Comparing Environmental Impacts from Insects for Feed and Food as an Alternative to Animal Production

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Abstract This chapter systematically compares and contrasts the known environmental impacts of traditional vertebrate animal production with insect production intended for both food and animal feed. There are major physiological and biological differences between traditional livestock species and insects, which often translate into lower environmental impacts from insect production. However, insect production systems are still in their infancy and there are still major improvements to be made. Based on our analysis, the greatest potential of insects is the prospect of feeding them various kinds of waste products from agriculture, industry and households. This chapter can serve as a reference guide for future research into the environmental impacts of insects for food and feed.

1 Introduction

Animal production is associated with a variety of environmental impacts. As a result of economic growth and dietary transition there is a rising global demand for animal products, like beef and cheese (Robinson and Pozzi 2011). The extent of the environmental impacts vary depending on a number of factors including species, farming system/production method under consideration, levels of consumption, nutritional value, feed composition and production period (de Vries and de Boer 2010; Tilman and Clark 2014).

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The environmental impacts of animal production also depend greatly on the type of digestive system of the animal in question. Production systems based on monogastric animals require high protein, easily digestible feed to achieve sufficiently high growth rates. The production of the high protein feed, especially soy beans, is associated with significant environmental impacts because they are often grown in regions where their production indirectly affects or directly encroaches sensitive ecosystems. Ruminants have a significant advantage over the monogastric animals in that they are able to metabolize and utilize cellulose and hemicellulose, and hence can digest more recalcitrant forage. However, this is problematic in that a by-product of this digestion is the potent greenhouse gas methane.

Insects, on the other hand, are physiologically and biologically different from other animal species. Insect metabolism does not require a constant body temperature like the vertebrate species traditionally used for human consumption. This means more efficient use of resources such as feed and water.

In this chapter, we systematically compare and contrast the known direct environmental impacts of traditional vertebrate animal production with insect production for both feed and food. We also discuss room for improvement and knowledge gaps to enhance our understanding of the comparative advantages of insect production systems over traditional animal production systems. The following traditional impact categories will not be discussed within this chapter, as they are considered of no or very minor relevance for the topic: ionizing radiation, ozone depletion, photochemical ozone formation.

2 Acidification

The main contributor to acidification and particulate matter formation from protein production is ammonia (NH_3), which is one of the reactive nitrogen (N_r) species in the overall nitrogen cycle of the biosphere (Sutton et al. 2011). Nitrogen enters protein production through fertiliser and biological N fixation by crops, which are then used as feed for animals.

2.1 Ammonia

Ammonia emissions and subsequent deposition have an impact on soil acidification (through nitrification in which ammonium is oxidized to nitrate under the production of hydrogen ions) and eutrophication of terrestrial and aquatic ecosystems. Furthermore, ammonia emissions contribute to formation of fine particle pollution ($PM_{10/2.5}$) of the atmosphere.

2.1.1 Animal Production

Animal feed N conversion efficiency varies greatly between different animal species, from less than or 20% for cattle, around 20–30% for pigs and 30–40% for poultry (Steinfeld et al. 2006). This variation results in a large variation in the proportion of N excreted as ammonium and organic N (100%-feed N conversion efficiency%). This means that loss of ammonia derived from animal manure and urine is substantial. According to Leip et al. (2015), 82% of all ammonia emissions in EU agriculture stem from livestock production. Nitrogen emissions also vary greatly between production systems (incl. feeding) and manure management, especially animal housing, manure storage and field application methods. Typical ammonia volatilisation from housing and manure storage from intensive livestock production systems has been estimated at around 20% of excreted total N, and an additional 20% may be lost during field application (Steinfeld et al. 2006). N volatilization may be significantly reduced by low-emission housing, storage and application technologies, such as ventilation air scrubbing, covered slurry tanks and slurry injection or acidification technologies. Hutchings et al. (2014) quantified the overall N flows and balances of Denmark in 2010, where advanced low-emission technologies have been in implemented in agriculture over the past three decades, and found overall ammonia emission to be as low as 21% of excreted manure N.

