From Plants to Animal Protein: Are Farmed Insects and Aquaculture Fish Less Competitive with Human Food Production than Traditional Livestock?

Jan Hüskens

MSc Thesis Plant Production Systems

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Contents

Abstract

Will there be enough food in the future to feed the global population with an adequate diet? In this thesis, I aim to explore the environmental impacts and resource claims related to the production of animal protein. I compare aquaculture fish and farmed insects with traditional livestock products in order to assess the potential of these relatively new sources of animal protein to reduce impacts and claims. Environmental impact and resource claim indicators are expanded to include competition for food between humans and animals, which is an aspect often hindering interpretation of life cycle assessment studies. A literature search was carried out to select life cycle assessment studies that cover both feed composition and feed conversion ratio. Despite the modest number of life cycle assessment studies published to date for new sources of animal protein, two studies on farmed insects and eight studies on aquaculture fish complied with the selection criteria. Given the large variation in livestock systems around the world, I only focussed on the most productive systems for the comparison. These are production systems in which the animals are primarily kept for the edible products. Livestock products were modelled with the tool FeedPrint and are representative for conventional production systems in the Netherlands.

Intensively produced beef has the largest claim on land and fertilizers that could have been used to produce food for humans directly. For a kg of protein from intensively produced beef – slaughtered at 12 months – 86 m^2 out of the 95 m^2 and 145 g P out 154 g P fertilizer is in competition with human food production. Compared to beef the competitive claim of pork is 53 m^2 and 103 g P lower, and 62 m^2 and 81 g P lower for chicken. Aquaculture fish and farmed insects have total land use claims between 5 and 40 m^2, similar to values found for eggs and milk. For milk, only a minor share of all impacts related to feed production is in competition with human food production. For crickets, all of the impacts and claims come from competitive feed ingredients. But because the global insect farming sector is still small scale and not oriented towards large-scale production of insects for human consumption, little information is currently available on alternative production methods that are less competitive.

In salmon and pangasius aquaculture, small claims on land and fertilizer are required for the cultivation of vegetal feed ingredients. Fishmeal and fish oil are important feed ingredients for these carnivorous and omnivorous species. Higher prices – due to increased demand – have led to ongoing substitution of these ingredients by vegetal based ingredients. As a result of these substitutions the land and fertilizer claims may become similar to those observed now for herbivorous species such as carp and tilapia. Changes in feed composition could lead to new natural resource claims and environmental impacts, and possible trade-offs need to be taken into account.

Producing more animal protein with the same or smaller amounts of resources and environmental impacts can best be achieved by substituting products with high competitive footprints for those with lower ones. However, still a significant knowledge gap exists on the potential of aquaculture and farmed insects as low footprint alternatives.

Samenvatting

Zal er in de toekomst voldoende voedsel zijn om de wereldbevolking van een gezond dieet te voorzien? In deze thesis, onderzoek ik de aan dierlijke eiwitten gerelateerde milieu druk en beslag op natuurlijke hulpbronnen. Ik vergelijk daarvoor gekweekte vis en insecten met de meer traditionele vleesproducten om te onderzoeken of deze relatief nieuwe eiwitbronnen een mogelijkheid bieden om de druk op milieu en natuurlijke hulpbronnen te verlagen. Indicatoren voor milieu en hulpbronnen worden verder uitgebreid om ook de competitie voor eten tussen mensen en dieren aan te geven. Een aspect wat doorgaans niet goed geïnterpreteerd kan worden in levenscyclusanalyses. Ik heb een literatuuronderzoek uitgevoerd om studies naar levenscyclusanalyses te selecteren die zowel de voedercompositie als de voederconversieratio beschrijven. Ondanks het geringe aantal gepubliceerde levenscyclusanalyses tot op heden met betrekking tot dierlijke eiwitten, waren er twee studies over gekweekte insecten en acht studies over gekweekte vis die voldeden aan de selectie criteria. Vanwege de grote diversiteit in veehouderijsystemen wereldwijd heb ik mij voor de vergelijking alleen gericht op de meest productieve systemen waarbij het vee alleen voor het vlees gehouden worden. Vee werd gemodelleerd met het programma FeedPrint en is representatief voor de gangbare veehouderijsystemen in Nederland.

Rundvlees uit de intensieve veehouderij legt de grootste claim op land en meststoffen die ook gebruikt hadden kunnen worden om ander voedsel te produceren voor menselijke consumptie. Voor een kilogram eiwit uit intensief geproduceerd rundvlees – geslacht na 12 maanden - is 86 m^2 van de 95 m^2 en 145 g P van de 154 g P kunstmest in competitie met menselijke voedselproductie. Vergeleken met intensief geproduceerd rundvlees is dat voor varkensvlees 53 m^2 en 103 g P minder en voor kippenvlees is dit 62 m^2 en 81 g P minder. Het totale beslag dat gekweekte vis en insecten op land leggen is tussen de 5 en 40 m^2 per kilogram eiwit. Dat is vergelijkbaar met melk en eieren. Slecht een klein gedeelte van de druk op milieu en hulpbronnen dat melk legt is gerelateerd aan veevoer ingrediënten die in competitie met menselijke voedselproductie zijn. Bij gekweekte krekels is alle druk afkomstig van competitieve voer ingrediënten. Omdat wereldwijd de insectenkweek sector nog klein is en niet gericht op grootschalige productie van insecten voor menselijke consumptie is er ook nog weinig informatie beschikbaar over alternatie kweekmethoden die minder concurrerend zijn.

