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REVIEW ARTICLE

The environmental sustainability of insects as food and feed. A review

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Abstract With a growing world population, increasingly demanding consumers, and a limited amount of agricultural land, there is an urgent need to find alternatives to conventional meat products. Livestock production is, moreover, a leading cause of anthropogenic-induced climate change. To mediate this, more sustainable diets are needed, with reduced meat consumption or the use of alternative protein sources. Insects are promoted as human food and animal feed worldwide. In tropical countries, edible insects are harvested from nature, but overexploitation, habitat changes, and environmental contamination threaten this food resource. Therefore, sustainable harvesting practices need to be developed and implemented. We provide examples of (1) aquatic insects whose populations are threatened by pollution, (2) caterpillar species in Africa that are disappearing due to overexploitation and habitat change, (3) edible insects species that are considered pests in agro-ecosystems, and (4) edible insect species that can be conserved and enhanced in forest management systems. Insect farming can be conducted either on small-scale farms or in large-scale industrialized rearing facilities. We review the environmental sustainability of insect farming compared to livestock production. The major environmental advantages of insect farming compared to livestock production are as follows: (1) less land and water is required; (2) greenhouse gas emissions are lower; (3) insects have high feed conversion efficiencies; (4) insects can transform low-value organic by-products into high-quality food or feed; and (5) certain insect species can be used as animal feed or aqua feed. For instance, they can replace fish meal, which is becoming increasingly scarce and expensive. However, edible insect species intended for production should be screened for risks to humans, animals, plants, and biodiversity.

Keywords Climate change · Edible insects · Environmental impact · Feed conversion efficiency · Insect farming · Life cycle analysis · Overharvesting · Pollution

Contents

1 Introduction

Insects are being proposed as an alternative protein source for humans, livestock, and fish (Van Huis et al. 2013). In tropical countries, there is a history of insect consumption by humans

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(Bergier 1941; Bodenheimer 1951; DeFoliart 2012). It is only recently that they have been considered as human food in the western world. Furthermore, there is an increased interest in using them as feed for pets, pigs, poultry, and fish. This growing academic interest is illustrated by the number of scientific publications on the topic. Using the term "edible insects" on the Web of Science (accessed 1 August 2017) yielded 53 publications for the year 2016, while in the 5-year periods 2006–2010 and 2011–2015, it was 25 and 83, respectively.

In tropical countries, edible insects are traditionally harvested from nature (Fig. 1). They contribute to food security, as they are often used for home consumption, or they provide a source of income when marketed. They are a seasonal product as most species depend on host plants. Increased deforestation, agricultural intensification (e.g., pesticide use), and environmental pollution may threaten the resource, while higher demand and increased prices could lead to overexploitation (Ramos-Elorduy 2006). The prices of edible insects, e.g., edible grasshoppers (Agea et al. 2008) and palm weevils (Ayemele et al. 2016), are often higher than those for meat products.

Apart from being collected from nature, insects can also be reared in confined industrial facilities (Oonincx and de Boer 2012). Western countries are now investigating the potential of this approach, prompted by the need to find alternative protein sources. These alternatives are needed because demand for meat products is increasing while the available land area for livestock production is limited (Van Huis 2015). In addition, current livestock production contributes greatly to a number of environmental problems such as acidification due to leaching of ammonia, climate change due to greenhouse gas emissions, deforestation, soil erosion, desertification, loss of plant biodiversity, and water pollution. These are highlighted in Steinfeld et al. (2006) and later in other publications (Gerber et al. 2013; Herrero et al. 2015; Herrero et al. 2016). The question is whether the production of insects as an alternative protein source is environmentally more sustainable than the production of conventional animals (Abbasi et al. 2015, Gahukar 2016).

Sustainability in an agricultural setting can be defined as practices that meet current and future societal needs for food and fiber, for ecosystem services, and for healthy lives and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered (Tilman et al. 2002). Another definition goes even further, stating that sustainable systems should be "socially supportive" and "commercially competitive" (Gold 2016). This review focuses on environmental aspects of sustainability. For an extensive review of ecosystem services from edible insects, we refer to Payne and Van Itterbeeck (2017).

If insects are to be considered as feed (Fig. 2), the market will require huge and guaranteed quantities of a high and standard quality. The feed market increased by 14% between 2011 and 2015, totaling 464 million t for poultry, 254 million t for pigs, 35 million t for cultured fish, and 23 million t for pets (Alltech 2016). This means that there is an enormous potential market for insects as feed, But the question is whether insects would use fewer natural resources than livestock (Marone 2016).

In the following paragraphs, we discuss the urgent need to find alternative protein sources, the necessity to change our diets, the environmental issues related to harvesting from nature, the environmental impact of farming insects as mini-livestock compared to the conventional livestock species, and the risks associated with insect farming (Fig. 3).