An important difference between mammal livestock and poultry is that mammals mainly excrete nitrogen as urea whereas poultry excrete nitrogen mainly as uric acid (Sommer and Hutchings 2001). Urea is quickly hydrolysed to ammonium after excretion, leaving it prone to volatilization, whereas the oxidation of uric acid is much slower. This typically results in lower free ammonia concentrations in poultry litter and means that ammonia loss from is generally less but more variable, depending on storage conditions and time, compared with other types of manure.

2.1.2 Insect Production

Similar to production systems based on vertebrate animals, ammonia emissions are also likely to occur from many types of insect production systems. To achieve fast growth, feed with high protein content is often used in these systems and this also means that excess nitrogen is likely to be excreted by the insects. Like birds, most insects excrete nitrogen as uric acid. Usually the insect excreta, or frass, are rather dry, which also means that the conversion of the uric acid to urea and ammonia should be relatively slow, thereby reducing ammonia emissions. During storage, emissions will depend very much on storage conditions, temperature, pH and moisture. Uric acid conversion could be rapid and significant and thus result in significant loss of ammonia if the manure is stored with exposure to moisture, but no actual measurements on insect frass are available to support this for insects.

Very little empirical data exists about ammonia volatilization from entire insect production systems. Oonincx et al. (2010) found ammonia emissions of five insect species[1], suitable for animal and human consumption, to be lower than emissions from beef cattle and pigs. For example, the ammonia emissions of pigs are eight to twelve times higher per kilo of growth when compared to *Acheta domesticus*, and up to fifty times higher than *Locusta migratoria*. Under most circumstances ammonia loss can probably be assumed similar to or lower than for poultry given the fact that the dry matter content is higher than in poultry manure (Halloran et al. 2017).

3 Climate Change

When compared to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have considerably greater global warming potentials (GWPs). In order to express the GWP on a CO_2-equivalent basis, the Intergovernmental Panel on Climate Change assigns CO_2 a GWP of 1 CO_2-eq. In comparison, CH_4 has a GWP of 25 CO_2-eq, and N_2O has a GWP of 298 CO_2-eq. (IPCC et al. 2007). Herrero et al. (2016) estimate that the livestock sector was responsible for GHG emissions of 5.6–7.5 Gt CO_2-eq. per year between 1995 and 2005.

In a life cycle assessment, Halloran et al. (2017) found that cricket farming had a lower GWP than broiler chicken farming. When looking across the spectrum of GWPs attributed to animal source foods (Fig. 1) one can see that broiler chicken farming in Thailand has a lower global warming potential than pork, beef, and lamb but a higher global warming potential than farmed salmon, mealworms, chicken production in Denmark, crickets and wild herring. While there is large disparity in the data (even data within livestock categories), cricket farming is one of the most environmentally sustainable animal source food production systems available.

3.1 Methane Gas Emissions

3.1.1 Animal Production

On a worldwide basis, livestock production is estimated to produce 14.5% of all anthropogenic GHG emissions (Herrero et al. 2011). Beef and milk production from cattle account for the majority (41% and 20% respectively) of the livestock's sector's emissions, while pig meat and poultry meat and eggs contribute a total of about 17% (9% and 8% respectively) (Gerber et al. 2013). Methane is a product of normal anaerobic fermentation of feedstuffs in the animal or feedstock in collected

[1] *Tenebrio molitor*, *Acheta domesticus*, *Locusta migratoria*, *Pachnoda marginata,* and *Blaptica dubia*

