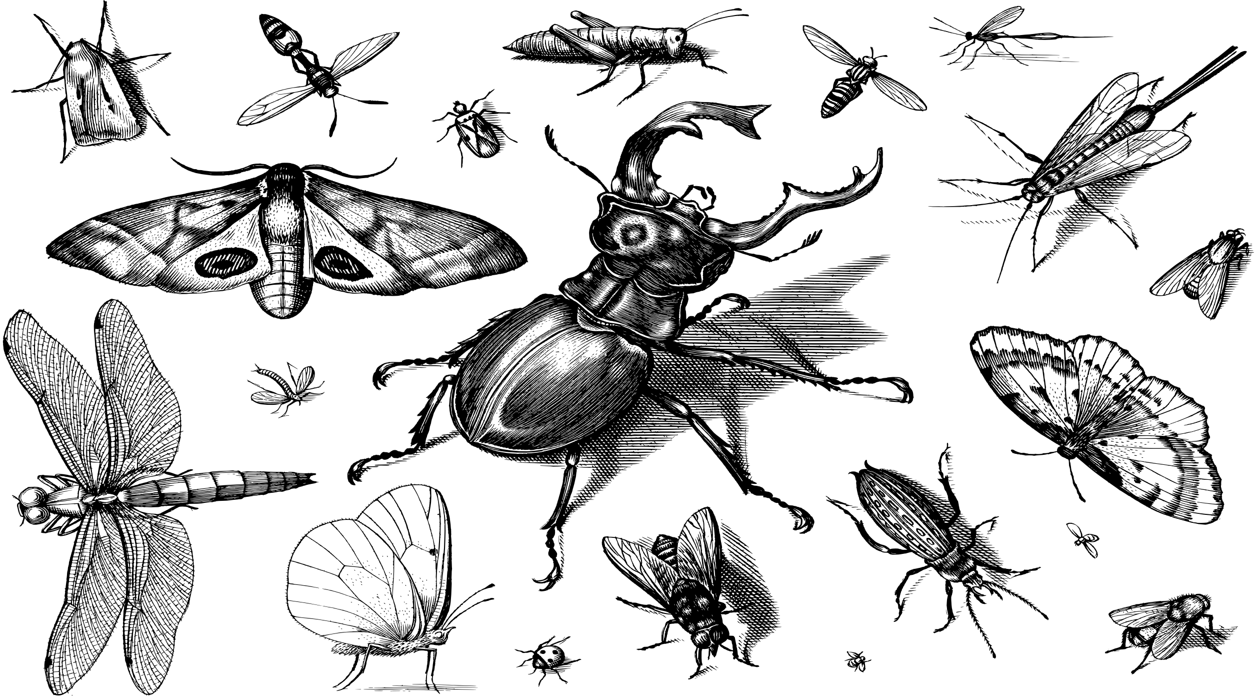

Introductory Research Essay

The Use of Invertebrates as Alternatives to Vertebrates in Food Production: Opportunities and Challenges

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The Use of Invertebrates as Alternatives to Vertebrates in Food Production: Opportunities and Challenges

Användande av evertebrater som alternativ till vertebrater i matproduktion: möjligheter och utmaningar

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Abstract

In its current form, food production adds pressure to climate change, biodiversity loss, antibiotic resistance, the emergence of zoonotic diseases, and other threats to human health. An alternative towards a more sustainable food system is the use of insects to replace vertebrate animal products. Insects are nutritious, can be fed crop residue, and their by-product—frass—can be used as organic fertilizer. In this essay I discuss and outline challenges and opportunities for scaling up insect farming.

