Environmental impact of food waste bioconversion by Black Soldier Fly insects: food waste consumption and production of an alternative protein source for livestock

LWS 548 Major Project Proposal

By

Alex Henson

Master of Land and Water Systems

Faculty of Land and Food Systems

University of British Columbia

Executive Summary

This study investigates food waste bioconversion and ascertains whether it could provide a viable livestock protein source to mainstream alternatives such as soy, from both a production and an environmental perspective. The paper analyses bioconversion using insects as a method to refine food waste to produce protein in the United Kingdom examines the resultant reduction in terms of the environmental impact and draws a comparison with the production of soy. Whilst there is a body of research regarding food waste, the area of bioconversion is relatively new with areas of limited primary research. This paper, therefore, focuses on research available, coupled with data from Insect industry sources.

The findings of this paper show that the UK generates approximately 13 MT of food waste annually which leads to greenhouse gas emissions from decomposition and incineration of 27 MT of CO_2 per year. Due to UK regulation, bioconversion can only be deployed on pre-consumer food waste however this still provides a meaningful bioconversion source as studies suggest that ~50% of UK food waste generated is of this type. Local bioconversion of waste using insects creates a valuable alternative protein source for livestock (processed insect larvae) which could provide a viable alternative to imported soy. Refining food waste via bioconversion before full decomposition also reduces emissions from food waste which offers another tool in the race to meet emissions targets as stated in the Paris Climate Agreement.

The study suggests that insect feed produced by bioconversion is more environmentally friendly than soy-based animal feed. This is due to the extent of land required for the production of soy and the related deforestation coupled with biodiversity loss associated with farming this crop. However, insect feed requires more energy consumption than soy, potentially leading to an increase in global warming, although this can be mitigated by the use of renewable energy. Emissions savings relating to local insect production rather than soy importation is negligible as food is transported before being categorised as a waste product and then further transported to the insect farms and finally distributed as a product.

The study concludes that insect protein farming is both a viable replacement for soy farming and a more environmentally friendly alternative. However, insect protein farming as an industry is still in its early stages and it requires further innovation and research to determine the full potential of its application both as a food waste processor and as an alternative protein source.

Introduction

Background

Developed countries are working to reduce their carbon footprint and 197 countries have signed up to the Paris Climate Agreement. Part of this pledge is the reduction of food waste and improvements to reduce food losses as well as preparation for future estimates in global increases in population. Food waste presents a major issue; many developed countries produce vast quantities. Furthermore, food waste is accredited with producing large amounts of anthropogenic CO_2; globally this equates to 8-10% of greenhouse gas emissions (*UNEP Food Waste Index Report*, 2021) much of these emissions come from discarded food that never reaches the consumer. Decreasing this waste is a relatively easy way to reduce emission rates.

Bioconversion specifically offers a solution to the problem of gases released by decomposing food waste as it involves taking food waste and feeding it to insect larvae such as BSF (Black Soldier Fly). The larvae consume the food waste before full decomposition and therefore before the release of the majority of greenhouse gases. Larvae are efficient converters of such food waste, partly due to their voracious appetites. The by-product of converting food waste in this manner is the BSF larvae themselves which, when processed, become a high-grade alternative source of protein. Using this high-quality animal feed instead of traditional protein sources for livestock will reduce the carbon footprint of the meat produced and decrease importation emissions making it less damaging to the environment (van Huis, 2017). Decreasing the need for plant-based protein sources for animals will change current agricultural farming practices. Larvae require a minimum 150 m^2 farming area and all the water they require comes entirely from the agricultural food waste they consume. Compare this to traditional farming practices for soy that require thousands of acres of land and millions of litres of water for irrigation and it is clear why Insect farming is growing in popularity (Fig 8).

Food waste

Food waste presents a global problem that impacts numerous social, economic and environmental processes. When food decomposes it releases greenhouse gases, primarily methane, as well as carbon dioxide when incinerated. Estimates show that up to 1/3rd of the food created by agriculture globally is wasted which equates to approximately 1.3 BT annually (FAO, 2013). A study in Scotland found that the waste levels for vegetables on farms during the primary production phase ranges from 20% to as high as 50% (Beausang et al., 2017). Another study found that on-farm grading of fruits and vegetables to meet aesthetic standards in the UK resulted in 7%-31% of produce being discarded (Porter et al., 2018).

The balance of food waste globally is disproportionate to population size, and industrialised countries produce far more waste than developing countries. Per capita, food waste by EU and North American households is calculated at 95-115 kg/year, while in South East Asia it is only 6-11 kg/year (FAO, 2011). Industrialised countries need to reduce their food waste or find ways to harness it. Food wastage represents nutrients and resources that are being discarded unnecessarily. There is an impact of that loss, wastage compounds through the accompanying waste of the natural resources used to produce it. This impact comes in the form of greenhouse gas emissions during the growing and in the post-use phase, overuse of land, extra water usage and biodiversity loss. Water loss presents one example of how food waste can result in environmental, social and economic impacts. Water for crop irrigation that gets wasted becomes an economic loss on the cost of the water, compounding the issue of water scarcity where agricultural and low-income populations often bear the brunt of the impact. Projections regarding water scarcity indicate increasingly negative effects on biodiversity and loss of habitat (FAO, 2014).

