A Nuffield Farming Scholarships Trust Report

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The future for Insect Bioconversion Products in poultry feed

Dr Aidan Leek

July 2016

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A Nuffield (UK) Farming Scholarships Trust Report

Date of report: July 2016

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

Title	**The future for Insect Bioconversion Products in poultry feed**
Scholar	Dr Aidan Leek
Sponsor	Micron Bio Systems
Objectives of Study Tour	• To understand the emerging insect production industry and how it is developing in different areas of the world • To identify the opportunities for the UK poultry industry to utilise insect products from experiences in other markets • To identify if insects could be a potential solution for waste materials from the poultry industry
Countries Visited	France, Spain, Italy, Belgium, Holland, Denmark, Finland, Germany, Czech Republic, China, Vietnam, United States of America.
Messages	1. Poultry feed could contain products of insect bioconversion in the future. 2. Development of a commercial insect production industry in European countries is faced with 3 major hurdles currently; legislation, cost, and scalability. 3. More research is required to satisfy consumers and EFSA of the preservation of food safety when using insects produced on different organic materials. 4. As a fishmeal replacer, insect protein has a higher value and will be firstly used in pet and aqua feed before poultry feed. 5. Insect oil, as a by-product of insect processing for pet or aqua feed, may actually feature in poultry diets before insect protein. 6. There may be functional benefits associated with the consumption of live insects in poultry that requires further understanding.

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1.0. Personal introduction

From an early age I had a passion for animal nutrition. My father, a qualified veterinary physiologist and biochemist, was a primary influence on this interest. His research area was rumen function: however my future focus was to be on monogastric nutrition and, more specifically poultry nutrition. The obvious career route would probably have been to follow my father into veterinary science. However, it was primary agriculture and animal nutrition that really interested me. I pursued my BSc (Hons) in Agriculture and Food Science, specialising in Animal Science at the University of Nottingham. I then undertook an MSc in Agriculture at University College Dublin, and after a year in the commercial feed industry returned there to undertake a PhD in Agriculture. In both cases my postgraduate research focused on environmentally-sensitive nutrition and management in pigs. Broadly speaking, I explored ways to limit nutrient and odour emissions through dietary manipulation and examined how different welfare practices influenced production and nutrient utilisation. Although my career focus has since switched to poultry, the themes of my research work remain of interest to me; i.e. effective use of the nutrient resources we have available for commercial livestock production.

Since leaving my studies 13 years ago, I have worked as a poultry nutritionist/technical specialist in industry. I am a member of the AIC Feed Advisor Register and am the UK commercial representative on the European Branch of the World's Poultry Science Association Working Group 2 on Poultry Nutrition. My commercial roles have covered a wide range of experiences and equipped me with knowledge beyond nutrition and feed production; including broiler production and processing, breeders, egg production and genetics. Reflecting the profile of the UK poultry industry, chickens are my principal focus; however I also work with turkey, duck and game nutrition and even ratites occasionally. At times my work has taken me outside the UK and Europe and, quite literally, around the world. I have been involved in pig and poultry feed projects in Russia and worked with the poultry and feed industry in Africa, Asia, Australia and the Americas: experiences I would never have thought possible when I set out on this career path.

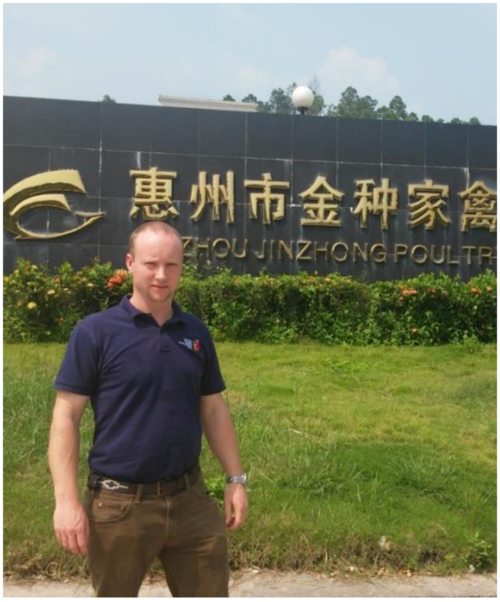

Figure 1: The author, Aidan Leek, pictured during his travels in China

Following a job change during my Nuffield Farming Scholarship, my focus has returned to the UK market, being employed as a poultry techncial manager with Trouw Nutrition GB. My role interfaces with clients across the poultry industry, including home-mix egg producers, national and regional compounders, large scale egg producers, and poultry integrators and processors. I also help my family to farm a small flock of sheep and a cider apple orchard in Herefordshire for 'relaxation' from the day job!

2.0. Glossary of terms

Bioconversion – The conversion of low value or 'waste' organic materials into useable products or energy by a biological process involving an intermediary organism, e.g. microbes, insects etc (https://en.wikipedia.org/wiki/Bioconversion)

Chitin – A long chain polymer of N-acetylglucosamine, a glucose derivative. A significant component of insect **exoskeleton** (https://en.wikipedia.org/wiki/Chitin)

Chitinase – An enzyme that digests **chitin** (https://en.wikipedia.org/wiki/Chitinase)

Circular bioeconomy – The concept of a circular bioeconomy is to conserve, regenerate, and reuse resources within a system and by linking across different sectors. (http://www.susvaluewaste.no/wp-content/uploads/2016/06/SusValueWaste-2016-The-circular-bioeconomy-in-Scandinavia.pdf)

Exoskeleton – The external skeleton (shell) that supports and protects an insects body https://en.wikipedia.org/wiki/Exoskeleton

Entopreneurs – Insect business entrepreneurs (http://www.bloomberg.com/news/articles/2015-09-10/edible-insect-farming-hatches-new-breed-of-entopreneurs-)

Entomology – The study of insects (https://en.wikipedia.org/wiki/Entomology)

Entomophagy – The consumption of insects (https://en.wikipedia.org/wiki/Entomophagy)

Frass – Insect excrement and unconsumed growth substrate (https://en.wikipedia.org/wiki/Frass)

Insects – A class of jointed limb invertebrates within *Phylum Arthropoda* that have a 3 part body, hard chitinous **exoskeleton**, 3 pairs of jointed limbs, and one pair of antennae (https://en.wikipedia.org/wiki/Insect)

Insect Biorefinery – A facility for the **bioconversion** and **valorisation** of organic material (biomass) into more valuable products (e.g. insect protein meal, insect oil etc.) through the use of a biological process (http://www.ynsect.com/job_slides/final-products-insect-biorefinery/)

Larva – The active immature form of an insect. Often differs greatly from the adult form and forms the stage between eggs and **pupae** (https://en.wikipedia.org/wiki/Larva)

Pupa – The transformational life stage of some insects between **larvae** and adult form (imago stage) (https://en.wikipedia.org/wiki/Pupa)

PIP – Processed insect protein

PAP – Processed animal protein

Substrate – Material on or from which an organism lives, grows, or contains nourishment (http://www.oxforddictionaries.com/definition/english/substrate)

Valorisation (in relation to waste biomass) – the process of transforming low quality (waste) materials to high(er) value products (http://www.eubren.com/waste-valorisation)

3.0. Background to study

There has been a lot of 'buzz' about flies recently! Insects for feed and food have been receiving increased coverage, both in the mainstream media and in the specialist animal nutrition press in the 1-2 years prior to my application for my Nuffield Farming Scholarship. Much of this coverage surrounded the potential for insects to play a role in objectives for more sustainable protein production. Over the course of my Scholarship, this trend has continued as more trials, reports and commercial projects in the area are announced. As a poultry nutritionist, it is not often that an opportunity for such a novel raw material presents itself. A college acquaintance and former colleague, Michelle Sprent-Broadwith, had given mention to insects as a potential new protein source in her 2014 Nuffield Farming Scholarship report 'Sustainable pig nutrition'. Feeling that the interest in insects as a future feedstuff demanded more attention, I decided to investigate the subject further from my perspective of the poultry industry.

Over my career, my work in the poultry nutrition industry has taken me into many different markets around the world and exposed me to many different and challenging raw materials. Most materials, either straights or by-products, have been used for many years and the feed industry has a great deal of understanding of their nutritional values and the risks associated with each material. Insects, and insect products however, are much more unchartered territory although there have certainly been advancements in our knowledge over the last few years.

Through my Nuffield Farming Scholarship I hoped to investigate insects as a potential feed product for the future. There were many aspects that I set out to cover though my visits:

- Research and development of insects and insect products for feed
- How insects are, or will be, produced
- Current use of insects in poultry feed
- Feed markets for insects besides poultry. Who would the poultry industry compete with for access to this material?
- Consumer acceptance of insects as food or feed
- Legislation of insect use in feed

In exploring these areas I was hoping to identify the true potential of insects within poultry feed and how they might be used in the future. Also, I will investigate if the poultry industry would be a primary user of insect product. By gaining an understanding of how insect meals would be produced, I hope to provide insight into potential commercial opportunities for production of a new farmed species. Lastly, I plan to identify if there could be opportunities within the UK agri-food industry to utilise by-products of other processes for the production of insects thereby reducing environmental impact and increasing revenue from low nutritive value biological materials.

In answering these questions in the course of my Nuffield Farming Scholarship, I hope to provide an insight to the UK farming and feed industries to prepare for future availability of this novel ingredient. Also, I hope to examine opportunities that may exist to pursue further research into both production and utilisation of insects for economic, social, and environmental benefits.

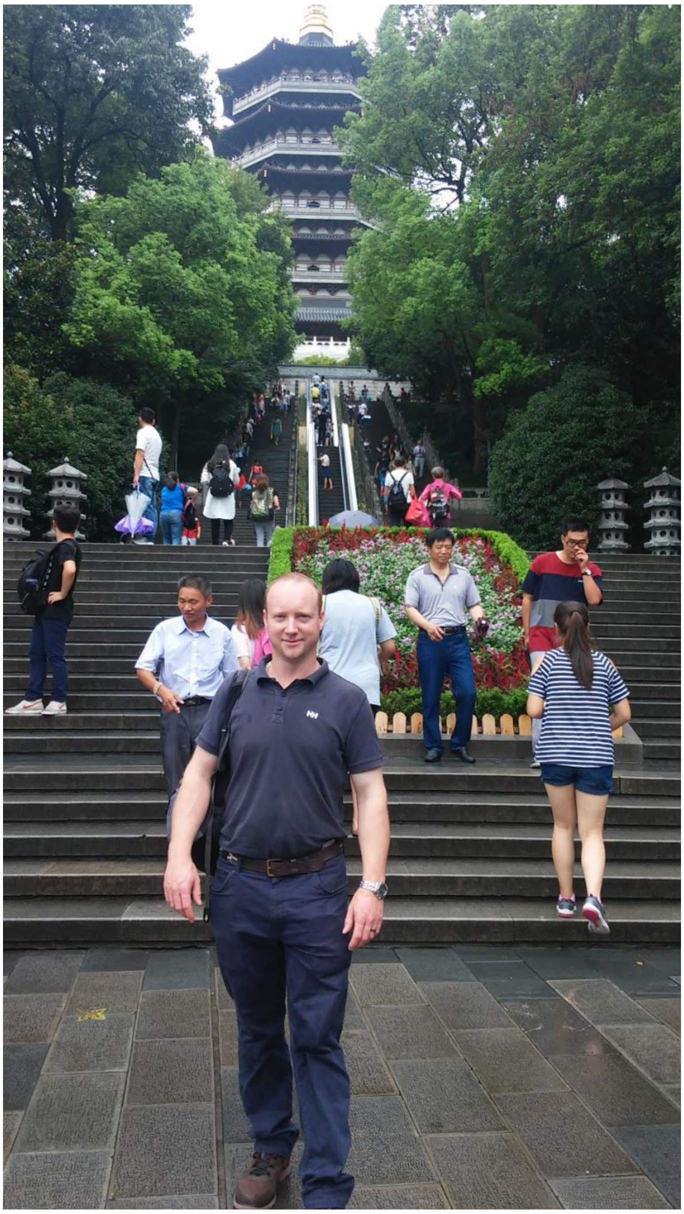

Figure 2: Many steps on the quest for enlightenment!
The author at Leifeng Pagoda, West Lake, Hangzhou City, China

4.0. Study tour

The objectives of my study tours was to understand better the production of insects for use in feed, research on the use of insects in feed, and the opportunities to the farming industry for insect bioconversion. Locations for visits were largely determined by activity in this field. During the early stages of my planning it became clear that, because of foreseen commercialisation opportunities and protection of Intellectual Property, not all the places on my original plan were willing to meet with me. However, with the kindness of everyone that I met with I was able to undertake a full schedule of fascinating and diverse visits.

4.1. Countries visited

4.1.i Spain

In May 2015, my study began with a visit to Professor Santos Rojo and Dr Berta Pastor at the department of Zoology in the University of Alicante in Spain. The university is a project partner of ProteInsect and has recently launched a spin-off company, Bioflytech, to generate value from commercialisation of the insect breeding and rearing research that has been undertaken in the university.

Figure 3: Professor Santos Rojo and Dr Berta Pastor, the University of Alicante & Bioflytech

4.1.ii. Italy

Following the visit to Spain, I travelled to Rome to meet with Dr Paul Vantomme of the Food and Agriculture Organisation of the United Nations (FAO). Dr Vantomme and FAO had been instrumental in organising the 'Insects to feed the world' conference held at Wageningen University in 2014. There was also a timely opportunity for a brief insight into a "WHO/JAO Expert meeting on hazards associated with animal feed", which was in conference at the FAO office on the day of my visit. During a break in session I met with Dr Adrian Charlton of FERA Science Ltd, York, who was involved with the ProteInsect project. After Rome, I travelled to Cuneo in north western Italy to visit Alberto Franco and his team at Franco SRL, an agri-technology company with interests in insect production technology. I then travelled on to meet with Dr Michele de Marco and colleagues at the University of Turin where research on the nutritional value of insects in feed was being carried out.

Figure 4: Dr Paul Vantomme, on the rooftop of the FAO headquarters in Rome

4.1.iii. France

During April 2015 and later in June 2015, I had several meetings in France. Commercialisation of insect meal production is at an advanced stage at Ynsect, a company moving from pilot scale to commercial scale insect production having received €5.5 million in funding in 2014. I met with Antoine Hubert, CEO of Ynsect and President of International Producers of Insects for Food and Feed (IPIFF). The IPIFF organisation is an umbrella group of European insect producers that is campaigning for legislative change and clarification for the production and use of insects for food and feed. In France a project known as DESIRBALES is running. The project is a €1 million research programme examining the rearing, production, fractionation, nutritional value, and consumer acceptance of insect products.

I visited the co-ordinator of the DESIRABLES project, Dr Samir Mezdour, at Paris AgroTech at the Massey campus. The site is dedicated to food processing research and Dr Mezdour is a food scientist specialising in protein chemistry and physical properties of food, working on fractionation and processing of insect material. Within the same project, I subsequently visited Prof. Fédéric Marion-Poll, of Paris Agrotech at the Giff-sur-Yvette campus. Prof. Marion Poll is an insect sensory physiologist and he and his team are working on greater understanding of insect growth substrate. I also had a meeting with Jean Fraçois Kleinfinger, of NextAlim, a start-up company developing insect bioreactors for valorisation of organic by-product. A further meeting had been set up with Mohammed Gastli, of Next Protein which unfortunately fell through. However, I subsequently had a Skype discussion with Mohammed and his business partner Ms Syrine Chaalala, from their offices in Tunisa, about their company's plans for insect bioconversion using locally sourced materials.

Figure 5: Dr Samir Mezdour, Paris AgroTech, Massey, explains the Ento-refinery concept

Case Study: DESIRABLES Project

This 4 year French project commenced in 2013 with a €1 million grant from Agence Nationale Recherche (ANR). The project aim is 'Designing the Insect Biorefinary to contribute to a more sustainable agro-food industry'. The objectives of the study are to quantify the input to insect bioreactors for the valorisation of underused industrial by-products by insect bio-conversion upstream, and the relevance and sustainability of insects as a source of animal feed downstream. There are 11 project partners involved across the full spectrum; 9 from research and academia (entomology, food chemistry and animal nutrition) and 2 commercial partners. These include INRA, AgroParisTech, CNRS, CEA, IRSTEA, IPV food and Ynsect.

4.1.iv. Denmark

In 2013, I had attended the European Symposium on Poultry Nutrition in Berlin where I heard a paper by Dr Sanna Steenfeld, a lecturer and researcher on poultry production and nutrition from the University of Aarhus. This was probably my first introduction to the potential for insects in poultry feed and was possibly the stimulus for proposing this subject for my project. During May 2015, I spent a week in Denmark, visiting with Dr Steenfeld at the University of Aarhus. Sanna also introduced me to Neils Finn Johansen of SEGES, an agri-technolgy and knowledge transfer organisation. Along with Sanna and Neils, I then met with Dr Ricarda Engeberg (Univeristy of Aarhus) and Dr Lars Lou Heckmann and Dr Chistian Holst Fischer of the Danish Technological Institute to review the findings of the 'Bioconval' project which had recently completed examining the potential to convert poultry waste into a feed protein for laying hens in an organic system. Niels had previously taken me to the poultry farm where the trial was run.

Afterwards I travelled to Copenhagen to gain more understanding of the role and acceptance of insects in food chain with meetings with Afton Halloran, a doctoral researcher on the GreenInsect project at the University of Copenhagen. The GreenInsect project is studying how the industrialised farming of edible insects model of Thailand can be transferred to Eastern Africa as a means of local sustainable protein production.