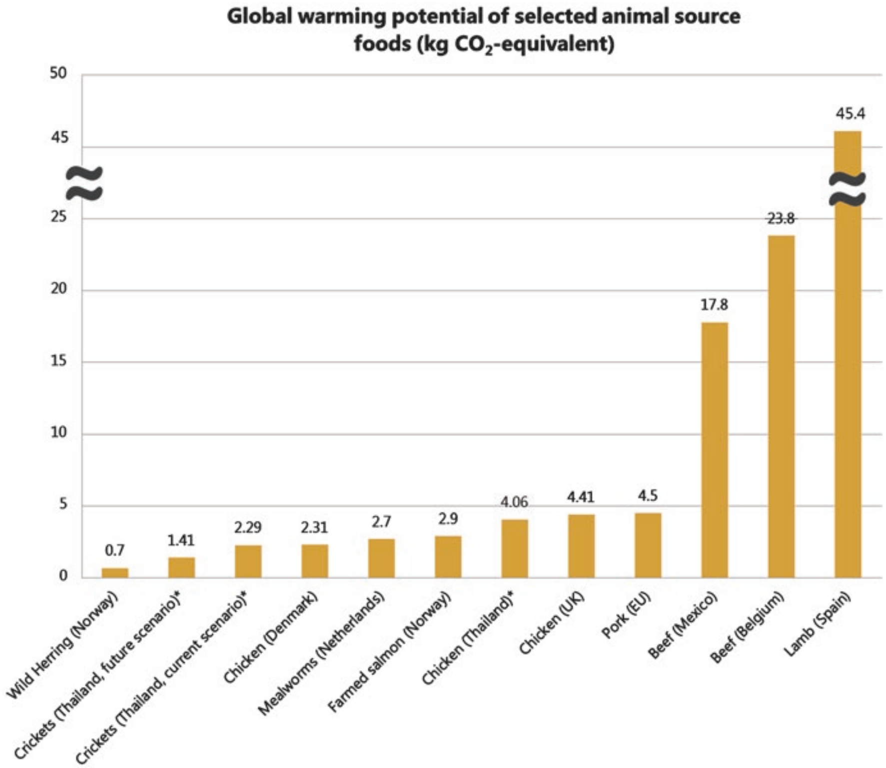

Fig. 1 Comparison of the global warming potential (kg CO_2-e) of selected animal source foods per kg of edible mass (*indicates results from Halloran et al. 2017, and pork (EU), beef (Belgium) and lamb (Spain) were based on an average of different production systems) (Sources: Halloran et al. 2017; Jacobsen et al. 2014; Kool et al. 2010; Leinonen et al. 2012; Nielsen et al. 2012; Oonincx and de Boer 2012; Ripoll-Bosch et al. 2013; Rivera et al. 2014; Winther et al. 2009; Ziegler et al. 2013))

manure. Methane is produced by methanogenic microbes of the taxonomic domain: Archaea. These microbes use either the acetate or the carbon dioxide and hydrogen produced during carbohydrate degradation to produce methane. This process prevents H_2 buildup that will stop the digestion process in the animal. The produced methane can be a source of biogas energy when fermenting manure, but the methane expelled from the rumen or hindgut is a loss of feed energy to the animal. The amount of total gas produced during digestion varies greatly according to the total feed intake. The proportion of methane produced varies due to the carbohydrate composition of the feed, which in turn helps determine the microbial population. Abatement measures via animal breeding, production management, dietary strategies and microbial manipulation are the subject of much research (Eckard et al. 2010).

3.1.2 Insect Production

Methane production also occurs in the guts of some insects. Termites (Isoptera) are responsible for between 5% and 19% of total CH_4 emissions globally (Jamali et al. 2011). Methanogenic archaea can also be found in the proctodeum (hindgut) of most tropical representatives of millipedes (Diplopoda), cockroaches (Blattaria), and scarab beetles (Scarabaeidae). Other arthropod taxa do not appear to emit methane (Hackstein and Stumm 1994).