Keywords: sustainable food systems, circular food systems, insect production, frass, organic fertilizer

Table of contents

List of figures

Introduction

The United Nations' second sustainable development goal aims to "end hunger, achieve food security and improve nutrition" by 2030. This goal will not be achieved. About 2.3 billion people experienced moderate to severe food insecurity in 2020 (FAO 2021) and the global population is expected to continue growing, mostly in the poorest regions(Gaigbe-Togbe et al. 2022). To fulfil current needs and meet the rising demand, we need to produce more food—particularly protein. However, there are caveats to producing more food. Currently, agriculture is the main driver of biodiversity loss due to conversion of natural landscapes, intensive agricultural practices[1], and pollution (Dudley & Alexander 2017; Sánchez-Bayo & Wyckhuys 2019). Loss of biodiversity within agriculture is bad because many of these organisms—such as soil biota and pollinators—play a vital role in ecosystem services that directly affect food production. Terrestrial vertebrate production is also problematic because it is resource intensive and antibiotic use is pervasive. Furthermore, animals within these systems are reared in high densities in confined spaces, which can facilitate disease transmission. Increasing food production—especially (vertebrate) animal products—will increase these problems. And these factors add pressure to climate change, biodiversity loss, antibiotic resistance, and the emergence of zoonotic diseases, all of which threaten human health and further complicate food production, leading to a negative feedback loop.

Part of the solution is to rely more on other sources of protein, like insects. Replacing food produced from terrestrial vertebrates (e.g., cows, pigs, and chickens) to food produced from invertebrates (i.e., insects) can contribute to a

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[1] Intensive agricultural refers to the increase of inputs and outputs per unit of agricultural land area. Increased insecticide or fertilizer applications are examples of intensive agricultural practices.

more sustainable food system. Insects can be a valuable food resource for humans because they are more efficient to produce, both in terms of energy (Smetana et al. 2021) and land use (Alexander et al. 2017). In this paper, I expand on the problems of vertebrate-based food production, describe the nutritional composition of insects and their feed requirements, and discuss the use of frass as fertilizer, and conclude with a discussion on the opportunities and challenges for insects to become a major staple in people’s diets worldwide.

Current vertebrate-based food production and its problems

The global demand for vertebrate-based food is expected to increase, in part, as a result of population growth (Thornton 2010). However, increasing reliance on vertebrate animals for food is likely to have large negative impacts both for the environment and human health. Livestock rearing requires a high amount of food and water resources. An estimate of 35% of global food production is allocated as (vertebrate) animal feed (Foley et al. 2011) and 29% of global water use in agriculture is related to livestock rearing (Mekonnen & Hoekstra 2012). Livestock rearing also takes up a lot of space. Around 70% of arable land is used for livestock (Van Zanten et al. 2018). Continuous conversion of natural landscapes for intensive agriculture around the globe will fragment habitats and perpetuate biodiversity loss (Chaudhary et al. 2016). For example, agricultural expansion is estimated to decrease insect species diversity by 40% within the next several decades (Sánchez-Bayo & Wyckhuys 2019). Furthermore, large scale rearing of livestock—especially cattle—contributes heavily to greenhouse gas emissions. Herrero et al. (2016) estimated that livestock contributed between 5.6 and 7.5 gigatons of equivalent carbon dioxide from 1995 to 2005, with main sources of these emissions being methane (CH_4) from enteric fermentation and animal manure (43%), N_2O from manure and slurry management (29%), and CO_2 from land use changes and fossil fuel usage (27%).

The overuse of antibiotics within livestock rearing can lead to serious consequences for humans. Antibiotics are widely used in (vertebrate) animal production systems as therapeutics, for preventative care, and as growth promoters (O 'neill 2015). In particular, low dosages of antibiotics for growth promotion can facilitate antibiotic resistance and be transmitted to other animals and humans outside the rearing facility (Robinson et al. 2016; Espinosa et al. 2020). If antibiotic resistance spreads to humans, the consequences can be extreme. An estimate of 10 million deaths will be attributed to antibiotic resistance by 2050 (O’Neill 2014). Furthermore, many infectious diseases are zoonotic (i.e., transmissible from vertebrate animals to humans), like covid-19 and monkey pox. Large scale livestock production involves rearing high densities of animals, typically of a single breed (meaning, genetically similar), in closed spaces. This creates an environment where pathogens can spread quickly, and the likelihood that a pathogen will mutate and evolve increases (Espinosa et al. 2020).