However, some see food wastage as a business opportunity and a way to create value from a "waste resource". Bioconversion as a process creates value from food waste and also reduces greenhouse gas emissions from decomposition/incineration by ensuring discarded food is not consigned to landfill. Insect species each have varying dietary requirements meaning different types of insect can be deployed on a range of industrial, domestic and commercial food waste relative to what they eat (e.g. coffee pulp and rice straw) (Fowles et al., 2020). This paper explores one specific form of bioconversion using Black Soldier Fly larvae and the resultant impact on the environment.

Bioconversion

Bioconversion involves taking food waste and feeding it to insect larvae. These larvae consume pre-consumer food waste before it can decompose and release greenhouse gases. Some insects are more efficient than others: currently, Crickets, Black Soldier Fly, Housefly, Codling Moth and Mealworms are some of the insect larvae being used for bioconversion (Fowles et al., 2020). These insects are used in a variety of ways and provide different outputs ranging from protein powder to dyes. Each type of insect has a preferred/useable diet which makes their use appropriate for different services. BSF is arguably the most efficient species for pre-consumer food waste due to their range of diet, quick growth rate and efficient conversion into proteins and fats. This presents a 'green' approach to producing protein and providing feed because the process uses food waste which would otherwise decompose and release greenhouse gases. Specifically, the process reduces the emissions that would be released from food waste that goes to landfills (Black Soldier Fly Biowaste Processing, 2017). This process mirrors the functions of insects in the wild where they would be breaking down decomposing organic matter in ecosystems and it can be optimised within the facilities to cater for the specific insect species being used.

The resultant insect larvae can then be used to gain value from the elimination of food waste. Selling processed insect larvae as livestock feed provides a high-grade, regionally sourced, protein alternative. Farmers using the alternative sources can replace imported traditional feed which has been transported long distances, further reducing the emissions footprint of the farmers and the livestock. A reduction in the demand for imported feed also decreases the need for extensive soy farming which can be destructive to land and water resources, which often rely on herbicides and chemicals. The area required to farm insects effectively is significantly less than that required for all other current protein sources. Incorporating insect protein into the food chain would decrease agricultural emissions and consumption of water, whereas current practices are water-intensive and land-intensive by comparison.

Objectives

This paper explores the use of bioconversion to upcycle food waste to lower greenhouse gas emissions and produce alternative protein sources locally rather than importing them. It examines the extent to which greenhouse gas emissions can be decreased by this technology and the resultant reduction in the land and water required for animal feed production. It quantifies how much food waste can be upcycled through this process, the volume of gas emissions saved by food waste consumption and offers suggestions for how this technology could be further implemented in food waste management. This paper includes comparisons of land and water use between larvae farming and traditional animal feed production. Soy is one traditional protein source and its products can be damaging to the environment if farmed intensively. Comparisons of this nature reveal whether larvae feed has a better environmental impact than plant-based protein feed. This paper focuses on food waste concerns in the UK and how these compare to global food waste concerns.

Methods

The research for this paper revolves around food waste and environmental impacts from livestock feed production, as well as reviewing data on bioconversion farms operating around the world. The study determines the opportunity presented by deploying bioconversion and estimates the resultant impact on emissions using the UK as the case study. Secondary data and web-based research are the primary means of gathering information for this project. Secondary data is used in a qualitative systematic review style to:

- estimate how insect farming could change emissions in the form of imported feed reductions and upcycled food waste
- determine the size of the prospective market
- determine the estimated volume of larvae produced and therefore food waste consumed
- determine the impact of traditional protein sources for animal feed on the environment
- Make comparisons with larvae farming.

The technology for farming Black Soldier Fly larvae is relatively new; many companies in this area are start-ups and have had varying degrees of success. Analysing these companies provides estimates for average food waste consumption per farm and the calculation of emissions savings.

Primary literature for this project includes:

- FAO Reports (FAO, 2013) (FAO, 2011)
- Black Soldier Fly Biowaste Processing reports (Black Soldier Fly Biowaste Processing, 2017)
- Insect based bioconversion research, academic and business (Singh et al., 2021) (Sohal, 2020) (Salomone et al., 2016)
- WWF reports (Bioconversion, Soy trading, Soy farming, Food waste) (WWF, 2014) (WWF, 2021)

Results and Discussion

Food waste emissions and reductions

BSF insect farms deploy bioconversion to convert food waste into larvae-based protein and the primary requirement is food. The type and quality of food available to process vary between jurisdictions because of different food safety concerns/regulations. The UK discards approximately 13 MT of food annually, of this some 50% can be attributed to pre-consumer stages of food production (Jeswani et al., 2021). This means that of the food being wasted in the UK, up to 50% could be available for bioconversion by BSF larvae.

Insect farms around the world deploy different methods to produce larvae and therefore they refine different volumes of food waste. BSF larvae farms are lucrative and environmentally friendly as the insects have a wide range in their diet and are highly effective at turning food matter into protein and fats. Very efficient conversion rates and quick growth rates result in a high processing rate for these farms; the BSF larvae biomass conversion rate is 25% of mixed food waste (Singh et al., 2021). The farms need to mimic the environment where BSF larvae would naturally occur to achieve optimised food waste processing rates. The flies have basic needs (Black Soldier Fly Biowaste Processing, 2017):

- Warm climate: between 24-30 degrees centigrade to facilitate proper eating habits and efficient growth
- Shade: as the larvae are averse to light and will develop slowly otherwise
- Food wastewater content: must be high (60-90%) as larvae need this for proper digestion of the food and efficient bioconversion
- Nutrients: food must be rich in protein and available carbohydrates are ideal for quick larval growth with more efficient conversion periods
- Particulate size: Larvae can consume smaller food particles quickly which reduces the growth period due to being able to feed on food waste more efficiently.

