A Nuffield Farming Scholarships Trust Report

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Farming insects for food: opportunities and challenges

Adam Banks

September 2019

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Nuffield (UK) Farming Scholarships Trust Report

"Leading positive change in agriculture. Inspiring passion and potential in people."

Date of report: September 2019

Title Farming insects for food: opportunities and challenges

Scholar Adam Banks

Sponsor The Food Chain Scholarship

Objectives of Study Tour

- To explore the insects as food sector and understand the main drivers for its growth around the world.
- To learn what opportunities exist for new entrants and what can be learnt from insect entrepreneurs in other countries.
- To build up a picture of what the future might hold for the emerging edible insect industry .

Countries Visited The Netherlands, Belgium, France,
Thailand and The United States of America

Messages

1. Despite a cultural aversion to eating insects in the West, most European consumers are aware that insects could play a role in our future diets. Children under the age of 12 are the demographic most receptive to the idea of eating insects.
2. Evidence suggests that insects are at least as nutritious as meat and may provide additional environmental benefits. Larger scale environmental studies and clinical trials are required to fully understand the impacts of producing and eating insects.
3. Although new food regulations have been problematic for European insect producers, they should improve public safety and retailer confidence going forward.
4. There is a strong pro-insect lobby in Brussels; post-Brexit the UK may fall behind the rest of the EU without government support. Those involved in the sector must collaborate to promote insect agriculture in the UK.

EXECUTIVE SUMMARY

Insects are promoted as a 'green' meat and a more sustainable alternative to traditional forms of animal agriculture. Although the wild harvesting of edible insects is practised around the world, farming insects for food is a new concept. My study aims to explore this rapidly evolving industry and understand the main drivers for its growth. Through my meetings with academics, entrepreneurs and industry organisations I have built up a picture of the current state of the sector and propose an idea of what the future might hold.

Despite forming an important part of our ancestral diets, there remains a cultural aversion to eating insects in the West. From a nutritional standpoint there is good reason to eat insects: they outperform other animal-based foods in many regards. What's more, clinical trials are now showing that consuming insects may have other positive health impacts, including improved gut health and reduced inflammation. From an environmental perspective, insects are a promising way of lessening the impact of livestock farming. Their increased feed efficiencies reduce land and water use and their global warming potential is relatively low. So, whilst ingrained dietary prejudices are difficult to overcome, there is mounting evidence that a diet enriched with insects may be beneficial for health and the environment. A recent YouGov survey found that a third of Britons, and nearly half of those aged 18-24, expected insect consumption to be commonplace by 2029. This mirrors industry forecasts, which predict strong growth for the sector over the next decade.

The number of companies around the world that are rearing insects for human consumption is increasing rapidly, with several facilities now having an annual output of over 100 tonnes. Almost all insect-based food products sold in the UK contain insects which are imported from North America, South East Asia or other European countries. There appears to be a good opportunity for local producers to command an increased domestic market share. The sector should further benefit from new EU novel food legislation which has specific provisions for insects. Although disruptive in the short term, these regulations will serve to increase safety standards and public confidence going forward.

Despite this optimistic outlook there are still significant technical hurdles to overcome if insect production is to become cost competitive with other forms of livestock farming. A lack of automation means labour costs are high and efficiency is further reduced by the small scale of most farming operations. Larger European insect producers have lobbied successfully for favourable policy change in Brussels through a well-funded, member-led organisation. Outside of the European Union, the UK stands to fall further behind its European competitors without similar support. Insect agriculture has the potential to help the UK achieve the goals of a future national food strategy. Government support will be essential to create an environment in which the sector can thrive.

I believe that insects have passed a tipping point and the question now is not *is there a market for edible insects?* but *how large will that market be*?

CONTENTS

EXECUTIVE SUMMARY ii
CONTENTS iii
1.0. Personal Introduction 1
2.0. Background 2
3.0. Why eat insects? 3
3.1. Eating insects around the world 3
3.2. Evolutionary context 4
3.3. Potential health benefits 4
3.3.i. A nutritional comparison between the banded cricket (Gryllodes sigillatus), yellow mealworm (Tenebrio molitor), beef, chicken, eggs and milk. 5
3.4. Potential environmental benefits 7
3.4.i. Trends in meat consumption 7
3.4.ii. Insects as a 'green' meat 8
3.4.iii. Greenhouse gas emissions 9
3.4.iv. Land and water use efficiency 10
3.4.v. Feed conversion efficiency 10
3.4.vi. Energy requirements 12
3.4.vii. Sustainability: grass-fed livestock vs insects? 13
4.0. Regulatory framework in the UK 14
4.1. Background 14
4.2. Novel Food Regulation (EU) 2015/2283 14
4.3. Transitional period 16
4.4. Data protection 17
4.5. General food law and food hygiene regulations 18
4.6. Labelling 18
4.7. Brexit 19
4.8. Legislation governing feed substrates for insects 19
5.0. Rearing insects for human consumption 21
5.1. General considerations 21
5.2. Facility design 21
5.3. Implementing HACCP principles 22

5.4. Pest and disease control 23
5.5. Species selection 26
5.5.i. Practical information for the farming of crickets and mealworms 26
5.6. Processing 27
5.6.i. Microbial safety 27
5.6.ii. Drying 27
5.6.iii. Producing a powder 27
5.6.iv. Extraction of protein, oil and chitin 28
6.0. Ethics of insect farming 29
6.1. Welfare regulations 29
6.2. Can insects feel pain? 29
6.3. The five freedoms 30
7.0. Consumer acceptance 31
7.1. The 'yuk factor' 31
7.2. Overcoming barriers to acceptance 31
8.0. Enabling insect agriculture in the UK 33
8.1. Government 33
8.2. Academic institutions 33
8.3. Private sector businesses and organisations 33
9.0. Prospects for insects as food 35
9.1. Public perceptions 35
9.2. Market analysis 35
9.3. Overview 35
10.0. Conclusions 37
11.0. Recommendations 38
12.0. After my study tour 39
13.0. Thanks and Acknowledgements 40
References 41
ANNEX A 44
Farming Crickets 44
ANNEX B 47
Farming Mealworms 47

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1.0. Personal Introduction

I grew up in Nottinghamshire on a family-run arable farm and went on to study Environmental Science at Nottingham University. Leaving university, I took up a position as an agricultural loss adjuster and, when the opportunity arose to work as an international adjuster based out of Mexico City, my partner Lauren and I leapt at the chance.

After some years abroad (and having truly tested the strength of our relationship during a 5-month tandem bicycle tour around Europe) we were keen to 'settle down'. Now, back in the UK, we live in Lincolnshire along with our new baby daughter, Daisy.

I came back wanting a new challenge. My time in Latin America had opened my eyes to the idea of insects being a part of people's diets and I began to explore the prospects of raising insects for human consumption in the UK. From there, I launched Instar Farming, rearing crickets as food and developing insect-based food ingredients.

Figure 1: The author Adam Banks posing with an enormous cricket outside a Thai village in Nam Phong District

I have since become a director of the Woven Network, which is an organisation that represents those with a commercial or academic interest in producing insects, either for human consumption or animal feed. I am grateful for the platform Woven has provided, connecting me with the edible insect community around the world.

Farming insects for food is a relatively new concept and therefore there is very little information available to help prospective entrants to the sector. This motivated my Nuffield Farming Scholarship study: *Farming insects for food: opportunities and challenges*. It will, I hope, provide a useful resource to those interested in this emerging industry.

I am very grateful to The Food Chain Scholarship Fund for making my scholarship possible.

2.0. Background

Like most people raised in the UK, I didn't grow up to see insects as food. It wasn't until I moved to Mexico that I experienced a culture in which insects were widely consumed and, indeed, considered to be a delicacy. At market stalls in Oaxaca, chapulines (a species of grasshopper) can sell for more per kilo than beef and, in Mexico City, tacuitos de escamoles (ant larvae and pupae) might be the most expensive plate on the menu.

Figure 2: Mexican chapulines (grasshoppers), fried and seasoned [Image credit: author's own photo]

I applied for a Nuffield Farming Scholarship hoping to meet entrepreneurs working at the forefront of insect agriculture and to gain better understanding of this rapidly developing sector. I soon realised that there were three primary barriers to insects becoming a widely accepted food in the Western world.

1. The technological challenges involved in farming insects at scale and in a cost-effective manner.
2. The regulatory barriers limiting the species and products which can legally be placed on the market.
3. Overcoming ingrained, negative Western attitudes towards insect-based food products.

Encouragingly, I have found there to be growing support for insect agriculture at both public and government levels. Much of this is down to the hard work of individual advocates, insect-focused start-ups and industry organisations. There is a long way to go before eating insects becomes mainstream in the West. However, I believe readers of this report may come to feel, as I do, that the possibility of this one day happening is both exciting and realistic.

3.0. Why eat insects?

3.1. Eating insects around the world

It is not just in Mexico that insects are widely consumed. In fact, the Food and Agriculture Organisation of the United Nations (FAO) notes that insects are eaten in 113 countries, with Europe and Central Asia being the only regions of the world without a significant recorded history of entomophagy. A project led by Yde Jongema from Wageningen University in the Netherlands has so far identified over 2,000 species of insect with a history of human consumption. Although, as was noted by professor Arnold van Huis when I met him at the University, the actual figure is likely to be far higher.

The vast majority of the different insect species that are eaten globally are harvested from the wild. Unfortunately, a growing human population, combined with extensive habitat loss and climate change, has put pressure on wild insect populations. According to a study by Sánchez-Bayo *et al.* (2019), one third of all insect species should now be classified as endangered. The focus needs to be on developing sustainable farming systems for the rearing of edible insects at an industrial scale. For every species of bird or mammal there are over 350 species of insect, so there is plenty of scope to find insects which thrive in a farmed environment.

Number of insect species consumed, by country

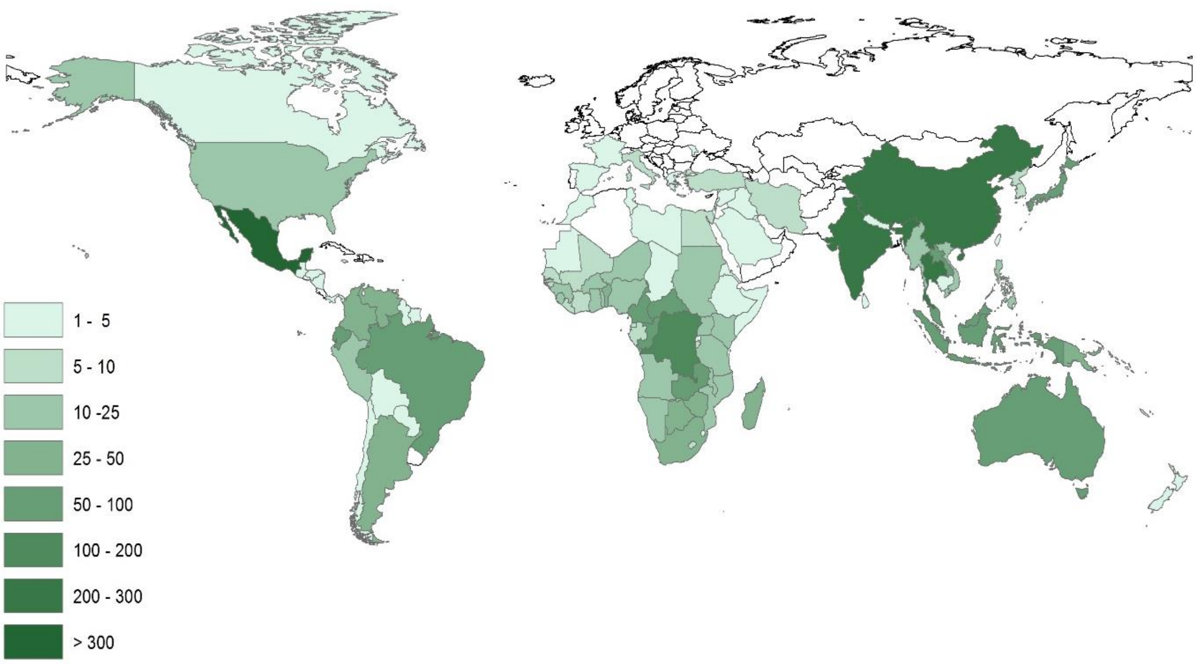

Figure 3: Number of insect species consumed, by country.
[Source: Ron van Lammeren Laboratory of Geo-information Science and Remote Sensing at Wageningen University using data from Yde Jongema]

3.2. Evolutionary context

Evidence suggests that insects may have formed an important part of our ancestral diet. We have eaten insects throughout our evolutionary history and only recently has the Western world shifted away from an insect enriched diet.

During my Nuffield Farming Study Tour, I was lucky to meet Dr. Julie Lesnik, paleoanthropological researcher at Wayne State University and fellow of the American Association for the Advancement of Science (AAAS). Working with colleagues, she has found evidence that insects have played a significant role in hominid diets for millions of years. By matching wear marks on *Homo habilis* bone tools with marks etched into termite mounds she was able demonstrate that early man could break open these nests to harvest the nutritious termites within (*Lesnik, 2018).*

The dates associated with these findings coincide with the beginning of a rapid increase in our cranial capacity. This has led some to consider the possibility that this readily available source of calories, as well as essential amino and fatty acids, may have been responsible, at least in part, for enabling us to develop our large, energy-hungry brains. Perhaps the current paleo diet trend, which encourages us to eat like our hunter gatherer ancestors, is missing a key component – insects!