2 Need to replace current protein sources

The demand for meat products is expected to increase from current levels by more than 75% in 2050 due to population growth and rising incomes. The per capita increase will be larger in developing countries (from 28 kg in 2005/2007 to 42 kg in 2050) than in developed countries (from 80 to 91 kg) (Herrero et al. 2015). Moreover, the relative increase in volume is more pronounced in developing countries (113%) than in developed countries (27%) (Alexandratos and Bruinsma

Fig. 1 Mopane caterpillar (*Imbrasia belina*)—sun dried. Photocredits and copyright: Hans Smid – www.bugsinthepicture.com

Fig. 2 Larva of the black soldier fly (*Hermetia illuscens*). Photocredits and copyright: Hans Smid – www.bugsinthepicture.com

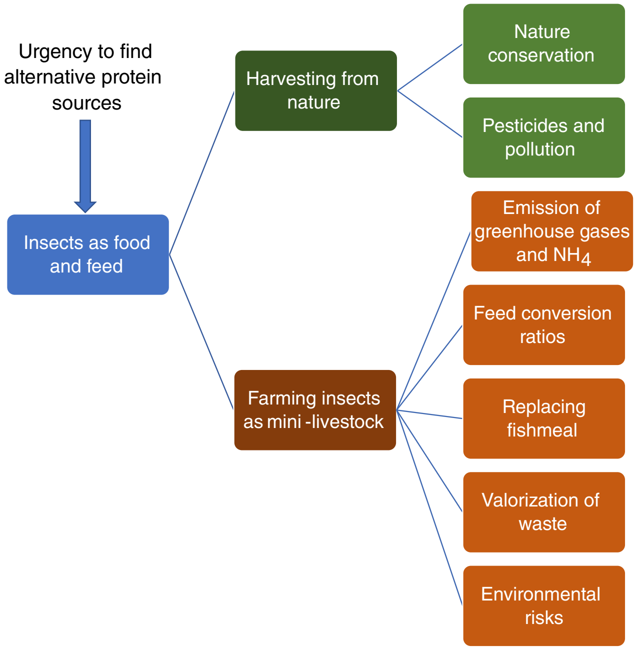

Fig. 3 Environmental issues involved when insects are harvested or when reared as production animals or mini-livestock

2012; p. 94). It is somewhat disproportional that meat represents 15% of the total energy in the global human diet, while approximately 80% of agricultural land (3,400 million ha as pastures and 500 million ha as crop land) is used for animal grazing or the production of livestock feed and fodder (Herrero et al. 2015; Herrero et al. 2016). Furthermore, livestock decreases food supply, since the grains fed to pigs and poultry could be used for human consumption. About a third of the world's cereal production is fed to animals (Mottet et al. 2017). The increase in global demand for meat and the restricted availability of land prompt the search for alternative protein sources.

2.1 Climate change and dietary changes

At the Paris climate conference in December 2015, 195 countries signed the first ever universal, legally binding global climate deal (Sutter and Berlinger 2015). The agreement sets out a global action plan to limit climate change to less than 2 °C above pre-industrial levels. The aim is to limit this increase to 1.5 °C, which would significantly reduce the impacts of climate change (Wollenberg et al. 2016).

Livestock is an important contributor to climate change. The 20 billion domesticated food-producing animals produce between 5.6 and 7.5 Gt CO_2 equivalents per year, cattle being responsible for 64–78% of these emissions (Herrero et al. 2016). The main sources are 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%). These emissions reflect non-efficient use of initial inputs and resources in the form of loss of energy, nutrients, and soil organic matter (Gerber et al. 2013; Herrero et al. 2016). These authors indicate that half of the mitigation potential for agriculture, forestry and land use sectors lies within livestock production. Examples of such measures are reducing the demand for livestock products, reducing emissions from manure, and increasing carbon sequestration in rangelands.

The first point about reducing the demand for livestock products is, at least in theory, a powerful mitigation option (Schösler et al. 2012; Hedenus et al. 2014; Davis et al. 2016; Herrero et al. 2016; Lamb et al. 2016). This is particularly true for ruminant meat. The production of 1 kg of beef requires about 50 times more land than the production of 1 kg of vegetables, while greenhouse gas emissions are about 100 times higher, all depending on the production system used (Nijdam et al. 2012). A noteworthy exception are marginal lands which can be used for ruminants, but are unsuitable for crop production (Van Zanten et al. 2016). Western diets are characterized by a high intake of meat, dairy products, and eggs, as a consequence of which the consumption of saturated fat and red meat exceeds dietary recommendations (Westhoek et al. 2014). Halving the consumption of these products would reduce greenhouse gas emissions by 65% in the UK (Scarborough et al. 2014) and by 25–40% in the European Union (Westhoek et al. 2014). This can be achieved by substituting animal protein with vegetable protein and making a transition from ruminants (e.g., cattle and sheep) (McAlpine et al. 2009; Tilman and Clark 2014; Bryngelsson et al. 2016) to lower impact species (e.g., pigs and poultry) (Steinfeld and Gerber 2010). Reducing meat consumption and combining this with land sparing have the potential to reduce greenhouse gas emissions (Lamb et al. 2016) and increase biodiversity (Phalan et al. 2011). Another mitigation measure is using feed with a low environmental impact for the production of fish, pigs or poultry.