The most basic farm requires 150 m2 of floor space for breeding and feeding to process 1 tonne of food waste per day (Fig 1.). Additionally, there is a requirement for office space and other staff facilities which varies with individual requirements (Black Soldier Fly Biowaste Processing, 2017). Farms vary by size and configuration depending on the available food waste; therefore they process food at different rates. The company Agriprotein currently has the capability to process 72 tonnes of food a day at their facility in South Africa. The value this creates comes in the form of insect meal, insect oil and fertiliser (Fowles et al., 2020). Extrapolating from data available, this would mean their facilities cover an estimated >10,800 m2 of floor space. Agriprotein is one of the companies that have the highest capacity for food processing with other facilities producing on average between 240 kg - 24 tonnes a day (Fowles et al., 2020).

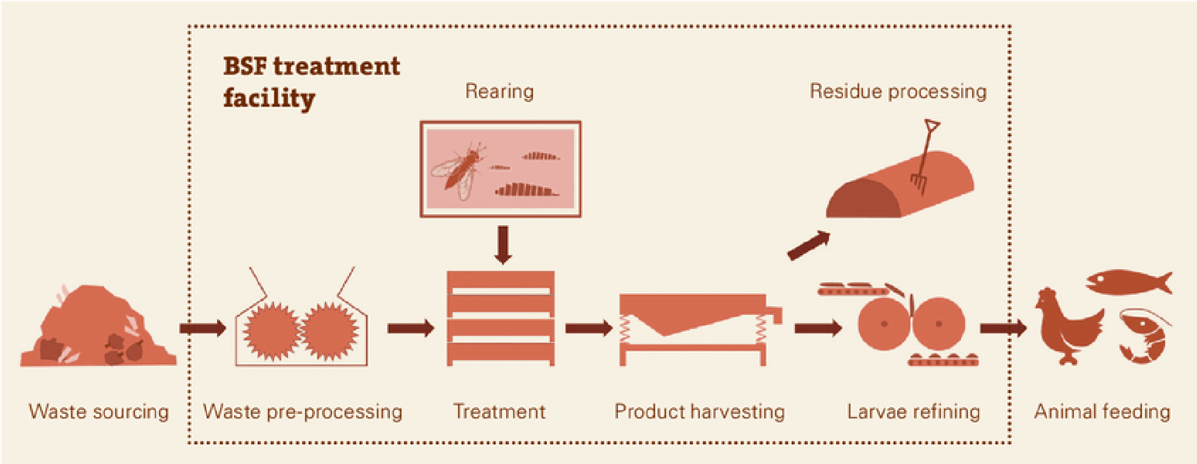

Figure 1. Graphic showing the steps involved in a BSF facility. The environment is monitored for optimum growing and breeding conditions. (Dortmans et al., 2017)

Calculating the emissions created from decomposing food depends on the type of food being processed. Plant-based food waste releases significantly fewer greenhouse gas emissions than meat and BSF farms primarily use plant-based agricultural waste. There are no available statistics for pre-consumer food waste emission rates, but household waste produces ~4.2 tonnes of CO_2 emissions per tonne of food waste (Quested et al., 2011). This can be used as a proxy to estimate BSF farm emissions savings from food waste processing. 72 tonnes of pre and post-consumer organic food waste a day processed by Agriprotein equates to ~302 tonnes of CO_2 emissions savings per day (South Africa has different laws around acceptable food waste for insect farms than the UK). For smaller facilities, 240 kg – 24 tonnes of food is processed per day, this equates to 1.05 – 100.8 tonnes of CO_2 emissions savings per day (Fig 2).

Figure 2. Infographic that illustrates different types of activity that also release 1 tonne of greenhouse gases. Illustrates the impact of food waste emissions. (Citizens for Public Justice, 2020)

This represents a significant reduction in emissions, but barely scratches the surface of food waste rates. Based on UK annual wastage (Jeswani et al., 2021) 17,808 tonnes of pre-consumer food is wasted per day, creating > 74,794 tonnes of CO_2 per day.

To hit the 40% reduction target for emissions, as stated in the Paris Climate Agreement, would require BSF farms to process 7,123 tonnes of food waste per day, this equates to approximately 1,068,450 m2 of facility floor space (11,500,700 ft^2). This represents a reduction in emissions of 29,916 tonnes of CO_2 per day. Bioconversion is not the sole technology/process deployed to reduce or recycle food waste, but insect farms currently outperform other processes such as vermicomposting (Singh et al., 2021). It would be a reasonable assumption that Insect farming could process 5%-10% of the UK's current annual food waste volume by 2030 (Fig 3) (WWF, 2021). Facilities would be processing between 890 – 1,780 tonnes of food waste a day which requires, at minimum, 133,500 – 267,000 m^2 of space for the breeding and feeding of BSF. The resultant reduction in CO_2 emissions is estimated at between 3,738 – 7,476 tonnes per day.