3.3. Potential health benefits

In general, insects are a complete source of amino acids. They are high in mono and polyunsaturated fatty acids, a source of dietary fibre and rich in bioavailable micronutrients such as iron, magnesium, zinc, riboflavin and biotin. As well containing several important vitamins, including vitamin A, E and B12.

Dr Charlotte Payne is a researcher based at the department of Zoology at Cambridge University and is an advocate for using insects to improve food and nutrition security. Using two nutritional value scoring (NVS) systems, a common method of determining the 'healthiness' of a food, she compared six different regularly consumed insect species to beef, pork and chicken. The results showed that none of the insects tested were less healthy than meat, and that the NVS for crickets, palm weevil larvae and mealworms were, in fact, significantly higher than for beef and chicken (*Payne, 2015*). For any oenophiles who also want to try insects, Charlotte helps run a not-for-profit venture called *Insects and Wine*, pairing wines with an assortment of insect-based dishes.

When travelling in the United States, I met with Dr Valerie Stull of the Global Health Institute of the University of Wisconsin-Madison. I spoke to her shortly after the publication of her findings from a double-blind, randomised crossover trial looking at the impact of insect consumption on the gut microbiota of adults (*Stull, 2018*). Although she was keen to point out that this was a relatively small trial, with 20 participants eating crickets daily for six weeks, the initial results were impressive. Consuming 25g/day of cricket powder resulted in a 5.7-fold increase in growth of the probiotic bacterium, *Bifidobacterium animalis*. The trial participants also showed significantly reduced plasma TNF-α, a cytokine associated with various inflammatory diseases including rheumatoid arthritis, Crohn's disease and some forms of asthma.

According to Nature Research, part of the scientific journal Nature, the write-up of her trial was in the top 100 most accessed papers published in 2018 (*as of June 2019)*. Considering that there are over 50,000 articles published each year on the site, this is an impressive statistic. As people become increasingly aware of the importance of gut health and the impact of gut microbiota on many aspects of our physical and mental wellbeing, it is possible that insects as a pre-biotic could become a more important component of our future diets.

Case study: MIGHTi – The Mission to Improve Global Health Through Insects

The MIGHTi project is headed by Dr. Valerie Stull at the University of Wisconsin-Madison, USA and is a collaborative research project designed to help address the complex factors that contribute towards global food insecurity. The project also forms part of a wider effort to create food systems which can respond to a changing climate.

MIGHTi focuses on insects as food and sees support from academia, industry and international development organisations.

3.3.i. A nutritional comparison between the banded cricket (Gryllodes sigillatus), yellow mealworm (Tenebrio molitor), beef, chicken, eggs and milk.

Well-intentioned but misleading comparisons between the nutritional content of insects and other foods are occasionally made by insect producers and the media. This was pointed out to me by Trina Chiasson, the co-founder of a US insect farming start-up called Ovipost, whilst attending an insect farming conference in Georgia. Coming from a background developing data analytics software, she has a keen eye for deceptive statistics. Although she has great confidence in the future of the edible insect sector, she is concerned that the industry could lose consumer trust if it promotes unfair comparisons, particularly if these are nutritional or health claims.

Some well-intentioned but potentially misleading headlines have been:

> *"Insects contain TWICE as much protein as meat and fish"* – The Daily Mail, September 2017
>
> *"It's healthier to eat a bug than it is to eat a steak"* – The Huffington Post, October 2015
>
> *"Eating insects as good for you as orange juice"* – BBC, July 2019

Before looking to make a nutritional comparison between insects and other livestock, it is important to note that there are various factors which can alter their nutritional composition. These could be what the animal is fed, its age, how it is processed, which parts of the animal are eaten etc. Such comparisons can be further complicated by the fact that insects are processed whole and not de-gutted. Farmed insects should be briefly starved before harvest to clear the contents of their alimentary canal and therefore what they are fed should not impact on their nutritional value. That said, it is not always possible to completely clear all harvested insects of all traces of feed material. This means, for example, that for an insect-based product to be marketed as gluten-free, the insects will have been fed on a gluten-free feed substrate, avoiding any possibility of gluten being present in the final product.

It is still useful to include a 'side-by-side' nutrient comparison of animal-based food products and for that reason I have put together the following the table overleaf:

Table 1: A table comparing nutritional differences between the banded cricket (Gryllodes sigillatus), yellow mealworm larvae (Tenebrio molitor), beef, chicken, eggs and milk.

Table compiled by author. [Sources: (where necessary linear regression has been used to calculate dry matter values) U.S. Department of Agriculture, Agricultural Research Service. FoodData Central, 2019. Bureau Veritas Laboratories analysis of *Gyrllodes sigillatus* and *Tenebrio molitor* from Entomo Farms, Canada (data available at www.entomofarms.com, accessed August 2019, product codes: CGO and COG).

	Banded cricket	Yellow mealworm	Beef	Chicken	Eggs	Milk
% of animal product consumed	100%	100%	45%	58%	89%	100%
Moisture content of consumed portion	69%	62%	62%	66%	76%	88%
Consumed portion	Whole insect	Whole insect	Meat, fat (20%)	Meat, fat, skin	Whole, no shell	Whole
On a dry matter basis, per 100g:						
Calories (kcal)	484	460	602	569	536	458
Protein	60%	58%	45%	55%	52%	26%
Fat	25%	20%	53%	44%	40%	27%
Of which saturated fat	8.7%	4.4%	21%	13%	13%	16%
Of which polyunsaturated fat	9.3%	7.7%	1.3%	9.5%	7.9%	1.6%
Of which mono-unsaturated fat	5.3%	6.8%	24%	18%	16%	6.8%
Of which trans fat	0.2%	0.1%	3.1%	0.3%	0.0%	0.6%
Total carbohydrate	8.6%	16%	0.0%	0.0%	3.0%	40%
Of which dietary fibre	6.2%	9.2%	0.0%	0.0%	0.0%	0.0%
Of which sugar	0.5%	0.0%	0.0%	0.0%	1.6%	42%
Cholesterol	234mg	157mg	187mg	221mg	1550mg	83mg
Sodium	318mg	190mg	176mg	205mg	592mg	358mg
Potassium	1,129mg	1,159mg	711mg	556mg	575mg	1,100mg
Calcium, Ca	113mg	85mg	47mg	32mg	234mg	942mg
Iron, Fe	2.1mg	4.2mg	5.1mg	2.6mg	7.2mg	0.3mg

Case study: 'Entoveganism', Josh Galt, entovegan.com

Entoveganism aims to combine the benefits of a plant-based diet with entomophagy and Josh has travelled the world as a proponent of this new movement.

Vegan diets, based on fruits, vegetables, nuts and whole grains, may be both healthy and environmentally sustainable, however, it can be difficult to ensure that vitamins, minerals and essential amino and fatty acids are consumed at sufficient levels. There is also some concern that an un-processed vegan diet which is very high in fibre, can lead to calorie deficits in young children. Josh believes that supplementing a vegan diet with insects is the most sustainable way to ensure that all nutrient and energy requirements are met, without the environmental or ethical burdens that conventional livestock production brings.

3.4. Potential environmental benefits

Most press articles covering edible insects have stressed 'sustainability' as a primary reason for the adoption of an insect-based diet. This reflects an overall increased public awareness that current food production methods have the potential to damage ecosystems and the climate. Whilst insects should not be viewed as a silver bullet, they may provide one option to help mitigate the environmental impact of traditional forms of livestock farming.

3.4.i. Trends in meat consumption

In 2018 the United Nations Environment Programme described meat as "*the world's most urgent problem*" based on its negative and growing impact on the environment.

The world population today is over 7.7 billion. It has doubled since 1972 and will exceed 9.5 billion by 2050. By then, according to figures from the FAO, meat consumption is expected to have increased by 73%.

see graph overleaf

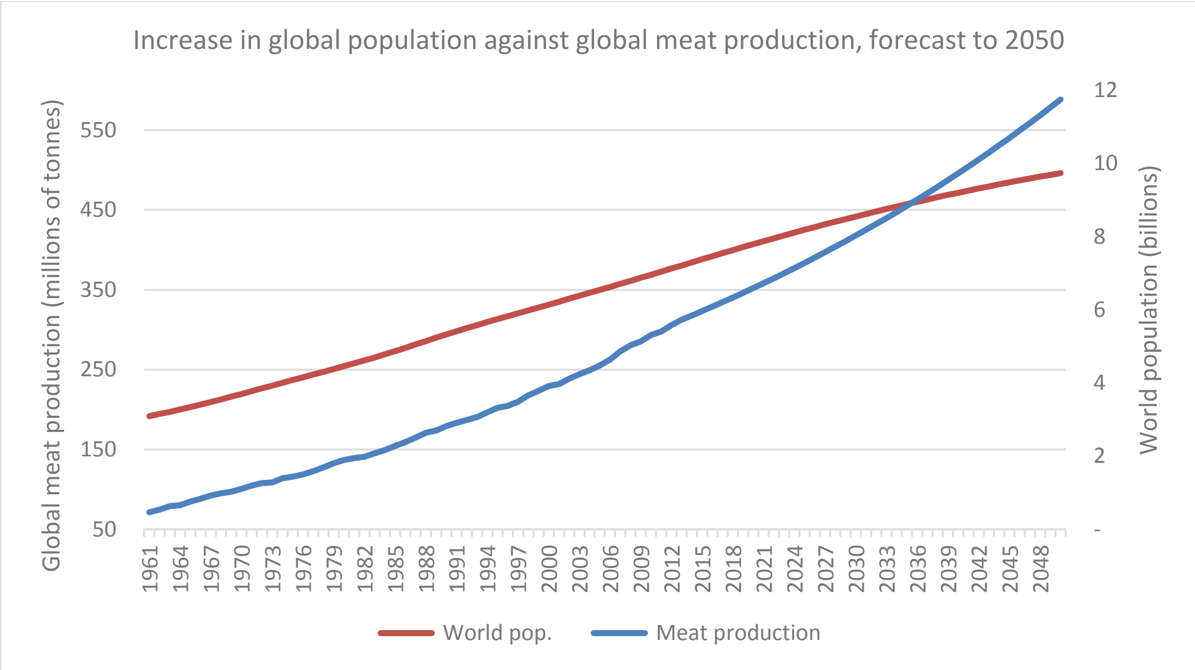

Figure 4 : A graph to show increase in global population against global meat production over time. Population forecast is based on UN 'medium prediction', meat consumption assumes annual global increase of 1.725% to 2050, which is the 10-year annual average to date. [Sources: UN DESA, Population Division (2019) and UN FAO (2017)]

3.4.ii. Insects as a 'green' meat

Meat is an energy-dense food that provides many people with essential nutrients missing elsewhere in their diet. Nonetheless, meat production has an environmental cost which is disproportionate to its contribution to our diets. Although 80% of farmland is used to produce livestock it provides just 18% of the calories in our diets and 37% of the protein.

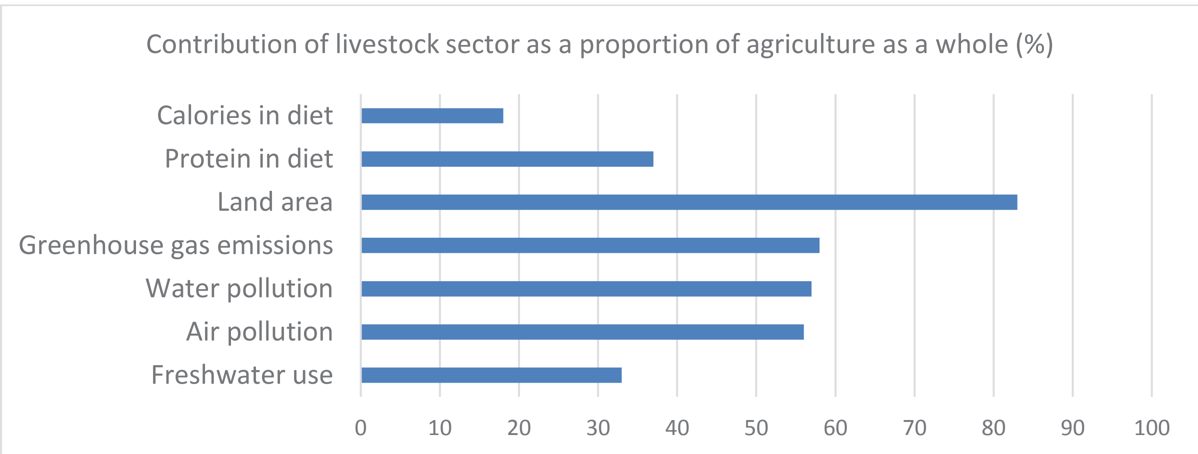

Figure 5: A graphic showing the impact of the livestock sector on the environment, using data from a recently published study in the journal Science [*Source: Poore, J (2018)*]

Farmed insects, in comparison to both traditional livestock and many alternative sources of protein, appear to have a relatively low environmental impact. A recent study by Smetana *et al* (2015) compared the impact of most known meat alternatives against chicken, which is generally regarded as the least environmentally damaging source of meat. Comparing foods on a cradle-to-plate basis, also known as a lifecycle analysis (LCA), they found that insects and soy-based meat substitutes were the least environmentally damaging overall. Cultured (lab-grown) meat and myco-proteins had the most significant environmental impact.