My last visit was to Robeto Flore, an agronomist by background, now turned head chef of the Nordic Food Lab. The lab is a non-profit, open-source laboratory researching food diversity and deliciousness. In 2013 it received funding from the Velux Foundation for a project, 'The deliciousness of insects'. The project focused on how insects in their own right could be developed for gastronomic purposes, adding taste, texture or nutritional value to food. Aptly, Roberto's birthplace of Sardinia is home of perhaps one of Europe's most recognised insect-containing foods, Casu Marzu, a sheep cheese produced and consumed with live maggots.

Figure 6: Dr Sanna Steenfeld, Dr Lars Lau Heckmann, Dr Ricarda Engberg, Dr Christian Holst Fisher and Mr Niels Finn Johansen during a visit to the experimental insect rearing room at the Danish Technologisk Institut.

Case Study: Bio Conval Project (Biological Conversion to Value)

Described by Bjerrum *et al.* (2013), this was a Danish project that ran from 2011 to 2013 that aimed to develop and demonstrate an integrated system for cultivating housefly larvae in poultry manure locally at the farms and use them subsequently as a dietary supplement for the hens. The project partners included: Danish Technological Institute, DTU Food (National Food Institute), Aarhus University and the Knowledge Centre for Agriculture (Poultry), EWH BioProduction and Farmergødning, Dorset Green Machines (Holland) and an organic Danish egg producer. Although the project concept was a success, legislative restrictions on the production and use of insects has meant that outcomes could not yet be commercialised.

4.1.v. Holland

Possibly the greatest activity on insect production for feed is coming from Holland. In May 2015, I visited several companies active in the area of insect production. In Drongen, I met with Tarique Arsiwalla, founder of Protix Biosytems and Vice President of IPIFF. Protix are commercialising the production of insect protein for feed. Also in the meeting was Paul Verboeket, Vice President of

Barentz Nutrition, a feed ingredients company that are marketing and distributing Protix's insect products to the feed industry. After my visit, Protix Biosystems were selected as one of the Technology Pioneers of 2015 at the World Economic Forum in Davos. This demonstrates the considerable interest that their activity is creating in wider society as an industry for the future.

Nearby in Tillburg I met Marian Peters of New Generation Nutrition, a food entrepreneur whom is looking at many aspects of insects within the feed and food chain. Marian is general secretary of Venik, the Dutch insect breeders association.

During a visit to Wageningen University department of Livestock Research, I met with Dr Rene Kwakkel, Dr Marinus van Krimpen, Dr Teun Veldkamp, and Dr Guido Bosch to discuss their research activities on the use of insects in feed. Later, I met with Maarten Hollemans, Innovation Manager with Coppens Diervoeding, a Dutch feed compounder that is evaluating the future potential use of insect products in their pig and poultry feed. In Amsterdam I met with Dr Walter Jansen, Founder and Managing Director of Amusca, a consultancy company for technology applied to the production and processing of insects; specially housefly for use in feed. Walter's knowledge in this area had been built up during his previous project with his company, Jagan, which with along with other partners from the waste management and animal nutrition industries, set up a pilot plant for insect bioconversion of municipal waste from Amsterdam.

Figure 7: Meeting Dutch insect entrepreneur Marian Peters at New Generation Nutrition, Tillberg, Holland

4.1.iv. Belgium

I combined my visit to Holland with a visit to Belgium to meet with Johan Jacobs, founder of Millibeter, a start-up company producing insect products from food waste for the nearby chemicals industries.

4.1.vii. Finland

In July 2015, I visited Helsinki to meet with Ilkka Taponen. Ikka had come to my attention through his blog ('Maggot Master blog @ http://ilkkataponen.com/) and Twitter activity (@IlkkaTaponen). In April he had submitted a thesis for his Bachelor of Business Administration to Helsinki Metropolia University of Applied Sciences on 'Supply chain risk management in entomology farms. Case: High scale production of human and food and animal feed' (https://ilkkataponen.files.wordpress.com/2015/04/ilkka-taponen-thesis.pdf).
Ilkka had recently returned from an internship with Ynsect in Paris. Ilkka is now working with Gold and Green Food Ltd, a Finnish start-up specialising in food products containing oats and beans.

4.1.viii. Germany

In July 2015, I visited Heinrich Katz, of Hermetia Deutschland GmBH, a division of Katz Biotech AG located in Baruth Mark, south of Berlin. Heinrich is also on the committee of IPIFF. Hermetia first started looking at producing insect protein in 2006, making them one of the first industrial companies to commercialise the concept. At the Federal Research Institute for Animal Health at Braunschweig, I met with Dr Jeannett Kleuss. The institute was planning trials to investigate the health and nutritional response of feeding insects to piglets, with special attention to immune response. The Institute is part of the Freidrich-Loeffler Institut whose namesake is widely credited as one of the earliest pioneers of virology, being the first to identify foot and mouth disease virus.

Figure 8: Mr Heirich Katz in the fly breeding room of of Hermetia Deutschland GmbH

4.1.ix. Czech Republic

In August 2015, I attended the European Symposium on Poultry Nutrition held in Prague, Czech Republic. This was an opportunity to meet with and listen to a presentation given by Dr Damian

Józefiak from the Department of Animal Nutrition and Life Sciences at Poznam Univeristy, Poland. Dr Józefiak is also CEO of Hipromine, a Polish start-up insect bioconversion company that later opened its R&D centre in November 2015.

Figure 9: Dr Damian Józefiak from Poland brings insect feeding to the main stage at the 20th European Symposium on Poultry Nutrition in Prague

4.1.x. China

During September 2015, I visited 3 Universities in China to gain insight into their research on insect meal production and use. My first visit was to Prof ZhiJian Zhang at ZheJiang University in the city of Hangzhou, south west of Shanghai. Prof. Zhijian was conducting work on bioconversion using housefly larvae, including projects to convert pig manure and municipal waste. From here I travelled to Wuhan to visit Prof. Fen and her team of students, Qiao Gao and Xiaoyun Wang at Huazhong Agricultural University. Prof. Fen is a collaborator in the ProteInsect project. The team here was working on several different fly species for feed use. My final visit in China took me south to the third largest city, Guangzhou, to visit Prof. Richou Han and PhD student, Guoyo Zhao, at the Guangdong Entomological Institute. Prof .Han is also a collaborator of the ProteInsect project. Again the work here was focused on housefly and trials were running on a poultry farm bioconverting the poultry litter material to insect protein for poultry and aqua feed trials

Figure 10: Prof. Fen, myself, Qiao Gao and Xiaoyun Wang at Huazhong Agricultural University, Wuhan, China

4.1.xi. Vietnam

To understand the commercial opportunities for insect meals in Asia, following my visit to China in September, I stopped over in Ho Chi Minh city, Vietnam. Here I met with Gaëtan Crielaard, a Belgian national who, after studying the potential for insects for food and feed for his Master's project, has set up a company called Entobel and is beginning to produce insect meal for feed.

Figure 11: Trần Hưng Đạo Statue overlooking the Saigon River in Ho Chi Minh City.
Military historians regard Trần Hưng Đạo as one of the most accomplished military strategists

4.1.xii. United States

In January, 2016, I attended the International Poultry Scientific Symposium in Atlanta, Georgia. Afterwards I visited Glen Courtwright and his team at Enviroflight, a company producing insect meal for feed use in Ohio. Then I returned to Georgia to visit Will Harris and Dr Dan Coady of White Oak Pastures, a ranching company focusing on alternative livestock production systems in one of the most remote areas east of the Mississippi. For the last couple of years, White Oak Pastures has been running a trial project producing and feeding insects to pasture-reared poultry.

Figure 12: Dr Dan Coady, myself and Will Harris at White Oak Pastures, Georgia, USA

4.1.xiii. UK

Over the course of my study there were several opportunities for contact with people interested in insects for feed and food in UK. These included speaking with Dr Elaine Fiches, lead researcher of ProteInsect at Fera Science Ltd in York. Dr Fiches was most helpful in guiding me on the early stages of my study and kindly provided me with advice and introductions to contacts for my subsequent travel.

I also attended Insects as Food and Feed Workshop organised by Charlotte Payne at the Oxford Martin College in December, 2015. This was a full day of papers and posters including a chance to speak with Dr Richard Quilliam of the University of Stirling about his project on insects for salmon feed. In April 2016, I attended the Woven Network conference at my *alma mater*, the School of Biosciences at University of Nottingham. One of my former lecturers was even in the audience: however insects as feed or food was certainly not on the curriculum 20 years ago!

Figure 13: Edward Barns, Minerva Communications, presents findings from ProteInsect project at the WovenNetwork conference, University of Nottingham, April 2016

Case Study: ProteInsect project (http://www.proteinsect.eu)

ProteInsect is a €3 million, 3-year EC co-funded project coordinated by the FERA Science Ltd in York, completing in May 2016. The aims of the project were:

- The development and optimisation of fly larvae production methods for use in both developed and developing countries at small and large scale.

- Determination of safety and quality criteria for insect protein products.

- Evaluation of processing methodologies and the evaluation of crude and refined insect protein extracts in fish, chicken and pig feeding trials.

- The determination of the optimal design of insect-based animal feed production systems utilising the results of a comprehensive life cycle analysis.

- To build a pro-insect platform in Europe to encourage adoption of sustainable production technologies to include examination of the regulatory framework.

In addition to FERA, there are 12 partners in the project across 7 counties including; CABI (UK), ABN (UK), Nutrition Sciences N.V (Belgium), KU Leuven (Belgium), Minerva UK Ltd, EUTEMA GmBH (Germany), GrantBait (UK), Guangdong Entomological Institute (China), Huazhong Agricultural University Wuhan (China), Fish for Africa (Ghana), Institute D'Economie Rurale (Mali), BioFlyTech (Spain) and Institute of Aquaculture, University of Sterling (UK).

In November 2015 the project was presented a European Innovation Award for having 'demonstrated exceptional business or social innovation potential'. The project reached an audience of 7 million people with coverage on BBC Countryfile in November 2015. The "Proteinsect.eu" website received over 68 thousand 'hits' on the evening following the broadcast.

On 27th April 2016, ProteInsect published a white paper "Insect Protein – Feed for the Future" on their findings at a meeting in Brussels.

4.2. Why have insects become a hot topic?

The role of insects in the food chain is not new. It is estimated that over 2 billion people regularly consume insects as part of their regular diet (*FAO, 2013a*). Even on the feed side, research in insects as fish and poultry feed was being published in the 1950s. It was even practice in the past to hang a carcass over a fish pond. Flies would lay eggs in the carcass and the developing larvae dropped off into the pond as feed for the fish! It has been estimated that since 2012 there had been almost a doubling of publications related to insects for feed and food. Clearly the need to be more resource efficient, particularly in relation to our protein supply, is driving this growth in interest. Indeed the 2013 FAO 'Edible Insects' report (*FAO 2013a*) has one of the highest ever impacts and this report and the subsequent conference in 2014 have provided inspiration for many entrepreneurs in this field.

But what stimulated this report and why was it the forestry division of FAO that was active in it? The report came about following an expert meeting in 2012 but the story went back to 15 years previously to the first Congo War (1996-1997). Here the FAO noted that despite a dramatic shortage of bushmeat that formed a significant part of the animal protein intake to jungle dwellers, the rates of malnourishment were lower than expected. After investigating this, it was found that insects were contributing a significant part of the animal protein intake, especially during the rainy season. FAO subsequently realised that they were underestimating the potential for insects to provide a source of nutrient in both the feed and food chain; scoring highly on the sustainability matrix.

Figure 14: Top level discussions. On the roof of the FAO overlooking the Colosseum (left shoulder) and Circus Maximus (right shoulder), Rome, Italy

4.3. Current legislative status of insects in the food chain

This study and much of the preparation of this report was undertaken prior to the "Brexit" vote of 23rd June. 2016. At the point of writing the situation regarding the future applicability of European legislation with regards to animal feed controls and food safety to the UK is unknown. For this reason the topic will be covered as is the "current situation" i.e. that European law remains in situ for the immediate future. At this point it would be impossible to speculate on how the situation may change over the coming years as the future relationship between the UK and the European Union evolves.

No discussion on the use of insects in feed or food in Europe can avoid a discussion on legislation. The situation is extremely complex and, in some areas, unclear, as insects fall into categories of feed legislation that were written without consideration at the time that they may become a part of the feed chain for food producing livestock. One of the principal aims of the IPIFF group is to lobby for both clarification and amendment to the legislation concerning the use of insects in feed and food. Many of the commercial insect producers within Europe are members of IPIFF and their different membership levels depending on company size and needs.

With regards to insect use in feed, there are at least 6 pieces of EU regulation either requiring amendment or consideration:

1. The most significant legislative hurdle to the use of PIP is the Transmissible Spongiform Encephalopathies (TSE) regulation EC 999/2001, introduced principally in response to the BSE outbreak. This regulation prohibits the feeding of all processed animal proteins (PAP), with the exception of hydrolysed protein, in production animal feed.
2. Within the catalogue of feed materials (68/2013) there is no entry for 'insect meal' although there is an entry for whole or parts of terrestrial invertebrates. Whether or not this covers insect meal needs clarification.
3. As with any feed material, insect meals need to comply with directive 2002/32 on Undesirable Substances in Animal Feed. This sets out limits for feed contaminants such as heavy metals, Dixons, PCBs.
4. Processing of insects must be in accordance with the Animal By-Products Regulation 1069/2009. Within this regulation, non-pathogenic insects are classified as category 3 materials and therefore feed use would be possible. A 'grey area' here may be the interpretation of which insect species are non-pathogenic.
5. Regulation 56/2013 has relaxed the use of non-ruminant processed animal products (PAP) in aquaculture, which included invertebrate material. However it requires registration of slaughterhouses and currently there is no registration system for insect slaughter. Although this is a significant block it is one that is seen as being overcome with relative ease by application of best practice from other livestock slaughter processes.
6. As with other feed materials, controls on feed hygiene are applicable under regulation 183/2005.

Outside Europe the regulation of insects for feed is far more relaxed. In China and Vietnam there appears to be little or no restrictions. In the US, approval for use of insect meals is more complex. I understand it to be State, source, and target species specific, although data on this is difficult to come by. Unlike in Europe there is no publication of permitted feed materials and so, from my discussions, I understand that positive approvals have been given to specified sources and target species by the FDA on a state-by-state basis. In Canada, approval for whole dried larvae (not meal) was given in April 2016 following a 4 year approval process by the Canadian Food Inspection Authority for use in broilers. Further applications are under review for aquaculture and processed meal in poultry.

(continued on next page beneath the photo of European Parliament in Brussels)

Figure 15: The European Parliament in Brussels, visited by the 2015 Nuffield UK group on our Pre-Contemporary Scholars Conference in Reims, France, February 2015.
It remains to be seen what role European legislation may play on the use of insects in UK

Rather perversely in the UK, the regulation for insects for direct human consumption is, or at least has been up until this year, less restrictive. Insects as a foodstuff come under the new EU-wide Novel Food Regulation 2283/2015, which will come into force in 2017. This states that foodstuffs proven to have been consumed to a ‘significant degree’ prior to 1997 do not require risk assessment: i.e. this protects the status of existing foods.

By strict interpretation, this regulation would forbid importation, sale, marketing or production of whole or processed insects for human consumption, unless use prior to 1997 can be proven, or a full risk assessment has been undertaken. Although this position is quite clear, presently there are differences in interpretation between member states since the new regulation is not yet in force. Insect food products are on the market in UK, Holland, and Belgium, whereas in Denmark insect products were withdrawn from supermarket shelves after just 2 days of being launched for sale in March, 2015, after warnings that they were not legal. The Belgian Federal Agency on Safety of the Food Chain even goes so far as to list 10 species of insects that it considers safe for human consumption, provided food safety standards are met and no processing occurs: African migratory locust, giant mealworm, common mealworm, lesser mealworm, greater wax moth, American desert locust, banded cricket, lesser wax moth and silk moth (http://www.afsca.be/foodstuffs/insects/).

Similar rules are in place in Holland. Currently the position of the FSA in the UK is that whole edible insects are not regarded as novel foods. However, following the updated novel food regulation, the FSA currently advises that historic consumption, needs to have been first evidenced prior to May, 1997, in order for the insect in question to avoid being classed as a novel food. The FSA requested existing edible insect businesses to provide this information by 21st September 2015.

In the US the situation as food is less clear.

It is estimated that more than 1900 different insect species are consumed by around 2 billion of the world’s population as part of a normal diet.

4.4. Risks associated with insects in the food chain

During my visits in Europe, most of the people that I spoke to were waiting with keen anticipation for a European Food Standards Agency (EFSA) opinion on the risk profile of insects in food and feed. It was considered that this option would provide an indication for future direction, amending some of the legislative hurdles mentioned previously. The opinion was published on the 8th October 2015 (EFSA Scientific Committee, 2015). The document covers a long list of risks considered relevant to insects in the food chain, including:

- Microbiological hazards
    - Bacteria
    - Viruses
    - Parasites
    - Fungi
    - Prions
- Chemical hazards
    - Heavy metals and arsenic
    - Toxins produced or accumulated in insects
    - Veterinary drugs and hormones
- Allergens
- Impacts of processing and storage
- Environmental hazards

The overall conclusion of the EFSA Scientific Committee document is that "*further research for better assessment of microbial and chemical risks from insects as food and feed including studies on the occurrence of hazards when using particular substrates like food waste and manure is recommended*". The more general conclusion of the report is that insects fed food or feed grade materials should pose no increase of risk through their entry into the food chain.