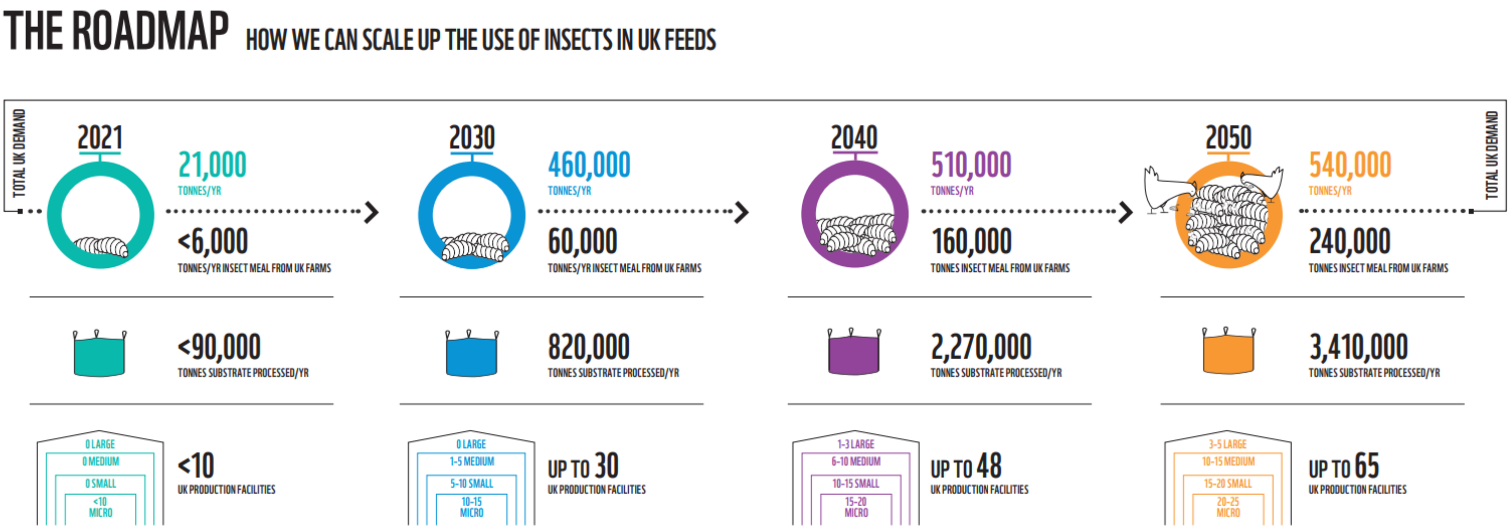

Figure 3. Graphic depicting the potential scale up or "The Roadmap" of Insect farming for livestock feeds in the UK. Urban farming and use of alternative spaces can reduce the physical footprint of facilities as the industry scales up. (WWF, 2021)

Offsetting Import Livestock Feed Emissions

All of the BSF food processing described above creates a valuable product in the form of an alternative source of protein; BSF larvae protein and oil. This is used for poultry and fish feed as well as pet food. Currently, insect feed competes with traditional protein sources such as soy-based feed, which is the industry standard. The UK imported around 3 MT of soy meal in 2019 and 90% of this soy was used to feed poultry, fish and swine. The majority of soy comes into the UK from South America and the USA where farming practices have led to large-scale deforestation and negative environmental impacts (Ryan, 2019).

One factor to consider when importing food is the emissions cost of transport. Transporting feed for livestock from across the world impacts the carbon footprint of the feed and therefore the livestock that consumes it (McSweeney, 2015) (Fig 4). The transportation method is important when determining the emissions footprint of livestock feed because different methods produce more emissions than others. Food transported by air rather than water can have an emissions footprint hundreds of times higher due to airplane emissions. Analysis of US food emissions trends by Weber & Matthews indicates that the transportation of foods equates to 11% of carbon emissions in the food system (Weber & Matthews, 2008). Whilst a relevant part of the larger picture on emissions, considered in isolation this data can be misleading and should be evaluated alongside other factors. In general, however, reducing the need for importation from abroad will, in most cases, reduce the overall emissions footprint.

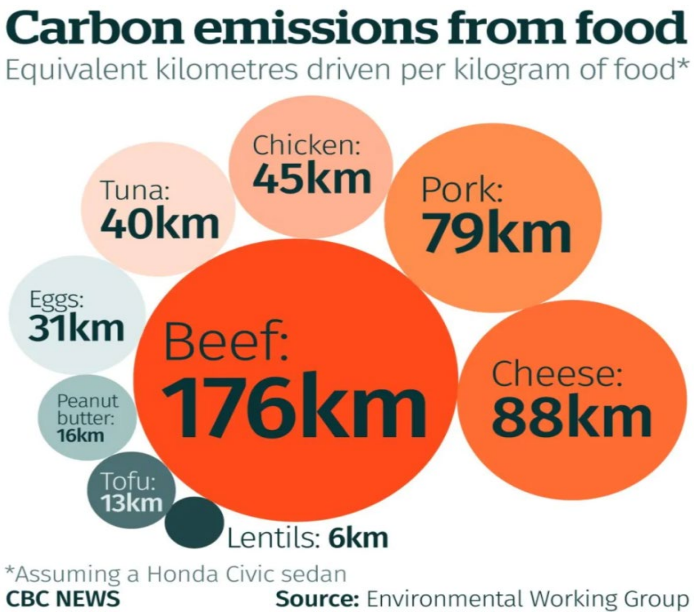

Figure 4. Infographic that illustrates the average UK carbon footprint of various protein products. (Chung, 2018)

By using Weber & Matthews's analysis on importation emissions it is possible to estimate the importation costs of transportation. The average carbon footprint of chicken in the UK and Europe is 4.6 kg CO_2e kg-1 as of a 2018 study (Carbon Trust, 2018). Therefore, a reasonable estimate for the UK's poultry footprint would be 11% x 4.6 kg CO_2e kg-1 i.e. 0.506 kg CO_2e.