3.4.iii. Greenhouse gas emissions

It is estimated that livestock production accounts for 14.5% (*FAO, 2013*) of greenhouse gas (GHG) emissions globally, and 9.1% (*EC, JRC, 2011*) within the European Union. A shift towards insect agriculture could be an effective way to mitigate one of the key drivers of climate change.

Most studies have shown that insects perform favourably against conventional livestock in terms of their GHG emissions. Ruminants do particularly poorly in comparison, due to their high methane emissions and low feed conversion ratio (FCR). The 100-year global warming potential of methane is 23x higher than CO_2 and therefore farmed insects such as crickets and mealworms, which do not produce methane, have lower GHG emissions in terms of CO_2 equivalent.

Researchers from the Universities of Copenhagen and Khon Kaen carried out an LCA to determine the environmental impact of cricket farming (*Halloran, 2017*). Another study by Oonincx *et al* (2012) used a similar approach to carry out an LCA for farmed mealworms. By using data from these studies alongside figures supplied by DEFRA (*Foster, 2006*) it is possible to compare the relative GHG emissions of conventional livestock against insects:

Table 2: Table to show the relative GHG emissions of conventional livestock against the yellow mealworm (*Tenebrio molitor*) and the house cricket (*Acheta domesticus*)

1 kg of liveweight gain	produces _ kg CO_2-eq
Beef	34.6
Lamb	17.4
Pork	6.35
Chicken	4.57
Mealworms	2.7
Crickets	1.85

It is worth noting that the kg CO_2-eq given here for crickets was calculated using a farm in Northern Thailand, whereas the figure for mealworms comes from a farm in the Netherlands. There is limited real farm data (as opposed to data from laboratory scale studies) available to show the global warming potential of crickets farmed in temperate climates.

3.4.iv. Land and water use efficiency

Speaking to people over the course of my Nuffield Farming study I found that terms like 'space efficient' and 'land use efficiency' were often used when trying to market insect farming systems, particularly those in an urban environment. This is true in terms of the total mass of insects per m^2. A mealworm farm could hold over 100kg/m^2 of edible larvae, whereas a broiler shed (at the maximum density allowed by the Animal and Plant Health Agency (APHA)) could house 39kg/m^2. However, 99% of the land used to rear both mealworms and poultry comes from the production of their feed rather than the actual housing of the livestock. The same issue arises with water use. The direct water requirements of insects and poultry are only a tiny fraction of the total amount of water required to feed and produce them. Again, most of the overall water use relates to the production of their feed.

A better way to compare land and water use efficiency could be to compare feed conversion ratios (FCR). A better FCR should mean that less land and water will be needed for every kg of livestock produced.

3.4.v. Feed conversion efficiency

'Feed conversion ratio' is defined as the quantity of feed inputs on a dry-matter basis required to produce one kilogram of liveweight gain.

Birds and mammals are homeothermic, meaning that they maintain a stable body temperature by regulating their metabolic processes. Insects are poikilotherms, which means that their internal temperature can vary considerably due to changes in the ambient environmental temperature. Using energy to increase body temperature will result in less energy being available for growth. On that basis the FCR for an insect, which is not expending energy to produce body heat, will be lower (better) than a bird or mammal. Weight for weight, a poikilotherm will, on average, require just 5-10% of the energy of a homeothermic animal for survival (*Campbell, 2002*).

This is not to say that insects don't generate excess heat. Cellular processes are reliant on ATP (adenosine triphosphate), which is produced through metabolism. This process is inefficient, with around 60% of available energy being converted to heat rather than to ATP. If you could stick your hand into a tray of mealworms, you would notice that it is very warm; this is excess heat generated through the respiration of the larvae.

By keeping homeothermic animals at a suitable temperature, it is possible to greatly reduce the amount of energy they expend through thermoregulation. However, even with precise temperature control in livestock housing, birds and mammals cannot match the energy efficiency of insects. The air temperature in a cricket farm should be the same as the optimum body temperature of the cricket, around 30°C. The body temperature of a chicken should be 41.5°C, yet if poultry housing is maintained at this temperature the birds cannot survive. The optimum air temperature for an adult bird is closer to 20°C, which gives some indication of the amount of energy which is unavoidably lost to thermoregulatory metabolic heat production.

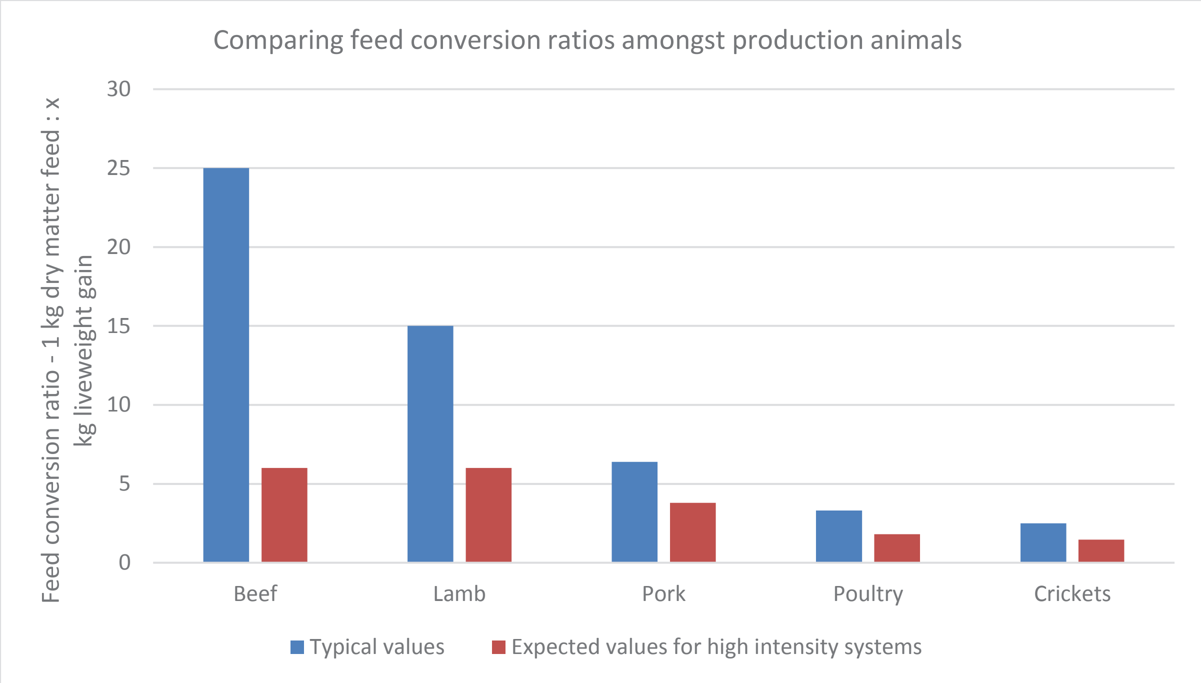

Figure 6: A chart demonstrating the varying feed conversion ratios between various production animals. The stark differences in FCR between 'typical values' and 'high intensity systems' for beef and lamb are due to the performance decreases for livestock fed on forage as opposed to high energy, grain-based feeds. Sources: Typical livestock conversion efficiencies are global averages given as reported in Alexander *et al*. (2016). Expected values for high intensity systems are target values taken from a variety of sources including farming publications and government performance guidelines – actual FCR's are likely to vary farm to farm. Values for crickets refer to *Acheta domesticus* and are taken from Halloran *et al.* (2017).

In a recent study Lundy *et al* (2015) found *A. domesticus* crickets fed on poultry feed had a hatch-to-harvest FCR of 1.34. This showed them to have a significantly better performance than poultry fed on a similar quality feed – in the UK the average FCR for broilers is around 1.75 (*van Horne, 2014*). It is important to note that most of the low FCR's for insects come from similar small-scale studies, rather than from studies of commercial farming operations. Halloran *et al* (2017) found that the actual FCR on a cricket farm in Thailand, with an annual output of 36,741 kg, was 2.5 on a diet of modified poultry feed.

Nutritional research and artificial selection have played a significant role in improving the efficiency of conventional livestock production. With a similar approach, optimised insect feeds could be developed to improve performance and selective breeding could be used to develop more productive strains. The time required for poultry to proceed from one generation to the next is around 20 weeks. Over the same period crickets might pass through three generations and produce over 100,000 descendants. This means that more efficient or higher yielding strains of insect can be produced in a relatively short period of time.

see Case study on next page

Case study: 'Super crickets', James and Kathleen Rolin, Cowboy Cricket Farms

Cowboy Cricket Farms, in Montana USA, received a grant of approximately $60,000 in 2017 to develop, through selective breeding, a 'super cricket' with much higher concentrations of omega-3 fatty acids than standard A. domesticus crickets.

The goal is to produce a heart healthy food, which is an affordable alternative to oily fish and grass-fed meat.

3.4.vi. Energy requirements

Most studies, as noted in a review by van Huis A *et al* (2017), have shown that the energy requirements of insect production systems in temperate climates to be high compared to conventional livestock systems. This is largely due to the elevated temperatures which are required for the insects to be reared in a reasonable time period. From my own experience, house crickets raised at 34°C can mature in as little as 30 days whereas those reared at 18°C may take several months to achieve the same increase in size. The lesser mealworm, *Alphitobius diaperinus,* has been shown to be similarly sensitive to temperature changes (*Bjørge, 2018):* at 31°C they can achieve a growth rate of 18.3% per day, whereas at 16°C they will cease growing entirely. To put this figure in perspective, the daily growth rate of a pig for slaughter is typically around 5%.

Commercial insect farms that I have visited in Europe have been heated by either gas, mains electricity, biomass burners or a combination of these three. Ooninicx *et al* (2012) looked at the environmental impact of mealworm production at a facility in The Netherlands and found that, of the 34MJ of energy required to produce 1kg of fresh mealworms, 34% related to gas heating and 21% was from electricity usage. By comparison, to produce 1kg of chicken was estimated to require 16-30MJ of energy.

Better insulation, heat exchangers and adaptive ventilation systems could all be employed to ensure that energy is used more efficiently on insect farms. A sealed building, housing a high population density of insect livestock and with good quality insulation could potentially retain more heat than it loses.

Case study: Efficient heating, David Perry, Peregrine Livefoods

Peregrine Livefoods breeds insects for the pet food trade and is one of the largest wholesalers in the UK. Although they are not currently breeding insects for human consumption, the steps they have taken to make their rearing houses more energy efficient and sustainable provide a useful example.

Having tried various heating options, including the burning of insect frass in their biomass burner, the business recently invested in a pair of 16kW air source heat pumps in one of their rearing areas. Combined with a buffer tank and radiators, the building can be kept at a constant 33.5°C far more efficiently than would be possible with standard electrical heating systems.

3.4.vii. Sustainability: grass-fed livestock vs insects?

When discussing insect farming in the UK I am often asked whether grass-fed sheep, beef or even venison might not be a more environmentally sustainable source of animal protein. The argument being whether an indoor production system where insects are fed crops grown for feed is less sustainable than an extensive one in which livestock graze upland areas not suitable for growing crops.

The answer is not straightforward and can be influenced by different interpretations of the term 'sustainable'. The difficulty in defining sustainability was an issue that Dr Aiden Leek discussed in his 2016 Nuffield Farming Report '*The future for insect bioconversion products in poultry feed'.* He highlighted the potential pitfalls of the various existing methods of assessing sustainability, including the FAO's four pillars scoring system, and suggested that measurement of outcomes was important in identifying an 'effective' system.

We can use this approach to compare intensive insect agriculture and extensive pastoral systems. By measuring the environmental outcomes of both systems, we can directly compare their effectiveness. Using figures from a report by Edwards-Jones (2008), '*The carbon footprint of sheep farming in Wales'*, total emissions from grazed systems were found to be on average 4,747 kg CO_2-eq ha^{-1} $year^{-1}$. This equated to 15.4 kg CO_2-eq per kg of lamb produced and is consistent with other studies. In comparison, Ooninicx *et al* (2012) found that producing mealworms in The Netherlands generated 2.7 kg CO_2-eq per kg of mealworm output. This would mean that grazing sheep, to produce lamb, has over 5x the global warming potential of intensive mealworm production.

Using the same studies, we can also compare the amount of land required to produce 1kg of both lamb and mealworms. The Welsh lamb required 32.5m^2 per kg and the Dutch mealworms 3.56m^2.

It has been suggested that grazing less favourable areas (LFAs) can "*play a substantial role in improving the environment through the removal of CO_2 from the atmosphere"* (*QMS sustainability key facts 2013*). This is, to an extent, true, a comprehensive review by the Food Climate Research Network at the University of Oxford (*Garnett, 2017*) found that well managed grazing could offset a maximum of 60% of livestock emissions. However, this figure still shows pastoral systems to be net contributors to GHG emissions and not a net carbon sink as proposed by some. Accounting for a possible 60% sequestration, Welsh lamb might be contributing 9.2 kg CO_2-eq per kg output, rather than 15.4; though this figure is still significantly higher than the 2.7 kg CO_2-eq per kg generated by mealworms.