Following publication of the report, IPIFF issued a press release on their website welcoming it as a positive step towards insect meal in aquaculture. Many of the concerns raised in the report related to substrate, whereas European IPIFF members use only plant-based feed grade materials. I will cover substrates in a later chapter.

4.5. Insects: a natural feedstuff of poultry

Birds naturally eat bugs! Hardly an earth shattering observation but worth noting for its relevance to this study, as modern farming techniques have moved them to an almost completely vegetarian diet. A study by Hurst and Stringer (1975) determined a ratio of 79:21 animal:plant material (by dry weight) in wild turkey poults feeding in fields one week after hatching. The study was conducted in Mississippi and the 'animal' material was 'mostly' insects; beetles (Coleoptera), true bugs (Hemiptera), grasshoppers (Orthoptera) and leafhoppers (Homoptera). Interestingly, by 38 days, the proportion consumed had dropped to 13:87. In other studies reviewed in Dickson 1992, insect consumption is affected by habitat type and vegetative conditions; however the profile of insect species consumed reflected their availability and abundance in the environment.

As a child I recall observing the chickens scratching around the yard looking for insects and grubs. The cockerels would find a particularly large worm or beetle and, rather than consuming it themselves, call over the hens to share the find. Insects also seemed to elicit a particular behaviour in chicks; they would dart around catching flies and running around with them making quite distinctive noises. What drove this behaviour in the birds? Was it fulfilling a nutritional need or some innate behaviour or preference for a live, living food source? Dr Candy Rowe, Reader of Animal Behaviour and Cognition at Newcastle University Institute of Neuroscience described this 'worm-running' behaviour of the chick to me as possibly being associated with the formation of a dominance hierarchy within the flock.

My interest in the role of live insects in the diet of the bird was stimulated by a couple of discussions during my study. In Denmark, Dr Engberg described to me how it was observed that birds offered less than 5 grams of fresh live larvae per day had higher bodyweight and a calmer behaviour than birds fed a control or processed larvae diet. During my visit in Germany it was described to me that live insect larvae had been fed to turkey flocks that had begun pecking under veterinary supervision. When outbreaks of pecking occur, it often becomes habitual and difficult to stop; however within 2 days of receiving live larvae in this case, the pecking had stopped. In September 2015 it was announced that ForFarmers, a Dutch feed company and significant feed supplier in the UK market, had commenced trials at Wageningen University examining the impact of live larvae feeding to broilers. In May, 2016, it was reported in Farmer Weekly (*McDougal, 2016*) that the trial was very satisfactory, that the birds ate the larvae enthusiastically, and that the larvae encouraged 'free-ranging' behaviour.

Clearly there is more to understand on live insect feeding. Are any benefits related to a complex behavioural effect or simply a direct nutritional effect? In June 2016 it was reported (*Hogenkamp, 2016)* that a Dutch egg producer, Ekoz Poultry, has started supplementing the diet of one of their flock of birds with 20% live BSF larvae sourced from Protix. Better health is reported in the flock and the eggs from these birds are being marketed as 'het Oerei' which translates as 'the primordial egg'.

Interestingly, live insects would not encounter some of the legislative restrictions mentioned earlier as they would not be killed or processed. However, there is no specific listing for live insects as a permitted feed material for poultry even though consumption would happen in a pastured situation. It is not clear if intentional feeding of live insect to food producing livestock would contravene any regulation or directive. Of course other risks would still exist with regards to food safety and those regulations would have to be observed so as not to compromise food hygiene (e.g. rearing on manure etc) and avoid the introduction of pathogenic bacteria, toxins, or residues. Logistically, the production and delivery of live insects to a commercial farming system would be difficult to achieve. However in free range systems, insects would naturally be part of the environment and encouraging insects within the pasture may have some benefits.

When I visited the University of Aarhus, the concept of 'range enrichment' was beginning to be investigated. The study would observe ranging behaviour and crop content in free range organic broilers in pastures with different grass and plant species known to attract insect species (e.g. chicory), along with coproduction of agro-forestry (energy willow) to encourage insect biodiversity on the range. The work was a part of a follow-on from previous work carried out at the University and published by Horsted and Hermansen (2007) which had shown different levels of insect and earthworms in crop contents of free range organic laying hens on different pastures. The authors did not report how the different crops affected availability of insects and worms, however. In a second study, Horsted *et al*. (2007), reported more insect consumption in laying hens fed a wheat only diet rather than a balanced compound diet, indicating that birds self selected for insects to fulfil a nutritional shortfall.

One note of caution regarding encouraging worm consumption is the risk of blackhead, a parasitic disease transmitted via earthworms. Turkeys are especially susceptible to blackhead infection and outbreaks have been reported in free range hens. Also the contribution of foraged insects to the diet of the free range bird will be extremely variable with season.

Figure 16: Willow and herbs planted on an experimental organic enriched range at Folum research station, University of Aarhus, Denmark

Figure 17: Free range broiler foraging trial site, Gothenborg, Denmark.
The experiment, co-ordinated by the University of Aarhus, will examine the impact of range biodiversity on the crop content of conventional and slow growing broilers, including recording insect intake

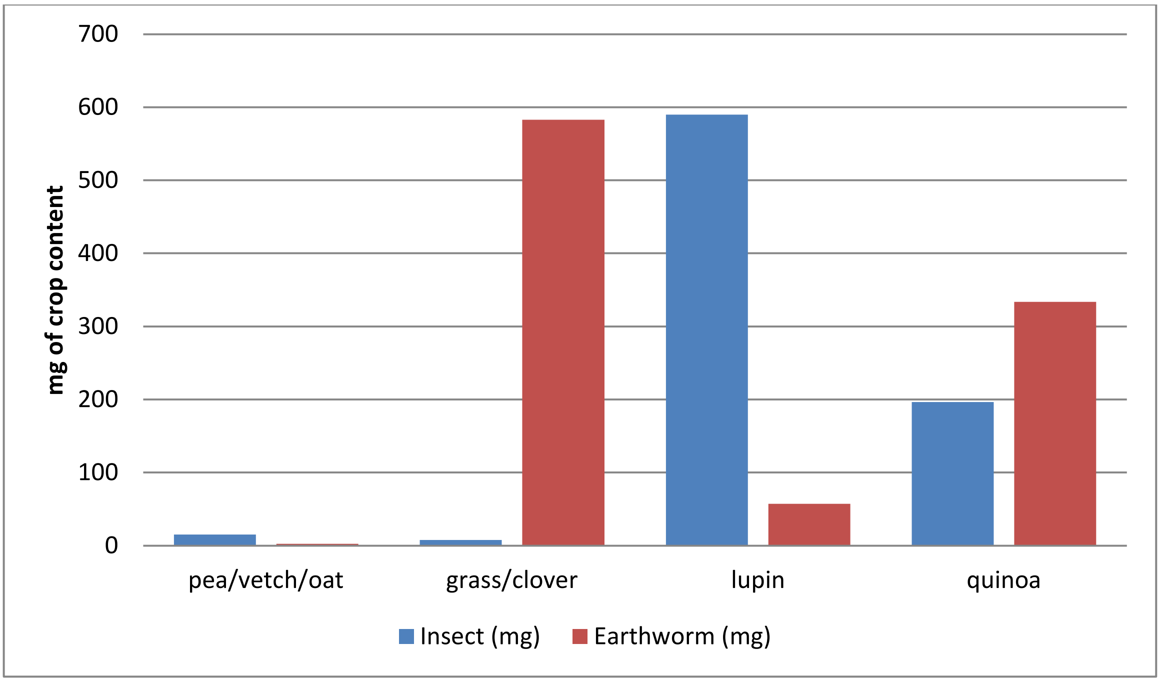

Figure 18: Insect and Earthworm crop contents of organic laying hens on different pastures
(Horsted and Hermansen, 2007)

Case Study: The varied diet of the Danish free range hen
Around 22% of egg production in Denmark is under organic rules. Although it allows for a higher rate holding size that under UK rules, the rules surrounding feed are the same. Organic sector demand has largely driven interest on the use of insects in poultry diets and there is other advanced thinking in Denmark on alternative, sustainable feed materials. Another example is the use of forage in laying hens. What is unusual is the smell of silage that hits your nose when you enter an organic laying house in Denmark. It is common place for hens to be fed an ensiled mix to complement a nutrient-adjusted layer compound diet. This mix can be either high energy (whole crop cereals) or high protein (pea, bean, alfalfa mix). Even some root crops are used e.g. carrots. The silage is either delivered from the clamp or from wrapped bales. It is then dropped into a robotic dispensing system that chops and spreads the forage over the scratch or veranda areas 3-4 times per day. On the farms I visited, forage intake was around 40g/bird/day in addition to 120g of pelleted feed. Structural fibre is recognised as a benefit to the birds' digestive system. Levels of production were excellent and the bird clearly performed well on this system, still achieving 94% production at 39 weeks.

On a similar note, 2 posters were presented at the International Poultry Scientific Forum in Atlanta from researchers from the University of Kentucky and Kentucky State University. In the first study *Jacob et al. (2016a*), reported differences in species and quantity of insects collected from pastures of grass or alfalfa as well as the high level of seasonality. The second study, *Jacobs et al. (2016b),* indicated that increasing the legume content of the pasture (Crimson clover, Birdsfoot trefoil and Alfalfa) increased the insect population of a grass ley.

Figure 19: Forage feeding system by JH Staldservice A/S in operation, Jutland, Denmark

So, clearly insects are a significant factor in the natural diet of poultry species and there may even be productivity, health, and behavioural benefits. However, under intensive and year round systems of production, natural access to insects will not be possible, which returns us to the industry of producing and processing insects for use in feed.

4.6. Species of Insects of interest in feed

There is estimated to be in excess of 1900 edible insect species in world. The species of greatest interest for feed, and the ones that I was introduced to in the course of my study are:

- Black soldier fly (*Hermetia illucens*)
- Housefly (*Musca domestica*)
- Kelp fly (*Coelopa frigida*)
- Cockroach (*Blattodea*)
- Common Mealworm (*Tenenbrio molitor*)
- Giant Mealworm (*Zophobas morio*)
- Lesser Mealworm (*Alphitobus diaperinus*)

In all cases these are harvested for use at the larval or pre-pupae stage of the growth cycle, not the adult fly or beetle stage. Choice of insect species will largely depend on the properties of the available growth substrate, the climate or production conditions and what is permitted under local regulation. The production of other species groups e.g. locust, cricket, silkworm or grasshopper, is more targeted for specialist pet or zoo animal markets or for human consumption. In Italy projects are underway to revive the silkworm industry that was once prevalent in the country, providing additional income to rural communities in the northern areas. The team that I visited at the University of Turin were considering the potential for a silk by-product meal to feature in feed to add value to the waste from the industry to increase its commercial viability. I also understand there is interest in India for developing this market for the silk worm by-product. There has also been interest in blowfly, cockroach and palm weevil production and, whilst they came up several times in discussion, I did not actually have the opportunity to visit facilities working with these species.

4.6.i. Black soldier fly (BSF)

Black soldier flies are possibly the most widely studied and the earliest referenced paper for their use as a poultry feed protein source is Hale in 1973. BSF are large tropical flies that have a short, non-feeding lifespan of around 4-5 days in adult form; literally just long enough to mate and lay their eggs. They avoid human contact and are not generally considered a pest or pathogen vectoring species. Over recent years, with increasing temperature, their natural environment has been moving further north, occurring in the wild in parts of Italy, Southern France and Spain. One justification for using BSF is that, should a release occur from a production facility in temperate parts of Europe - such as in the UK - lower temperatures mean that they would not survive or reproduce in the wild and so do not pose a threat to the environment or to human populations surrounding the production site. However, in some countries where the fly is non-native e.g. Denmark, it is not permitted even to import them for production. In most other EU countries where production is allowed, releasing of the live larvae would likely fall foul of laws on non-native species.

Black soldier fly prefer a moist/semi-moist substrate of decaying organic matter and have a high rate of bioconversion. They are polyphagous, feeding on a wide range of materials but are particularly suited to vegetable and plant wastes. Each individual growing larvae can process up to 500mg of substrate per day or 2-3 grams over its growth cycle; greater quantities than any other known fly species. Just prior to the pupae stage, they will empty their gut contents and escape from the substrate to seek a place to pupate. This makes them 'self harvesting'. In practice however most people that I spoke with preferred to mechanically harvest them as part of a batching process. Growth uniformity is critical to the production, which is essentially run like an 'all-in, all-out' type system.

Figure 20: Dried black soldier fly larvae. The dark larvae in the lower part of the picture is closer to pupation.

One of the challenges with BSF is to get them to reproduce. Each female will lay around 1000 eggs, so the offspring of one female will process around 2-3 kg of substrate with bioconversion rate of around 50-75% depending on material. One of pioneers of mass insect farming, Jason Drew from the South African company AgriProtein, discusses this in his book, ‘The Story of the Fly and how it could save the world’ (*Drew and Joseph, 2012*). The secret to successful rates of mating and oviposition is a closely guarded secret by those who have perfected it and certainly nobody that I visited would disclose any details on this to me. Light wavelength and intensity is very important and mating under artificial light can be very challenging suggesting that a natural light spectrum is required. The fly mates ‘in flight’ so there must be sufficient flying area and then the correct conditions (moisture, light and physical structure/surface) for oviposition must be provided. In both the adult and larvae stage they require a warm temperature of 29-32^{o}C. Heat could be a significant factor in the cost and productivity of the system between different locations. Climatic differences mean that a 45-day cycle under European conditions may be only 30 days in South East Asia. It is estimated that 7-8,000 T of BSF larvae (fresh weight) was produced globally in 2015 compared to less than 1,000T in 2014. Investments in projects in Holland, South Africa, USA and Canada are likely to double that figure again in 2016 to around 14,000T of material.

4.6.ii. House fly

Rearing of house fly for insect meal is possibly more emotive than BSF. House flies are regarded as human pests and vectors of disease. They live longer in adult form (around 1 month) and unlike BSF, adults feed (by pre-digestion) and excrete, which is how they spread disease from one contact food source to another. Their preference is for more putrid and moist decaying matter than BSF so are better suited for manure or abattoir waste bioconversion. It is thought that house fly larvae feed directly on the organic matter as well as the microbes that populate it so there is a symbiosis between the larvae and the bacteria in the substrate. The larvae are smaller than BSF larvae and, as a result, can be difficult to separate from the substrate if it is still moist or a similar size of particle to the larvae. In China I observed separation by either mechanical sieving or by forcing them out of the growth substrate using high temperature.

House fly are easier to breed, produce more eggs/adult (around 2000) and have a shorter larvae life cycle of around 5-6 days in summer or 10 in winter. House fly also require warm conditions of between 25-30^{o}C, albeit slightly cooler than BSF. One advantage of the shorter life cycle is that it would allow faster colony recovery should a collapse occur which would ameliorate some of the risk that may exist with other longer cycle species. Studies in Wageningen UR have reported higher levels of protein in house fly larvae than in BSF (65.7 vs 38.9% Dry Matter).

See photo of house fly on next page.

4.6.iii. Mealworms

Mealworms are been commonly used as a supplementary feed for insectivorous zoo and pet species. This is a niche, high value market and there already exists an industry supplying this demand. However it is possibly not on the scale of industrialisation for volume and cost of production that would satisfy the animal feed market as yet. Mealworms are a larvae form of beetles within the Tenebrionoidea family group. Essentially there are three species under consideration for use in feed; common meal worm (*Tenenbrio molitor*), lesser mealworm

(*Alphitobius diaperinus*) and giant mealworm (*Zophobas atratus*). Lesser mealworms have a preference for dry substrate whilst common mealworms prefer more moist conditions and low light conditions. They are regarded as a human pest in stored food and can harbour and vector pathogens. By the nature of their natural food source they are well suited to cereal by-products (e.g. brewery or ethanol grains, milling by-product). Production already exists for supply to the zoo and pet markets, however the challenge is to scale this up to more commercial levels demanded by the feed industry and to reduce costs. Meal worm production currently is estimated at around 1,000 T (dry weight) for both human and animal consumption.

Figure 21: House fly larvae growing on municipal organic material in China

Figure 22: Lesser mealworms, produced in Holland for human consumption

Mealworms have a longer development time than the fly species, around 3-4 months, but do not require such high levels of heat, being suited to 18-20^{o}C. Common mealworms have a much lower rate of reproduction than fly species. An adult female will produce only 160 eggs in her 3 month life. Oonincx and de Boer (2012) reported the FCR to be around 2.2 kg/kg on a grain/vegetable based diet – considerably less efficient than the conversion rates achieved by most commercial poultry, egg or even pork producers.

Case Study: Aquafly project (http://nifes.no/en/counting-insects-future-fish-feeds/)

Norwegian funded project (13 million NOK in funding) over 4 years. Commenced in 2014, the project partners include, Bioforsk, the Norwegian University of Life Sciences (NMBU), the University of Bergen's Centre for Scientific Theory, Uni Research, the Norwegian Agricultural Economics Research Institute (NILF), Gildeskål Research Station (GIFAS), EWOS Innovation, Protix Biosystems BV (The Netherlands), the Irish Seaweed Research Group at the National University of Ireland, Galway, the Department of Environmental Science and Technology at the University of Barcelona (Spain), and the Department of Biological and Environmental Sciences at the University of Stirling (UK). The project is focused on 'tailoring' the insect product to suit the nutritional requirement of the fish, including provision of protein and omega-3 fatty acids.