2.2 Alternative protein sources

One suggested alternative protein source is *in vitro* cultured meat (Post 2012). Although with large uncertainty ranges, life cycle analyses indicate that the overall environmental impacts of cultured meat production could be lower than those of most conventionally produced meat (Tuomisto and Teixeira de Mattos 2011; Mattick et al. 2015). However, a great deal of research is still needed to establish an industrial-scale culturing system (Fayaz Bhat and Fayaz 2011). Other alternative protein sources investigated both as food and feed are as follows: seaweed (Mohamed et al. 2012; Makkar et al. 2016), duckweed (Appenroth et al. 2017), canola/rapeseed (Campbell et al. 2016), micro-algae and other microbes (Vigani et al. 2015), and insects (Van Huis et al. 2013). The latter option is the primary focus of this review.

3 Sustainability of gathering edible insects from ecosystems

Most of the approximately 2,100 insect species consumed by humans in the tropics (Jongema 2017) are harvested from nature (forests, waterways, or agricultural fields). Utilizing this food resource requires safeguarding their environment. For example, care should be taken when using pesticides to control forest caterpillars as they are sources of protein, minerals and vitamins for people in Central Africa. Insects contribute significantly to the food security and livelihoods of the poor, especially women and children, who sell insects on the market or use them for personal consumption (Kalaba et al. 2013; Lindsey et al. 2013; Vantomme et al. 2004).

When harvesting a popular, high-priced insect from nature, one of the dangers is overexploitation, which can endanger future harvests. In Australia, honey ants and wood grubs (both Lepidoptera and Coleoptera) were important edible insect species for the aboriginals (Yen 2005; Yen et al. 2016). However, increased exploitation by the indigeneous population, for restaurants and for ecotourism, threatens their availability (Yen 2009). Ramos-Elorduy (2006) recorded 18 species from the state of Hidalgo, Mexico, threatened by pollution, habitat change, and overexploitation. This is called "anthropocene defaunation" by Van Vliet et al. (2016); humans cause a local population decline or even species extirpation. We give examples of aquatic insects whose populations are threatened due to pollution: caterpillar species in Africa, which are disappearing due to overexploitation and logging; edible insect species considered pests in agro-ecosystems; and insect species that can be conserved and enhanced in natural ecosystems.

3.1 Aquatic insects threatened by pollution

The eggs of aquatic true bugs (Hemiptera) called "ahuauhtle" were regarded as a delicacy by the Aztecs, and even the Spanish conquistadores called them 'Mexican caviar' (Bachstez and Aragon 1945). The eggs, measuring 0.5 to 1.0 mm, come from *Krizousacorixa* spp., *Corisella* spp., *Corixa* spp. (Hemiptera: Corixidae), and *Notonecta* spp. (Hemiptera: Notonectidae) and are collected from lakes in central Mexico (Guérin-Méneville 1858; Bergier 1941: p. 154–155). Great quantities of these eggs are deposited on the surfaces of aquatic vegetation throughout the year. Nowadays, the insects are lured to deposit their eggs on artificial lakebed nurseries (Parsons 2010). These are made by manually inserting clumps of grass into the shallow lake bottom using a wooden or iron stake in long U-shaped lines about 1 m apart. It was estimated that 3,900 MT of insect eggs could be harvested in pre-Columbian times on the original lake surface of 10,000 ha. Nowadays, the eggs go for a high price, especially during the week before Easter, the Christian holy week. However, dried up lake beds (Ramos-Elorduy 2006) and pollution due to inappropriate waste treatment (Badillo-Camacho et al. 2015) are endangering this practice.

The Loktak lake is the largest freshwater lake in northeast India. Aquatic insects are vanishing from its natural habitat due to ongoing degradation of the lake's water quality (Samom 2016). The lake is host to 31 aquatic edible insect species. One of the most popular, the giant water bug *Lethocerus indicus* (Lepeletier & Serville, 1825) (Hemiptera: Belostomatidae), is locally called 'Naosek'. In summer, it was abundantly available in paddy fields, the lake periphery, and on the local markets. Due to continued use of pesticides and fertilizers, the bug is slowly vanishing from its habitat. Aquatic insects that disappear from their habitat directly impact both Manipur's lake ecosystem and the food culture of the people living there, who have an age-old tradition of consuming these giant water bugs.