Insects as a food resource

Insects have always been important to the food chain. Many species of amphibians, reptiles, birds, and mammals are insectivores (i.e., animals that feed primarily on insects). And other animals, including humans, incorporate insects as part of their diet. In fact, it is estimated that over 2 billion people incorporate insects into their main diet, particularly in tropical and subtropical regions (Pal & Roy 2014). Furthermore, it is too costly to completely remove insects from food during harvest and processing. Thus, insects are consumed unknowingly in many different food products, such as flour, tomato-based sauces, chocolate, and ground spices (USFDA 2018). One could argue that all humans eat insects. In response, the insects' unintended presence in our food is subject to regulation. For example, in the United States, the Food and Drug Administration permits certain levels of whole insects and insect parts (e.g., eggs, larvae, segments) in many food commodities[2]. This furtive insect medley does not seem to have any hazardous effects to human health. In fact, some insects are quite nutritious.

Insects are well known to be a good source of protein, fats, and other vitamins and minerals (Fig. 1). In some cases, insects are even comparable to meat products from vertebrates. Orkusz (2021) showed that a 100g portion of the house cricket (*Acheta domesticus*) had 20.5 g of protein and 5.06 g of fat, while 100 g portion of beef sirloin had 20.1 g of protein and 3.5 g of fat. Similar protein and fat composition has been found also in other species. Zielińska et al. (2015) analysed the nutrient content of yellow mealworms (*Tenebrio molitor*), adult tropical house crickets (*Gryllodes sigillatus*), and adult locusts (*Schistocerca gregaria*) and found that these three species contained 52-76% protein, 12-24 % fat, and were rich in magnesium, copper, iron, and zinc. As with other animals, the nutrient composition

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[2] For example, in wheat flour it is allowable to have an average of 75 insect fragments per 50 grams

of the insects can differ based on the species, sex, stage of development, method of processing (e.g., blanching, drying, baking), and its diet. For example, Oloo et al. (2020) in the context of small-scale cricket farmers in Kenya, found that kale and sweet potato vine diets produced crickets with higher crude proteins compared to commercial cricket feed products.

Figure 1: Primal Future brand protein powder made from crickets (Acheta domesticus). Photo by Primal Future from Pixabay

The most common types of feed for mass reared insects are poultry feed, grain, and soybean (Fernandez-Cassi et al. 2019; Bawa et al. 2021; Jucker et al. 2021). However, in nature insects have a wide range of diet and can consume plants, seeds, and other animals. A major benefit of rearing insects as food is that they can be fed plant biomass inedible to humans, like crop residue (i.e., plant biomass leftover after harvest) and food waste. Several recent studies have explored crop residue, food waste, and other plant by-products as feed for insects with varied levels of success. Sorjonen et al. (2019) explored the effects of potato protein, barley mash, barley feed, and compressed leftover of turnip rape on the growth and development of the house cricket and the two-spotted cricket (*Gryllus bimaculatus*), and found that crickets fed high protein turnip rape and barley mash diets had the best growth performance. Jucker et al. (2021) tested maize grain distiller, fruits and vegetables, grape marc, and two types of brewery waste on growth metrics of the house cricket and found all diets, except for maize grain distiller, resulted in high mortality. Cappellozza et al. (2019) used a mixed diet of fruit and vegetable market leftovers to rear black soldier fly larvae (*Hermetia illucens*), but larvae fed on a standard diet[3] had higher growth performance. Introducing plant by-product diets as either a complete or partial substitute to

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[3] The standard diet—also known as the Gainesville stable fly diet—is composed of pelleted peanut hulls, alfalfa meal, wheat bran corn meal, meat and bone meal, brewers' yeast, and brewers' dried grains

conventional diets is a very sustainable alternative because plant biomass inedible to humans can be used to produce protein.