Very few measurements have been conducted from insects that are currently used for food and feed. In a study of the GHG emissions of five insect species, Oonincx et al. (2010) did not detect CH_4 emissions in *Acheta domesticus*, *Tenebrio molitor* or *Locusta migratoria.* However, *Pachnoda marginata* and *Blaptica dubia* (two insect species used as feeder insects for reptiles, birds, etc.) were found to produce more CH_4 than pigs but less than beef cattle per kg of weight gain. Halloran et al. (2017) detected insignificant levels of CH_4 in a farming system of *Acheta domesticus* and *Gryllus bimaculatus* in Thailand.

The reason for the low emissions from the tested insects is likely due to the fact that they are fed mainly on protein rich sources without cellulose to enable high growth rates. For this reason, they do not use microbes to breakdown cellulose or hemicellulose in their feed. However, in the future, other feed sources such as grass cuttings, household waste or maybe even garden waste is likely to be considered as feed sources for insects. These sources contain cellulose, hemicellulose and complex lignocellulose compounds and it is therefore likely that methane emissions may be a problem from these systems.

3.2 Nitrous Oxide Emissions

3.2.1 Animal Production

As opposed to methane emissions that occur as a product of feed degradation in the animal or in the manure, nitrous oxide (N_2O) emissions come primarily (90%) from agricultural crop, soil and waste management practices (Eckard et al. 2010). Nitrous oxide is mainly produced in agricultural fields through the two nitrogen transformation processes of nitrification and denitrification. The emissions ascribed to animal production are therefore related both to the production of feed and the nitrous oxide emissions occurring as a consequence of fertilizers used for the crop as well as the nitrous oxide emissions occurring as a consequence of the application of manure on agricultural fields. The scope of the total worldwide emissions is difficult to estimate, but expansion of agricultural lands and use of fertilizers (mineral and manure based) make a significant contribution (Reay et al. 2012). Galloway et al. (2010) estimated that on a global scale, agricultural activities contribute 57% of global N_2O emissions, and of this, two-thirds comes from land with intensive animal production systems.

3.2.2 Insect Production

As with vertebrates, the main emission of N_2O that must be ascribed to insect production systems occurs in the fields as a consequence of feed production and manure application. The denitrification process occurs under conditions of low oxygen content in soil. Therefore, it may be argued that N_2O emissions, after application of dry insect manure, would be less than when wet livestock manure is applied. However, it may turn out that the nitrogen will only be stored in the soil until the next rain event, whereafter denitrification would commence because the soil is temporarily depleted of oxygen. In conclusion, insects are only likely to be associated with lower N_2O emissions to the extent that they are more efficient at converting protein into animal protein as this will be reflected in both the amount of feed that needs to be produced and also the amount of manure that will be produced.

There are, however, also minor emissions of N_2O from the guts of both vertebrate animals and insects. *Locusta migratoria* were found to emit approximately half the N_2O per kilogram of growth than pigs, and *Acheta domesticus* emitted one quarter less (Oonincx et al. 2010). Another study found that farmed *Acheta domesticus* and *Gryllus bimaculatus* emitted insignificant levels of N_2O (Halloran et al. 2017). No other studies have measured the direct N_2O emissions from insects for food and feed.

3.3 Carbon Dioxide Emissions and Carbon Sequestration

3.3.1 Animal Production

Carbon dioxide (CO_2) emissions due to animal respiration is generally not considered when calculating greenhouse emissions (Steinfeld et al. 2006). This is because the respired carbon is considered to be offset by the carbon dioxide fixed by photosynthesis during production of the forage used for feed. However, animal production contributes to CO_2 emissions due to effects on soil organic carbon stocks, e.g. through land use change (e.g. from native vegetation to grassland, or grassland to cropland), but also contributes to net CO_2 binding through soil carbon sequestration from e.g. manure application to arable land (Menzi et al. 2010). The dominant impact of livestock production at the global scale comes from tropical deforestation for pasture and croplands and soil degradation/desertification (Asner and Archer 2010). The potential of carbon sequestration due to grazing land management has been researched, but with widely differing results, that have polarized the scientific community (Steinfeld et al. 2006). If grazing management can remove dead or unproductive forage and allow more, new vegetation, this may lead to larger residual carbon inputs, and the balance of soil carbon sequestration will be in favor of grazing as opposed to no grazing. However, methane production from the grazing animals or nitrous oxide emissions and fossil fuel energy use if the alternative to grazing is crop production must be considered respectively against and in favor of grazing as well (Asner and Archer 2010).