3.2 Edible caterpillars threatened in Africa

The Bisa people in the Kopa area of the Miombo woodlands (*Brachystegia* spp.) commercially harvest two Zambian edible caterpillar species (*Gynanisa maja* Strand and *Imbrasia zambesina* Walker (Lepidoptera: Saturniidae) (Mbata et al. 2002). Traditionally harvesting was regulated by (i) monitoring host plant abundance and changes in ecosystems; (ii) protecting vulnerable life stages; (iii) protecting specific habitats, e.g., late woodland fires destroy both host plants and moth eggs and larvae, so early burning is recommended (Leleup and Daems 1969; Holden 1991); and (iv) restricting harvesting to certain periods (Holden 1991). This was enforced by (i) roles assigned to the people that monitor, i.e., village headmen and other authorities; (ii) taboos and regulations on caterpillar harvesting, e.g., people are said to go insane when consuming young instars or be bitten by a snake or struck by lightning when picking too early (Holden 1991); and (iii) social and religious sanctions associated with caterpillar harvesting. The Bisa people, young and old, internalized these traditional management practices through various rituals, ceremonies and other cultural processes. However, traditional rules are disappearing because of westernization (Kenis et al. 2006) and people cut down trees to harvest caterpillars. Population pressure, poverty, and high demand for caterpillars from outside buyers cause these changes (Hobane 1995). Mbata et al. (2002) recommended that the government encourage the traditional resource use and management system of the Bisa people.

In the Central African Republic, companies selectively logged sapelli (*Entandrophragma cylindricum* Sprague), which is a host tree of the edible caterpillar *Imbrasia oyemensis* Rougeot (Lepidoptera: Saturniidae) (Vantomme et al. 2004). The loggers left one tree per 10 ha in order to allow natural regeneration. However, this is one tenth of the pre-cutting frequency, which significantly reduced both the caterpillar supply and the regeneration of the sapelli tree.

In some parts of Botswana and South Africa, caterpillars, in particular the mopane caterpillar, *Imbrasia belina* (Westwood) (Lepidoptera: Saturniidae) (Fig. 1) was affected due to overexploitation. Moreover, bush fires, debarking, and the collection of branches and trunks for firewood and construction purposes compromised the caterpillar population (Illgner and Nel 2000). Mopane caterpillars have one generation emerging between November and January and a second between March and May. Gondo et al. (2010) proposed three strategies for sustainably harvesting these caterpillars: leave sufficient fifth instar larvae to pupate and produce the next generation; do not harvest pupae; and conserve the mopane woodlands. Therefore, some communities restrict harvesting to certain time periods and impose a fee on harvesters. Community-based natural resource management systems need to be institutionalized to make this successful (Akpalu et al. 2009).

3.3 Harvesting insects from agro-ecosystems

Agricultural intensification strategies focus on attaining higher yields. However, this should be done with a minimum impact on the environment. Therefore, Godfray and Garnett (2014) call for "sustainable intensification." For edible insects, this means also paying attention to the services they provide, besides their role as a source of nutrients. Payne and Van Itterbeeck (2017) reviewed such ecosystem services worldwide and classified a selected group of edible insect species according to provisioning, regulating, and maintaining and the cultural services they provide.

The most common way of controlling insects in agriculture, even the edible ones, is to use chemicals. However, if they are edible, why not control them by harvesting them for food and feed? The advantages are threefold: (1) nutritional, contributing to food security; (2) economic because no pesticides are purchased; and (3) environmental, as there is no pesticide contamination, and pest resurgence or secondary outbreaks are prevented. We provide examples of locusts and grasshoppers from Latin America, Africa, and Asia.

A suitable species is the Mexican grasshopper *Sphenarium purpurascens* Charpentier (Orthoptera: Pyrgomorphidae). This species is a pest of corn, bean, pumpkin, and alfalfa in central and southern Mexico. However, it has also been exploited for human consumption since prehistoric times. Currently, 200 t is consumed per year (Cerritos and Cano-Santana 2008). If this species were harvested from the more than 1 million ha of these agroecosystems in Mexico, the potential annual yield would be 350,000 t. Therefore, Cerritos et al. (2015) proposed changing the practice from chemical to mechanical control.

In sub-Saharan Africa, more than 60 grasshopper and locust species are eaten, most of which are crop pests (Van Huis 2003). These orthopterans are millet pests in the Sahelian region; however, their sale yields more revenue for farmers than the millet sales (Van Huis 2016). This is one of the reasons why farmers prefer not to treat their crops with pesticides.

The Bombay locust *Nomadacris succincta* (Johannson) (Orthoptera: Acrididae) was a major pest of corn and sorghum crops in Thailand between 1960 and 1970 (Chen et al. 1998). Aerial spraying did not successfully control the pest, and from 1978 to 1981, a campaign was held to revive an old practice from the past, i.e., capturing and eating the locust (Hanboonsong 2010). Farmers started to collect them for personal consumption and as a market commodity; hence, it is no longer considered a pest. On the contrary, 170 t is imported annually from Cambodia (Ratanachan 2009, cited in Hanboonsong et al. 2013).