4.6.iv. Other species

Almost exclusively my discussions on insects as a feed source included the 3 species listed above. However, a couple of other species did get mentioned. A study underway at the University of Stirling is examining the potential of kelp fly (*Coelopa frigida*) as part of the Aquafly project. This is a native fly to the UK that specifically feeds on seaweed and the project is examining the potential to commercialise this process to use these larvae in aqua feed.

There is also some interest in Blow-fly (*Calliphoridae*) outside of Europe at least, i.e. China and in Africa. Blow-fly are particularly suited for decaying meat type material e.g. carcasses or abattoir waste. However, it is highly unlikely such substrates would be accepted for entry to the food chain in Europe (see later discussion). Blowfly is also a pollinator species and there is even a project in China looking at the possibility of sterilised blow fly as an alternative pollinator species to bumble bees.

4.7. Insect production

The structure of a farming system for BSF (or indeed any insect) bears a striking similarly to the poultry industry. As with other type of farm-reared livestock there is a risk to health from a variety of challenges (viruses, microbial etc). The topic came up in several discussions with producers, some of whom had suffered 'colony breakdown' previously. Veterinary knowledge of insects is understandably limited. The approach is to have a highly bio-secure breeding colony, similar to the poultry industry. Generally breeding stock will be housed separately and fed a very 'clean' substrate to avoid introducing any pathogen that could harm the breeding colony or introduce pathogen transfer to the growing larvae.

Essentially there are two models for insect farming; single site or contractor. In a single site model, breeding would be performed centrally and the eggs or freshly hatched larvae 'shipped out' to contract producers who would rear the larvae. In the case of shipping larvae they would require access to nutrient and moisture during transport, similarly to a chick transported over long distances, and perhaps some of the early feed chick products would be appropriate for this. The 'growers' would then either use the larvae for their own purpose, supply to local third parties, or they would be transported back to a central processing factory. The advantages of this system are that risk is reduced by multisite production; capital outlay on facilities by the breeder/processer is smaller, with contract producers financing their own facilities. Contract producers could take advantage of locally available substrate materials. However, there would be some loss of traceability within the system, less automation, and logistic costs would be higher.

The other model is to build a large scale insect "bio refinery" where the whole system would be fully integrated on one site. This would be the model that the majority of insect meal producers are following. A single site model gives more control and traceability with higher levels of scale, automation and efficiency. However, it would also bring with it more risk from colony collapse due to disease, equipment failure etc. Transport of substrate would be inefficient so locating a production site close to the source of substrate material would be seen as most efficient. It is estimated that access to around 30,000 T of material per annum would be needed to justify a commercial scale insect rearing facility. At that scale, at least one company that I spoke to would have an interest in developing a project.

Figure 23: Housefly breeding room at a Chinese facility.
The boxes on the walls are nest boxes for collection of eggs

4.7.i. Insect farming technology

Like many other intensive farming systems, insect production will be highly reliant on technology to sense and control the environment. It would include monitoring and adjusting heat, humidity for the preferred optimum, and also gasses (e.g. oxygen, carbon monoxide, ammonia, hydrogen sulphide, methane) that could limit growth or simulate premature pupation. Monitoring systems and control systems within the growth substrate itself would also be likely to increase productivity. For example, ensuring the conditions remain at the correct temperature and moisture, remain aerobic and that there is sufficient nutrient provision for growth. Heat requirements in the substrate may vary with the stage of growth, initially requiring heat input but subsequently requiring heat dissipation as the metabolism of the microbial and larvae biomass gets established.

Technology to remotely monitor and adjust the airspace temperature, humidity and air quality should be transferable from other industries such as horticulture or intensive livestock. Systems to manage the growth substrate may require more novel specialist technology. Small scale, low tech systems are labour intensive, and whilst that model may work in Asia, for the developed world more automation would be required in order to keep production costs down. Indeed, labour is seen as a major constraint to commercialisation in Europe. Land use productivity for insect production is quite high because they can be vertically farmed in trays. However, actual surface area use is quite high as the substrate must be oxygenated. This limits the depth of substrate to several inches. Developing a larval rearing system that could batch-rear insects in a large 'container' system by creating and maintaining the correct substrate conditions would give labour savings and increases in efficiency.

For the most part the insect producers that I met with were reluctant to share their technology and I fully understood their position and would not wish to compromise any intellectual properties. Some people, like Walter Jansen of Amusca in Holland, had started their work as 'open source' but the commercialisation opportunities were too big to ignore, and investors demanded a more closed book approach. Walter is now in the business of selling technology solutions for insect breeding and rearing. Entering "black soldier fly" and "animal feed" brings up around 25 patents in a Google patent search currently, and that will not be, by any means, the full list. In an emerging industry with a lot of potential, the prize is of course considerable for those that 'crack' the system for scaled up insect meal production.

Figure 24: Franko Srl, Cuneo, Italy, have an interest in insect production and are applying their experience in livestock environmental control technology to the insect industry

4.7.ii. Industry development

Developing a new industry has considerable challenges to overcome. Without material you cannot create demand. Without demand you cannot get investment to create the material! I sensed that much of the development in Europe was in close cooperation with several different stakeholders including end users, waste management companies with funding from government, and venture capitalist investors. Examples of Protix being selected as a Technology Pioneer by the World Economic Forum in August 2015 and the purchase of Enviroflight by Intrexon Corp shows the conservable commercial interest there is in this new business of insect bioconversion. Demand led development is a much safer way for the insect industry to develop. But is poultry feed driving this demand?

4.7.iii. Substrates for rearing insect larvae

By selecting the most appropriate insect species, it is possible to bioconvert many different biological materials into insect protein. The ultimate objective would be the utilisation of insects to recover nutrients from non-feed grade biological materials. As previously mentioned, the European industry of insects for feed or food is working almost exclusively with food or feed grade vegetable-based materials in order to satisfy current legislative requirements and avoid introducing contaminants into the food chain from non-feed or food materials. In countries outside of Europe, food controls permit a much wider range of substrates to be used. The range of substrates I saw used outside Europe included manure, pre and post consumer waste including meat products (i,e. food factory and restaurant waste respectively), municipal organic waste, and blood and abattoir waste. It was even pointed out during the Woven meeting at the University of Nottingham by a delegate from Africa that, not only could meat from livestock fed on insects be imported to the EU, there may be no restriction on the substrate used to rear the insect.

The EFSA Scientific Committee (2015) report provided an excellent analysis of the potential food chain risks associated with different substrate materials. It remains to be seen what material will be permitted in European insect production beyond what is currently in use. It was explained to me that the short term objective of IPIFF is to permit insects reared on 100% vegetable material to be used in aqua, poultry and pig feed. A longer term objective is for former foodstuffs to be an approved substrate material. Manure is not, and most that I spoke with would suspect would never, be a substrate option in the EU for production of insects entering the food chain at any point. Even the classification of 'former foodstuffs' is likely to be quite restrictive and follow the rules that currently apply to the use of former foodstuffs in feed (e.g. biscuit meals and used cooking oils).

See photo on next page: House fly larvae feeding on pig manure in China.

There are a number of potential vegetable substrates that could be applicable in the UK that are already being used or considered in other countries:

- Cereal and cereal processing by-product
    - Brewery and distillers grains
    - Ethanol by-product
    - Starch by-product
    - Wheatfeed
    - Grain screenings

- Vegetable processing by-product
    - Salad trimmings
    - Potato peeling
    - Beet pulp
- Fruit processing by-product
    - Juicing pulp, including cider pulp
    - Peelings
- Coffee granules

Although outside of the 100% vegetable strategy of IPIFF, it would also be likely that milk processing and egg processing by-products could be permitted as they are recognised as feedstuffs.

Figure 25: House fly larvae feeding on pig manure in China

Figure 26: A truck load of vegetable waste, a potential insect feedstock, heading for bio-digestion, Shrewsbury, Shropshire, UK

Questions in selecting these products will be:

1. performance of the insect on them
2. consistency, and
3. supply volumes.

The economic uplift of insect bioconversion of a material that is already supplied direct to feed or to bio digestion will be critical. In terms of supply, locally sourced material to the production facility will be preferred. In all likelihood larvae performance will be optimised when a combination of materials is used to provide a balanced nutrient profile to the larvae, just as we do with other farmed livestock. In fact, I was told that BSF larvae and mealworms grew very well on poultry feed compared to a vegetable substrate blend.

Knowledge of insect nutrition is sparse and insect producers are researching substrate preference by providing choice feeding and measuring growth rate and conversion on different substrates and combinations. Different approaches are being used from simply testing different blends, to conducting full scale laboratory preference or choice feeding experiments, as I observed in France. Insect production sites will be equipped with their own insect feed mill or blending plant. Perhaps unsurprisingly, one challenge that has been found with vegetable and fruit based materials is the presence of pesticide residues – unsurprisingly they are not very conducive to larval growth and survival! High sodium levels in processed food stuffs have also proved problematic.

Figure 27: Mealworm feeding trials in France. In the laboratory, choice feeding trials were set up to measure the larvae's preference for different materials

Feed generally represents more than 70% of the input cost of most monogastric livestock. However with insects, the proportion of production cost that feed input represents will vary with the choice of substrate. Production on low value materials will offer price stability for products, which of course will fluctuate in value depending on other feed commodities. That creates some significant profit opportunity for producers at times of high commodity price. However, the use of feed grade materials as inputs to insect production that compete with use in the feed industry will result in more fixed profit levels as both the input and output will become commodity market linked.

Figure 28: Inside my first feedmill for Insects.
The Envoroflight LLC team in the feed preparation room:
L-R; Mr Glen Courtright, Ms Sarah Wildman, yours truly, Ms Cheryl Preyer, Mr Ron Tribelhorn

4.7.iv. Methods for feeding insects

As previously mentioned, each insect species has its own environmental optima in terms of temperature, humidity, nutrient levels etc. Indeed, the interaction between the insect (larvae) and the substrate is believed to be quite complex and it is not even certain if all larvae species feed directly on the substrate or through a secondary consumption of a microbial biomass that has already formed on the substrate. Certainly, insect growth using both Housefly and BSF appears to be enhanced by pre-treatment of the substrate with a bacterial or yeast culture to begin fermentation.

Figure 29:. House fly larvae rearing beds in China. The larvae increase in age from near-to- far and the sections are topped up with feed daily but depth remains quite shallow.

A significant limitation to scalability of insect production is that the substrate must stay aerobic in order for the larvae to survive. This really limits depths to no more than 10-20 cm depending on species. Therefore, there is a need for large surface area rearing, in stacked trays rather than high volume bioreactor rearing in a large vessel. Not only is this the former inefficient in space it also increases labour and it is necessary to 'top up' feed to the trays several times in the development of the larvae. Clearly, one of the goals for scalability will be the intensification of the process to reduce labour and increase yield per m^2 of floor area. 'Vertical farming' is one solution that is being employed. No doubt the commercial companies are well advanced on this and it is probably the single most likely reason that many are reluctant to show visitors their facilities.

4.7.v. Mass balance of an insect production system

Understandably, many of the insect producers that I visited were reluctant to discuss the figures behind they're system. In fact, given that large scale production is still in its infancy, most figures would be based on the pilot scale plants anyway.

I did get some indication of the mass balance being achieved in Asia, however, using Black Soldier Fly on food waste material.

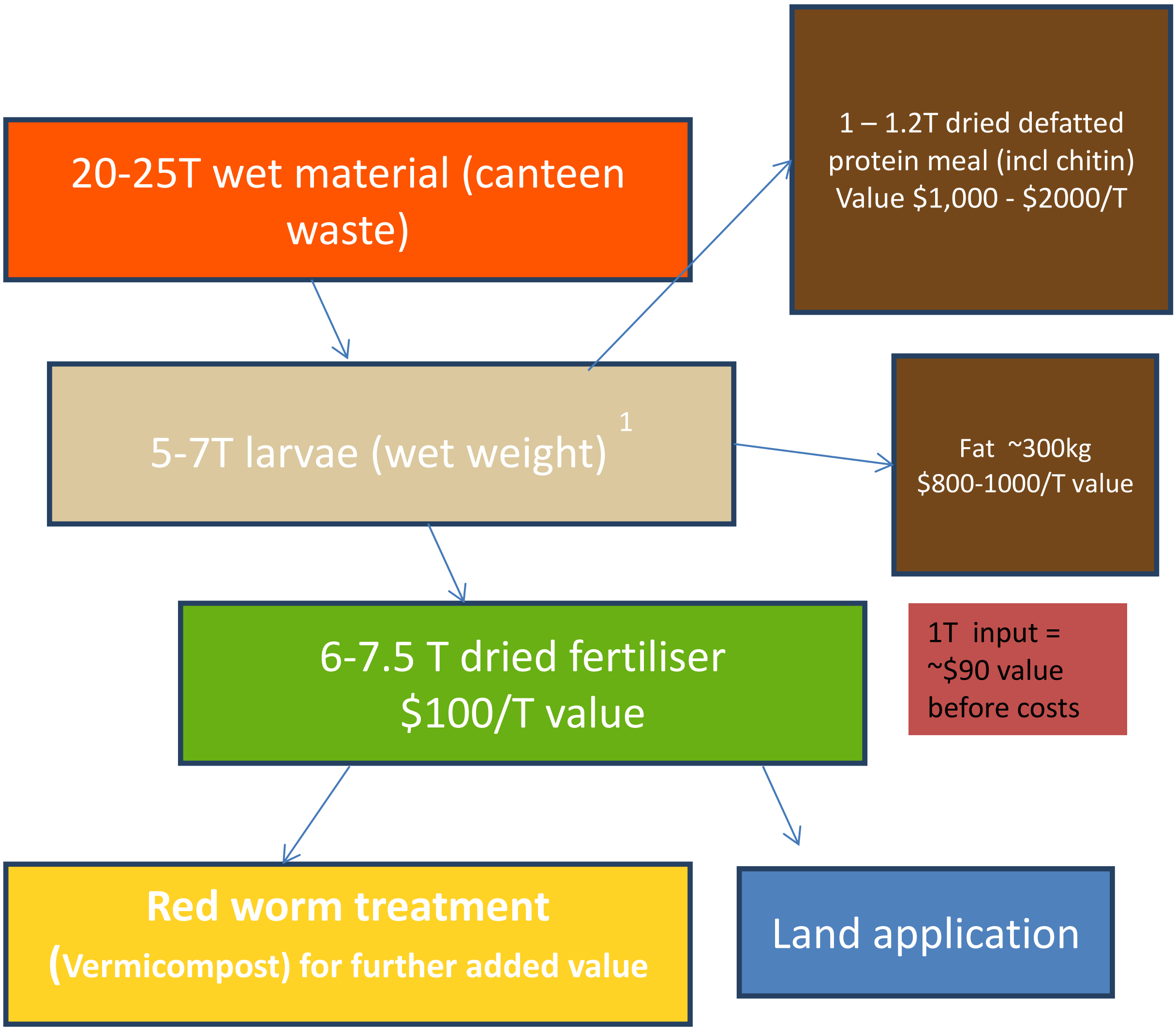

Figure 30: Example mass balance from an Asian fly facility

There are several points to note in the above example. Firstly, conversion rates are lower than would typically be seen in fish or poultry production so it is important that the input materials are not materials that could otherwise be directly fed to livestock. Secondly, the value of the input material based on what is generated is around $90/T before other production costs are considered. If it would cost more than 90$/T to source the input material, the economics of production are unlikely to be favourable.

4.7.vi. Managing risk in insect production

Illka Taponen, whom I met in Finland and also presented at the Woven Network Conference in Nottingham, wrote his thesis on risk in insect farming (*Taponen, 2015*) and has become known for his "Maggotmaster blog" *(@IlkkaTaponen).* One of the biggest challenges of the insect rearing will be biosecurity. Knowledge of disease and health management in intensive insect rearing is in its infancy. Just as with any living system, insects are susceptible to pathogen challenge. Insects do not have a learned immune system and cannot be vaccinated. Medicinal treatments are as yet undeveloped. The industry should be modelled on the poultry industry: high levels of biosecurity, both in the breeding colonies and the rearing farms. Within Europe, there are already two distinct approaches to risk. One model is a single site large scale facility. The other model is for smaller scale contractor type facilities with centralised breeding and processing. Both have their pros and cons, however; the risk associated with a colony breakdown on the single site is clearly higher than in dispersed sites.

Reliability and consistency of supply is a significant concern for the industry. Having established a market for insect products, the consistency of supply must be there to provide continuity of use. The animal feed industry has the capability of switching materials. This continuity of supply question appears to be holding back further use of insects by the pet food industry in Europe. They are demanding multiple supply chains of consistent and safe material in sufficiently large volumes to satisfy their demand and justify the expense of changing formulations and marketing insect based petfood. Insects with longer cycle times e.g. mealworms, will be more prone to supply disruption in the event of a disease event in comparison to species with short life cycles e.g. house fly.

4.7.vii. Insect processing

Without exception, the consensus view is that insect meals would be dried and defatted in order to make them attractive as a feed material. In soya processing, the most commonly used technique for oil separation is solvent extraction. This removes a greater proportion of the oil than mechanical expeller methods and the result is a product with a higher percentage protein. However, it is costly and complex. None of the insect producers I spoke with were considering solvent extraction of their meals, preferring a simpler, less technical and safer mechanical expeller process. In their 2016 whitepaper, the ProteInsect group did report that solvent extraction "*achieved the best results for physical, chemical and enzymatic profiles*". The downside of this is that expelling does not remove as much of the oil, or concentrate the protein in the meal, as solvent extraction would.