3.3.2 Insect Production

Most of the mechanisms leading to emissions of CO_2 for vertebrate production systems will also be active for the insect production systems. Production of insect feed leads to CO_2 emissions through land use change if natural systems are converted to cropping systems. The conversion process releases the stored carbon as CO_2. Cropping systems based on grass contain more C than systems based on annual crops and may therefore be less problematic in terms of CO_2 emissions. For this reason, insect production systems will be very similar in terms of CO_2 emissions, to the vertebrate systems that are based on the same feedstuff. However, to the extent that insects are more efficient at converting feed into animal protein, the emissions may be smaller.

Energy-related CO_2 emissions are also noteworthy. Halloran et al. (2016) noted that energy consumption in insect production depends heavily on the kind of production system in question as well as the geographical location of the farm, with the same information applying to animal production. Oonincx and de Boer (2012) found that mealworm production in the Netherlands consumed significant amounts of energy for heating. However, larger mealworms were also found to produce surplus heat which, in turn, generated heat for the smaller mealworms, thus large scale production of insects may require much less heating even in colder regions. The need for heating is influenced by the conversion efficiency of the insect species and the density of insect biomass in question.

4 Ecotoxicity and Human Toxicity

Toxicity to either humans or ecosystems may be caused by various aspects of vertebrate or insect protein production. This can occur from pesticides, herbicides or other chemicals used in feed crop production, mineral additives used in animal feeds, or medicinal residues from drugs used to treat diseases in livestock. Some countries allow growth promoters, which can be excreted and may be endocrine disrupters in humans or have detrimental effects on aquatic organisms if the excrement pollutes waterways (Steinfeld et al. 2006).

4.1 Soil Contamination

4.1.1 Animal Production

Soil contamination from animal production derives mainly from the use of zinc (Zn) or copper (Cu) oxides in animal feeds as prophylactics against diarrhea, especially for weaners and piglets in swine production and for young birds in poultry production

(Menzi et al. 2010). Both elements are essential micronutrients for plants and animals, but can also be toxic for microorganisms, soil fauna, plants, and further through the food-chain to humans, when present in excess concentrations. Many countries with intensive animal production have lowered the requirement and therefore necessary use on Zn and Cu in animal feeds, and the EU is currently considering a complete ban on these, so the problem is expected to be reduced in the near future. The drawback of a required reduced use of heavy metal minerals as a prophylactics is a possible increase in the demand for other feed additives that may fulfill the same role, like antibiotics or antimicrobials. These could end up in the soil via manure application, with a potentially large ecotoxic effect on soil organisms.

4.1.2 Insect Production

As insect production is still in its infancy with only limited commercial production, very little is known about the need for and usefulness of prophylactic use of Cu and Zn oxides as well as antibiotics. The intestinal tracts of insects are completely different from mammals and birds and the need and the ability of these compounds to increase productivity in large scale production could range from unnecessary to important. The use of antibiotics and other medicine is known to be widespread in shrimp production, a large scale arthropod production system. It is, however, unlikely that the experience from these water-based systems can be translated into insect production. Some commercial cricket farms in the USA like Big Cricket Farms currently advertise their crickets as antibiotic and steroid free.