Switching to BSF larvae feed rather than soy does not mean that these emissions will be completely eliminated. All food has some emissions footprint that can be attributed to their food supply chain, even BSF larvae need to be transported from production to retail/farms. BSF larvae which are produced and delivered locally/regionally have a smaller footprint than soy feed that has been produced in South America and transported to the UK (McSweeney, 2015).

As stated above, the importation of soy meal averages 3 MT annually in the UK. The Agriprotein facilities mentioned above are capable of producing 9 tonnes of oil and 16 tonnes of insect powder products from the 72 tonnes of food waste that they process daily (Fowles et al., 2020). Ergo, BSF farms are capable of producing 0.125 tonnes of oil and 0.25 tonnes of protein per tonne of food waste. BSF feed has similar nutritional content as soy meal, but with higher amounts of protein and lipids making it a more efficient fattener of livestock. Analysis of BSF and soy meal shows that they are likely interchangeable. The nutrition value per tonne is broadly the same for both feeds whilst poultry appears to prefer BSF over soy (Heuel et al., 2021). As BSF feed has a shorter supply chain transportation stage than soy meal (local production vs international importation) we can infer that the emissions from transportation will be lower at 5-7% when considering both the short supply chain and the final delivery stage (Weber & Matthews, 2008). For the average UK chicken, this would lower the carbon footprint from 4.6 kg CO_2e to between 4.37-4.278 kg CO_2e.

Environmental Impact Comparison – Soy vs BSF

Soy feed provides the main protein source for the poultry, fish and pig industries in the UK, Europe and around the globe (Reporters, 2019) (Ryan, 2019) (Fig 5). Traditional soy farming methods have a negative impact on the environment due to the land required to grow it. It is possible to farm soy responsibly; however, only a fraction of imported soy currently produced meets these standards and there is mounting pressure in consumer countries for this to change. The EU has amended its guidelines to commit to sustainable sources of soy. In 2017 it was revealed that EU imports of soy were 22% from responsible sources and 13% deforestation-free. The UK fared slightly better with 37% from responsible sources and 14% deforestation-free (Reporters, 2019). The change to sustainable soy development has been slow and remains ongoing; protein alternatives represent an opportunity to move away from soy dependency and the associated environmental impacts that are associated with its land use.

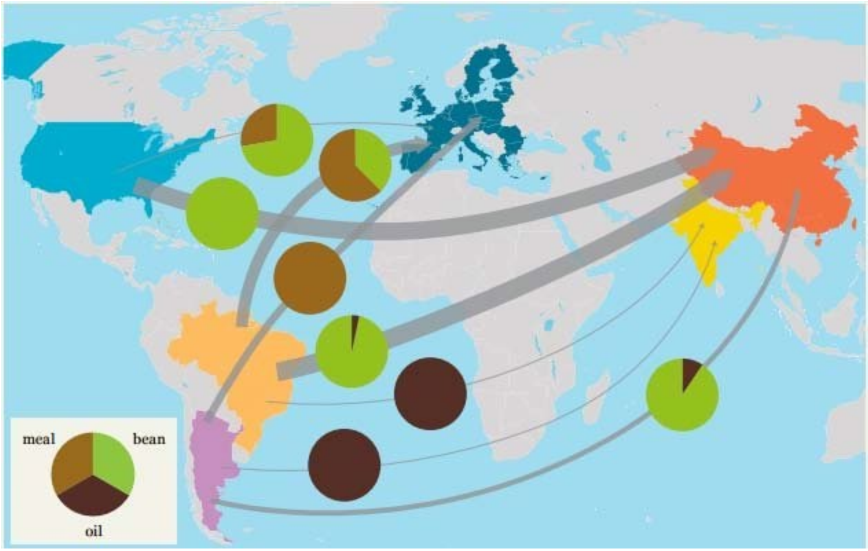

Figure 5. Global soy trade flow. Indicates how reliant countries are on soy production from the Americas. (Galvão et al., 2016)

The UK imports the majority of its soy meal from South America and the USA. Many countries in South America have less stringent regulations than Europe regarding the sustainable growth of soy. An increase in global demand has led to farming practices that have damaged the environment as farms expand to meet supply. Brazil and Argentina produce most of the soy in South America and these countries are where the biggest environmental impacts have occurred (Galvão et al., 2016). The problem is not with soy itself, the plant is actually a nitrogen-fixing plant, but with the farming practices.

The initial expansion in soy farming in South America was linked to clearing large areas of forest and grassland. (WWF, 2014). This trend continued until consumer countries began demanding sustainable soy and recognised the damage being done to the Amazon (Fig 6). While consumer pressure has slowed the destruction of these ecosystems it has pushed the problem onto different, but similarly vulnerable ecosystems (Fig 6) (WWF, 2014). Despite this, soy products are being advertised as “Amazon free” and consumers, therefore, assume that they are sustainably farmed products. Research shows there is a strong link between an increase in the demand for soy and deforestation in South America; soy cropland expansion was responsible for 17% of Brazilian deforestation between 2001 – 2004 (Sohal, 2020). Cattle ranchers were responsible for the rest of the Amazonian deforestation, but much of this is driven by soy production on nutrient-poor pastures once they have been depleted by cattle grazing. The ranchers subsequently move grazing to new areas, often resulting in further deforestation as new pastures displace tracts of the old jungle (WWF, 2014). Deforestation is the primary concern associated with soy farming as it leads to other problems, including an increase in emissions, loss of biodiversity, changes in water security and related societal impacts.