Insect frass as a fertilizer resource

Figure 2: Frass from crickets (Acheta domesticus). Photo by Sara Capitan

A by-product of mass insect rearing is frass. **Frass**[4] is a mixture of insect feces, molted exoskeletons, and leftover food and substrate (Fig. 2). Frass contains many essential nutrients for plants and can be valuable as a fertilizer. A review by Beesigamukama et al. (2022) compared the frass composition of nine different edible insect species and found the macronutrients nitrogen, potassium, phosphorous, calcium, magnesium, and sulfur and the micronutrients manganese, zinc, copper, iron and boron present in all frass from all insects, though some species had higher amounts of macronutrients than others. The presence of micronutrients in frass is valuable, as micronutrients can facilitate nutrient use efficiency of plants and are generally uncommon in synthetic fertilizers.

Frass is unique compared to other conventional fertilizers because it is an organic insect-based fertilizer that contains chitin, a primary component of insect exoskeletons[5]. Chitin has many beneficial properties in agroecosystems. A derivative of chitin—chitosan[6] – has been used as an insecticide, as a suppressant of various fungal and viral diseases in crops and has been shown to exhibit

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[4] In some environmental studies, frass is defined as only insect feces. Other sources defined frass as debris and excrement. However, in the context of mass insect rearing, frass is feces, molted exoskeletons, feed and substrate leftovers because all components effect the composition of frass as a fertilizer product

[5] Chitin is also found in crustacean shells and the cell wall of fungi

[6] Chitosan is produced when chitin oligomers are deacetylated

antimicrobial properties (Sharp 2013). Chitin also elicits plant defenses. Chitin is recognized by membrane-localized pattern recognition receptors in plants that trigger immune response (Jones & Dangl 2006; Lo Presti et al. 2015). Frass may also contain beneficial microbial communities, which can improve soil fertility and increase crop yield. For example, certain genera of bacteria (e.g., Bacilli) found in insect guts can stimulate plant growth and improve plant tolerance to biotic and abiotic stressors (Porto de Souza Vandenberghe et al. 2017). Insect guts can host a diversity of microbes, including fungi, bacteria, archaea, and protists (Hongoh 2010; Barcoto et al. 2020). However, microbial communities in frass can be affected by many variables, such as rearing conditions, diet, species, and development stage of the insect.

Insect frass is still a novel fertilizer and the effects of frass on plant growth are still largely unexplored. There have been several recent greenhouse studies on nutrient use efficiency in crops with applied frass treatments. In a pot experiment with maize, Beesigamukama et al. (2020) found that black soldier fly larvae (*Hermetia illucens*) frass had positive effects on nutrient uptake and chlorophyll concentrations. In another pot experiment, Houben et al. (2021) analyzed nutrient availability of yellow mealworm frass in Italian ryegrass (*Lolium multiflorum*) and found that frass effectively supplied phosphorous and potassium. Wichern et al. (2021) explored the biological properties of frass from yellow mealworms (*Tenebrio molitor*), black soldier fly larvae (*Hermetia illucens*) and buffalo worms (*Alphitobius diaperinus*) and found that all three types of frasses facilitated carbon and nitrogen mineralization and bacterial and fungal abundance. Short term pot experiments like these are very valuable in understanding how chemical and biological properties of frass impact plant growth and may show how frass may be used for sustainable plant production.

Opportunities of insect production

Insects alone are not the solution to ending hunger and mitigating climate change. It is just one viable part towards more sustainable food systems. Rearing insects for food will likely aid in meeting rising food demands without increasing reliance on vertebrate animal products and the vast negative impacts that follow with this industry. This is because insects use less land, energy, and water. Also, insects have the potential to be reared on plant biomass inedible to humans, such as crop residue and other plant by-products. All this combined shows insects' potential as a sustainably produced nutritious food. Furthermore, insect frass has shown value as an organic fertilizer containing essential nutrients, chitin, and other potentially beneficial microbes for plants.