From an environmental standpoint, there may be an argument to restrict grazing and encourage the reforestation of LFAs. The climatic treeline for most of the UK is around 600m, meaning that many areas could potentially be reforested. In a government-commissioned report, *'Carbon Abatement Potential of Reforestation'*, it was found that managed forests had a greater potential for carbon abatement than managed grazing (*O'Driscoll, 2018*). The report also found that reforestation of grassland would improve biodiversity, reduce flood risk and increase soil fertility. Shifting food preferences from grazed livestock to insects may be one way of freeing up land for reforestation and reducing the overall environmental impact of UK agriculture.

4.0. Regulatory framework in the UK

4.1. Background

For most of the last 20 years insects have fallen into a legal grey area in terms of their status as a food in the EU. In Italy, Spain, Sweden and much of Eastern Europe the marketing of insects as food was prohibited, whereas in the UK, Belgium, The Netherlands and Denmark it was not. The reason for this confusion came from differing interpretations of the first EU Novel Food Regulation (EC) 258/97 between member states. The regulation defined any food ingredients isolated from animals, which were not widely consumed in the EU prior to 1997, as 'novel' and therefore subject to pre-market authorisation.

As insects were not widely consumed in Europe before 1997, there was an argument to say that they were novel and should be subject to authorisation before they could be placed on the market. However, some state authorities disagreed with this interpretation. The UK Food Standards Agency (FSA) felt that whole insects and ingredients consisting of whole insects were not 'isolated from animals' and therefore not within the scope of the regulation. Up until the enforcement of new regulations in January 2018, many species of edible insect and arachnids were widely available to buy in the UK.

Case study: Novel food impact, Nick Cooper, Snow Pony Ltd t/a Crunchy Critters

Based in Derby, Crunchy Critters has been selling insects and other 'critters' in the UK since 2012. Originally inspired by challenges on "I'm a Celebrity Get Me Out of Here", Nick had sold 14 different species before the new EU Novel Food Regulations were introduced. Now the Crunchy Critters website has products made from just 4 species listed for sale.

4.2. Novel Food Regulation (EU) 2015/2283

New Novel Food Regulations were introduced in 2015 and came into force in January 2018. The principle that any food that wasn't consumed in the EU before May 1997 should be considered 'novel' remained unchanged. However, the wording was been expanded to address various questions and conflicts which arose as a result of the original legislation, including this re the status of insects:

Regulation (EU) 2015/2283 (8) *"The scope of this Regulation should, in principle, remain the same as the scope of Regulation (EC) No 258/97. However, on the basis of scientific and technological developments that have occurred since 1997, it is appropriate to review, clarify and update the categories of food which constitute novel foods. Those categories should cover whole insects and their parts."*

As a novel food, all species of insect must now be authorised before they can be marketed in the EU. The aim here is to confirm: a) the food is safe, b) it is not misleading for the consumer and c) that it will not replace traditional foods in a way that would put consumers at a nutritional disadvantage.

There are two routes to approval:

1. Traditional foods from third countries

   This applies to foods which have been consumed, by a significant number of people, for at least 25 years in a country outside of the EU but have no history as a food in the EU before 1997. Although this definition could arguably apply to various species of insects, no applications have yet been submitted via this route.

   This is a simplified route to authorisation and, if no objections are received from the EFSA or other Member States within four-months, the product will be authorised and placed on a Union List of approved novel foods.

2. Full novel food application

   Here a full set of evidence will be required by the Commission including a description of the novel food, the production process, nutritional compositional data, as well as proposed uses and use levels.

   The preparation of a full dossier of information to support an application is a costly and time-consuming task. Laboratory testing is required to determine how novel food might be absorbed, distributed, metabolised and excreted. Evidence will be required to show the toxicity of the food as well as its allergenicity and this may require lengthy studies and, possibly, animal testing.

The cost of preparing a full application will vary from case to case. In the past the Confederation of the Food and Drink Industries of the European Union (CIAA) has reported a cost of over €5 million incurred by some of its members to bring a novel food product to market. A more recent successful application from PhtytoTrade Africa for Boabab dried fruit pulp is said to have cost under €100,000. The EFSA has stated that the approval process under the new regulations should take 8-14 months, nonetheless, the majority of pending applications have already exceeded this.

At the time of writing this report the following species are being considered by the EFSA for approval as a novel food: the house cricket (*Acheta domesticus*), banded cricket (*Gryllodes sigillatus*), mealworm (*Tenebrio molitor*), lesser mealworm (*Alphitobius diaperinus*), Honeybee drone brood (*Apis mellifera* male pupae), migratory locust (*Locusta migratoria*), and black soldier fly (BSF) (*Hermetia illucens*).

It is possible that application dossiers for further insect species will be submitted for approval over the coming years. Some prime candidates include the black field cricket (*Gryllus bimaculatus*), Jamaican field cricket (*Gryllus assimilis*), morio worm (*Zophobas morio*) and silkworm (*Bombyx mori).*

If an application is successful it will be placed on the Union List, a searchable catalogue of approved novel foods is available here:

http://ec.europa.eu/food/safety/novel_food/catalogue/search/public/index.cfm

At the time of writing this report there were no insect species on the list.

4.3. Transitional period

Article 35.2 of Regulation (EU) 2015/2283 details transitional measures which are designed to ensure that foods which were lawfully placed on the market in a Member State before January 2018 may remain on the market until 2020 (though this period could potentially be extended if authorisations are still pending).

The FSA has confirmed the position in the UK is as follows:

Whole insect species marketed in the UK before 2018 can continue to be sold in the UK under transitional arrangements in Regulation (EU) 2015/2283 subject to two conditions:

1) *that an application for authorisation or, if appropriate, a notification of a traditional food from a third country is made to the European Commission under the provisions of the new legislation by 1 January 2019 at the latest, and*

2) *that those making applications / notifications provide evidence to show that the species were marketed in the UK before 2018.*

Figure 7: Silkworms, *Bombyx mori,* feeding on mulberry leaves. Silkworms have been a food source for centuries and now, thanks to the Chinese Chang'e-4 lunar lander, there is even a silkworm colony on the moon. [Image credit: author's own photograph]

Figure 8: Until recently fried silkworm pupae were available in the UK. Regulatory changes mean they can no longer be sold without EU Novel Food authorisation. [Image credit: Crunchy Critters].

4.4. Data protection

Once a novel food application is approved it becomes generic and all producers of that species are then entitled to place products of that species freely on the EU market. It is important to note that the product must be produced to the same specifications as those which have been approved. If, for example, a producer wishes to market an insect protein isolate and the approved application only covers whole insects, then a new application may be required.

There are three conditions under which data protection for an application can be sought:

1. For newly developed, proprietary scientific evidence or data.
2. Data that the applicant has exclusive rights over.
3. Information without which the novel food could not have been assessed.

Where data protection applies The UK Novel Food (Amendment) (EU Exit) Regulations 2019 state:

"…during the period of data protection [five years] the novel food is authorised for placing on the market within the United Kingdom only by the applicant… unless a subsequent applicant obtains authorisation for the novel food without reference to the proprietary scientific evidence or scientific data protected in accordance with Article 26 or with the agreement of the initial applicant."

In cases where only data-protected applications have been submitted for a species, producers of that species who have not submitted their own application may encounter issues when the transitional period ends. Some companies are currently and legally selling insect products which could soon be covered by data-protected novel food applications. Even those who have benefited from the transitional period because another producer's application covering their product's species had been submitted, may have to withdraw their product from the market once that producer's data protected application has been approved.

I have met with several UK companies who use the cricket *G. sigillatus* in their products, either farmed by themselves or purchased from another producer. For now, products containing *G. sigillatus* can be sold in the UK because there is a pending novel food application for that species. However, only one application has been submitted, by the French company Micronutris, and it is data protected. If approved, products not containing *G. sigillatus* crickets from Micronutris may be blocked from the market. Obviously, other producers could submit their own applications to continue to market their product, though the cost of doing so may be prohibitively high for many smaller businesses.

Case study: Pooling resources for Novel Food application, Belgian Insect Industry Federation (BiiF)

BiiF members have joined forces to fund and prepare three EU novel food dossiers which have been submitted to the EFSA. These non-data protected applications cover the house cricket, yellow mealworm and migratory locust.

This is an excellent example of how smaller players can join forces to ensure uninterrupted market access for their products. Going forward there are sure to be further opportunities for smaller companies to collaborate to address regulatory challenges. Industry organisations, such as BiiF or perhaps the Woven Network in the UK, can play a key role in this regard.

4.5. General food law and food hygiene regulations

Businesses farming and processing insects for food in the UK must comply with The Food Safety and Hygiene Regulations 2013 which are based on EU Regulations (EC) No. 178/2002, 852/2004 and 853/2004. It would be beyond the scope of this report to explore these regulations in any detail. Briefly, they contain no provisions specific to insects and deal with all matters of traceability, presentation (to ensure that the food's labelling is not misleading to the consumer), measures for the withdrawal or recall of unsafe food placed on the market and microbial safety.

4.6. Labelling

Food labelling laws in the UK are based on the European Food Information to Consumers (FIC) Regulation 1169/2011. A couple of key points relevant to insects are as follows:

1. It is currently not a legal requirement to include the species or life stage of the insect as part of the mandatory food information. This can be seen on the packaging of some products on the market, which will list 'crickets' or 'mealworms' as an ingredient with no indication of the species.
2. FIC regulation does not specify insects as a potential allergen and there is therefore not a legal obligation to label insects as such on packaging. However, given that there is clear evidence that people can be allergic to insects, it would be irresponsible and potentially damaging to the industry not to label them as potentially allergenic. IPIFF recommends the following description for packaging:

'People who are allergic to molluscs and crustaceans and/or dust mites may have an allergic reaction to insect consumption'

Figure 9: Rear of the consumer packaging for Eat Grub cricket powder.
Note that the species of cricket is not included. [Image credit: author's own photograph]

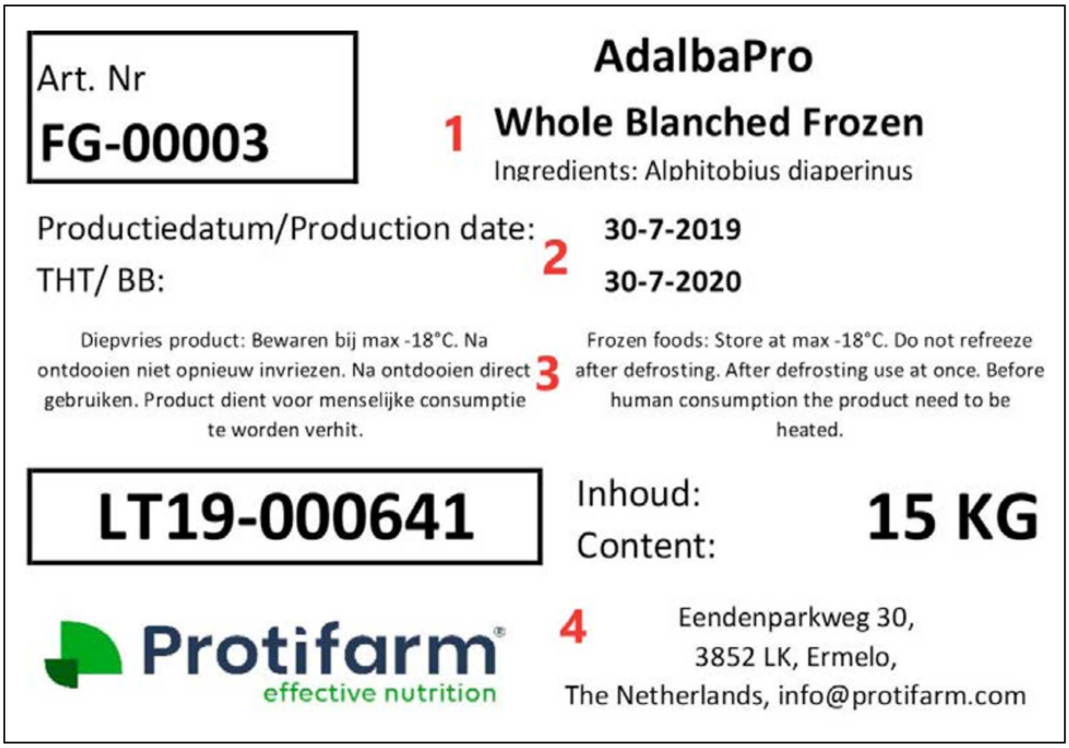

Figure 10: Labelling information from the wholesale packaging for frozen lesser mealworms [Image credit: Protifarm]

4.7. Brexit

At the point the UK leaves Europe, the European Union (Withdrawal) Act and subordinate legislation will come into effect. The provisions of the EU Novel Food Regulation as well as other relevant EU food legislation will then become law in the UK. Unless there is a significant change in UK food laws, the regulatory situation for insects in the UK is unlikely to change immediately post Brexit.

