70
Percentage	-0.26	-0.10	-0.15	-0.13	-0.05	-0.08	-0.18	-0.15	-0.04
Asia Pacific									
Difference	-72.60	51.20	-123.70	-30.00	32.30	-62.30	-11.70	19.40	-31.10
Percentage	-0.15	0.11	-0.26	-0.06	0.07	-0.13	-0.02	0.04	-0.07
Europe									
Difference	-31.60	16.70	-48.30	-15.50	9.60	-25.10	-8.30	4.20	-12.60
Percentage	-1.90	1.01	-2.91	-0.93	0.58	-1.51	-0.50	0.25	-0.76
Latin America									
Difference	-161.10	106.40	-267.50	-83.40	53.40	-136.80	-37.30	27.90	-65.20
Percentage	-0.98	0.65	-1.63	-0.51	0.32	-0.83	-0.23	0.17	-0.40
North America									
Difference	-78.00	7.30	-85.20	-38.10	3.80	-41.90	-17.60	2.50	-20.10
Percentage	-1.28	0.12	-1.40	-0.62	0.06	-0.69	-0.29	0.04	-0.33
Oceania									
Difference	-69.00	9.50	-78.50	-36.90	4.90	-41.70	-18.70	2.20	-20.90
Percentage	-2.49	0.34	-2.84	-1.33	0.18	-1.51	-0.67	0.08	-0.75
¹ AGRI = total direct emissions from agriculture; LULUCF = emissions from the land use, land-use change and forestry.									

The total impact in Scen1 corresponds to a cumulative decrease in GHG emissions (in CO₂ equivalents) of around 0.5%, as compared to the baseline. Emissions related to agricultural production (denoted 'AGRI' in the table) go up in all regions except for Africa, where emissions are reduced as domestic livestock production is replaced by imports. Not surprisingly, the largest contributing region to the emission changes is Latin America, which is the top soybeans producing region. It is the region where agricultural emissions increase the most due to additional livestock production, but also the region where land use changes lead to the largest reduction in GHG emissions.

6. Discussion

The insect farming industry is expanding and there seems to be an abundance of food waste to support it. Even if the UN SDG 12.3 of halving per capita global food waste at the retail and consumer level is achieved, there remains large quantities of food waste available for insect feed. Moreover, insect farming could play an important role in attaining SDG 12.5 of substantially reducing waste generation through recycling. One question that arises

is what would happen if SDG 12.3 was achieved and food waste consequently became scarcer? The remaining food waste would most likely become more expensive to collect and perhaps ITM would only be used in aquaculture where it would attain a premium price compared to oilmeals due to its nutritional composition, which is similar to fishmeal.

More generally, the question is whether the costs of collecting and processing the food waste into a form that is suitable for insect production are low enough for it to make sense economically on a large industrial scale. In the literature on insect farming, or more generally on food waste valorisation or upcycling, there is surprisingly little discussion of this issue. These studies tend to take an experimental approach and even the life cycle analyses focus on quantities and environmental impacts without any mentioning of costs and revenues of the different alternatives. There is, however, a separate literature on waste management that analyses the costs of managing different types of waste. For example, Hogg *et al.* (2003) report costs of landfill and incineration at EUR 55 and 90 per tonne municipal solid waste (MSW), respectively. The costs of separate collection and composting of biodegradable

waste is estimated to be in the EUR 35–75 per tonne range. Note that these figures are based on waste management practices in place already in the EU and are partly the result of regulatory policies. Note also that existing insect farms, producing on an industrial scale, typically rely on inexpensive food waste. Some use consumer waste whereas others are built near food processing plants to reduce insect feed costs (Fowles and Nansen, 2020). This is a mutual benefit for both the food processing plants and insect farming industry, who both want to promote a socially and environmentally suitable production.

The analysis presented shows that an expansion of the insect feed industry could have a large impact on the price of oilseed and protein meals. Specifically, utilising 50% of the available food waste leads to declines of 17, 7 and 28% in the projected world price of protein meal, vegetable oils and fishmeal, respectively. These are the price changes needed to rebalance the global markets in the Aglink-Cosimo model. In this scenario, oilseed prices are reduced by roughly 10% and 4 million hectares of land are converted from oilseed production to other crops and pasture. This leads to lower land prices, taking 1 million hectares of marginal land out of agricultural production. So the addition of ITM and ITL to the current agricultural commodity markets leads to large market adjustments, especially when taking into account that they do not directly compete for agricultural resources. In that sense, the 18% price reduction of oilseed meal seems in line with a 10% reduction in oilseed prices.

An important finding is that a large expansion of the ITM industry does not lead to a large reduction in GHG emissions. GHG emission reductions from agricultural land use change are sufficiently high to offset the additional GHG emissions from crop and animal production in all scenarios, so that the net result is a marginal decrease in GHG emissions. It is somewhat surprising that land use changes offset the higher supply of animal products resulting from the additional supply of feed proteins, which leads to lower feed costs. However, it confirms that recycling of waste is indeed a sustainable practice (c.f. SDGs 12.3 and 12.5). When recycled food waste goes back into the food system as feed, it will lead to more food being produced, but the lower crop production intensities and marginal expansion of forest area will lead to slightly lower GHG emissions. That being said, the introduction of a large scale ITM feed industry based on recycled food waste will not solve the climate crisis by itself.

There are several caveats that deserve mentioning. First, in the analysis the insect industry is considered to be a price taker and is assumed to utilise 100, 50 or 21% of all available food waste, regardless the resulting protein meal price (which declines by 31, 18 or 9%, respectively, in the three scenarios). Would the industry actually be able to cover their

costs at these prices? This is not an easy question to answer in the absence of a mature insect industry. In relation to this, we are not considering a second by-product from ITM production called insect dejecta or frass. This is essentially manure from insect larvae, which has the potential to be upcycled to a valuable fertilising product. In the future, with a lower fossil fuel supply due to concerns over climate change from GHG emissions, revenues from insect farming could be strongly dependent on this by-product and it might even affect the fertiliser industry to some degree. A final caveat relates to the other insect by-product that we actually do include in the analysis, namely ITL. We did not consider how the additional oil supply would potentially affect the biofuel mandates in biofuel producing countries. We leave these issues for future research.

Supplementary material

Supplementary material can be found online at <https://doi.org/10.3920/JIFF2021.0007>.

Supplementary Material S1. Technical annex.

Conflict of interest

The authors declare no conflict of interest.

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