In most of Asia, rice field grasshoppers of the genus *Oxya* spp. (Orthoptera: Acrididae) are traditional food. In Korea, during the 1960s and 1970s, the government attempted to modernize the countryside, mandating the use of insecticide in rice fields. This greatly reduced grasshopper populations (Pemberton 1994). In the 1980s, the government changed and put less emphasis on the countryside. Farmers, especially in some highland areas, stopped using insecticides, and there was a revival of grasshoppers as food. Also in Japan, grasshoppers of the genus *Oxya* are one of the most consumed insects. In the past, their collection was widespread, but it has now declined. Both sellers and consumers attribute this to increased pesticide use in the final quarter of the twentieth century (Payne 2015).

During outbreaks and plagues, locusts are popular food in Kuwait. Locusts that invaded Kuwait during the winter of 1988–1989 were analyzed for pesticides. These contained chlorinated pesticides and relatively high concentrations of organophosphorus pesticides, which made consumption of these insects a health risk (Saeed et al. 1993).

3.4 Conserving and enhancing the availability of wild insect populations

How can the predictability and availability of wild populations be increased to avoid overexploitation? Van Itterbeeck and Van Huis (2012) mention providing egg-laying sites of reed and grasses for aquatic Hemiptera in the lakes of Mexico and manipulating host trees to facilitate the collection of palm weevil larvae and foliage-consuming caterpillars.

In Cameroon, the traditional harvesting of larvae of the African palm weevil *Rhynchophorus phoenicis* (Fabricius) (Coleoptera: Curculionidae) involved facilitation. This yielded 35 larvae per trunk, while a semi-farming system yielded 50 larvae (Ayemele et al. 2016). In the semi-farming system, fewer (20–35%) trunks are cut. However, a single collector can cut down 1100 raffia trunks per season, and this is an unsustainable practice. Muafor et al. (2015)

developed a system in which palm weevils were collected and put into boxes containing fresh raffia. This system uses 75% less raffia compared to the semi-farming system and can be implemented throughout the year.

Another example of conserving trees concerns the bamboo caterpillars, *Omphisa fuscidentalis* Hampson (Lepidoptera: Crambidae), which were traditionally collected by cutting down entire bamboo clumps. However, it is now proposed to cut a rectangular hole at the internodes hosting the bamboo caterpillars. This makes it unnecessary to cut down the whole plant. The infested bamboo culms are used for bamboo handicraft and construction poles, which are actually stronger than the non-infested ones (Hanboonsong et al. 2013).

The Asian weaver ant *Oecophylla smaragdina* Fabricius (Hymenoptera: Formicidae) is one of the most favored edible insects in Lao PDR and Thailand. It also functions as a biological control agent in tropical crops, including mango orchards. Providing the ants with a small amount of cat food and some sugar water doubled the yield and can be considered as ant farming with a dual purpose: biological control of pest insects and obtaining a food source (Offenberg and Wiwatwitaya 2009).

The conservation and enhancement of edible insects from the wild should also take into account the complex and dynamic relationships between ecosystems, collectors, consumers, traders, timber producers, and the different exogenous drivers of change (such as climate change) that either affect the social or the ecological components of the system (Van Vliet et al. 2016). The focus should not be solely on maximum yields based on ecological principles, but also on social interaction leading to adaptive resource management and governance. Conducive agroforestry practices are needed, and tenure and access should be part of it, with their corresponding institutional frameworks and regulations regarding conflict management between different stakeholders (Lindsey et al. 2013; Vantomme et al. 2004). Vinceti et al. (2013) consider the challenge of the next few decades in areas where gathering is firmly rooted in rural cultures: (1) maintaining wildlife species within a network of protected areas and (2) meeting the rural demand for proteins through sustainable harvesting.

Vantomme et al. (2004) call for more research into captive rearing of forest-based insect species and host plants. However, when insects are promoted for human consumption or for animal feed, the amounts necessary are so large that wild populations cannot satisfy the demand and then insects need to be farmed.

4 Environmental impact of insect production

In this section, the environmental impact of farming insects as mini-livestock will be compared with that of raising common production animals in terms of greenhouse gas emissions, energy, land and water use, and feed conversion efficiency. The ability of insects to convert low-value organic side-streams into high-value protein products will be discussed and also whether they are able to replace fish meal as a protein ingredient in feed.

4.1 Life cycle assessment

When insects are produced, either as a source of food or feed, this has an impact on the environment. This impact can be divided into direct and indirect impact. For instance, due to the respiration and metabolism of these insects and their feces, CO_2, CH_4, N_2O, and NH_3 can be emitted. Direct emission levels were only quantified for five insect species. However, these levels seem to be lower than for conventional livestock (Oonincx et al. 2010). Additional studies on direct greenhouse gas emissions from edible insects are needed to provide a more complete picture (Halloran et al. 2016). These are interesting from a physiological perspective. However, indirect emissions, as well as other parameters of environmental impact, should also be considered. The method of choice for such assessments is the life cycle assessment (LCA), which has a supply chain approach that quantifies environmental impact of a product through the entire chain. To date, LCAs have only been published for mealworms, house crickets, black soldier flies, and houseflies (Oonincx and de Boer 2012; Miglietta et al. 2015; Roffeis et al. 2015; Van Zanten et al. 2015; Smetana et al. 2016, Halloran et al. 2017).