4.8. Legislation governing feed substrates for insects

What insects intended for human consumption can and cannot be fed is dealt with in Annex IV of Regulation (EU) No. 142/2011. The feed substrate must only contain products of non-animal origin or the following products of animal origin:

(a) fishmeal;

(b) blood products from non-ruminants;

(c) di- and tricalcium phosphate of animal origin;

(d) hydrolysed proteins from non-ruminants;

(e) hydrolysed proteins from hides and skins of ruminants;

(f) gelatine and collagen from non-ruminants;

(g) eggs and egg products;

(h) milk, milk based-products, milk-derived products and colostrum;

(i) honey; or

(j) rendered fats.

Regulations also state that substrate for the feeding insects must not contain manure, catering waste or other 'waste'. When considering by-products and organic side streams from other industries it is important to confirm that they do not fall foul of this definition.

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A UK Nuffield Farming Scholarship consists of:

(1) A briefing in London.

(2) Joining the week-long Contemporary Scholars' Conference attended by all new Nuffield Farming Scholars worldwide, location varying each year.

(3) A personal study tour of approximately 8 weeks looking in detail at the Scholar's chosen topic.

(4) A Global Focus Tour (optional) where a group of 10 Scholars from a mix of the countries where the scheme operates travel together for 7 weeks acquiring a global perspective of agriculture.

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The Nuffield Farming Scholarships scheme originated in the UK in 1947 but has since expanded to operate in Australia, New Zealand, Canada, Zimbabwe, France, Ireland, and The Netherlands. Brazil, Chile, South Africa and the USA are in the initial stages of joining the organisation.

5.0. Rearing insects for human consumption

5.1. General considerations

In many ways farmed insects are no different from any other farmed animal. They require secure housing, feed, water and fresh air; whilst generating waste products which must be removed. The goal of the insect farmer will be to rear, harvest and process the insects in a way which is efficient (both in terms of material resources and time), whilst producing a product which is safe, hygienic and, ultimately, profitable.

Cattle, pigs, sheep, goats and poultry have all been kept by people for thousands of years; in comparison, crickets, mealworms and locusts have been captively bred for only a few decades. This means that the significant body of knowledge that exists in the livestock sector is largely absent for farmed insects. This is a very important consideration when looking at the viability of rearing insects at an industrial scale, when, for example, a lack of knowledge about the treatment of a certain disease could jeopardise an entire business.

This situation is changing rapidly and any company launching a new insect farming venture today has access to significantly more information and resources than a similar business would have done just 10 years ago. So, whilst there is still a great deal of trial and error associated with establishing an insect farm, some of the guesswork has been removed.

5.2. Facility design

An indoor, climate-controlled facility with an appropriate humidity, ventilation and air-conditioning (HVAC) control system is essential. Lighting, temperature, humidity and fresh air exchange must be closely monitored to ensure the welfare of the insects. Most species can survive a wide range of temperatures and, although some overwintering species will survive freezing, most insects farmed for food will not tolerate temperatures lower than 16°C and will need considerably higher temperatures to thrive.

Humidity control is essential: too low and insects can become dehydrated and struggle to moult successfully: too high and mould, bacteria and mites will become a problem. High humidity is often cited as the most common cause of colony failure in crickets and mealworms. Although mealworms are more tolerant of humidity changes than other farmed insect species, they are sensitive to fungal pathogens at a high humidity levels.

Fresh air exchange is required to introduce oxygen and remove carbon dioxide (CO_2) and ammonia. A closed environment with a high population density of insects will cause CO_2 levels to rise rapidly. The UK Health and Safety Executive (HSE) publication 'EH40/2005 Workplace exposure limits' provides the following workplace exposure limits (WELs) for CO_2: 8-hour exposure limit of 5,000 ppm; 15-minute exposure limit of 15,000 ppm. All insect farms should monitor air quality and alarms should be installed to notify those working within the farm of any dangerous increases in CO_2.

Within this climate-controlled space, air quality can be further improved by using dust and carbon filters. Dust, particularly in mealworm farms, has been found to cause skin and eye irritation in some people; it may also aggravate the symptoms of asthma sufferers. Activated carbon filters are used to remove organic compounds from the air and thereby reduce odour in farms.

Both temperature and humidity can be hard to control without adequate internal air circulation. Ceiling-mounted de-stratification, and wall-mounted or floor-standing fans are used to move air within the building.

The importance of lighting will vary greatly between species and life stages. Mealworm larvae and beetles will tend to shy away from direct light and therefore a well-lit substrate may reduce feeding efficiency. On the other hand, adult black soldier flies will only reproduce if exposed to sunlight or intense artificial light with wavelengths of 332 to 535 nm.

5.3. Implementing HACCP principles

For those looking at designing a facility to rear and process insects I would strongly recommend the International Platform of Insects for Food and Feed (IPIFF) Guide on Good Hygiene Practices. It is an excellent resource designed to help insect producers from both food and feed sectors achieve a high level of consumer protection by effectively applying EU food and feed safety legislation and Hazard Analysis and Critical Control Point (HACCP) principles.

A free copy of their guide is available at:

http://ipiff.org/wp-content/uploads/2019/03/IPIFF_Guide_A4_2019-v5-separate.pdf

Case Study: IPIFF (The International Platform of Insects for Food and Feed)

IPIFF is an EU non-profit organisation which represents the interests of the insect production sector towards EU policy makers, European stakeholders and the public. The association was founded in 2012 and is now composed of 52 members. The current cost of ordinary membership is €10,000.

Most IPIFF members are European small and medium-sized enterprises producing insects for the European market. Members are, very roughly, split with 60% focused on insects for animal feed and 40% on insects for food.

HACCP is a globally accepted way of managing food safety hazards and the Food Standards Agency recommends that all food safety procedures should be based on HACCP principles. Strictly speaking HACCP procedures are only required to be implemented for the handling of foodstuffs and do not apply to activities defined as 'primary production'. In the case of insect rearing, primary production would include all farming activities up to and including the point of slaughter. However, having in place a clear written plan, based on HACCP principles, covering all on farm activities will make it much easier to demonstrate that your product is safe.

Any business handling insects beyond slaughter will be required to register as a food business. From my own experience and in speaking to other producers who have been through the registration process, it appears that local authorities will pay particularly close attention to insect farming and processing activities, given their novel status. Any producer who cannot clearly demonstrate the safety of the insects they are supplying will not be approved to sell their product as a food. Implementing HACCP principles throughout the production process is therefore the simplest way to demonstrate to the relevant authorities that an insect-based product is safe.

5.4. Pest and disease control

As with any intensive monoculture production system, pests and disease can pose a serious problem to insect producers. These risks can be broken down into three categories: predators, parasites and pathogenic microorganisms.

Predators are other organisms which prey on the farmed insects and a facility containing millions of insects will become a beacon to potential predators. Rats, for example, have an excellent sense of smell and may cause serious damage to insulation and other fixtures.

Parasites come in all shapes and forms, from a parasitic fungus in locusts to hairworms in crickets. Not all parasites will kill their host, but they will invariably reduce their fitness and therefore can decrease a facility's output. With the exception of the Varroa mite in honeybees, there has been little research focused on the study of parasites affecting farmed insects. Whilst there have been very few reported instances of parasites being a serious problem in such facilities, they may become more of a concern as the number and size of farms increase.

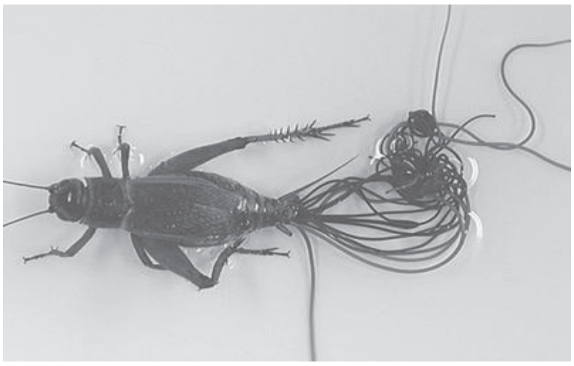

Figure 11: Gordian worms leaving their cricket host. Many parasites, like this one, rely on multiple hosts to complete their lifecycle and are therefore unlikely to become a problem in well managed insect farms [Image credit: Hairworm Biodiversity Survey]

Figure 12: V. destructor is an ectoparasitic mite of honeybees. As well as reducing the fitness of the bees they are vectors for harmful viruses and are thought to be partly responsible for colony collapse disorder [Image credit: USDA Agricultural Research Service]

Diseases resulting from pathogenic microorganisms are likely to pose the most significant risk to insect production systems. These are caused by the spread of fungi, bacteria and viruses and can very quickly wipe out a production system. During my Nuffield Farming study several producers have described to me how disease risks have influenced their business decisions; be that having a separate breeding facility, strict sanitation and bio-control measures, selecting disease resistant species or, often, by employing all these measures.

Case Study: *Acheta domesticus* Densovirus (AdDNV)

AdDNV causes paralysis and death in *A. domesticus* crickets and can wipe out captive populations completely. Kreca Ento-Feed/Food BV is a large insect farm based in The Netherlands. During an outbreak in 2000 they lost 50% of their stock within 12 hours of the infection first being identified.

Having already devastated insect farms in Europe a virulent strain of the virus reached the US in 2009 and by June 2010 Lucky Lure Cricket Farm, which was one of the largest cricket suppliers in the state of Florida, went out of business having tried unsuccessfully to eradicate the virus. Despite investing in equipment to sterilise rearing areas, the farm was unable to raise any new disease-free populations and the company went into bankruptcy with debts of nearly USD 500,000.

In response to the threat of disease, Ghann's Cricket Farm in Georgia switched from raising *A. domesticus*, which had been bred on the farm since 1952, to *Gryllodes sigillatus*, a species of cricket native to Southwest Asia which is resistant to AdDNV.

One US company, Armstrong Crickets, was able to protect its *A. domesticus* by using a bio-safe breeding facility, separate to its main farm. They also employ stringent sterilisation measures, which include flushing their rearing areas with ozone (O_3) between generations.

Cricket viruses are a good example of how damaging an outbreak of disease can be. So far six viruses have been named, affecting ten species of cricket (*Eilenberg, 2017*). The number of viruses and species susceptible to them will be far higher than this. The study of infectious diseases in insect production systems is in its infancy and unless an outbreak is particularly notable it is likely to go unrecorded.

Over the page I give a table showing a selection of measures which could be taken to tackle pests and diseases.

continued overleaf

Table 3: Some measures which can be taken to reduce the risk of pests and disease.
[Source: author's own]

Some measures which can be taken to reduce the risk of pests and disease:			
Measure	*Outcome*	*Effectiveness*	*Relative cost*
Sealed doors and filtered air supply	Prevents entry of larger predators	High	Low
Separate breeding/rearing facilities	Prevents spread of disease	High	High
Regular cleaning of rearing areas and sterilisation of equipment where possible	Prevents development spread of disease	High	Moderate
Quarantine of any incoming stock from off farm	Reduces risk of introducing parasites and pathogens	Moderate	Low
Precise temperature and humidity control	Limits growth of potential pathogens	Moderate	Moderate
Reduce population (stocking) density	Maintains healthier production stock and limits spread of disease	Moderate	Moderate (in terms of loss of production)
Periodic, random laboratory testing of individuals in population	May identify diseases, particularly if caused by pathogenic parasite, bacteria or fungus	Moderate	Moderate
Identification and removal of potentially diseased stock	Removes insects which may harbour disease from production system	Low	Low
Checking of substrates (feed, bedding etc.) before use	Remove pests and potential pathogens harboured in substrate	Low	Low

These are just a selection of measures which could be taken to tackle pests and diseases and those looking to develop a more comprehensive strategy could look to more established industries, such as the pig and poultry sectors for further inspiration.

5.5. Species selection

Only insect species which are approved by the European Food Safety Authorisation (EFSA), in accordance with Novel Food Regulation (EU) 2105/2283, can be legally placed on the market in the UK and EU. At the time of writing we are in a transitional period as the new regulations are implemented. During this period, insect species which were already on the market before the new regulation was introduced, and for which a novel food application dossier has been submitted to the EFSA, can remain on the market.

There would, unfortunately, appear to be a strong inverse correlation between how easy a species is to mass-rear and how likely it is that the Western consumer will be willing to eat it. Black soldier fly larvae and house fly larvae are arguably the most suited to mass-rearing. They are substrate-dwelling and therefore easy to handle, able to achieve a high FCR on a wide variety of feed materials, as well as having a short life cycle and incredibly fast growth rate. Companies looking to produce insect meal for animal feed are likely to turn to these species in the first instance. However, consumers offered whole or processed fly larvae (typically termed 'maggots') are, for the most part, reluctant to try them.

Locusts perhaps represent the other end of the spectrum. Often referred to as a 'gateway bug', they are one of the most approachable insects for consumers. They are also difficult to efficiently mass-rear, being highly mobile, able to climb smooth surfaces, and fly. They also require a diet of fresh leafy greens.

This general 'law' can be illustrated as follows:

	Whole dried product	*Typical food-grade wholesale price*	
More likely to consume ↑	Locusts	> £100.00/kg	More challenging to mass-rear ↓
	Crickets	> £50.00/kg	
	Mealworm larvae	< £10.00/kg	
Less likely to consume	BSF larvae	< £5.00/kg	Less challenging to mass-rear

The four species most commonly farmed in Europe for human consumption are the house cricket (*Acheta domesticus*), banded cricket (*Gryllodes sigillatus*), mealworm (*Tenebrio molitor*), lesser mealworm (*Alphitobius diaperinus*).