Although insect chitin may have some quite specific nutritional benefits, its presence in the meal dilutes the nutritional value. However, separation of chitin is costly and complex and so the insect meal producers I spoke with had no immediate plans to separate it. Conversely, companies that were looking to rear insects on non-feed/food grade materials for industrial purposes were interested in chitin separation as a potential and significant value stream from their process.

The method employed to dry the insect meals could also be critical to their nutritional value. According to the EFSA Scientific Committee (2015) report, a heat treatment step as applies to non-ruminant PAP, may be required under regulation 1069/2009 to reduce microbial risk to feed. Protein can be damaged by excessive heat and a loss in digestibility can result. The highest quality fishmeal is heat treated at low temperature (LT-Fishmeal) to maintain the protein digestibility of the meal, using an indirect steam source. The same logic could apply to insect meals. In China, microwave drying was also being considered. This produced a denser material which may have better bulk handling properties. In Vietnam, and more tropical locations it is possible to sun-dry the larvae meals, significantly lowering the cost and environmental impact of production. Sun-drying would certainly not be feasible in our more temperate climate or fulfil the requirement to heat treat for 'sterilisation'. The method used to heat treat could introduce variation in nutritional value by source, irrespective of similar species or substrates being employed, and those conditions should be reported when publishing results of insect meal evaluations.

Figure 30: Microwaved housefly larvae

Figure 31: Oven dried housefly larvae

4.8. Demand for insect protein in different feed markets

With the exception of Asia, and despite considerable research on the potential application in poultry, commercial developments in Europe and North America are currently targeting the aqua feed and pet food markets. There are several reasons for this. Firstly, the legislative block in Europe is preventing development of a market in livestock feed. Secondly, the cost of material is too high relative to other protein sources used in poultry feed. Unless it could be demonstrated that there is an "added value" or extra nutritional benefit over and above the indefinable nutrient value (e.g. energy, protein, minerals) feed producers are unlikely to pay a premium for using insect protein. At current prices of $1400/T for defatted, 50% Crude protein BSF meal quoted in March 2016 in North America, insect protein simply does not compete with the common protein sources used in poultry diets. In China the price was slightly lower at the equivalent of 10,000 RMB/T (around £850/T) for dried housefly meal. Entry price for high volume uptake poultry diets would need to be in the region of £300-400/T at current soya prices. At current prices, BSF is on a par with fishmeal, which over recent years has all but disappeared from most livestock diets as the price has increased. Consequently in all but specialist or organic diets the direct fishmeal replacement opportunity does not exist.

4.8.i. Pet food

Petfood volumes in Europe exceed aqua feed at 5.7 million tonnes. The UK petfood market stands at almost 1.5 million tonnes (http://www.petbusinessworld.co.uk/news/feed/uk-pet-food-market-grows-to--2-8bn). This makes pet food an important potential market for insect protein in Europe. In regard to insect protein, pet food is currently the only animal category to which live insect, and non-hydrolized PIP produced from 100% vegetable and dairy or egg, can be fed (*IPIFF, 2014*). This means that, besides trials in aquatic and livestock species, any industrial PIP production in Europe is currently solely for the pet food market. Besides specialist reptile or aviary markets, the major volume potential here is for cats and dogs. Insects are a natural part of feline diet. Dogs possess a chitinase digestive enzyme capable of breaking down the chitin rich exoskeleton of insects although cats do not (*Urich, 1994).*

The opportunity is for 'value-added' or differentiated products positively marketed to contain PIP, e.g. sustainable, natural, soya free, hypoallergenic, PAP free etc. It was also mentioned to me that there were benefits in palatability and processing using insect meals in pet food products which further enhances value to the petfood industry. In June 2014, **Petfoodindustry.com** reported that Jonkers Petfood BV in Holland launched a dog food with insects as the only source of animal protein. The pet food market also use fish oils so insect oils may also find a market here too. It is not clear if the petfood supply would generate more insect oil than it requires. Surplus would then become available to other markets. Interest in that opportunity is already developing in Holland as I will discuss later.

Dr Guido Bosch, whom I met at Wageningen UR, published his findings on comparative protein quality of different insects in pet food in Bosch *et al.* (2014). Housefly and BSF were found to have high protein and amino acid scores but low digestibility. Crickets scored highly for protein content and digestibility compared to fishmeal. Cockroaches scored poorly on essential amino acid profile and digestibility. Product safety and owner perception were identified as important for future application of insects in pet food.

The Pet Food Manufacturers Association reported that the UK petfood market grew by £10 million in 2014 to have a value of £2.8 billion. Pet food brands are high value and appetite for risk is extremely low. Insect protein, locally produced and where the entire process and supply chain is under the control of several key partners, may be seen by petfood companies as a more controlled risk than existing materials. Although pets are not in the food chain, the demands from the petfood industry on product quality will be as high, if not higher.

4.8.ii. Aqua Feed

Aqua feed is the fastest growing feed market in the world which is having a significant impact on demands for feed protein inputs. In 2013 in their annual feed survey, Alltech estimated that output grew 17% in a single year to 34.4 million tonnes. In Alltech's 2015 survey, aqua feed output was reported to have reached 41 million tonnes, just 3.2 million tonnes of that in Europe. Comparatively, total global feed manufacture grew at 2% annual increase. By 2030, it is estimated that over 60% of fish will be farmed representing a further 20% growth over current levels. Many common species of farmed fish are carnivorous: salmon, trout, sea bass, turbot, shrimp and prawns. They require a source of animal protein in their diet in order to grow efficiently and that need is most commonly satisfied with wild-caught fishmeal and fish processing trimmings. Approximately 70% of fishmeal and 75% of fish oil is used in aqua feed (*FEFAC, 2014*). Over the last 12 years fishmeal prices have more than doubled to around $1400/T driven by aqua feed demand and declining production through depletion of natural sea stocks.

A key sustainability goal of the aquaculture industry is to find an alternative to fish proteins for aqua feed and so this industry has much to gain from the potential to use novel proteins from insects, algae or single cell culture. Results from the ProteInsect project indicated that insect protein could replace more than half the fishmeal utilised in salmonid diets (*Koeleman, 2016*). Other alternative proteins including algae and single cell protein are also possible replacements being considered. Non-ruminant processed animal protein (PAP), including insect meal, has been permitted in European aqua feed since 2013 following regulation 56/2013, although there remains the hurdle of appropriate slaughterhouse registration *(IPIFF, 2014*).

Although PAP could offer a significant and more sustainable alternative to fishmeal in aqua feed, uptake of PAP of porcine or avian origin has been slow due to negative media coverage and retail and consumer resistance. Insect PIP would appear to be less controversial. Insect derived oil containing less than 0.1% protein is permitted in aqua feed.

4.8.iii. Poultry feed

After pet and aqua, poultry is generally considered as the 3rd market that will develop for PIP in Europe, regulatory changes permitting. This is a similar view to the US. In Asia it might be considered number 2 to aqua feed. The pet food demand in Asia is not as developed; however the opportunity for aqua feed there is much greater than in Europe. Currently there are two significant hurdles to overcome before PIP will feature in poultry feed: legislation and cost. Few, if any, published studies report any detriment to including PIP in poultry feed. As a poultry nutritionist, I would almost discount this as a significant hurdle provided there is sufficient knowledge of the nutritive value of the meal being used.

Even in North America, where legislation would permit the use of PIP in poultry, the cost is currently too high for it to be considered as a cost effective ingredient. At its current price level it competes with fishmeal rather than vegetable proteins most commonly used in poultry diets. Since its increase in price, fishmeal has largely disappeared from poultry diet formulation in all but very specialist diets. Organic diets may still be formulated with fishmeal, mainly as a source of methionine where synthetic methionine is not permitted under organic rules. Some high protein starter diets, such as those used in turkey diets, may still contain a small percentage (<5%) of fishmeal. In this situation, fishmeal offers the nutritionist a source of high quality protein without an overreliance on soya, which at high percentage inclusions is not ideal for the bird due to high levels of potassium, anti-nutritional factors, and indigestible carbohydrate. Relatively low rates of insect meal inclusion were tested in boilers as part of ProteInsect project; 2% of whole insect meal and 1.25% of extracted proteins. Reportedly neither level showed any negative effect (*Koelman, 2016).*

The way poultry diets are formulated has also changed. The supplementation of synthetic amino acids and formulating with digestible amino acids has also, in part, reduced the reliance in fishmeal. Indeed, fishmeal used to have an almost mythical benefit when diets were not formulated to such a high degree of precision they are now. Modern diets apply knowledge of standard ileal digestible amino acid requirement and ingredient quality, rather than simply attaining 'crude protein' target in the diet which was more commonplace over 20 years ago. This way of formulating did not necessarily provide a good quality of protein rich in essential amino acids, whereas the quality of protein in the fishmeal supplied higher quantities of essential amino acid per unit of protein. As a result performance would improve and be attributed to fishmeal rather than to specific nutrients that it contained.

So the opportunity for PIP in mainstream commercial poultry will take off when the insect production industry develops to a point where economies of scale and efficiency have reduced the cost to a point whereby it competes with soya or existing protein sources in the diet.

Should the volumes of oil by-product generated by the feed and pet food markets exceed the oil demand in those diets, it is quite plausible that insect oil will begin to feature in poultry diets as production develops. The composition of the oil could be quite variable, with indications that insect oils can reflect the substrate on which they were produced. In some cases there may be a potential added value if the oils were to contain a high level of omega 3 fatty acid for example.

Another unique feature of some insect oils, especially those from BSF production, is the presence of high levels of lauric acid. Lauric acid is a medium chain fatty acid, most commonly sourced from coconut fat which has recognised antibacterial properties. Whilst the cost of coconut oil usually precludes its use in poultry diets, feed additives already exist that contain lauric acid for beneficial effects on gut health and performance. It is possible that BSF oil in particular could capitalise on that benefit and thereby command a premium over and above its energy value against vegetable fats in the feed market. Already, this is something that Dutch feed company, Coppens Diervoerding, hopes to capitalise on with insect protein sourced from Protix Bio-Systems (*Byrne, 2016*). The challenge in the UK market would be that, whilst animal fats are allowed under EU legislation and tallows are commonly used in feed on the continent, UK retail and food service companies have been reluctant to allow animal fats into diets.

Trial work undertaken at the University of Turin was also indicating that birds fed diets containing 5% mealworm PIP consumed more feed and consequently grew faster. One suggestion from the research team there was that a component of the PIP may be inhibiting a satiety receptor in the bird. This could be a significant beneficial feature in poultry diets where intake may need to be encouraged in order to obtain better performance.

4.8.iv. Pig feed

Pig feed is likely to follow poultry feed in terms of uptake. Again, the opportunities will possibly be quite niche, targeted at high protein diets towards the early stages of production e.g. piglet pre-starter and creep feeds where fishmeal may still feature in formulation. There is also interest in the potential immunological function of insects in feed and one of the groups that I visited in Germany planned to study this in the future.

4.9. What could compete with insect protein in feed?

The biggest threat to development of PIP in poultry feed in the UK probably comes from the potential reintroduction of Processed Animal Protein (PAP) into poultry diets. The cost of PAP would likely be highly competitive with existing protein materials and could further increase the cost:value spread on PIP in poultry feed. The topic of PAP reintroduction has been debated by European legislators for nearly the last decade, but so far no progress has been made. The block is principally due to the assured and verifiable separation and segregation of PAP types to avoid contamination and a cost effective means of reliable testing. Progress on this has been recently achieved, although a timeframe for reauthorisation has yet to be set. Any reintroduction would apply to non-ruminant PAP only and intra-species cycling would not be permitted; so porcine PAP could be fed to poultry and vice versa.

Other potential novel proteins such as algae and single cell protein are also the subject of research and development and it would be premature to even speculate which novel protein source could win out over vegetable proteins in the future. However there may be considerably less regulatory barriers to these materials if they possess a lower food safety risk profile.

4.10. Nutritional composition

The phrase ‘you are what you eat’ really seems to apply to insect larvae. Certainly in the case of BSF, the substrate they are grown on appears to determine their amino acid composition, mineral uptake, and fatty acid profile. Some data on this was shared with by Enviroflight in Ohio.

continued on next page

4.10.i. Protein and amino acid concentration

Variations on the amino acid profile were observed with the use of different substrates. This will have quite an impact on the way nutritionists would formulate with insect meals. For nutritionists it will be important to know the substrate used and the amino acid profile that it will generate. Consistency of the substitute material will also be important to maintain consistency of the protein quality, i.e. the amino acid profile, in the final product. The variation in amino acid profile will be challenging for the feed industry to know the nutritional value of the insect material that is received, as it is not commonplace for routine direct measurement of amino acid levels in feedstuffs. Normally, amino acids are a calculation from an assessment of crude protein by wet chemistry or Near Infra Red (NIR) spectroscopy.

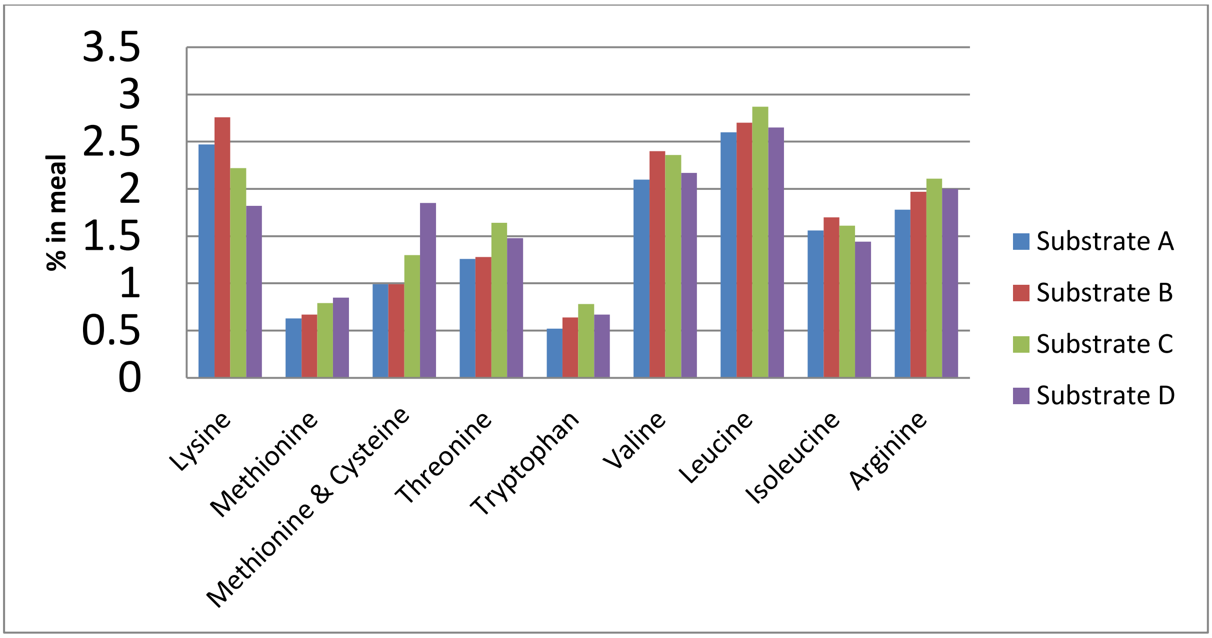

Figure 32: Amino acid concentration in BSF larvae meal reared on different substrates (Source: Enviroflight)

Figure 33: Dried whole BSF larvae waiting to be defatted. At 12% moisture, this material would typically contain around 40% Crude Protein, 36% Fat, 9% Ash and 2.5% calcium.

Figure 34: Defatted BSF meal after processing

4.10.ii. Oil and fatty acid concentration

Where insect fats are being used in feed, the variation in fatty acid profile will also be important to understand. This is particularly relevant where functional values are being ascribed to particular fatty acids, rather than just an energy source e.g. high lauric acid for intestinal health or high omega 3 or 6 for product enrichment. The energy level of insect meals will be affected by the oil level in both full-fat meals or defatted meals. Estimates on energy vary between 14.2MJ and 17.9 MJ in the literature (Józefiak *et al*., 2016).