These LCAs enable comparisons of insect production systems with benchmarks. Mealworms, used as a protein rich food, can be compared to meat and milk. Houseflies and black soldier flies, as protein rich feed ingredients, can be compared to fish meal and soy bean meal. These studies indicate that the energy use of insect production systems is high compared to benchmarks. Energy requirements are high due to the need for relatively high temperatures during rearing. This is because insects are poikilothermic: their body temperatures depend mainly on ambient temperatures. On the other hand, it also means that the feed consumed by insects can be efficiently used for growth: energy in the feed does not need to be used for maintaining a constant body temperature.

The production of feed is a major driver of environmental impact in conventional livestock systems and insect production systems are no exception. This seems obvious for land use; as an example, the production facility for mealworms was associated with 0.2% of the total land use, whereas the feed used in this facility was associated with 99% of the land use (Oonincx and De Boer 2012). Similarly, the direct water use of that facility was only a fraction of the water (including rain water) needed for the production of feed (Miglietta et al. 2015). When compared to chicken, 1 g of edible protein requires two to three times as much land and 50% more water compared to mealworms (Oonincx and De Boer 2012; Miglietta et al. 2015). A gram of edible protein from beef requires 8–14 times as much land and approximately 5 times as much water compared to mealworms. Also with respect to greenhouse gas emmissions, mealworms have a lower environmental impact than convention livestock systems. Broiler chickens are associated with 32–167% higher emissions, and beef cattle emit 6–13 times more CO_2 equivalents, when compared to mealworms on an edible protein basis (Oonincx and De Boer 2012).

Similarly, poultry production in Thailand is associated with 89% higher greenhouse gas emissions, on an edible protein basis, than crickets (Halloran et al. 2017). These authors report several more indicators of environmental impact (15 in total). On most reported aspects cricket production had a similar or lower impact than poultry production. Smetana et al. (2015) compared the environmental impact of several meat substitutes, based on a similarly large selection of indicators. They concluded that insect-based and soy meal-based products were associated with the lowest environmental impact. As was also concluded by Smetana et al. (2016), insect-based food can be an environmentally friendlier alternative to conventional high protein products.

These studies indicate that the energy use of insect production systems is high compared to benchmarks. As said, the high-energy requirements are due to the need for relatively high ambient temperatures for these poikilothermic insects, but this also means they have relatively low requirements for dietary energy. Within the livestock and insect production chain, the majority of land and water use, as well as the total greenhouse gas emissions, is associated with feed production. The efficient use of feed therefore explains the relatively low requirements in terms of land and water in insect production chains compared to their respective benchmarks.

Comparing the environmental impact of housefly larvae, used as feed, with their benchmarks is less straightforward. Whereas fish meal is associated with high energy use and concomittant high greenhouse gas emissions, associated land use is negligible. In contrast, soy bean meal production requires a lot of land but uses a limited amount of energy. Greenhouse gas emissions associated with soy bean meal are low if only direct emissions are taken into account. When associated deforestation (so-called land use changes) is taken into account, these emissions are higher than for fish meal. If housefly meal is directly compared to a 50:50 mixture of fish meal and soybean meal, the land use decreases by 98%, global warming potential decreases by 61%, and energy use decreases by 38% (Van Zanten et al. 2015). However, the feed that is used for fly production would not be available for other uses, such as anaerobic digestion. If this indirect effect is taken into account, the net energy requirement of housefly meal is approximately 40% higher and the global warming potential is approximately twice as high compared to the previously mentioned 50:50 mixture. However, land use is still greatly reduced (97%). As stated before, the feed used in a production system greatly affects the environmental impact of such a system. These effects were quantified for black soldier fly larvae. What becomes apparent is that low-value by-products (e.g., chicken manure or DDGS) can result in a low environmental impact (Smetana et al. 2015). However, beet pulp, which can also be considered a low-value by-product, resulted in the highest environmental impact. This was because larvae developed poorly on beet pulp and therefore required a lot of feed and energy for heating.

When it comes to insects as feed, the context as well as the insects' feed utilized in the production process plays a key role. The design of energy-efficient facilities, combined with an efficient use of feed ingredients, is expected to lead to decreases in the environmental impact of insect production systems in the coming decades. More LCAs should be conducted to evaluate such novel facilities. Also, a wider range of production locations should be considered as this can greatly influence environmental impact, especially energy use. Furthermore, a wider range of impact categories could be considered for evaluating the strengths and weaknesses of insect production systems (Halloran et al. 2016).