5 Freshwater, Marine and Terrestrial Eutrophication

Diffuse pollution of groundwater and surface waters with nitrogen (N) and phosphorus (P) is a problem in many regions of the world, especially in areas with intensive agricultural production. In surface waters (marine and fresh), these losses cause problems with eutrophication and algal bloom, and in areas that rely on the use of groundwater, high nutrient concentrations can be a problem for the potable water quality. For drinking water the EU limit has been set at a nitrate concentration at 50 mg L^{-1} (EU Drinking Water Directive, 98/83/EC). Nutrient losses to aquatic systems mainly occur by leaching through the soil profile and through surface runoff when the infiltration capacity of the soil is exceeded. Appropriate management and use of mineral fertilizers and organic residues is therefore essential for minimizing nutrient losses and the environmental impact of agriculture. Freshwater eutrophication is mainly caused by losses of phosphorus while marine eutrophication is caused by nitrate which to lost to surface water from where it eventually ends up in estuaries and coastal areas. Terrestrial eutrophication is mainly caused by loss of ammonia that is deposited in sensitive areas.

5.1 Freshwater, Marine and Terrestrial Eutrophication

5.1.1 Animal Production

Loss of nutrients to the aquatic environment occurs during production of feed for animal production, whether these are planted roughages for ruminants, or grains or other concentrated protein-and energy rich feed. The magnitude of these losses depends on a wide range of biophysical factors, such as level of nutrient input compared to crop demand, soil type, climate, crop rotation/ sequence and management (e.g. use of catch crops). Losses of N from feed crops are moderate only if mineral fertiliser is applied at adequate rates (Jarvis et al. 2011), typically less than 20% leaching loss of applied N.

5.1.2 Insect Production

As for animal production, production of feed for insect production systems will also result in losses of nitrate. The losses will therefore most likely only be smaller than for animal production to the extent that the insect metabolism is more efficient than livestock metabolism in terms of converting feed protein into animal protein.

5.2 Manure Handling

5.2.1 Animal Production

If animal manure, which contains substantial quantities of organic matter, N and P, is partly or fully used to supply the crop nutrient demand, losses may be large. This is mainly due to the organically bound N in manure which mineralises gradually, also at times where crops do not have a nutrient demand (Sørensen and Jensen 2013). This mineralisation is slow, so when manure is applied initially, losses are small, but with long term repeated applications the N losses may increase to 25–30% of the applied total N.

5.2.2 Insect Production

Currently, no study has analysed the fertilizer values of, or nutrient losses after application of insect manure. As described above a large proportion of the nitrogen could exist in the form of uric acid which is gradually mineralized in the soil after the manure has been applied. Therefore the manure is also likely to behave similarly to poultry litter which has a somewhat uncertain fertilizer value due to the moderate release rate and plant availability of the N (Jensen 2013).

6 Water Depletion

Water, in animal production, is consumed directly and indirectly as drinking water, feed ingredients and service water and used in some places for cooling. Miglietta et al. (2015) found that the water footprint per edible ton of mealworms was comparable to chicken meat. The water footprint of beef is approximately three times higher than mealworms (Miglietta et al. 2015).

6.1 Indirect Water Footprint of the Feed

6.1.1 Animal Production

The majority of water used along animal product supply chains occurs during the production of feed ingredients (Mekonnen and Hoekstra 2012). In fact, more than 8% of the global water usage is used by the livestock sector, with 7% of global uses going to the irrigation of feed crops for livestock (Schlink et al. 2010). Many of the major crops used for animal feed like soy and maize are grown in areas where there is a lack of water and are therefore supplemented by irrigation water. Therefore, it is the use of water demanding crops used for feed production and unfavorable feed conversion efficiencies of livestock which are, for the most part, responsible for the relatively large water footprint of animal products compared to vegetable products (Mekonnen and Hoekstra 2012).

6.1.2 Insect Production

The general higher efficiency of insect production compared to conventional livestock production means that less feed is needed. For this reason, the water footprint of insects also has the potential to be smaller than for vertebrate livestock. Other sources of feed which could be used for insects, especially different kinds of waste, could be give rise to production systems with a very low water footprint.