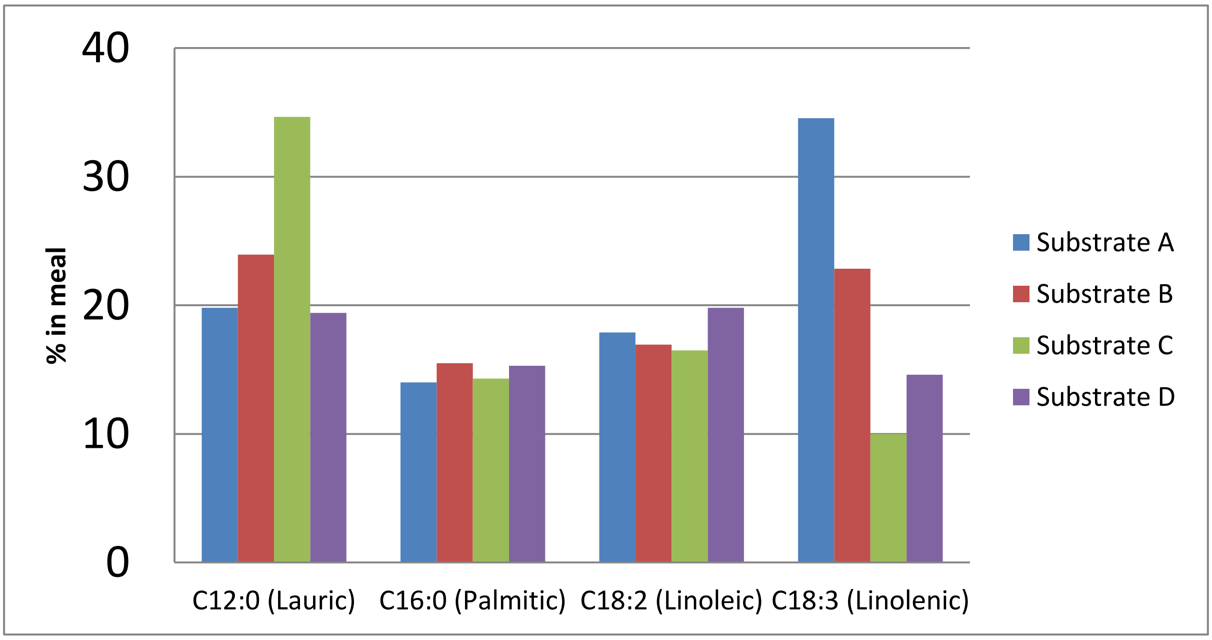

Figure 35: Fatty acid profile of BSF larvae fat reared on different substrates (Source: Enviroflight)

Figure 36: Expelled BSF larvae oil. The picture was taken at warm room temperature (around 25°C) where the oil remained solid, indicating a high level of saturation and higher melting point than many unsaturated vegetable oils. This could cause handling difficulties for food producers as the storage and dosing systems would require hearing.

4.10.iii. Mineral concentration

In the course of my study, I found little information on minerals was available, but previously, differences in mineral uptake by BSF larvae on different substrates has been reported by Newton *et al*. (2005).

Substrate	Poultry Manure	Pig Manure	Diff
Crude protein	42.1%	43.2%	3%
Oil (A)	34.8%	28%	24%
Ash	14.6%	16.6%	12%
P	1.51%	0.88%	72%
K	0.69%	1.16%	40%
Ca	5.0%	5.36%	7%
Mg	0.39%	0.44%	11%
Mn	246ppm	348ppm	29%
Fe	1370ppm	776ppm	77%
Zn	108ppm	271ppm	60%
Na	1325ppm	1260ppm	5%
Cu	6ppm	26ppm	77%

Figure 37: Mineral concentration of BSF larvae produced on different manure substrates (from Newton et al., 2005)

Mineral levels could be a limiting factor in the use of insect meals in poultry. In particular, calcium was identified as a potential limiting factor during several discussions. If we take a 5% level of calcium from the example above and suppose a 10% inclusion, the insect meal would be providing more than 50% of the target calcium level for a broiler diet. This means that when background levels from other ingredients are considered, calcium levels may be pushed above a level that would be desirable. Obviously, for laying hens where calcium is needed, that is less of a concern. Over-addition of other minerals such as potassium and sodium would also not be desirable. Trace minerals, copper, manganese, iron and zinc are limited in feed by European regulation to prevent their accumulation in the environment. As mineral accumulation in developing larvae appears to be influenced by and reflect those in their substrate, this raises concerns about bioaccumulation of heavy metals. Levels of heavy metals are strictly controlled in feed. A particular issue mentioned to me appears to be the concentration of cadmium in larvae grown in green leaf substrate and lead in post-consumer waste streams.

4.10.iii. Bioactive antimicrobial peptides

Certain species of insects are known to produce bioactive antimicrobial or antifungal peptides or polypeptides. The use of larvae to clean up wounds and treat infections is already recognised (*Drew and Joseph, 2012*). Anyone who has experience with sheep would understand this; an area of fly-strike becomes infected after the maggots are cleared off or stop feeding. In the future, insect-derived products might be a tool for the fight against antibiotic resistant infection. Given the unsanitary materials that insects feed in, this is possibly a self-defence mechanism. It has even been reported that pathogenic microbial loads are reduced with larval activity in manures (*van Huis et al., 2013*).

Very little is known about the presence or potential for bioactive peptides in the insect species considered for feed use. Would these peptides, which could be heat sensitive, survive harvesting and processing into the meal? Could they explain the reason that small quantities of live, unprocessed larvae may outperform their nutritional contribution as discussed in a previous chapter? During his presentation at the 2015 ESPN conference, Dr Damian Józefiak referred to the example of protein extract from cockroaches (Blattoptera spp), included at just 0.2% of the diet enhancing broiler growth (*Józefiak and Engberg, 2015*). A research group at Shihezi University in China reported that housefly maggot antimicrobial peptides reduced the infection rate of *Salmonella pullorum*-challenged poultry (*Zhou et al., 2014*). In the trial, the peptide production was stimulated by exposing the housefly to inactivated *S. pullorum*. What if similar effects could be achieved for *Campylobacter jejuni*! Besides that potential, given the pressure that the livestock industry is under to reduce antibiotic use, could insect derived antimicrobials offer a future alternative treatment?

Results of the ProteInsect piglet feeding trial reported by Byrne (2016) also indicated a positive shift in the gut microflora with more lactobacilli present in the gut of insect-fed pigs. As the meals would have been heat processed and any bioactive properties are likely to have been denatured, the effect may be due to a fermentable carbohydrate acting as a prebiotic e.g. chitin.

4.11. Mycotoxin control

One area receiving attention is the potential for insects to 'decontaminate' mycotoxin-infected grains. Mycotoxins are formed during adverse crop growing or storage conditions as products of mould growths from species such as *Fusarium*, *Aspergillus* or *Penicillium*. The feed industry is increasingly recognising the prevalence and impact of mycotoxin contamination and in some cases maximum limits of specific mycotoxin levels have been established under European Regulation.

Where these limits are exceeded, contaminated feedstock cannot enter the feed or food chain. Research conducted by Sarah van Broekhoven at Wageningen University has demonstrated that contamination of the substrate (wheat flour and wheatfeed) with deoxynivalenol (DON) did not affect the growth of *Tenebrio molitor* larvae. Furthermore there was no reported presence of DON or DON derivatives in the larvae themselves. The larvae excretions contained between 14-41% of the DON consumed which indicates that some form of detoxification might be occurring. This is an area that researchers that I spoke with - from Germany and Canada - are planning to investigate further. Canada in particular has suffered with high mycotoxin contamination in previous years, rendering corn unfit for consumption in poultry and pig diets. Processing by insects is seen as a potential means of detoxification thereby reducing grain wastage.

4.12. Sustainability

It would not be possible to cover the topic of insect bioconversion without the mention of sustainability as this is seen as a key driver for insect production and the application of insect protein in feed. One comment that resonated as I undertook my study was made at my first Nuffield Farming Conference in 2014. During the questions, a Scholar was challenged after their presentation about what did the word sustainability actually mean. The Collins dictionary defines it in an ecological context as *'the ability to be maintained at a steady level without exhausting natural resources or causing severe ecological damage'*. A lot lies behind that description and the meaning in different contexts could differ greatly. I considered it important to understand more about how to define sustainability in this particular context.

4.12.i. How should we define sustainability

Over recent years we have become familiar with the term 'sustainable intensification', yet almost conversely to this terminology we hear the words "organic" and "sustainable" used together. So what is sustainable: intensive or extensive? During the early stages of my study I read *'Resources for our Future: Key issues and best practices in resource efficiency'* by Weterings *et al*. (2013). The book includes a chapter by one of my Dutch hosts, Marian Peters of Next Generation Nutrition on insect protein in feed. However, an example from another chapter also caught my attention. The article describes the experience of DutchSpirit, the world's first 'eco-effective' clothing brand. Initially the company chose organic cotton as their ecological solution, before the founder realised that it was 'worse than bad' and switched to a 'climate-neutral' business model. This got me wondering if we need to better define a different system of 'sustainable agriculture' that can feed the growing global population in a resource-efficient way?

During my visit to SEGES I discussed how sustainability was being evaluated in Denmark. The FAO Sustainability Assessment of Food and Agriculture Systems (SAFA) guidelines (FAO, 2013b) were being followed which uses a spider plot scoring system to rank sustainability credentials across a balance of criteria based on 4 pillars of Environment, Social, Economy and Governance. All too often the "environmental" pillar is used alone to define sustainability which is over-simplistic and even potentially misleading. Just as Dutch Spirit realised this, a more balanced system moves farm sustainability scoring away a more traditional 'conventional' or 'organic' classification to a more holistic evaluation. Whilst both conventional and organic farming systems may score highly on one or two criteria; an alternative 'ecological' type system would have more clearly defined sustainability scores on a balance of criteria. This could then result in a farm scoring high for sustainability taking best practice from both organic and conventional systems.

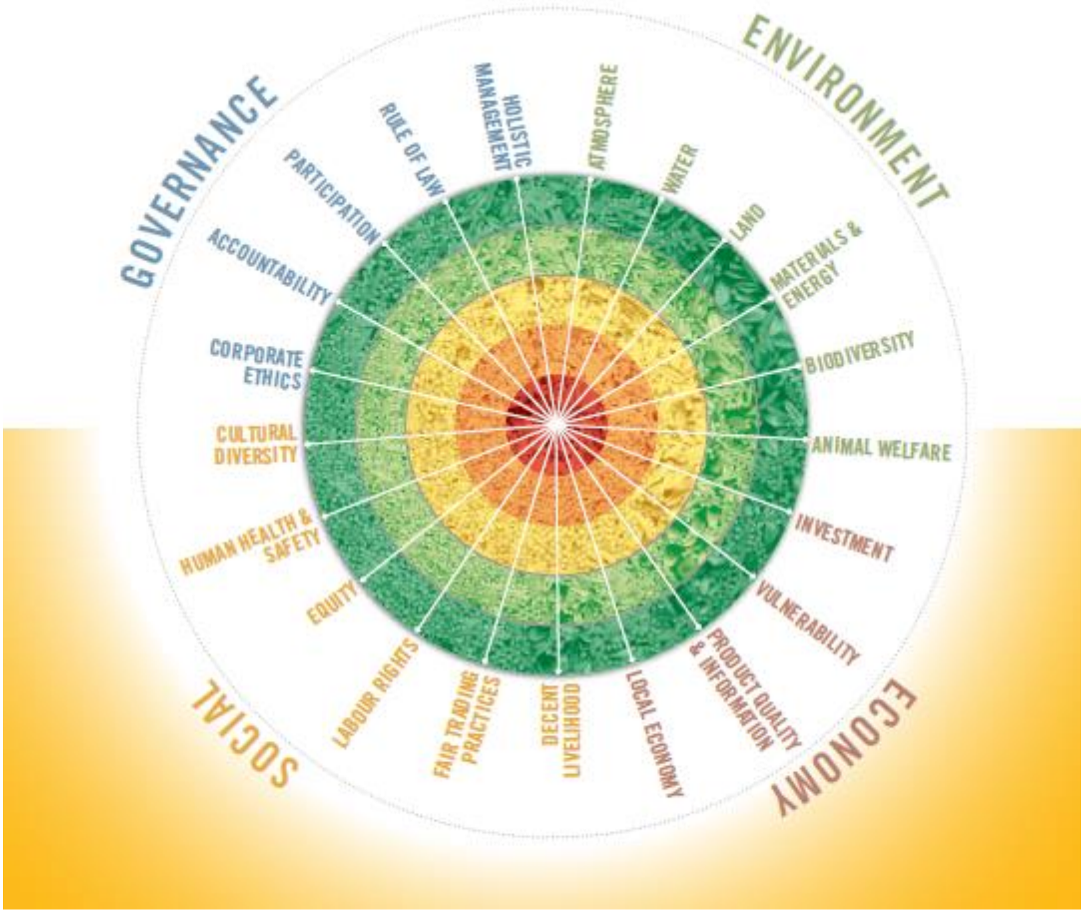

Figure 38: FAO SAFA guidelines scoring system (FAO, 2013b)

A report published by Garnett *et al*. (2015) reviews what is meant by the terms 'sustainable' and 'efficiency'. Where a policy of sustainable intensification may lead off in an unintended direction would be in the example of a pastoral grazing system. Would it be more sustainable to move to large scale zero grazed livestock systems? A multitude of quantifiable and, in some cases, unquantifiable, environmental and social benefits appears to support the idea that a holistic pastoral approach is more 'sustainable', albeit less 'efficient'. In their conclusions the authors suggest that definitions of sustainability and efficiency are highly subjective to the individual and propose replacing 'sustainable' with the term 'effective'. Effective systems can be more defined in their outcomes and so more clarity and direction would be possible.

The global feed industry is currently moving towards a system of defining 'Product Environmental Ratings' (PEF) for feed materials and feed in order to provide an indication of environmental impact. In this case, the methodology is Life Cycle Analysis based applying the FAO-led Livestock

Environmental Assessment and Performance Partnership (LEAP). So far, the database includes calculations for maize, wheat, barley, cassava, and soya beans with further ingredients, such as insect products, to be added in the future. With over 45% of livestock emissions attributed to feed, the system is really an emissions calculation tool. So, whilst it is the first step in defining one pillar of sustainability, it should not be interpreted as an overall sustainability assessment of animal feed materials.

Sourcing organic protein is a challenge for organic feed. Insects may offer an opportunity for organic feed producers to replace imported proteins (e.g. soya or sunflower meals) or those that may have a lower sustainability score (e.g. fishmeal). In Germany the organic certification scheme Naturland has, legislation permitting, indicated its support for the use of insect meals for fish and poultry. Unlike other organic certification schemes in Europe, Naturland does not allow the use of fishmeal in organic diets. Naturland. Finding an organic solution to protein supply was a significant reason that insects were of interest in Denmark as 22% of the Danish egg industry is classified as organic, albeit their rules appear to differ slightly from those in the UK organic sector. To qualify as 'organic' the process of insect production will need to be 'organic' which may limit the potential input materials and increase the cost. One company based in Tunisa, Next Protein, that I spoke with had identified an organic input stream from local sources of vegetable based by-product.

Towards the end of my study I witnessed the holistic approach to sustainability in action on a grand scale with Will Harris of White Oak Pastures in Georgia. He is building a highly successful agri-food brand on his farming enterprise and promoting the Allan Savory principals of holistic grassland management. Within this model, insect bioconversion of materials from the farm using BSF was playing their part in the farms' poultry production systems. Here was a system that was effectively experimenting with integrating insects within a broadly sustainable or effective business model; an excellent example of successfully developing and marketing a circular bio-economic system within a farming enterprise.

Figure 39: Pastured broilers at White Oak Pastures, Georgia, USA. The farm has been experimenting with supplementing the birds' diet with live BSF larvae produced on the farm.

4.12.ii. Environmental awareness in China

The portrayal of the Chinese environment has not generally been positive in the Western media over recent years, with stories and images and reports of river and air pollution. During my time in China I certainly got the impression that attitudes were changing, especially in the more urbanised Western and Southern regions. People realise that destruction of the environment by industry is not a sustainable future. More polluting industries are being increasingly controlled, which has led to factory closures or relocation to less densely populated regions to the North and East. Some would even attribute these pressures to control pollution to the recent slow-down in industrial output and economic growth China has experienced. This increased awareness of resource efficiency is certainly driving the interest in nutrient recovery from waste stream by insect production in China. Insect bioconversion projects here include the bioconversion of pig and poultry manure and municipal organic waste.

4.12.iii. Effectiveness of insect production

Considering commercial insect production, one of the biggest challenges for sustainability is substrate source and energy use. Work carried out at Wageningen UR and published by Oonincx and de Boer (2012) determined that, under Dutch conditions, the energy use of 1kg of mealworms for human consumption to be 35 Mega Joules (MJ). This is a higher energy use than is reported for poultry or milk production. Of the total, 35% of energy was from gas used for heating and 21% was for electricity. 56% of the energy use was from the production and transport of the feed substrate, in this example, carrots and mixed grains. This equated to a greenhouse warming potential (GWP) of 2.7 kg of CO_2-eq and a land use area of 3.6m^2 per kg of fresh worms. As the substrate was 'food grade' rather than from a by-product source this adds significantly to the feed inputs and land use values in this model. However, it does indicate that even for mealworms, with a lower temperature requirement than fly larvae the energy inputs are high and a significant cost and 'sustainability' factor to consider.

With future legislation in Europe likely to allow only 'food or feed' grade materials to be used for insects entering the food chain, achieving sustainable insect production for feed is going to be quite challenging. For example, it would make little sense from a nutrient efficiency perspective to take a material that is already utilised by the feed industry (e.g. cereal by-product, bakery by-product) and divert it to insect production to make insects for feed. Why introduce an extra feed conversion step where effective nutrient conversion could be lost? There would only be a real effective nutrient gain if food or feed grade materials that are currently going to land fill or bio-digestion were diverted to insect production. One example that was given to me was palm kernel meal, a low nutritive and highly indigestible by-product of palm oil processing in South-East Asia and Africa which can be bioconverted by BSF.

In the case of diverting products from bio-digestion, the efficiencies of nutrient and energy recovery would have to be evaluated against microbial break-down or insect bioconversion. A conflict may arise between the established (and heavily subsidised) bio-digestion industry and a new (most likely non-subsidised) insect industry. Due to the potential of subsidised market distortion, the value gain from insect bioconversion would need to be much greater to compete for this substrate. Over recent years, and particularly since the development of the grain ethanol industry, feedstock commodity prices have become closely linked to energy markets. For the most part insect producers targeting the non-niche markets are conscious of this and plan to locate facilities close to a source of under-utilised material (e.g. vegetable processing, grape pulp etc). However access to these types of material is likely to be somewhat opportunistic and finite.