4.2 Feed conversion efficiency

One of the main reasons why insects are considered as potentially sustainable sources of animal protein is because of their high feed conversion efficiency (Nakagaki and deFoliart 1991; Berenbaum 1995; Gullan and Cranston 2005; Ramos-Elorduy 2008; Premalatha et al. 2011; Looy et al. 2013). The reason for this expectation is that insects are poikilothermic. This, however, does not necessarily lead to greater efficiency. High efficiency requires optimal diets and therefore knowledge of the nutritional requirements of insect species needs to be established. Furthermore, much like in conventional farming, genetic selection can further help to create efficient strains. There are, however, indications that several insect species accumulate protein very efficiently (Oonincx et al. 2015b). Whereas poultry provided with optimized diets converts 33% of dietary protein to edible body mass, yellow mealworms utilize 22–45% of dietary protein, black soldier fly larvae about half (43–55%), and Argentinean cockroaches 51 to 88%. The latter species is able to do so by using endosymbionts. These data illustrate that the starting level of protein efficiency, without optimizing genetic background or diets, is already high compared to conventional livestock.

Whereas optimal diets would lead to more efficient use, this is not necessarily the most sustainable and economic way to produce insects. When seen from an environmental point of view, valorizing unused or underused substrates, such as certain organic side-streams, should be explored further

(Oonincx et al. 2015b, Halloran et al. 2016, Halloran et al. 2017).

4.3 Reducing organic waste

A number of species can successfully be grown on organic side streams, converting low-value organic by-products into high-value proteins. This is particularly important considering that on a yearly basis, 27% of all our agricultural produce is wasted and 22% if only the edible part is taken into account, or globally 1.6 and 1.3 billion t, respectively (FAO 2013). Agricultural waste was valued at US$750 billion annually (The Economist 2014). The by-product that can be used depends on the insect species. Mealworms can be raised on dried organic waste materials from fruit and vegetable origin (Ramos-Elorduy et al. 2002). Van Broekhoven et al. (2015) and Oonincx et al. (2015b) mixed dried by-products from beer brewing, bread/cookie production, potato processing, and dried distiller grains with solubles dried distillers grains with solubles (DDGS), a by-product of the biofuel industry. The mealworms developed well on several of these mixtures and had a fairly constant nutrient composition.

Part of the same diets were also given to house crickets (*Acheta domesticus* (L.) (Oonincx et al. 2015b). These, however, did not do well on most of these mixtures. Similarly, Lundy and Parrella (2015) found that the nutrient requirements of this species has narrow ranges and concluded that its potential as a source of sustainable protein depends on the availability of relatively high-quality by-products, preferably not currently used in livestock production.

The oriental ground cricket, *Teleogryllus testaceus* (Walker), farmed as food in Cambodia, seems to have a broader diet and can be grown on unused resources such as leaves from taro and cashew and cassava tops (Megido et al. 2016). Miech et al. (2016) found that this species performs well on cassava plant tops, but also on several weeds, in particular *Cleome rutidosperma*.

The best-known species for utilizing waste streams, such as rice straw (Manurung et al. 2016), coffee pulp (Larde 1990), fish offal (St-Hilaire et al. 2007), DDGS (Webster et al. 2015), catering waste (Surendra et al. 2016) and swine, chicken and cattle manure (Sheppard et al. 1994; Newton et al. 2005; Oonincx et al. 2015a) is the black soldier fly (Fig. 2). It utilizes this waste and can simultaneously kill pathogenic bacteria such as *Escherichia coli* or *Salmonella enterica* present in, for instance, chicken or cattle manure (Erickson et al. 2004; Liu et al. 2008). It has even been proposed as a sanitation method for getting rid of human feces (Lalander et al. 2013; Banks et al. 2014). Furthermore, the black soldier fly can be used to produce biodiesel and biofuel (Zheng et al. 2012; Li et al. 2015; Surendra et al. 2016). The housefly can also be grown on manure (Cicková et al. 2012; Shah et al. 2016). The suitability of Diptera for transforming organic waste into high protein feed products was outlined by Pastor et al. (2015). However, they indicated that other fly species such as Muscidae (houseflies), Stratiomyidae (soldier flies), Calliphoridae (blowflies), Sarcophagidae (flesh flies), and Syrphidae (hover flies) should also be considered. The choice of substrates used depends on legislative frameworks; e.g., in the European Union, the use of organic by-products such as catering waste and manure is prohibited. Furthermore, food and feed safety issues need to be taken into account, especially when organic by-products are used; for a review see EFSA (2015).

4.4 Insects replacing fish meal as feed

Whereas aquaculture provided only 7% of fish for human consumption in 1974, this share had increased to 44% by 2014 (FAO 2016b). In 2014, about 10% of total fish produced (captured and aquaculture) was reduced to fish meal and fish oil. Fish meal is made from small wild-caught marine fish that contain a high percentage of bones and oil, and are usually deemed unsuitable for direct human consumption. Fish meal is a high-quality feed ingredient for pigs, poultry, and aquaculture and is used extensively. However, it is becoming increasingly scarce and expensive. This is partially the result of overexploitation of wild fish stocks (more than 30% of fish stocks in 2013) (FAO 2016b). Therefore, between 1988 and 2010, the poultry sector decreased the use of fish meal from 60 to 12% of the total available amount. However, the aquaculture sector increased its use of fish meal from 10 to 56% in the same period. Although increasing fish meal prices have led to lower inclusion percentages in aquafeed, this effect is offset by the rapid growth of the aquaculture sector (Olsen and Hasan 2012; Msangi et al. 2013). This fuels the search for alternative sources, for instance the use of plant material. Plant sources have a number of drawbacks such as a lower protein content and the presence of anti-nutritional factors, which reduce nutrient availability and counteract with vitamins (Olsen and Hasan 2012). These drawbacks can partly be mediated by chemical and mechanical processing (Hall 2015).