6.2 Direct Water Footprint Related to the Drinking Water

6.2.1 Animal Production

The consumption of water by production animals depends on many variables such as dry matter intake; diet composition; water availability and quality; water temperature; the ambient temperature and the production system in question. Water requirements are especially high for livestock under warm and dry conditions (Steinfeld et al. 2006).

6.2.2 Insect Production

Like livestock, the amount of drinking water that insects require is dependent on the food source and the climate. Being poikilothermic, insects do not rely on evaporation of water to keep their body temperature low. For this reason, they are much more frugal in terms of water consumption. Some desert insects can even survive solely on metabolic water i.e. the water which is released by oxidizing energy-containing substances in their food (Zachariassen 1996).

Murray (1968) suggests that *Tenebrio molitor* do not need additional drinking water when farmed under appropriate conditions of humidity and are provided with carrots and an optimal ratio of bran/grain. In Thailand, for example, crickets are usually supplied with small trays of water that are changed every few days. Overall, water consumption is low.

6.3 Service Water Consumed During the Farming Stage

6.3.1 Animal Production

Service water also varies between production systems. Industrialised animal production systems will inevitably require larger quantities of service water. Service water is used to clean pens/units, wash animals, cool down facilities as well as animals. Service water is also used for waste disposal, especially in pig production (Steinfeld et al. 2006).

6.3.2 Insect Production

In order to maintain a high standard of hygiene and prevent disease, pens which contain the insects must be cleaned regularly. Water use consumption for service water depends largely on the facility, housing structure and length of the insect life cycles. However, overall service water use should be lower for insect production than for animal production.

7 Resource Extraction

A range of critical and limiting resources are used for modern agriculture. The most significant ones include rock phosphate and crude oil. Rock phosphate is mainly used for production of fertilizer while crude oil is used for diesel production, which is subsequently used for a range of processes including field tillage, grain drying and processing. Livestock production is mainly responsible for the consumption of these resources through the use of feeds which require the use of phosphate fertilizer as well as work which is provided mainly by use of diesel.

7.1 Animal Production

Efficient recycling of animal wastes could reduce the huge need for phosphate in livestock feed production. Unfortunately, the production of feed is, to a great extent, spatially separated from the animal production. Although there are exceptions, animal waste is most commonly applied in the vicinity of the animal production. This means that phosphorus typically accumulates in the soils close to the animals while the soils from where the feed is produced are gradually depleted or have to be supplemented from mineral fertilizers produced from rock phosphate (Naylor et al. 2005). Accumulation of phosphorus in soils also means that the risk of runoff (via erosion and particulate transport on the surface) or leaching (dissolved/dispersed through the soil to drains and ground water) to the environment is increased (Steinfeld et al. 2006).

7.2 Insect Production

It is difficult to determine if insect production will also concentrate or deplete phosphorous or other resources in specific areas. The unfortunate separation is to a large extent more a consequence of socio-economic factors than it is a consequence of optimization of the production. Therefore insect production systems could be better in this respect or even worse – this will largely depend on the structural and economic development of insect production in the future.

8 Direct and Indirect Land Use and Land Use Change

Land use refers to the total amount of land required to produce a given good, which in the case of this chapter is meat, milk, eggs or insects. Land use not only refers to the land needed for grazing in either free range or planted pasture systems, but also the amount of land required for producing feed. Land use change refers to the human induced conversion of one land use to another. This, for example, could be the conversion of virgin forest or savanna to create farm land. Global dietary transition is one of the main drivers for an increased need for land resources and land use change (Alexander et al. 2015).