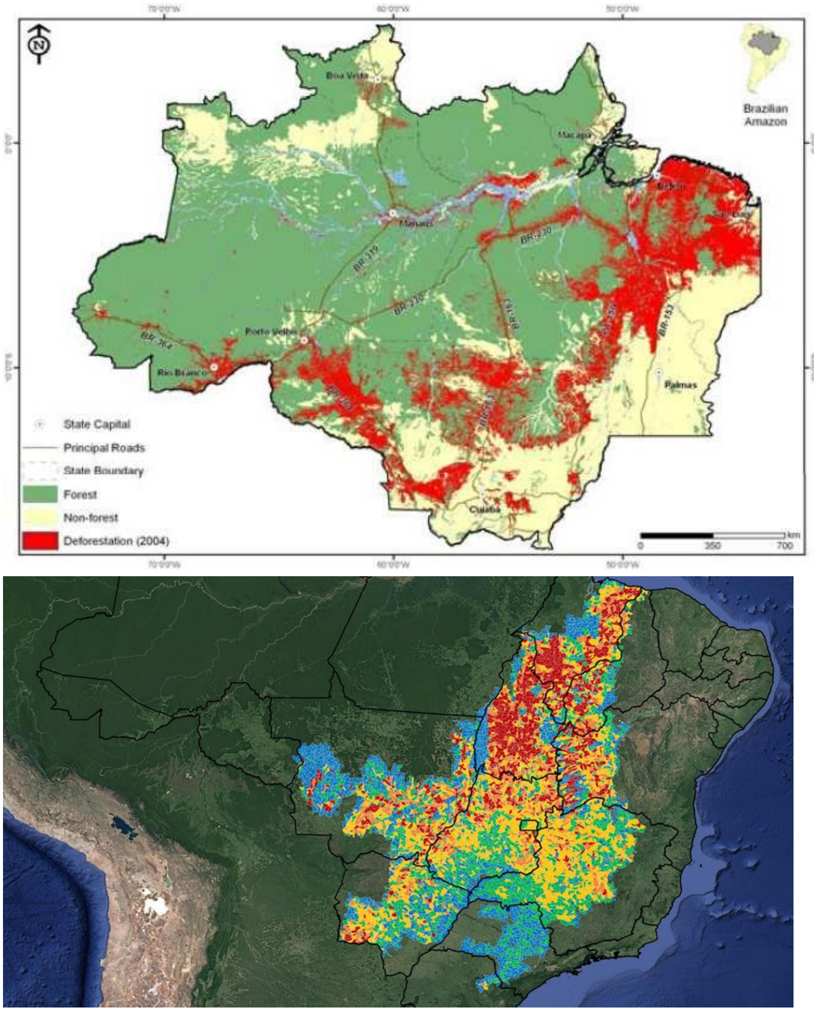

Figure 6. Hotspot images depicting the extent of deforestation in two of Brazil’s most forested and biodiverse areas, The Amazon (Above) and The Cerrado (Below). Vast tracts of land have been cleared for agriculture and livestock use, 1 million acres in 2018 alone. These regions have dense biodiversity. (PRODES, 2004) (*Soybean*, 2016)

Deforestation leads to the degradation of the natural environment. Trees perform a variety of important processes within jungles that are related to fauna, flora and the physical environment. Globally 9/10 animal and plant species reside in forested areas. In Brazil, one of the regions with the most intense logging activity, the Cerrado basin, is home to thousands of unique species - accounting for an estimated 5% of all species on earth (Sohal, 2020) (Fig 6). Deforestation robs these species of their habitats and leads to a loss in biodiversity. This problem is twofold with deforestation bringing an increase in greenhouse gas emissions and causing major disruption to ecological processes (WWF, 2014). Increasing emissions is evidently a global issue and removing trees not only releases gases but it decreases the forest's ability to sequester carbon. Disruption to ecological processes is a topic that has historically been overlooked, but many countries are starting to experience the negative effects. Forests remain key in regulating terrestrial soils and water systems with deforestation clearly associated with decreasing water quality, decreasing soil quality, a lack of pollinators and a subsequent increase in crop pests (WWF, 2014).

Water quality and security is an issue that faces many countries due to global warming and it is not limited to irrigation for agriculture. Many South American countries already struggle to supply drinking water and increased deforestation coupled with a warming climate will only exacerbate the problem in the future (Rondinel-Oviedo et al., 2020). Deforestation, therefore, compounds other social and agricultural concerns surrounding water security.

The decrease in soil quality due to deforestation presents another significant issue. Most forested land cleared for agriculture is initially nutrient-rich and grows almost anything due to ecosystem processes nourishing the forest floor. Many farmers abuse the land and make little attempt to maintain it for future crop use, as evidenced in Brazil where farmers grow crops on deforested land until it is no longer viable and then clear additional tracts of forest for further planting or livestock rearing (WWF, 2021). The lack of ecosystem processes means the land used for crop growth will increasingly be depleted. Although soy is a nitrogen fixator, which has a positive effect on the soil, not all deforested land is replanted with soy and therefore much of it remains depleted. Rewilding these areas is difficult as forests have specific processes that keep them healthy and the removal of nutrients from the soil means that these processes (carbon sequestration, above-ground biomass accumulation) cannot simply begin again. Trees also perform important physical processes; primarily they function as a limiter for erosional processes. Tree roots hold the soil together both on exposed slopes and river banks. Removal of trees increases the occurrence of erosion which leads to slope failure and cutting away of river banks which can result in full river ecosystem collapse (Richardson et al., 2012). Deforested land is unlikely to recover to the same level as the original ecosystem due to the lengthy amount of time it takes for forests to mature, but restoration projects can restore some important ecosystem processes that control water quality and the rates of soil erosion.