However, certain insect species might also serve as alternative protein sources without these drawbacks, in particular the black soldier fly *Hermetia illucens* (L.) (Diptera: Stratiomyidae). Tests conducted with Atlantic salmon showed that complete replacement of fish meal had no adverse effects on net growth of the fish, histology, odor, flavor/taste, and texture (Lock et al. 2015). Similarly, meal made from the black soldier fly is a suitable protein source for a number of other farmed fish species, such as African catfish *Clarias gariepinus* (Adeniyi and Folorunsho 2015; Anvo et al. 2016), channel catfish *Ictalurus punctatus*, and blue tilapia *Oreochromis aureus* (Bondari and Sheppard 1987).

Another insect species, the yellow mealworm (*Tenebrio molitor* L.; Coleoptera: Tenebrionidae), has also been evaluated. Yellow mealworm meal could partially (35%) replace fish meal in the diet of European sea bass (*Dicentrarchus labrax*) without affecting mortality or growth (Gasco et al. 2016). However, replacing 70% of the fish meal did depress growth. A similar trial conducted with rainbow trout (*Oncorhynchus mykiss*) found that weight gain was not affected at higher inclusion levels of mealworm meal, while the protein content increased and lipid contents of fillets decreased, compared to the control (Belforti et al. 2015). A complete replacement of fish meal by yellow mealworm meal increased the fat content of Pacific white shrimp, but did not affect its growth or feed conversion (Panini et al. 2017). In contrast, common catfish (*Ameiurus melas* Raf.) fingerlings and African catfish, *C. gariepinus*, grew slower when large proportions of the fish meal were replaced (Ng et al. 2001; Roncarati et al. 2015).

It seems that partial replacement is possible but, depending on the fish species, might affect production characteristics. Furthermore, replacing fish meal by yellow mealworm or black soldier fly meal decreases the concentration of long-chained omega-3 fatty acids, which may then need to be added to the fish diet (Makkar et al. 2014).

5 Environmental risks of insect farming

Questions are often asked about the potential environmental risks of replacing the current livestock systems with insect farming systems. Is there a danger for humans, plants, animals, and biodiversity? The legislative framework in a country should be checked, e.g., does a country have a list of animals that are allowed to be produced?

Then it depends on whether an organism can be considered a quarantine pest, which is “a pest of potential economic importance to the area endangered thereby and not yet present there, or present but not widely distributed and being officially controlled”, as defined under the International Plant Protection Convention (IPPC), an international agreement that aims to protect cultivated and wild plants by preventing the introduction and spread of pests. Worldwide there are nine Regional Plant Protection Organizations (RPPOs) of the IPPC (FAO 2016a). The task of these organizations is to protect the world’s cultivated and natural plant resources from the spread and introduction of plant pests. This is done by regulating the imports of insect species and vehicles thereof. If the insect species is not endemic, would be able to survive in nature if it escaped, and would pose a danger to humans, animals, plants, or biodiversity, the use of this species can, and maybe should, be prohibited.

A proper identification of the insect species is necessary as is information about their origin. Risks assessments are made by the National Plant Protection Services and the National Food Safety Authorities which are part of Ministries of Agriculture.

Besides the species that fall into the Q organism category, other species produced for food or feed can be a nuisance. For example, a farm producing house flies should not let these escape, as they can bother the general public. Hence, precautions should be made to keep insects inside; for instance, all openings to the rearing should be sealed or filtered.

6 Conclusions

In tropical countries, increased insect consumption leads to higher prices and, consequently, increased collection from nature, which may jeopardize the long-term sustainability of this practice. In order to assure future harvests, it is necessary to develop sustainable harvesting practices. Other threats to this natural resource are habitat changes, pesticide use, or pollution.

Furthermore, the increased use of insects as food and feed is expected to require more volume than can be harvested from nature. Therefore, farming the insects as mini-livestock is advisable. The high environmental impacts connected with meat production and the increase in demand up till 2050 require dietary changes. Insect-based meat substitutes are potentially more sustainable but require more advanced cultivation and processing techniques (Smetana et al. 2015). Such advancement is expected as the whole sector of insects as food and feed is just emerging.

In comparison to current production practices, this potential abundant food source can contribute to a more sustainable food and feed production, as certain insects can be reared on organic side streams, including manure. However, food and feed safety issues need to be considered.

Insect production has great potential with respect to sustainably providing food for the growing population. However, further technological development of this sector and monitoring of the effects of these developments on the environmental impact of insect production are needed.

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