5.5.i. Practical information for the farming of crickets and mealworms

Please refer to Annexes A and B, which are included at the end of this report, for tables containing information related to the rearing of crickets and mealworms. This material is gathered from a variety of sources, including the author's own experiences, and might provide a useful starting point for anyone considering breeding insects commercially.

5.6. Processing

Some insect producing companies will sell live, food grade insects direct to the customer. Being a 'primary producer' avoids the additional regulations that come with registration as a food business premises. Though some restaurants and more adventurous home cooks may be happy to receive live insects, most customers would prefer insects that are easy to handle and have a longer shelf life.

5.6.i. Microbial safety

Because insects are typically eaten whole, and not de-gutted, it is vital that any potentially harmful pathogens are inactivated before consumption. This is normally achieved through heat treatment and food safety legislation recommends food to be heated to a minimum internal temperature of 75°C. A cricket, for example, has a gut-transit time of less than 6 hours and therefore a starvation period of 24-hours prior to slaughter is more than enough time to clear farmed insects of any feed material in their system

5.6.ii. Drying

Many companies use conventional drying ovens or dehydrators to remove moisture. Oven drying at 120°C may take 4 hours or so; drying at 70°C in a dehydrator will take significantly longer than this. A moisture content of under 5% should be the target. Microwave drying has been shown to be an effective way of drying insects in a relatively short amount of time.

Both convective and microwave drying can impart a 'toasted' taste on the insects. Whilst this is not unpleasant, it may not be ideal if the end goal is a product with neutral flavour. Freeze drying may be a good alternative, although, it is significantly more expensive per unit output. Freeze drying alone is not considered a good control of microbial safety and, if used, another control step such as heat treatment should be first employed.

One function of the exoskeleton (external skeleton) of an insect is to prevent moisture loss. This means that drying whole insects can take longer than might be expected. If the dried insects are later to be processed into a powder, then dying time/costs can be reduced by grinding the insects into a paste before drying.

Most batch drying methods can be achieved as a continuous process for larger processing facilities. Such facilities may also consider more capital-intensive options such as centrifugal ring driers or pneumatic flash driers.

Spray drying has been used successfully by a number of insect companies and can produce a very fine grade powder.

5.6.iii. Producing a powder

As a food ingredient, insects are most versatile as a powder. Milling insects can be challenging due to their fat content. Furthermore, whole dried insects do not flow well through smaller milling systems and can block chutes and augers. Disk mills and high speed, bladed mills are the most commonly used options. Sieving of the milled product will typically be required to produce a uniform product. A mesh size of <0.5mm (n.35) will produce a suitably fine powder.

5.6.iv. Extraction of protein, oil and chitin

Currently few food producers will go beyond creating a whole insect powder. However, further processing of the insects is possible. Most commonly mechanical and/or hexane extraction is used to remove lipids from the product to create an insect oil and a high protein concentrate. This is standard practice for companies producing insects as animal feed. Very high protein products can be created by using sodium hydroxide to extract protein from the dried, de-fatted insect meal. This yields water soluble isolates of over 95% protein.

Chitin, in the form of chitosan, is valued by the pharmaceutical industry. It is chemically extracted from the insects in a process that destroys proteins and fats, so should be used only after these have already been extracted.

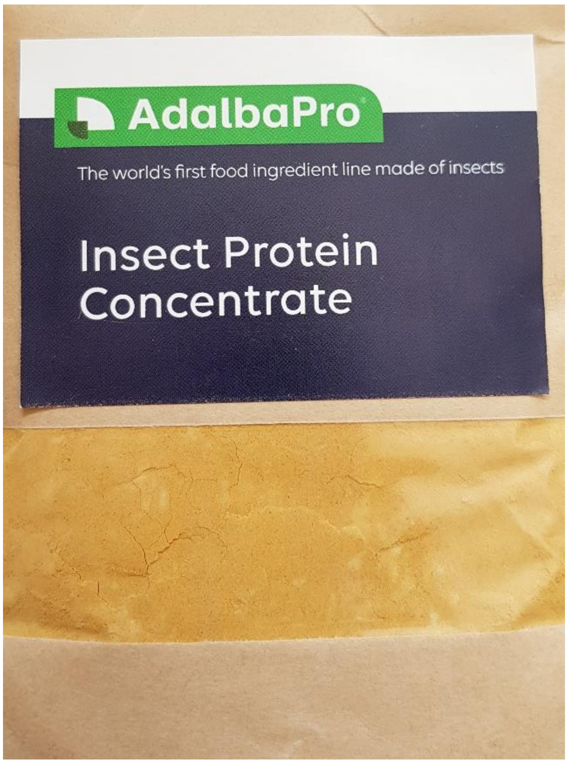

Figure 13: Insect protein concentrate from *A. diaperinus*, produced by Protifarm as part of their AdalPro ingredient line [Image credit: Author's own photograph]

Figure 14: 'Insect butter' a concept product produced by Biteback using mealworm oil [Image credit: Biteback]

6.0. Ethics of insect farming

6.1. Welfare regulations

It is generally accepted that insects are not covered by existing UK animal welfare acts or EU legislation. The Animal Welfare Act 2006 defines 'animal' as a vertebrate and therefore excludes insects. However, it does give authorities the right to extend that definition to include invertebrates of any description where appropriate. This right can only be exercised '*if the appropriate national authority is satisfied, on the basis of scientific evidence, that animals of the kind concerned are capable of experiencing pain or suffering.'* To what extent insects are cable of experiencing pain or suffering is unclear and I am unaware of any instances where authorities have exercised this right.

6.2. Can insects feel pain?

If pain was defined as a purely physical response, then it would be hard to argue that it was not experienced by insects. Nociception is a physical response to potentially harmful stimuli and is a reaction shown by insects.

Pain should be defined as something more than just a reflex response and is normally seen as having an emotional aspect which is usually termed 'suffering'. This is a subjective, internal experience which cannot be measured. Instead, through argument by analogy, we must decide from an insect's physical responses how likely it was that it felt something that we would consider to be pain.

It turns out that insects can show many of the typical pain responses which one would expect from vertebrates. In a study by Heisenberg *et al* (2001) looking at operant behaviour in fruit flies it was found that flies displayed complex, learned responses to harmful stimuli, which were consistent with having experienced pain.

Degrees of pain are important and if physical responses are the same for both very minor harm and for major harm it might be argued that the insect's ability to experience pain is limited in some way. At least for some species of insect this does not appear to be the case. One study by Walters *et al* (2001) showed that the severity of non-reflexive, physical response was closely linked to the level of potential harm. Nonetheless, there are instances where insects show behaviours which are very inconsistent with how we would expect an animal to react to a situation which was painful. For example, it is often cited that locusts will carry on eating whilst themselves being eaten from the other end.

Based on the evidence available it is impossible to say to what extent insects can feel pain or experience suffering. I would tend to agree with Annechien ten Have, 2014 NSch, who was co-author of a paper produced by the Dutch Council on Animal Affairs, *The Emerging Insect Industry (2018).* We should use the precautionary principle and give insects the benefit of the doubt when it comes to their potential to suffer. As such we should take every reasonable precaution to ensure that insects are raised in way which ensures their welfare is not compromised.

6.3. The five freedoms

It was proposed in the FAO's landmark 2013 paper, *Edible insects, future prospects for food and feed security,* that Brambell's five degrees of freedom were a good foundation for the reduction of suffering in insect agriculture. IPIFF later expanded on this with a declaration of how those freedoms should be put into practice.

1. **Freedom from hunger and thirst:** Provide enough food and water during transport and housing. Provide adequate temperature and ventilation conditions.
2. **Freedom from discomfort:** Respect the physiological needs of the insects, providing them with the most adequate environment to foster their optimal growth, such as through climate control. Work towards optimal transport conditions; whenever possible, limiting transport time, and ensuring adequate temperature and ventilation during transport remains within the bandwidth of natural habitat.
3. **Freedom from pain, injury, or disease**: Refrain from using materials that are likely to injure the insects. Limit cannibalism by managing optimal density and adequate space, in accordance with each species' needs. Only use killing methods that ensure the rapid death of the insect to reduce the potential pain risk.
4. **Freedom to express normal behaviour:** Only use housing or husbandry practices that allow for a normal behavioural pattern providing optimal temperature, light, humidity and density levels according to each species' needs.
5. **Freedom from fear and distress**: Keep abreast of the latest science regarding the potential experiences of fear or distress in insects.

To expand on direction given above that producers should: *'only use killing methods that ensure the rapid death of the insect to reduce the potential pain risk*'. The most common method of slaughter is freezing. This is generally accepted as the most humane method of killing the insects, as the cold temperatures may first induce a dormant state before the internal temperature of the insect drops below freezing. Other methods include heat treatment and maceration.

7.0. Consumer acceptance

7.1. The 'yuk factor'

In the opening chapters of this report I discussed the potential health and environmental benefits of eating insects. I also discussed entomophagy from an evolutionary perspective, where there is growing evidence to show that insects formed a cornerstone of our ancestral diets. Why then, is the idea of eating insects so often met with disgust? In fact, nearly 1/3 of the world's population view eating insects as a normal. It is Western food preferences and the global spread of Western culture which has driven insects off the menu in many parts of the world. Europe's cooler climate and harsh winters limit the abundance and seasonal availability of insects, which has resulted in them coming to be considered as more of a pest or nuisance than a food source.

"In entering upon this work I am fully conscious of the difficulty of battling against a long-existing and deep-rooted public prejudice. I only ask of my readers a fair hearing, an impartial consideration of my arguments, and an unbiassed judgment. If these be granted, I feel sure that many will be persuaded to make practical proof of the expediency of using insects as food." – Vincent Holt, 1885

The idea that insects could be a useful food source has been promoted in the West since the Victorian era and yet the idea has not caught on. The aversion is deep rooted and evidence to date has shown that simply being aware that insects are nutritious might not be enough to get consumers to eat them. Marijn Poortvliet explained this issue well in his aptly named 2019 paper *'Healthy, but disgusting: an investigation into consumers' willingness to try insect meat'.* An example he describes is the 'insect burger', which is said to have seen little growth in demand despite being available on the Dutch market for 10 years.

7.2. Overcoming barriers to acceptance

There are clearly significant cultural barriers to overcome before eating insects can be normalised. Someone who has done excellent work to investigate how the adoption of insect foods can be encouraged is Dr Tilly Collins of Imperial College London, whom I met in August 2018. Working alongside Pauline Vaskou, now Corporate Sustainability Manager at Tesco PLC, they used school-based and online surveys to develop a marketing strategy for insects.

Their findings, which are expected to be published in Annals of the Entomological Society of America later this year, show that the children aged 6-11 are by far the most likely demographic to try insects. By the age of 12 consumer prejudices are likely to have formed and willingness to try insects reduces significantly. It was also found that children had a strong influence on the shopping habits of their parents, therefore parents with children keen to eat insects were much more likely to try them themselves.

Beyond that there are several trends worth mentioning:

- In children, girls are more likely to try insects than boys; in adults, women and men are equally willing to try them. However, women are less likely to try insect foods with visible insect parts.

- People who exercise regularly are more willing to purchase insects. Health and fitness is seen as a key marketing avenue.
- Meat eaters are more willing to pay for insect products. Those who are vegetarian or vegan for environmental, rather than ethical, reasons may try insects.
- ‘Supermarket availability’ and ‘safety guarantee’ were the two factors most likely to make consumers eat insect foods regularly.
- There may be a value-action gap for insect products. So, although consumers may state a preference for insect products on environmental grounds, the price competitiveness of the product will dictate whether or not they actually buy it.
- Celebrity endorsement and peer-to-peer marketing have more of an influence over people’s willingness to try insects than nutritional or health claims.
- Those insect products with the greatest chance of mainstream market success will be competitively priced snacks or meals, in the form of familiar-looking foods, with no visible insect parts.

Case Study: Eating Insects: novel foods in Welsh Schools, Dr Verity Jones, University of West England, and Dr Sarah Beynon and Andy Holcroft of Bug Farm Foods Ltd, Pembrokeshire.

With funding from Innovate UK and the Welsh Government, Bug Farm Foods have developed a mince-like product called VEXo, made from a blend of insect and plant proteins. It has similar nutritional qualities to beef but 80% less saturated fat and is intended to be a sustainable way of tackling childhood obesity.

The project has seen VEXo introduced in school meals for 12-15 year olds and, after a successful pilot launch, the project is expanding to schools in three further local authorities.

Although the project is ongoing, I am told that the initial results are encouraging. The Welsh school children have been very receptive to the insect-based dishes and, given the choice, will often chose them over more traditional meal offerings.

8.0. Enabling insect agriculture in the UK

8.1. Government

As a sector, insect farming for animal feed has seen considerably more growth and investment over the last 10 years than has insect production for human consumption. It has also seen greater government support. This is, in part, because there is a pressing need to find sustainable animal feed solutions, particularly for the aquaculture industry which relies heavily on fishmeal. Aquaculture is the fastest growing animal food sector globally and the UK is the world's third largest producer of Atlantic salmon. This means that there is an obvious market opportunity for insect meal to be used as a replacement for fishmeal.