Insect farms do not face the same predicaments as traditional farms; they require significantly less space to accomplish the same volume of protein production. They do not require deforestation of forested areas and consequently do not impact the environment in the way traditional soy farms can. The flexibility of location means that these farms could be built in urban settings. Furthermore, high-rise farms reduce the land use of the farms and can increase climate control efficiency. Insect farms also require significantly less water because BSF farms use food waste with a high water content and so further water is rarely required during feeding (Black Soldier Fly Biowaste Processing, 2017).

The environmental impacts of BSF farms stem from the machinery required to transport and process food waste, to rear BSF larvae and to dry and prepare larvae for feed. BSF farms have a high energy usage due to the climate-controlled environment required for the rearing and feeding of BSF larvae as well as the drying and packaging required. This is the most significant environmental impact of insect farms (Salomone et al., 2016). Food waste has environmental impacts associated with it due to the 'loss' of resources it represents and the transportation required, however food residue mixed with insect waste from larvae feeding creates compost. This compost presents significant advantages over N fertilisers when it comes to environmental impact and could partly replace them thereby eliminating yet another source of emissions. While BSF farms have a slightly higher global warming potential and higher energy usage than soy farms, they do have significant benefits when it comes to land use (Salomone et al., 2016) (Fig 7.).

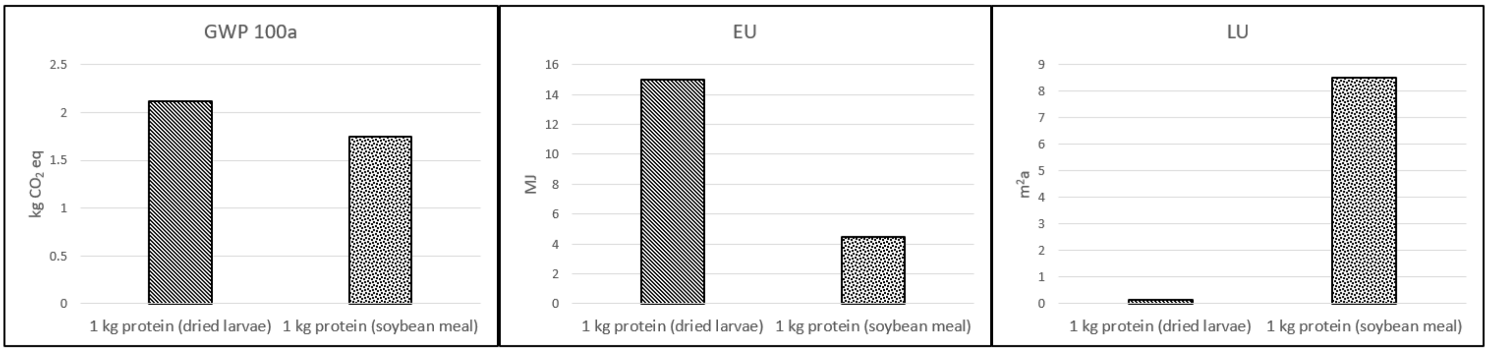

Figure 7. Comparison between dried BSF larvae and soybean meal using 1 kg of protein. Global warming potential-GWP, Energy usage-EU, Land usage-LU. (Salomone et al., 2016)

Land-use change is the most significant aspect of insect farming vs soy farming. The possibility of agricultural land becoming scarce in the future means that minimal land use for the production of feed and compost makes it even more compelling as an approach regardless of the associated emissions and energy usage (Fig. 8 land-use efficiency comparison). Less extensive land use would lead to less deforestation of ancient forest/jungle and introduces the potential for ecosystem restoration in areas affected by deforestation.

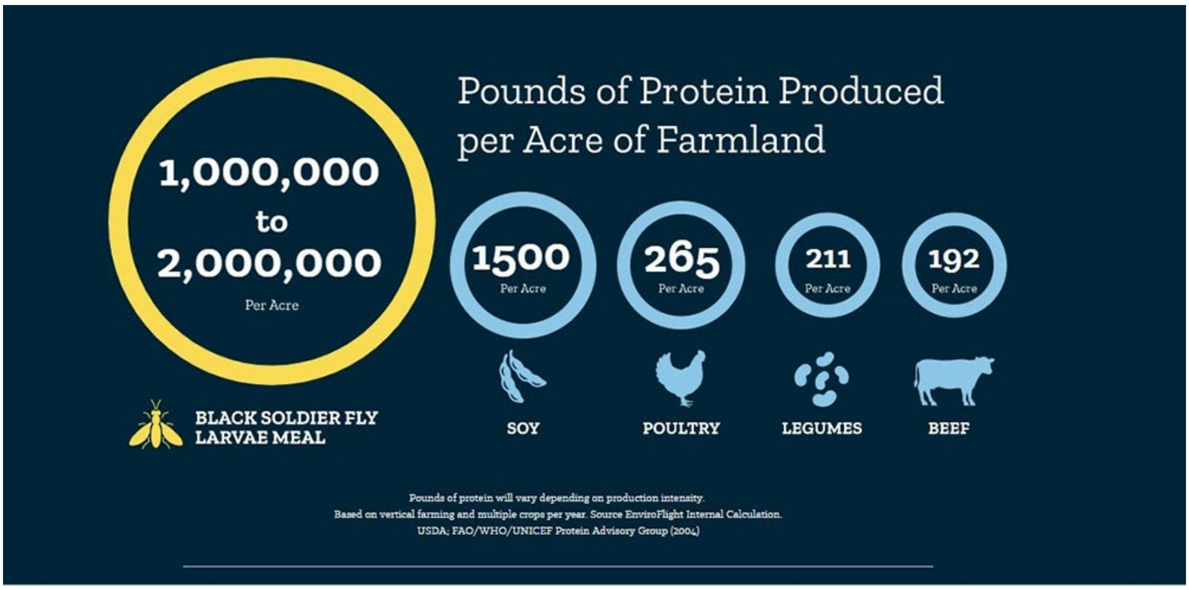

Figure 8. Protein source comparison. This illustrates how efficient insect farming is and how much land is currently used for protein production per year. (Pollon, 2019)