4.13. Public acceptance of insect as a feed

In October 2015, the results of a six-month study by the ProteInsect team were published. The opinion canvassed the views of 700 respondents on their attitudes towards the use of insect protein in livestock feed, including for fish. The key outcomes were as follows:

- 81.7% regarded insect protein in livestock feed as totally acceptable, compared to 60% for fishmeal, 45% of meat and bone meal, 44% for GM crops and 36% for feather meal. Seaweed, non-GM crops, and grass did achieve higher preference scores.
- When asked about consuming meat from animals fed insect meal the number decreased slightly to 75.4%.
- 77 % of respondents perceived little or no risk to human health from consuming insects, whereas 27% perceived risk from GM crops and 23% perceived risk from meat and bone meal. Interestingly, 65% perceived risk from fishmeal yet fish is generally considered a healthy food.
- 70% of respondents claimed basic knowledge of animal feed contents.
- When buying meat, consideration to the diet of the animal was given by 8.3% every time, 24.9% frequently, 24% occasionally, 24.5% rarely and 14% never (4.1% didn’t purchase meat).

The results of further surveys published in the ProteInsect white paper (2016) reported 70% acceptability of insects used in livestock and aqua feed, and 73% would be happy to consume meat produced on diets containing insects. A slightly lower proportion (64%) of the survey regarded insects as posing no or low risk to the food chain whist 88% said they needed more information on insects used in feed.

In China, where insects are permitted as a feed source, I did get the impression that there may be reluctance among the feed industry to use the material that was already being produced. Stocks of unsold insect protein material were reported to be increasing. It was not mentioned why this was, but China has been rocked by several food safety scares in recent years: melamine in milk products, hormones and antibiotics in meat, and pesticides in fruit and vegetables. Perhaps the Chinese consumer is also seeking the reassurances on food safety of insects that Europe is demanding.

See photo overleaf of fruit and vegetable shop at Wuhan Airport, China

Figure 40: Changing attitudes towards food and environment in China?
"Pollution Free" Fruit and Vegetable shop at Wuhan Airport, China

4.14. Public attitudes towards insects as food

I felt it was important to gain an insight into the perception of insects as a potential food for direct human consumption. If there was public support for insects in their own diet, surely this would transpose to acceptance in animal feed. In December, I attended the 'Insects as Food and Feed' workshop at the University of Oxford, Martin College. Around 100 people attended the meeting with many different areas of interest in insects in the food chain. Attendees included restaurateurs, chefs, academics and researchers from multiple disciplines, graphical design artists (3d printers and food art could be the next big thing!), lawyers (seeing an emerging field of opportunity), entrepreneurs (insect entrepreneurs) and even a Zimbabwean crocodile farmer (who was experimenting with insects on his farm). Much of the interest was focused on the use of insects as a potential food source.

Figure 41: Freeze dried locusts, produced in Holland and sold for human consumption

4.14.i. Insect products creeping into food

There are essentially two types of food that contain insect products. There are those where the insect forms a functional part of the product by imparting nutrition, flavour and texture and offering a real alternative to other ingredients. The other is where a small quantity of powdered or whole insect are mixed with other ingredients to give a 'marketing' story or, in the case of whole insects, delivering the 'yuck' or 'shock' factor with perhaps little more than novelty value. Often, the insects are reared on a modified chicken feed diet and transported long distances for manufacture so the 'sustainability' claims that accompany these products are currently a little fragile.

Certainly on my travels, I was not overly impressed with the unadulterated insects that I consumed in whole form. Besides their crunch and unfamiliar texture, there was, on several occasions, a lingering aftertaste of rancid fat. Perhaps I was unlucky. However when I passed comment on this people did agree that fat stability could be a challenge to storage of insect products. That could present a challenge to the feed industry also as rancid fats could impair consumption and reduce the nutritive value.

On the other hand, I experienced new flavour sensations of insect 'sushi' (wasp larvae, silk worm larvae, cricket and grasshopper) prepared in traditional Japanese way forming a functional part of the meal at the Insects for Food and Feed conference. At the Nordic Food Lab in Copenhagen, I experienced the delicate citrusy flavour of red ant extract (collected from Kentish woodland) that the Laboratory has used to flavour a gin made in Cambridge. The gin is made in small batch runs (selling batch #3 at time of writing) and a 700ml bottle is retailing for just over £200. The lab is also experimenting with flavours extracted from other insect species.

Figure 42: Jonas Pedersen and Roberto Flore with their Anty Gin
at Nordic Food Lab in Copenhagen, Denmark

Figure 43: Insect Sushi lunch at Insects for Food and Feed Workshop, December 2015, Cambridge, UK

4.14.ii. Insects in a vegetarian diet

At the 'Insects as Food and Feed' workshop, perhaps my biggest surprise was the revelation from several vegan and vegetarians in the workshop that they would be happy to eat insects. This could be considered somewhat ironic given that insect meals are being considered as "fishmeal replacer" or "alternative animal protein" in livestock diets. Besides a high quality protein source, insects would also supply vitamin B12 in a non-animal product diet. The motivation for veganism or vegetarianism can be diverse and personal. If the reasons to be vegan or vegetarian related to concerns about animal welfare or ethics, my preconception was that insects would be regarded as 'food with a face' and thus entomology would not be acceptable. However, that did not appear to be the case. Additionally if the choice to be vegan or vegetarian was based on ecological concerns then insect protein appears to tick a box.

It is possible that this divergence between the attitude towards vertebrate and invertebrate can be explained by the acceptance that at least some insect species exhibit nociception or acute pain response (*Erens et al., 2012*). But in the absence of any emotional response, they cannot experience chronic pain or suffering. It may also be fundamental that humans do not form the same emotional attachments to insects as they do to vertebrate animals. I am sure this will be a debated subject in the future and one which the insect producer must take into consideration.

4.14.iii. Insect welfare

Significantly, insects are included within the 2013 Wet Dieren (Animal Act) in Holland in relation to their rearing. This clearly shows insects will be considered as farmed livestock deserving of protection under the Five Freedoms. Slaughter has not been included in the Dutch Act, as the preferred methods are yet to be decided. Cold stunning and 'freeze killing' or high speed maceration are generally the techniques used in the industry. For large scale producers of insect meals, maceration will be more cost effective than freeze drying. Freeze drying can cost up to €3-4/kg and would be required for 'whole insect' food, pet and zoo markets.

Whilst the subject of insect welfare is in the early stages of debate as the industry develops, it is clear that the European consumer expects increasingly high welfare and that the insect rearing industry should be, and is, taking into account welfare sensitivity (*Erens et al., 2012*). As farmed livestock, insects fall under regulation 999/2001 (TSE regulation) concerning registration of slaughter facilities and methods. It is generally felt that this regulation could be amended to facilitate insect slaughter as insects were not considered as potentially 'farmed species' when the regulation was originally drafted. The general consensus is that farmed insects will perform best under conditions that reflect their natural environments and allow natural behaviours as much as possible.

4.15. Integration of insects with other farming systems

4.15.i. Aquaponics

Combining insects with aquaponics was a discussion that came up during my visit to Marian Peters ,CEO of New Generation Nutrition (NGN). Marian and her team were conceptualising a project to integrate insect products with aquaponics. Under conventional aquaponics, nutrient rich water from fish rearing ponds is cycled through a plant hydroponics system containing, for example, vegetables, herbs, fruit or flowers. The plants strip the nutrients from the water and the clean water is returned to the fish rearing ponds to begin the cycle again. Aquaponics offer opportunities for low land use vertical or urban farming models and are both nutrient and water efficient. Aquaponics is also developing rapidly in arid climates in Africa and the Middle East. Surprisingly the majority of income from the aquaponics system is the sale of the plant products rather than the fish themselves. Although it is a cyclical system, aquaponics still requires nutrient inputs in the form of fish food. However, there is the potential to replace some or all of the fish food with insects produced by biomass bioconversion as, or as part of, the fish feed where carnivorous species are produced.

Since my visit, NGN have been announced as a project partner in 'Blue Field', an Agri-Food Capital project (http://www.agrifoodcapital.nl/nl/projecten/de-blauwe-akker) that will test the application of insect protein as an alternative to fish protein in a closed cycle aquaponics system. The first trials are expected in mid 2016. Agri-Food Capital is an organisation that promotes the development of the North East Brabant region of Holland into "an excellent agrifood region with international appeal".

An example of insects integrating in aquaponics can be found on the blog of Symbi Biological, http://symbibiological.com/category/aquaponics/, the research and development wing of TomKat Ranch Educational Foundation in California.

On a related note, during a visit to Holland I also learnt that the concept of Aquaponics is being applied to dairy cow production in the city of Rotterdam, where a floating 60-cow city is to be built in the dock area (www.floatingfarm.nl) with a planned opening date later in 2016. The cattle waste will be used to grow grass that will be recycled to the cattle as feed. Milk and dairy products will be supplied to Rotterdam, cutting down considerably on transport. I don't believe the concept has a name as yet but perhaps it should be known as Dairyponics!

4.14.ii. Biodigestion

A concept from Denmark that I had read about when planning my project, was the opportunity to utilise the frass, waste material remaining after insect bioconversion, for biodigestion. After my visit to Denmark this proposal does not appear to have much potential. Although the larvae take significant amounts of nitrogen from the substrate, they also utilise significant amounts of carbon as an energy source. So, the resulting frass has a C:N ratio that is no better, or possibly even lower, than the original substrate which, in the case of most nitrogen rich substrates, would make it unsuitable for biodigestion without additional carbon. Ideal C:N ratio of biodigestion is around 25:1 whereas the example reported by Newton *et al*. (2005) shows the ratio decreasing from 12.2:1 to 10.22:1.

	Pig Manure Nutrient (ppm DM)	BSF Frass Nutrient (ppm DM)	Change (%)
N	923.7	414.5	-55.1
P	676.2	378	-44.1
K	358.7	169.3	-52.8
Ca	969.3	425	-56.2
Mg	299.3	175.96	-41.2
S	80.31	44.44	-44.7
Fe	6.63	6.8	+2.6
Mn	12.8	6.05	-53.0
Zn	23.53	12.91	-45.1
Cu	14.85	8.05	-45.8
C	11,248	4232.6	-62.4
Na	99.93	48.15	-51.8
pH	6.24	7	+12.2
C:N ratio	12.2:1	10.22:1	-16.2

Figure 44: Composition of BSF Frass following bioconversion by BSF (from Newton et al., 2005)

It was suggested to me that an opportunity to perhaps integrate bioconversion with biodigestion might be to utilise the heat generated by the biogas turbines in the insect rearing facility. With energy inputs being a significant challenge to the economics and sustainability credentials of insect rearing, opportunities like this would of course be a significant benefit for insect producers.

See photo overleaf: finding heat sources for insects

4.15.ii. Non-food chain opportunities of insect bioconversion

Whilst use of insect bioconversion for non-food/feed biomass is unlikely to be approved in the EU, there may still be opportunities for using other waste materials (e.g. manure, abattoir waste, post consumer waste) for non-food chain insect production and, indeed, several of the companies that I visited are working in this area and there is considerable interest in the valorisation potential from waste management companies looking for opportunities to reduce their input to landfill. Indeed waste management companies in France and Holland are involved in insect projects. It is estimated that there are 22-million tonnes of biowaste in France which is being re-routed from landfill to biodigestion and possibly in the future, insect biorefineries. The food waste figure for Europe is estimated to be between 80 and 120 million tonnes. European manure volumes are estimated to be around 1.5 billion tonnes.

Figure 45: Finding heat sources for insects. This giant timber processing Fibreboard plant in Germany supplies surplus recovered heat from their process to the insect rearing houses at Hermetia AG.

There is still relevance here to the poultry industry as industrial use may be an outlet for poultry litter. In Belgium for example, there are investigations underway on the use of pig slurry for insect production for industrial purposes. Indeed, poultry manure may be a better substrate than pig manure. However, in the Belgian region of Flanders particularly, output of pig slurry exceeds the local availability of land for disposal due to restrictions of nitrogen and phosphorous application. Insect bioconversion may hold the answer to the problem, whilst also supplying the local chemical industries. There are less regulatory restrictions in this industry and start-up producers could scale up and commercialise much more quickly. The business model is quite different from the insect for feed model, although production is based on the similar principals of insect bioconversion.

Opportunities that may exist include:

- Oil for biodiesel, although insect oils may not possess the ideal properties for biodiesel production and the current oil prices (c. $40/barrel) do not provide stimulus for developing this opportunity.
- Proteins – glues, pastes.
- Bioactive peptides may be a further area of interest that has hardly begun to be explored. These peptides are believed to have antibiotic properties, forming part of the insect's own defence mechanism against bacteria, fungi, parasites and even it is thought, some viruses (*Jósefiak et al., 2016*).

- Oil. The high lauric acid content of BSF oil gives it similar functional properties to coconut oil which may be of interest for cosmetics, cleaners and surfactants. BSF oils may claim higher sustainability credentials than coconut oils although consumer perception of insect oil compared to vegetable oil for skincare products may remain an issue. Lauric acid is used in some animal feed additives for gut health. Even at a level of purification, it would be unlikely that lauric acid produced from a non-feed substrate would be permitted for use in feed.
- Chitin. Seen by some insect producers as "the greatest opportunity" and in some cases was the basis for their commercialisation project where non-feed grade substrates were being used. One office I visited had an entire wall filled with a library of chitin chemistry and industrial application, including for agriculture. Yet chitin separation did not appear high on the agenda of feed insect producers. This may be because of the low recovery cost:value opportunity and possibly the negative effect that the process might have on the quality of the protein meal. Depending on species, chitin comprises around 2-5% of dried meals. Extraction of chitin from protein meal would involve either chemical and/or enzymatic processes. Some feed additives used to overcome the effect of mycotoxins contain chitin as a binding agent. As a polysaccharide, it may be fermented in the gut and Józefiak *et al*. (2016) report that chitosan derivative may have immune-modulating, antoxidative, antimicrobial and hypocholesterolemic effects. Industrial application opportunities for chitin are also considerable. Chitin can trade for between €6/kg for standard quality material to €50/kg for high value material. Standard material comes from shell fish processing (shrimp) and high value material comes from lobster. Insect chitin would probably have to compete in the standard market depending on the quality and purity that can be achieved. The global chitin market is worth around $60 billion and opportunities for chitin or its derivatives (chitosan and glucosamine) could include:

  - Agriculture
    - as technical feed additives for mycotoxin control.
    - soil improvement.
    - bio-pesticide plant protection.
    - frost-protective seed coatings.
  - Medical
    - Implant surgery and dissolvable surgical threads.
    - pharmacological applications.
    - 3-D bio-printing of human tissues.
  - Industrial
    - Bioplastics. Chitin-based food packaging is biodegradable and is reported to help to increase product shelf-life through protective effects. Maybe in the future chicken packaging could be made from insect based materials.
    - Filtering agent for water treatment, from swimming pools to nuclear waste.

See Case Study overleaf

Case study: M2LARV project

M2LARV project. During my visit with Johan Jacobs of Millibeter, I was told about their involvement with the M2LARVproject run in conjunction with Univeristy of Gent and ILVO in Belgium. The project was to examine the integration of fly farms on pig farms. This negated the requirement for a centralised site to become registered as a manure processing facility. Disposal of pig slurry is a big issue in Belgium, the area of Flanders alone produce 18 million litres of slurry per day and this project examined the potential for BSF to bioconvert to materials with other uses. Millibeter had also been involved in a second project, 'Chitinsect', which focuses on the application of insect chitosan for industrial uses. The project was supported by FISCH (Flanders innovation hub for sustainable chemistry), an organisation that promotes the development of new technologies starting from green and renewable chemicals (http://www.avore.be/en/cases/chitinsect/).

Figure 46: Chitin separated from BSF larvae for industrial use.

4.15.iii. Frass

Frass comprises the undigested substrate and insect by-product (excreta, secretions and exoskeleton castings) of the bioconversion process. Insect frass is receiving much interest as a biofertilsier. It has a NPK value of between 5:3:2 and 4:1:1 depending on the substrate used. Additionally, it also contains chitin. Chitin has functional properties that benefit plant health and, in its pure form, is receiving interest as a natural plant protection product. Chitin can simulate the plant's immune defence mechanism as well as improving the microbial health of the soil. Trials run by the University of Stirling in Africa, noted much higher vegetable plot yields in those treated with insect frass compared to inorganic fertilizer. I was also told that insect frass was particularly popular with organic vegetable farmers in Japan with lower disease rates in the crops when it was used. The quality of the frass can depend on the substrate used for rearing the insects. In one case reported to me, where pre-consumer processed food material was being used, the sodium level in the frass was so high it killed the plants that it was applied to.

Frass in its own right has potential as feedstock for omnivorous fish e.g. talapia, catfish and freshwater prawns. It was even suggested to me that insect frass could be a potential ingredient for the ruminant feed market in the US.

In Asia it was proposed to me that insect frass could be vermicomposted, for which it is ideally suited. The red worms themselves are used for fish feed and the remaining substrate applied as an enriched bio-fertilizer. The worm castings themselves are rich in humic substances and can be 'extracted' by making 'worm tea'. This humic substance rich material is reported to be beneficial for plant growth. To my surprise, there was even a poster presentation on humic substance benefits in broilers presented at the IPSF meeting in Atlanta from a Mexican research group (Maguey *et al*., 2016). A full paper from the same group was published by Gomez-Rosales and De L. Angeles in 2015, where improvements in growing broilers on nutrient digestion and retention and improved growth rate were reported.