In the past it may have seemed that the market opportunities for developing insect-based food products were not obvious. I propose that this is no longer the case. The public demand for sustainable meat alternatives is growing rapidly and insect-based products could potentially serve to satisfy this demand. A government-led initiative has greatest potential to develop the sector and would, I believe, be welcomed by the public.

The same model used to promote insects for animal feed, through the Food and Drink Sector Council's Insect Biomass Conversion Task & Finish Group (IBCTFG), could be used to develop a 'green' meat industry in the UK.

One recommendation could be that that the government devises and provides short term fiscal incentives to new enterprises for the discounting of domestically produced insect-based food products. This would incentivise the UK food and drink industry to adopt insects as an ingredient and would allow insect producers achieve cost competitiveness whilst they are scaling up.

8.2. Academic institutions

University-led initiatives have often paved the way for private sector stakeholders and collaboration between companies and academia is an important way to drive innovation. Knowledge Transfer Partnerships (KTPs) have been used to improve insect farming productivity and university projects have acted as the catalyst for the development of new insect-based food products.

A growing interest in insects as food is likely to attract more academics to the field and insect farming companies and organisations may benefit from opportunities to work with academic institutions.

8.3. Private sector businesses and organisations

Given that the industry is still in its infancy, it is not surprising that individual companies must play a proactive role in creating an enabling environment. Although pushing for support or regulatory changes might help a competitor as much as it helps you, it has been shown that the overall growth of the sector is the most important outcome. The Netherlands provides a good example of this point; here Kreca/Protifarm and Insect Europe emerged as early pioneers in the edible insect market. Much of the progress that has been made in developing the Dutch edible insect industry comes from their work with the Wageningen University and the Dutch government. Although they have created an environment which has helped establish several other insect farming companies, this competition has not affected their position as market leaders.

Organisations such as the North American Coalition for Insect Agricuture (NACIA), the International Platform for Insects as Food and Feed (IPIFF) and the ASEAN Food and Feed Insects Association (AFFIA) are formed of fee-paying members and act to promote the industry through networking, training and lobbying activities.

Case Study: The Woven Network, the UK-based organisation for insects as food and feed.

Woven Network is a community interest company set up in 2015 with the aim of supporting, through a set of membership services, entrepreneurs and researchers working with insects in the human food chain. Woven has four principal aims:

1. To create a voice on behalf of the 'insects for food and feed' UK community to speak to the public, Government, UK Government agencies and EU bodies.

2. To demonstrate the scale of the emerging sector and enable collective action to reflect this.

3. To turn individual actors into a powerful community that can become a viable sector with strong supply chain relationships and international connections/ market access.

4. To attract more businesses to the UK and into the wider European sector by demonstrating the opportunities which exist, making the UK an industry hub from which insect companies want to operate.

9.0. Prospects for insects as food

9.1. Public perceptions

The public's interest in farming insects for human consumption is growing, primarily as a result of extensive press and media coverage. Although the idea of eating insects is novel to a Western audience and lends itself to attention grabbing (dare I say, 'click bait') articles, the coverage is generally very favourable. The following graph plots Google trends over time and shows that overall interest, on the basis of various commonly used 'insects as food' search terms, has increased since 2010:

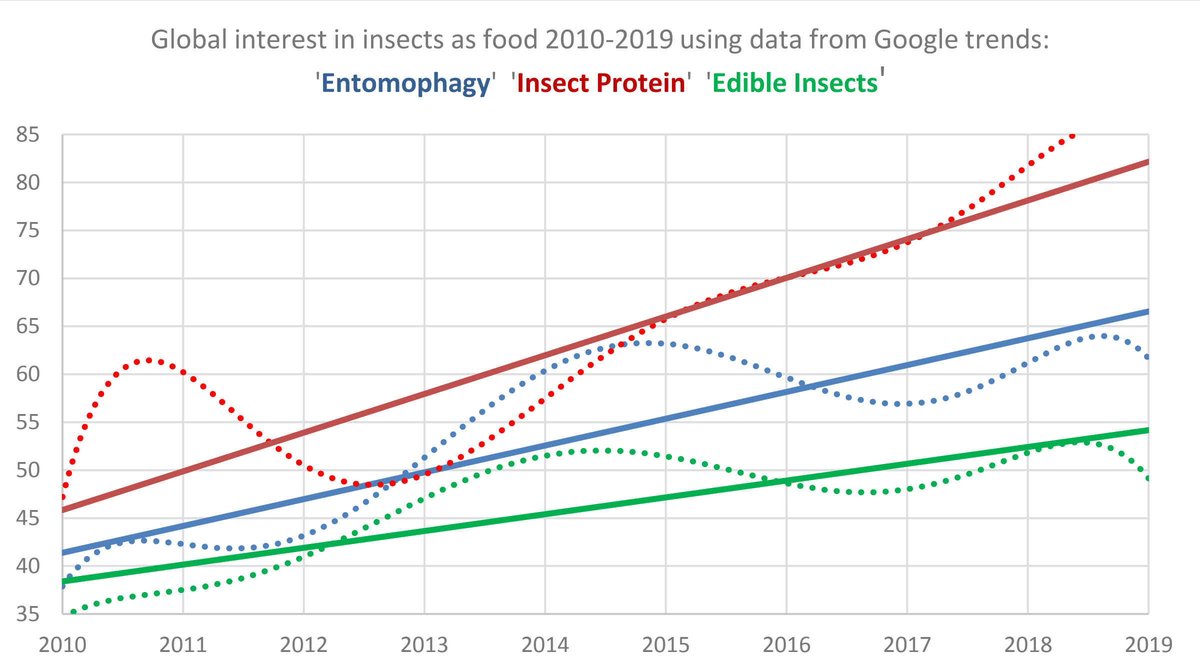

Figure 15: Chart to show global interest as food 2010-19, using data from Google trends. Moving average and straight trend lines for each term represent search interest over time. A value of 100 on the y-axis would represent the peak popularity for the term. A value of 50 means that the term is half as popular. A score of 0 means there was not enough search data for this term.

Several recent industry reports have forecast significant growth of the global edible insect market:

- March 2018, Research and Markets, 2018-2023, 23.8% CAGR
- April 2018, Persistence Market Research, 2017-2014, 6.9% CAGR
- June 2018, Global Market Insights, 2017-2024, 43.5% growth
- January 2019, Statista, 2018-2023, 34.4% growth

9.3. Overview

Becoming involved in a new and rapidly changing edible insect industry, where public interest is high and market expectations are strong, can lead to overly optimistic and risky business decisions. As should be clear from this report, there are technical and social barriers limiting the adoption of insects as a food. The book *Insects for food and feed*, published in 2017, listed twelve UK based start-ups either farming insects or selling insect-based products: of those, only four still exist today.

So, whilst the future looks bright for insects as food, businesses and entrepreneurs need to approach the sector with their eyes open to the challenges they are likely to face.

Case Study: Seeing an opportunity, Jo Wise, Monkfield Nutrition Limited

Having found it difficult to buy insects to feed their reptiles in the 1980's, Monkfield began to breed their own. They soon started to supply other companies and, today, Monkfield Nutrition Ltd has grown to be one of the largest commercial insect breeders in the UK - employing 120 people.

Up until recently, the insects they reared (some four million per week) were sold as live food for exotic animals. Seeing a potential opportunity to expand into a new market, Jo began looking into producing food-grade insects for human consumption. In 2015 the company was awarded a KTP grant of £198,482, from Innovate UK, to enable them to investigate ways of improving the efficiency of insect production. They also tested whether the nutritional quality of insect-based products could be improved through the manipulation of the insect's diet.

Monkfield has now moved to a larger facility, giving them significantly increased capacity to produce food-grade insects. With a potential output of 700kg of dried insects per week, they could become one of the largest suppliers of insect-based food ingredients in Europe.

10.0. Conclusions

1. There is a growing body of evidence to show that insects can be beneficial to health and that they are at least as healthy as meat from traditional sources.

2. Insect agriculture has a smaller environmental footprint than other forms of livestock production. Currently it also has less of an environmental impact than other meat alternatives such as cultured meat and mycoproteins. However, this situation could change in the future.

3. Energy use on insect farms in temperate climates is high compared to other forms of livestock production. There are various steps insect farms can take to improve energy efficiency, particularly with regards to heating.

4. A lack of automation and high labour inputs drive up production costs in insect agriculture.

5. The implementation of new EU novel food regulations has been problematic for the industry, particularly in countries like the UK where there were previously few restrictions on marketing insects. Nonetheless, the legislation will ensure legal consistency across the EU and provide better guarantees of consumer safety, which will benefit the industry in the long run.

6. The public interest in edible insects has grown considerably over the last 10 years and most market forecasts predict strong growth for the sector to 2025 and beyond.

7. There is still significant consumer resistance in the West to the idea of eating insects, despite most people now being aware of the potential benefits of doing so. Resistance may decrease as products become more widely available and cost competitive.

8. Despite an optimistic outlook, there are technical and social barriers still to overcome before insects as food can become mainstream in the West.

11.0. Recommendations

1. Winning over the public is vital if insects are to become a viable meat alternative for British consumers. Given that nutritional or environmental arguments alone are often not enough of an incentive for consumers to be willing to pay for insect-based products, I recommend to companies the following market strategies:
    a. News outlets have been very interested in insect agriculture and there is a clear opportunity for producers to work more closely with press and the media to ‘sell their story’. Grub Kitchen Ltd and Bug Farm Foods Ltd have shown that this strategy can be very effective.
    b. Children are far more receptive than adults to the idea of eating insects and there is great scope for those involved in the sector to work with schools in an educational capacity to promote insect agriculture.
    c. Where possible, every effort should be made to leverage celebrity culture to endorse products. Picking the right Instagram influencer, Youtuber or podcast could increase sales more than any advert in a food and drink magazine.
2. Other food products benefit from certifications and standards which help develop consumer confidence in the quality and safety of the product. The Red Tractor logo and Lion Mark are both examples of this; at the very least they help differentiate British produce from imports. Presently there is not even a recognised organic certification for insects. Industry organisations should work with relevant bodies, such as The Soil Association and Veterinary Invertebrate Society to develop:
    a. Organic certification for insect products.
    b. An assurance scheme to show insects are traceable, safe and British.
    c. Certification to show that insects are produced to a veterinarian assured welfare standard.
3. Many proprietary insect farming technologies have taken years of trial and error to develop. It is understandable that companies will not want to share details of equipment or practices which make their production more efficient. There are, however, other innovations that have been developed which confer no competitive advantage, such as in odour control. Open sourcing information like this can only benefit the industry as whole.
4. I recommend that certain measures, like those proposed by the IBCTFG to the government for insects for animal feed, be applied to innovators in insect-based foods who are trying to develop ‘green’ meat alternatives.

12.0. After my study tour

Perhaps more than anything else, my Nuffield Farming study tour has shown me how quickly the concept of farming insects for food can catch on. During my travels I had the privilege of meeting Dr Yupa Hanboonsong, Professor of Entomology at Khon Kaen University. In response to the economic hardships caused by the 1997 Asian financial crisis, she launched an initiative to train Thai farmers to rear crickets. Struggling rice farmers could raise the insects as an inexpensive source of protein for their families, given that they could no longer afford to buy meat. The concept caught on immediately and has given rise to a whole new industry. Despite the economic hardships of the late 90s having long since passed, there are now over 20,000 cricket farms in North Eastern Thailand and that number is increasing annually. These farms are no longer just supplying local markets but exporting a highly valued food ingredient around the globe.

Figure 96: Dr Yupa shows off some packaged insect snacks. Most insect-based foods exported from Thailand are destined for the Chinese market [Image credit: author's own photograph].

Figure 17: The author meeting farmers who have benefited from the cricket farming boom in Thailand. Insect agriculture supports nearly 100 families in this village alone [Image credit: author's own photograph].

As public awareness of the potential benefits of eating insects grows in the West, I believe that we too could be on the cusp of a boom in insect agriculture and I am excited by the prospect of being a part of it. I intend to continue to develop Instar Farming, expanding the current, pilot-scale facility. Having seen the importance of developing a brand and telling a story, I am working on a range of consumer-ready, packaged products under the 'Bugvita' trademark. Not only will this provide a way of adding value to my own farmed crickets but, if successful, will hopefully support other UK-based producers as well.

I also look forward to continuing my work with the Woven Network and through the organisation hope to promote awareness amongst stakeholders of the importance of working together to achieve positive change in insect agriculture.

Adam Banks
September 2019

13.0. Thanks and Acknowledgements

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I am particularly grateful to my Nuffield mentor, Holly Beckett. As I am not the most organised person at the best of times, I found the process of starting a business whilst travelling to meetings abroad, writing up this report and raising a new baby daughter, challenging to say the least. If it wasn't for Holly's helpful advice and gentle but persistent prodding, I may not have got very far at all!

Thank you also to the academics, entrepreneurs and entomophagy advocates who granted me interviews. In such a new and rapidly changing industry a degree of secrecy is to be expected and a tour of the facilities may not always be possible. Nonetheless, time and time again, I found people to be far more open than I had anticipated and willing to go out of their way to help answer my questions.