Because of these potential benefits, insect production fits well into the idea of **circular food systems**, a term derived from the idea of a circular economy, applied to food producers who aim to reduce the use of new inputs in food production by recycling inedible waste (Winans et al. 2017; Zanten et al. 2019). Specifically, insects are capable of recycling plant biomass inedible to humans and converting it into edible protein, and frass produced by insects can be used as an organic fertilizer. Popular mass reared insect species that have the potential to be used in circular food systems include the black soldier fly larvae (*Hermetia illucens*), yellow mealworm (*Tenebrio molitor*), house cricket (*Acheta domesticus*), tropical house cricket (*Gryllodes sigillatus*), and the migratory locust (*Locusta migratoria*) (Raheem et al. 2019). Only a handful of insects are reared in commercial scales (Ortiz et al. 2016), but as there are over a million described insect species, there are likely many other insect species that can also be used in circular food systems.

Challenges of insect production

Current insect production is nowhere near the scale of vertebrate-based food production. Therefore, there are many challenges to overcome before insects become a feasible alternative to vertebrate-based food products. Today, many mass reared insects in Europe and the US are intended to feed pets, livestock, and aquaculture—not people. Large efforts to further develop ecological knowledge of reared insects as well as the regulatory framework around insect industries are necessary for a future scaling up of the industry.

In many countries, regulation of insect production is underdeveloped or lacking (Bang & Courchamp 2021). There is a need for more regulation of insect species used in mass rearing at a national level, because insect production facilities can potentially rear insects that are not native to the country they are being produced in. This can lead to unintentional release of insects and potentially cause biological invasions (Berggren et al. 2019). Furthermore, there are few production standards for mass rearing insects and there is a potential for unwanted microbe introduction in and between rearing facilities(de Miranda et al. 2021a). Pathogenic microbes present risks to insect health, which can lead to outbreak, reduced yield, and economic loss (de Miranda et al. 2021b). Types of feed and substrates used, methods of rearing, processing and movement of animals between facilities likely impact the types of microbes present. In a circular food system context, using plant by-products as feed can introduce unwanted microbes into insect rearing facilities and applying untreated frass to agricultural systems can introduce bacteria and fungi harmful to crops.

In the European Union, certain insect species have only recently been approved for use as food for humans. In 2015, "whole insects and their parts" were classified as a novel food category (European Commission 2015) and in 2018, the European Commission explicitly addressed the use of whole insects as food. As of

February 2022, the European Commission has approved the use of the yellow mealworm, the migratory locust, and the house cricket as novel food items in frozen, dried and powder forms (European Commission 2022). In the United States, there is no law that specifically addresses the use of insects as a food item. Under the Federal Food, Drug and Cosmetic Acts, the Food and Drug Administration regards the presence of insects in food items as a defect and classifies insects and insect parts present in food as “filth” (USFDA 2018). Explicitly addressing the use of whole insects as food is the first step towards regulation within insect production here.

Compared to livestock, the amount of research on insects as food and fertilizer is very small. The lack of standardized practices in insect rearing complicates some of the applied research. The edible insect species that are for sale today likely have had different diets, rearing conditions, and are processed using different methods. This can affect the quality and nutrient composition of the food product. Plant by-products as a feed source for insects is very promising but requires more research to reach its potential. Designing successful diets for mass reared insects is a complex task. There are essential nutrients that insects need, and generally a successful diet contains proteins, lipids, carbohydrates, vitamins, and minerals (Cohen 2015). However, insect species require different proportions of these elements, and nutritional requirements can change throughout an insect’s life stage development. Diet also influences the composition of the resulting frass and this needs to be considered if insect frass is to be used as fertilizer. Furthermore, the effects of frass on plant growth are still largely unknown. Short term pot experiments of crops grown in the greenhouse are valuable, but it is unclear how results will scale if frass is applied on a field-scale. Further exploration of the chemical and biological properties—especially microbes present in frass—are needed to understand the effects of insect frass on plant growth.

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