5.0. Discussion

There is little doubt that insects are likely to feature within the food system of the future, be it in feed or direct for human consumption. The method of production, inputs, species, effectiveness, and food chain safety are possibly bigger areas for debate than the question of insect product nutritive value or application to feed. There is little doubt that insects form a natural part of the diet, not just of foraging poultry, but of fish, pigs and, even dogs and cats. As with any processed protein meal used in feed, analytical value will vary from production site to production site. Much of the variation in, for example sunflower or soya meal, is process related e.g. oil extraction efficiency, degree of heat processing. With insects, the potential variation in nutritional concentration as a result of the input material could be significant and in addition to process associated variation. The question facing nutritionists will not be, can they be used, but do we understand how they were produced and the true nutritional value of them in terms of amino acids and their digestibility, energy, macro nutrients etc. Single source supply, advanced use of mill intake analysis or supplier certificate of analysis, beyond what is presently commonplace, along with reformulation, may be critical in the appropriate use of these products. A very similar quality variation issue is seen in the US with the supply of maize distiller's grains from bioethanol production.

It is most likely that aqua feed, and to some extent pet food, is going to lead the market development for the insects-for-feed industry. As this industry develops, demand and continued growth in aqua feed is likely to utilise most of the production for several years. As aqua feed will give a price premium over poultry feed for insects, that will also be a more attractive market for producers, at least until the volumes demanded for that industry have been satisfied and cost of production has reduced. Achieving those efficiencies of scale may then provide the entry point for insect meals into the poultry industry.

Whilst legislation on insects in Europe may seem overly cautious, it is not without justification. Consumer safety is paramount. For an insect production industry to develop, gain and maintain consumer confidence, it must deliver the mechanism to justify it. At the point of preparing this report, the UK has voted in a referendum to leave the European Union. The terms of the exit are at present time unknown and uncertain. In several years it is possible that the UK faces less regulation of food, feed and farming than at present. That may open opportunities for insect products in the UK feed industry before other EU markets. However, it is likely that there will be no compromise on consumer food safety and further risk assessments and implementation of controls in relation to insects in the food chain will be required.

Any food safety issue that could be traced back to an insect producer would not just have implications for their own business but for the reputation of an entire industry. In this connected world, that could arise from contagion from a non-European event where food safety controls are not in place. Anybody involved in the poultry industry has seen the damage that food scares can do to an industry. Twenty-five years on and the UK egg market is still climbing to pre-salmonella scare consumption levels. There is an opportunity with insects to bioconvert materials that could be considered high risk to the food chain and the valorisation potential on those materials would be high. That could mean the system is open to abuse where controls are not in place and enforced. Presently, the surveys conducted by ProteInsect show that insects as feed, benefit from a good deal of public support. However there was also recognition, understandably, of a lack of consumer knowledge. That suggests fragility in support. A little more knowledge arising from a negative food safety event could easily swing opinion the other way. The role that ESFA and IPFF are taking to evaluate and develop insect production with feed and food safety as a core objective is both pragmatic and commendable. But the insect industry must also be open about their production. Secrecy creates fear and suspicion in the mind of the consumer. Who would have imagined 10 years ago that poultry farms would now be built with viewing areas for the public to see how their chickens or eggs are produced? Conventional agriculture as realised that positively engaging with the consumer is so important and this new emerging industry should take note.

See next page for Info-graphic of the potential future structure of the insect industry in relation to poultry and other markets

For insect products to have a role in the future they must deliver tangible benefits in terms of environmental impact and satisfy broader sustainability objectives. The way insects are commercially produced, the energy inputs and the substrate feedstock will be critical to delivering these objectives and a benefit over conventional feedstuffs. In temperate climates such as the UK, energy inputs will be a significant challenge, especially during the colder winter months. The opportunities may lie in integrating insect bioconversion with another industry. One opportunity may be a vegetable processor that is generating both a useable food safe by-product material and heat source from their process. Where insect protein is compared to marine protein, I am certain a sustainability gain will be realised. As a protein source in poultry, given the advances in sustainable soya production in recent years, yield gains from application of GM technology and multiple cropping, the gain may be more challenging to realise. However, I am not aware that any work has been done to evaluate this as yet.

Despite the high volume of potential input substrates that exist, availability may be limited: firstly by regulation relating to food chain safety and secondly, by having to compete with subsidised energy generation bio-digestion industry that has already seen significant growth and investment. As energy costs increase, this will place further pressure on substrate availability at an affordable level. However, future reductions in energy subsidy may make insect bioconversion a more attractive proposition in the future. The value of the protein will be a significant factor in the economic justification of insect meals. Presently, the value:cost ratio does not stack up favourably in poultry or pig diets where little fishmeal is now used. However, in diets that do rely on fishmeal such as aqua feed or pet food, the economic justification is different and can carry a higher value:cost justification on use. Other novel alternative proteins under development e.g. algae or single cell proteins or even the reintroduction of meat and bone meals, could put downward pressure on the value of insect proteins in feed. Insect producers will need to consider themselves as farmers, producing a commodity whose value will increase and decrease with supply and demand, currency fluctuation and pressures from other materials that compete on nutritional value. This could make working on a "fixed cost model" difficult outside of niche product markets e.g. pet food, sustainable/ecological aqua feed etc. On the other hand, geopolitics, protein security and 'sustainability' demands could increase the value of insect proteins and distort normal nutritional valuations.

continued two pages further on

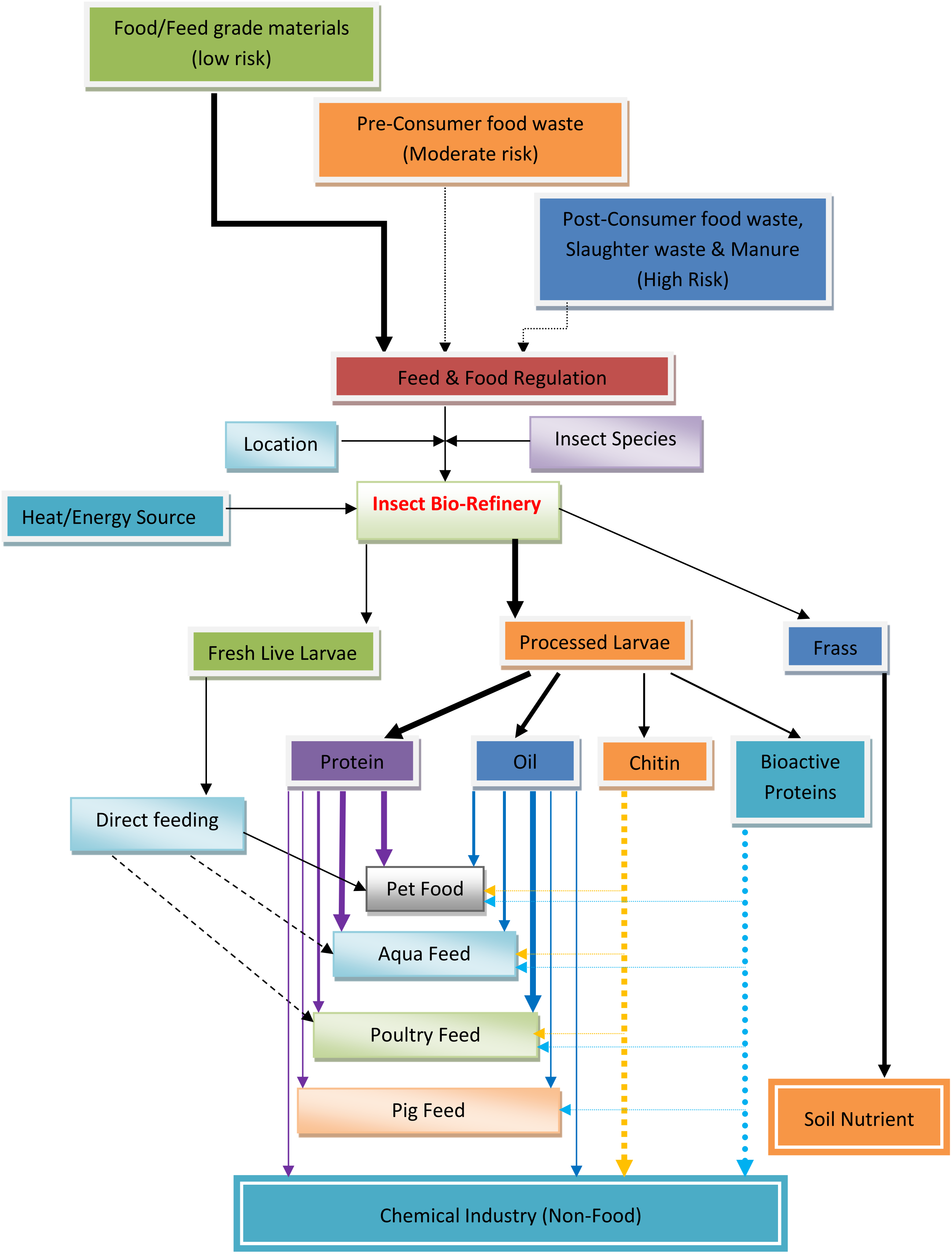

Figure 47: Info-graphic of the potential future structure of the insect industry
in relation to poultry and other markets. Dotted lines indicate 'yet to be' widely commercialised potential.
Gauge of line indicates volume potentials

Whilst much of the attention around insect as a feed has cantered around its value a source of protein, there are in fact other opportunities for insects in feed. It may come about that insect oil is a by-product of insect-protein production for pet and aqua feed markets. Consequently, the poultry feed industry may become a significant outlet for this material. The extra nutritional benefits of insects also require a greater understanding as do the potential differences of a live versus a whole dried and processed insect product. There seems to be evidence of health or immunity promotion either from specific components or via a more complex biological interaction. Predation of live food appears to be a strong natural behaviour that may have beneficial effects. Even under commercial production systems, delivery of live larvae may not be easily provided for, or indeed may present a biosecurity risk. Gaining an understanding of if, why and how live larvae exert an effect may allow this effect to be replicated in a way that could be delivered under a commercial farming condition e.g. extraction of bioactive proteins from insect larvae.

Opportunities for insect bioconversion of non-food agricultural materials and wastes are going to be limited to industrial non-food products. Nevertheless, outlets for biochemicals may already exist, or develop, particularly in relation to plastics and chitin based materials. This area is more embryonic in terms of identifying markets and the economics of production and material value. It may however hold a solution to manure disposal in areas of high livestock density and sensitivity to nutrient application.

6.0. Conclusions

1. Poultry feed could contain products of insect bioconversion in the future. The potential for insect products in poultry diets extends beyond the supply of high quality protein.

2. Development of a commercial insect production industry in European countries is faced with 3 major hurdles currently: legislation, cost and scalability.

3. More research is required to satisfy consumers and legislators of the preservation of food safety when using insects produced on different organic materials. The greatest opportunity for bioconversion is with the use of non-feed or food grade materials are used; however these materials will also present the greatest risk in terms of food safety.

4. As a fishmeal replacer, insect protein has a higher value and will be firstly taken up by the pet food and aqua feed industry. The poultry feed industry will be the "third phase" adopter as economies of scale reduce insect production costs. Initial use will target specialised diets e.g. organic or high protein starter diets.

5. Insect oil, generated as a by-product of insect processing for pet food or aqua feed, is likely to feature in poultry diets before insect protein and specific fatty acids could have some additional nutritional benefits beyond calorie provision.

6. There may be functional benefits associated with the consumption of live insects in poultry that requires further understanding.

7.0. Recommendations

1. Insect protein offers a real alternative to fishmeal use in feed and could offer significant sustainability benefits over ocean-caught fishmeal production. Fishmeal use has declined to a very low level in UK poultry diets over recent years but there is large potential for insect protein in aqua feed for carnivorous species as the growth in demand for sustainably produced farmed fish increases.

2. A more 'open-source' collaborative approach within the insect production industry and full chain stakeholder involvement from insect producer through to retailer would enable faster development of technologies and identification of opportunity as well as maintaining consumer confidence.

3. The opportunity for insects to valorise non-feed/food grade biomaterial from the agri-food industry needs to be recognised and both food and non-food market opportunities identified as a means to recover nutrients through bioconversion.

4. A greater understanding of the role of living insects within an extensive system is perhaps required. Would 'range enrichment' that encourages a more diverse flora and fauna have a benefit for bird performance and welfare? There is evidence that supplementation of diets with live insects has positive effects and more work is needed to understand the mechanisms behind this. It is possible that those effects could be replicated and harnessed for the benefit of an intensive system to create a differentiated product?

5. As we enter a period of political change, it needs to be recognised that UK sets a high standard on feed and food safety, and this should be upheld for the benefit of, and to maintain consumer confidence in, UK agriculture.

8.0. After my study tour

This study was a fantastic opportunity to meet with people outside my usual network of the poultry and animal nutrition industry. Being such a new and emerging field, almost everyone was an innovator, a pioneer, and an entrepreneur. I certainly recognise that I should be more proactive in embracing new opportunities in the future. I certainly have seen the sacrifice and dedication that people have put into projects that they are passionate about and believe in. To deliver the goal of what insects may present in the future of feed, demands focus on the final objective and dogged determination to achieve goals. As with any start-up industry the risk is high and not everyone I met or contacted had succeeded. Some meetings never happened because businesses had recently failed, others were with people who had rethought and adjusted their approach to the industry. But fear of failure will ultimately hold back the desire to innovate and that is a considerable mindset hurdle to overcome. I made a career change during my study which I believe was at least partly influenced by my Nuffield Farming experience.

Has the experience changed me? Absolutely! Whilst previously I had tendency to focus on the challenges in getting from A to B, I would now be much more focused on arriving at B and dealing with the challenges as they arise. I feel this makes me much more open minded towards new opportunities than I was before. I know I've missed some great chances in the past, but I think I would be less likely to pass up, or so quick to discount, new opportunities in the future. Also, while my previous work had involved international travel, travel as part of a Nuffield Farming study and arranging meetings with complete strangers is a much more independent experience and this has certainly increased my confidence of tackling the unknown on my own. For example, the thought of setting up and travelling solo in China was quite a daunting challenge and something that I never could have considered previously.

Would I consider the use of insects in feed? Absolutely, when legislation permits, but it will come down to a straightforward economic consideration on nutritional value against other available proteins unless there is another over-riding reason to use them: such as improved health, welfare or ecological considerations.

Would I invest, or start-up, in insect production for feed? Possibly, but at present it would be premature until changes to legislation permit more widespread use in feed beyond the pet food market.

What opportunities would I be seeking for an insect production facility? A location close to a stable and consistent supply of feed-safe substrate, preferably integrated on a site that generates surplus or low cost heat energy in reasonable proximity to the target market.

Did anything outside the subject area get my attention? Aquaponics! I see great potential in ways we can close the nutrient cycle in a food-safe way. The concept of a more circular bioeconomy is logical and it would seem that there are future opportunities for commercial poultry production to improve and delineate the nutrient cycle with imported protein.

9.0. Executive Summary

Countries visited: France, Spain, Italy, Belgium, Holland, Denmark, Finland, Germany, Czech Republic, China, Vietnam, and USA.

Insects as a foodstuff or feed material have been the subject of increased attention over recent years since the 2014 Insects of Food and Feed Conference at Wageningen University in Holland, at the impetus of the FAO. Insect protein is seen as a nutrient-effective solution for bioconversion of waste and protein supply. My study focused on finding out more about:

- Legislation of insect use in feed
- Research and development of insects and insect products for feed
- Consumer acceptance of insects as food or feed
- How insects are, or will be, produced
- Current and future use of insects and insect derived materials in feed
- Feed markets for insects, besides poultry. Who would the poultry industry compete with for access to this material?

Firstly, there is little doubt at this stage that insects could potentially feature in poultry diets – they are part of the natural diet. Further, although in its infancy as an industry presently, technology and knowledge are moving on apace and the commercial production of insects as a food or feed is becoming a reality. Producers were understandably very protective of technical 'intellectual property'. Getting into detail was sometimes difficult, or even just getting a meeting! Significant challenges do remain in terms of scalability and cost (labour and energy). The biggest area of uncertainty will be the substrate or feedstock to the insects due to the potential of insects to vector and bio-accumulate undesirable contaminants. In EU, subject to relaxation of current legislation, it is likely that substrates will be restricted to feed or food grade plant derived materials on the grounds of food chain protection. Less stringent restriction exists in countries outside the EU. At present, EU law remains in place in the UK and it is not clear what implications the future relationship between the UK and the EU will have on the future regulation of insects in feed. Substrate availability will have a big impact on both the economics and nutrient recovery effectiveness of insect production.

Besides protein there are other aspects of insects to consider. Insect oil is already being used by a Dutch feed compounder (legislation does not restrict this) and this could prove very interesting because of the fatty acid profile of some insect oils. The provision of live insects appears to have an "extra nutritional" impact on bird behaviour, health, welfare and productivity. This area is particularly interesting and requires more study. Insect bioconversion of non-food materials e.g. manure, may offer opportunities in industrial 'non-food' markets.

The big potential for insect protein is in the growing aqua feed market. Poultry feed will be a secondary development to this as both the value and need for poultry is lower. Legislation and cost competitiveness with other proteins are major hurdles for insect protein in poultry feed in the future, whilst the use of insect oils may develop sooner.

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