And thank you to Anne Beckett, whose edits and queries made this report so much better.

Most importantly, I would like to thank my long-suffering family, who are still speaking to me despite being left to look after several million hungry crickets whilst I was away on my travels.

see overleaf for References

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ANNEX A

Farming Crickets

This annex will provide a brief overview of some of the main considerations when rearing crickets. One of the biggest take home messages from my Nuffield study has been the importance of approaching any new insect farming venture with a great deal of patience and flexibility. The perfect system does not yet exist and finding a production process that works will require a certain amount of trial and error. This was put nicely in an entertaining talk delivered by Kevin Bachhuber at a conference I attended in 2018 organised by The North American Coalition for Insect Agriculture (NACIA) entitled; 'Crickets are stupid and will drown themselves if possible: A catalogue of errors.'

Overview of the characteristics and environmental requirements for two commonly farmed cricket species which may be useful to aspiring cricket farmers		
Environmental requirements	House cricket *Acheta domesticus*	Banded cricket *Gryllodes sigillatus*
Optimal temperature	34°C	31°C
Viable temperature range	27-36°C	27-36°C
Target humidity (egg to 1st instar)	>90%	>90%
Target humidity (from 1st instar)	55%	55%
Viable humidity range (from 1st instar)	40-70%	50-80%
Day/night cycle	12/12hrs – 16/8hrs	12/12hrs – 16/8hrs
Biological characteristics		
Adult body length/weight	18-22mm / 300-400mg	12-18mm / 150-300mg
Time to mature (at 30°C)	35-45 days	30-35 days
Max. density (cm^2 / adult cricket)	3	4
Realistic density (cm^2 / adult cricket)	6	8
Typical laying rate (eggs/ female/ day)	Approx. 10	Approx. 15
Viable laying period	20-30 days	10-20 days
Incubation period (at 34°C)	9-10 days	8-10 days
Typical hatching rate	60%	80%

Biological characteristics (continued)	House cricket *Acheta domesticus*	Banded cricket *Gryllodes sigillatus*
Mortality rate under ideal conditions	<5%	Approx. 10%
Hatchlings per ml	400-600	400-600
Lifecycle stages	Incomplete metamorphosis: all stages retain similar body plan	Incomplete metamorphosis: all stages retain similar body plan
Mobility	Active and able to climb most textured surfaces. Adults are winged and can fly, albeit reluctantly	Very active and able to climb most textured surfaces. Adults are wingless
Rearing methods		
Housing	Small plastic boxes, pallet boxes, smooth sided pens, open plan rooms	
Surface area maximisers	Moulded fibre egg trays, card cell dividers, textured polypropylene sheets	
Watering systems*	Poultry drinkers, drip/sprinkler irrigation, misters, saturated sponges or capillary matting, super-absorbent polymers such as polyacrylamide	
Feed*	Specialist cricket feed (food chain approved), poultry feed, supplemented by-products such as spent brewer's/ distiller's grains, beet pulp, fruit pulps, rapeseed meal, pre-consumer vegetable waste	
Laying substrate	Damp peat moss or coconut coir	
Harvest and processing methods		
Collection method	Mechanical agitation (shaking) of surface area maximisers	
Screening of crickets	Self-selection to separate healthy crickets from residual waste or dead/ unhealthy crickets	
Kill step	Freezing or heat treatment (blanching)	

More detailed information relating to the feeding and watering of crickets:

Many cricket diets used in laboratory settings, as well as commercially available diets for the live food industry, such as those developed by Purina and Mazuri, are not suitable for insects entering the food chain. Crickets are naturally omnivorous and most traditional cricket diets contain porcine meal and animal fat; in fact, liver powder has been recognised as a growth factor for house crickets since the 1960's. Commercial cricket nutrition is an undeveloped field and there is still a great deal of research required to find an optimum vegetable-based diet. Feed is likely to be one of the largest variable costs for an insect farm and it is therefore important that a feed is selected which will deliver the most favourable cost-to-output balance possible.

Most crickets farmed for food are fed on a diet modified poultry feed, which has been finely milled. It has been consistently shown that crickets do best on a high protein diet (*Nakagaki, 1991*) and growth rates and FCR will often peak at a feed protein level of around 30%. That said, there is a clear correlation between the cost of a diet and the level of protein it contains. Most producers will find that the additional output achieved on a 30% protein diet will not justify the additional cost and settle for a more economical ration that is 18-25% protein.

Most commercially available animal feeds will achieve these required protein levels with the inclusion of soybean meal. Growing soybeans for animal feed is widely regarded as environmentally damaging. The amount of soya which is imported to the UK for animal feed requires an area equivalent to 50% of all the UK's arable land to produce (*UKDFID, 2018*). Crickets can thrive on a huge variety of feed materials and there is great scope for farmers to find more sustainable formulations which suit their production system.

Insects are unable to synthesise sterols and it is essential that they are included at sufficient levels in the feed formulation. Non-animal sources include phytosterols, which can be found in vegetable oils, or ergosterols, as found in yeast (*Cortes Ortiz, 2016*).

It has been found that the B complex vitamins thiamine, pyridoxine, nicotinic acid, pantothenic acid, choline, and biotin are essential for cricket survival (*Ritchot, 1961*). The inclusion of riboflavin or inositol can significantly increase the growth rates of crickets and folic acid may increase survival rates. Vitamin K and the bioflavonoid rutin have also been shown to be significant growth factors for *A. domesticus* (*McFarlane , 1976 and 1982*) and may also be beneficial for other cricket species.

Hydrated feed presents a good way of feeding and watering crickets simultaneously but tends to spoil very quickly in the hot environment of the cricket farm. Unless the producer can feed crickets daily then a wet feed approach is likely to cause more problems than it solves.

Arguably more challenging than feeding crickets, is watering them. Given a diet of dry feed it is vital that the crickets are provided with a water source. Unfortunately, crickets are poor swimmers and this can result is mass drownings whenever open water is provided. Newly hatched crickets are particularly vulnerable; they can become trapped and drown in the smallest of water droplets and even the surface tension of condensation can catch them. Drinkers should be designed to provide a constant supply of fresh water without giving the crickets the opportunity to become immersed. Poultry drinkers with cloth, sponge, coir or similar filling the water trough are the most common solution. Such drinkers work well but must be cleaned regularly to prevent the water becoming fouled.

Watering crickets is an area with great scope for innovation and during my study I have seen the use of ultra-absorbent polymers, fruits and leaves, water wicked up through capillary matting, complicated sprinklers and drip irrigation systems. Plumbed in poultry drinkers can save time but leaks can be disastrous.

ANNEX B

Farming Mealworms

The two most commonly farmed species of mealworm are the lesser mealworm, *Alphitobius diaperinus,* and the yellow mealworm, *Tenebrio molitor*. Although referred to as 'worms', both species are the larvae of a large family of beetles known as darkling beetles. Mealworms have been considered a pest for centuries, with evidence of them damaging stored grain as early as the bronze age. It is their ability to feed on a wide range of organic material, their hardiness, resistance to control measures and prolific reproductive rate, which has resulted in them becoming such a serious pest. Nevertheless, all these characteristics have also made them ideally suited to insect agriculture on an industrial scale.

General overview of the characteristics and environmental requirements for two commonly farmed mealworm species		
Environmental requirements	Lesser mealworm *Alphitobius diaperinus*	Yellow mealworm *Tenebrio molitor*
Target temperature	29°C	27°C
Viable temperature range	23-33°C	18-30°C
Target humidity (with supplemental water)	65%	65%
Viable humidity range	40-90%	30-90%
Day/night cycle	Not required	14/10hrs
Biological characteristics		
Maximum larval length/weight	7-11mm / 40-80mg	20-25mm / 130-200mg
Maturation time larvae (at 28°C)	Around 35 days	Around 80 days
Population density (larvae/cm^3)	1.2 – 2.2	0.5 - 1
Maturation time pupae (at 28°C)	4-5 days	6 days
Laying rate (first month)	150-200	200-300
Viable laying period	1-3 months	1-2 months
Incubation period (at 30°C)	4 days	4 days
Typical hatching rate	75%	75%
Mortality rate	10-20%	10-20%

Biological characteristics (continued)	Lesser mealworm *Alphitobius diaperinus*	Yellow mealworm *Tenebrio molitor*
Lifecycle stages	Complete metamorphosis: worm-like larvae pupates to adult beetle	Complete metamorphosis: worm-like larvae pupates to adult beetle
Mobility	Larvae are substrate dwelling but may climb rough surfaces. Adults will fly at night	Larvae are substrate dwelling but may climb rough surfaces. Adults are unable to fly
Rearing methods		
Housing	Plastic or wooden trays, standardised plastic containers for automated handling	
Feed substrate*	Wheat bran/middlings, spent brewer's/ distiller's grains	
Water sources*	Chopped vegetables - often carrot, hydration of feed substrate	
Laying substrate	As feed substrate	
Harvest and processing methods		
Collection method	Sifting/ sieving to separate larvae from spent substrate and frass	
Kill step	Freezing or heat treatment (blanching)	

More detailed information relating to the feeding and watering of mealworms:

Although mealworms are reported to able to feed on a huge variety of materials, from bat guano to polystyrene, there performance is greatly influenced by the quality of their diet.

In the past most commercial mealworm facilities have used feed substrates comprised predominately of wheat bran. Mealworms can in fact survive on a diet of wheat bran alone, however, they benefit from the addition of various key supplements. More recently there has been a focus on reducing the cost of commercial mealworm diets through the utilisation of waste streams and by-products; again certain key nutrients have been found to be crucial for optimising growth and survival rates.

There is still some work required to find an 'ideal' diet which would be both cost effective and nutritionally complete, nevertheless mealworms are highly adaptable and, providing certain thresholds are met, will thrive on a wide variety of feed inputs. According to available research the optimum level of carbohydrate in the mealworm diet is 85% (*Fraenkel, 1950*), at levels lower than 20% the larvae will struggle to develop. The form of carbohydrate appears to have little impact on performance with the exception however, of dextrin, which has been found to increase growth rate (Davis , 1974).

Growth rate, development time and survival rate are all improved with the addition of protein in the mealworms diet. The level of protein required depends on the source and feed comprising just 2% protein has been shown to be beneficial. A study looking at the precise amino acid requirements of mealworms (*John , 1979*) found that threonine and tryptophan were limiting to growth when not present in the diet at a sufficient level. Alanine, arginine, aspartic acid, cystine, histidine, isoleucine, leucine, methionine, proline and valine were all found to be beneficial to growth. Phenylalanine was also found support growth but was only required at around 15% the level of threonine and tryptophan.

Mealworm diets should contain low lipid levels and fat concentrations of over 3% have been found to inhibit growth. Cholesterol has been shown to be beneficial up to a 1% concentration in feed (Morales-Ramos , 2013), however, as this is derived from animal sources it may not always be suitable for insects destined for human consumption. One issue with a fatty diet is that it tends to bind together the substrate in which the mealworms live, this can reduce oxygen levels and hinder movement.

Several supplements have been found to be beneficial for mealworm development. The addition of yeast not only provides a good protein source but has been shown to increase growth rate, FCR, and maximum larval size whilst decreasing mortality rates (*van Broekhoven, 2015*). Five B vitamins, thiamine, riboflavin, nicotinic acid, pyridoxin and pantothenic acid, are essential for development. Two further B vitamins are beneficial but not essential; biotin and pteroyl glutamic acid. Mealworms do not require a diet containing vitamins A, C, D, E or K. Unlike most animals, carnitine is an essential growth factor for mealworms, without which they cannot metabolise fats. Both experimentally and commercially carrot has been found to act as a feeding stimulant which benefits growth rate. Whilst some of this effect is likely due to the carrot being a good source of water, a recent study (*Oonincx , 2015*) found that carrot also improved FCR and efficiency of conversion of ingested food (ECI).

Mealworms have an incredible ability to retain water. At high levels of relative humidity, they can use active water vapour absorption (WVA) to draw moisture from the air into their bodies' cells via their rectum. At humidity levels of 90% or more the YMW can survive on a completely dry feed with no supplemental water. In practice this may not be an ideal solution as high humidity levels promote the growth of fungal and bacterial pathogens. Furthermore, WVA is energy intensive and would have the result of decreasing FCR and growth rates.

Unlike crickets, mealworms cannot readily drink from a fresh water source in their enclosure. Instead water should be provided through their feed, either from the direct hydration of the feed substrate or by providing supplemental feed materials with a high water content. During my study I have seen both systems being used successfully, and it is not clear that there are great advantages to either method of delivering water. In general, larger, automated facilities will use direct hydration of feed material. This means that an automatic feeding station will deliver feed and water simultaneously, either as a hydrated feed or as a blended feed where wet and dry components are mixed as they are added to the trays. On the other hand, smaller farms, manually feeding their trays, will tend to use a dry feed substrate and add a supplemental water source, such as pieces chopped carrot or potato.

Each farm will need to find a level of atmospheric humidity and substrate water content that works for their system. There will be a threshold whereby maximum growth rate at high moisture levels is balanced against the risk of increased fungal and bacterial growth.

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