Future Applications

There are different applications of bioconversion around the world dependent on which types of food waste are accepted for processing; this is due to variation in national legislation regarding production as well as testing procedures. There are many types of food waste and each type can be paired with the insect which is most efficient at processing that category of waste. BSF insects are particularly efficient at consuming agricultural and household waste due to the range of their potential diet when compared to other insects (Fowles et al., 2020).

The primary concern with Domestic, Industrial and Commercial waste relates to the transfer of pollutants, heavy metals, viruses and bacteria into the food chain (Fowles et al., 2020). Testing shows that there is little to no effect of heavy metals on the bioconversion process and that larvae are safe for consumption (Singh et al., 2021). However, the waste that insects produce can be toxic, which will limit its use in some cases, for example, as a fertiliser (van Huis, 2013) (Salomone et al., 2016). The limited research available on insect fertiliser indicates that the waste is characterised by micro and macronutrients that make it an excellent bio-fertiliser (Salomone et al., 2016). There are concerns about pollutants in insect waste depending on the origin of the food used in the process. However, insect fertiliser is more environmentally friendly when compared with current N-fertilisers because fewer emissions are linked to its production (Salomone et al., 2016). Currently, insect production remains low; however, increases in production will provide more motivation and opportunity for further research.

Protein from insects can also be eaten by humans. This is not a new concept, many Eastern countries regularly include insect protein in their diet and Canada has cricket flour available in supermarkets (*Cricket Powder*, 2021). The obstruction in western society is the stigma surrounding insects, many people are afraid of them, associate them with being dirty and do not consider them as an acceptable food source (V. A. P. B. S., 2015). Generally, insect protein is not packaged or branded as a meal per se but more of a snack. Consequently, many people do not consider it a primary protein source (V. A. P. B. S., 2015). It will take time for the stigma to change and insect protein products will need clever branding and interesting production innovations before they become a mainstream item on supermarket shelves.

Conclusion

Food waste optimisation offers a view into a more sustainable food chain and varied farming options. Food waste has many sources; Agricultural, Domestic, Restaurant and Industrial. When put into landfills, the decomposing food waste emits greenhouse gases— ~4.2 tonnes of CO_2 emissions per tonne of food waste for mixed food waste (Quested et al., 2011). Estimates show that up to 1/3rd of the food created by agriculture per annum globally, approximately 1.3 BT, is thrown away (FAO, 2013). This represents a massive volume of emissions, equating to 8-10% of greenhouse gas emissions worldwide (*UNEP Food Waste Index Report*, 2021). Food waste is clearly a significant problem to be solved as cited in the objectives of the Paris Climate Agreement for emissions reduction. Bioconversion technology clearly offers a viable option to reduce food waste greenhouse gas emissions and create alternative sources of protein for livestock feed.

Insect-based bioconversion of food waste offers sustainable livestock food chains, improved food security and a reduction in land use for protein production. Bioconversion allows for feed production using reclaimed resources that would otherwise go to waste and are not confined to traditional farmland locations. Bioconversion, therefore, shows promise and has proven sufficiently adaptable to work in a variety of locations. Countries have different views on types of food waste insects can consume and this results in differences in the uses of the technology, the types of waste processed and the species of insect employed. In the UK, only pre-consumer food waste is currently permitted for bioconversion (WWF, 2021). Industrial and commercial food waste can be paired with specific insect species to maximise bioconversion efficiency. Weather and climate alter local requirements for the farming process due to the insects requiring optimised climatic conditions for efficiency, climate also controls what food waste is locally available. Extra water use is minimal as insects require a diet with high water concentrations which is promising for countries facing water problems in the future.

Insect farms create alternative protein sources for livestock feed and would compete against soy feed in the marketplace. Insect products represent a less environmentally impactful livestock feed option than soy (van Huis, 2017) which is harmful to the environment due to the farming practices relating to deforestation and biodiversity loss (WWF, 2014). Large swaths of the Amazon rainforest and other significantly biodiverse regions in South America have been deforested to keep up with the global demand for protein. Large cropland area requires irrigation which uses millions of litres of water and contributes to water security and scarcity problems in regions that are already facing water problems due to climate change. Even when soy is farmed sustainably it still requires vast amounts of land, intense irrigation and results in deforestation.

Insect farming provides a new and improving production method for protein. Research and investment are required to optimise and increase the efficiency of the insect farming process. Insect farming facilities need to develop production methods that reduce electricity usage and therefore reduce their global warming potential. Despite this, insect farms provide a viable alternative to traditional protein farming and plant-based livestock feed and outperform many food waste management alternatives. With appropriate improvements and food safety precautions, insect bioconversion of food waste has the potential to become a powerful tool against food waste issues while providing an environmentally friendly alternative protein source that would decrease the carbon footprint of livestock whilst providing foodstuff for the growing, global population.

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