8.1 Animal Production

The livestock sector is a major user of land resources, representing approximately 30% of the world's surface land area (Steinfeld et al. 2006). Ruminants (e.g. sheep, goats and cattle) use the greatest amounts of land resources as they use both feed crops and graze natural or planted pasture. Trade-offs must be considered between the ability of livestock ruminants to convert human inedible cellulose to products for human use and uncontrolled manure expulsion and/or methane production. More land is needed when ruminants use marginal lands than from planted pasture or feed crops per unit product. Production efficiency per unit product increases while pollution per unit product can decrease when comparing ruminant production from grazing marginal lands with grazing planted pasture or planting crops. Despite the fact that both ruminants and monogastric livestock do not nutritionally require grazing, many countries take grazing and/or outdoor access into animal welfare and livestock ethical consideration.

Land required for the production of animal products has contributed to the majority of land use change (65%) over the past 50 years. According to Steinfeld et al. (2006), deforestation caused by expansion of pasture and feed crops generated 8% of the total anthropogenic CO_2 emissions. Land use change and biodiversity loss (Sect. 9) are therefore highly interconnected.

8.2 Insect Production

The production of the feed will be responsible for the majority of the land use and land use change for insect production systems. Oonincx and de Boer (2012) estimated that production of mixed grain feed was responsible for 99% of the land use in mealworm production. Smetana et al. (2015) estimated that the land use occupation of mealworm production to be 1.5–1.52 m^2 per kg. As feed production is responsible for the major part of the impacts, insect production is also efficient in terms of land use compared with traditional animal production to the extent that it is more efficient in terms of feed conversion.

9 Biodiversity Loss

The consumption of animal source foods is one of the greatest threats to biodiversity (Machovina et al. 2015). However, biodiversity loss is influenced by a complex web of variables that are, in turn, affected by multiple agents. It is therefore difficult to quantify the loss of biodiversity as a result of animal production (Steinfeld et al. 2006).

9.1 Animal Production

Livestock threaten biodiversity by modifying habitats; inducing climate change; influencing climate change; introducing invasive alien species, both directly and indirectly; overexploiting natural resources; and polluting ecosystems (Steinfeld et al. 2006). Livestock replacement of natural grazing animals has also been indicated as a loss of biodiversity (Alkemade et al. 2013) and grazing management a possible tool for biodiversity re-establishment, but scientific evidence is scant.

9.2 Insect Production

While there are over 2000 edible insect species (Jongema 2017), concentration on only a handful of edible species which could be farmed may draw attention away preserving the ecosystems where the majority of edible insect species are found. Further, the escape of non-native farmed species is of equal concern and threat to local biodiversity. Due to a lack of data on this issue, there is still a need for further studies into the dynamics of insect farming and biodiversity.

10 Conclusion

This chapter has systematically compared and contrasted the known direct environmental impacts of animal production with insect production for both feed and food. Clearly, animal production systems have substantial environmental impacts on the planet. However, switching part of the global animal production to insect production is clearly not a silver bullet which can solve all the problems associated with the production of animal protein, but, rather, holds the potential to reduce some environmental problems. In most cases the advantages are related to the fact that the insects are more efficient at converting feed into protein than other animals. This difference can be big in comparison to some products like beef and small in comparison with poultry meat.

Perhaps the greatest potential is the prospect of basing insect production on feed from various waste products from agriculture, industry and households. Insects are an extremely diverse group of animals and therefore it may be possible to devise systems based on insects that can digest more human inedible, fiber rich forage. If these systems are not hampered by the significant emissions of greenhouse gases and ammonia etc. that are associated with the digestive fermentation in ruminants, they could present a unique opportunity for producing animal protein in a more environmentally-friendly way. Finally, it may be possible to feed insects on waste products such as household waste, which could possibly improve their environmental sustainability. However, these systems have yet to be developed and therefore it is not known if the insects can achieve high enough growth rates for the systems to become economically viable.

Knowledge of the environmental impacts and experience with animal production systems is enormous in comparison to knowledge about insect production systems. In most cases, we can merely speculate on how the impacts would be different. For this reason, it is clear that more evidence is required to make comparisons between animal production systems and insect production systems.

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