Indirect leggen de kweek van zalm en pangasius weinig beslag op landbouwgrond en meststoffen voor de productie van voer. Vismeel en olie zijn belangrijke voer ingrediënten voor deze carnivoren en omnivoren. Hogere prijzen – door toenemende vraag – zorgen ervoor dat er een steeds groter deel van deze ingrediënten in het voer worden vervangen door plantaardige ingrediënten. Dit kan er toe leiden dat het beslag op land en meststoffen een vergelijkbare omvang zal aannemen als die van herbivoren als karper en tilapia op het moment. Veranderingen in voersamenstellingen kunnen leiden tot nieuwe en andere vormen van milieu druk en beslag op natuurlijke hulpbronnen. Mogelijke *trade-offs* moeten daarom in overweging worden genomen.

Het produceren van meer dierlijke eiwitten met eenzelfde of kleinere milieu druk en beslag op natuurlijke hulpbronnen kan het best bereikt worden door producten met een hoge competitieve voetafdruk te vervangen door een met een lagere voetafdruk. De potentie van gekweekte vis en insecten als alternatief met een lage voetafdruk is vooralsnog niet helemaal duidelijk.

Chapter 1: Introduction

Proteins are essential nutrients for the human body. They are necessary for maintaining body tissues and the building of new cells and enzymes. Furthermore, proteins serve as a source of energy for the body. Proteins can be derived from a variety of plant and animal products, each different in amino acid composition and quality. The amount of protein required to feed the global population – now and in the future - depends on population size and the protein content in the types of food consumed. On the other hand, the supply of protein depends on the available natural resources and the environmental impacts deemed acceptable during production.

The global population is expected to increase from 7.2 billion in 2013 to 9.6 billion in 2050, according to the most recent version of the United Nations medium variant. An increase or decrease of fertility level of 0.5 per woman compared to this medium variant could lead to 1.3 billion people more or less (UN, 2013). As a consequence of population growth, the demand for food is projected to increase by 60%[1] in 2050 compared to 2005/2007 (Alexandratos and Bruinsma, 2012).

In 2012-2014, about 805 million people are estimated to be chronically undernourished and 2 billion people suffer from deficiencies as a result of an insufficiently balanced diet (FAO, 2014). Per capita income growth leads to an increased demand of calories per person. Further increase in the demand for food is projected to come from a change in diet composition towards more animal products, vegetal oils and sugar consumption (Alexandratos and Bruinsma, 2012). It has been observed in many countries that a rise in income leads to a higher consumption of animal proteins. In 2050, the total meat demand is expected to be 455 Mt. An increase in supply of 1.3% per annum in the 2005/2007-2050 period is necessary to meet this demand (Alexandratos and Bruinsma, 2012). Most of the increase in demand is coming from developing countries.

With higher food production than demand in the past 150 years, hunger was in most cases not so much a consequence of scarcity, but of distribution and poverty. With a 70% increase in demand for food in the future, a time of new absolute scarcity might come (Koning et al., 2008). The question whether or not it is possible to feed a growing population is not new. Throughout history people - Tertullian 3rd century AD, Malthus 1798, Hung Liang-chi 1744-1809 - have worried about this topic. Some were pessimistic about the human potential to overcome biophysical constraints on food production. The solutions for raising agricultural productivity growth, even above that of the population growth, were beyond imagination. But with the help of cheap energy, machinery, the Haber-Bosch method to capture nitrogen, breeding, irrigation systems, better transport, and many other small improvements it was possible to increase the area for agriculture, reduce fallow periods, and increase yields.

Animals were traditionally used to convert inedible plant materials and food waste into edible food. The combination of the inventions and changes in practices mentioned above made it possible to produce surplus food that could be used to feed animals. As a result, more animals were kept and the share of the global grain harvest used as animal feed

[1] This is an aggregated total and includes heterogeneous commodity products such as cereals, meat, milk, fruits, vegetables, etc. The value in itself is fairly meaningless. Furthermore this value was based on a projected population of 9.15 billion instead of the most recent UN Revision of 2012 that predicts a total population of 9.6 billion for 2050.

increased from about 15% in 1900 to 20% in 1950 and to 35% in 1960 (Smil, 2013). Since the 1960s, the share used for feed fluctuated between 36-40% and total use continued to grow with the same pace as global grain harvest from 300 Mt in 1960 to 750 Mt in 2005 (Smil, 2013). Further increase in animal protein production to meet the demand in the future is closely linked to the increases in crop production.

Research has been carried out by Koning et al. (2008) Alexandratos and Bruinsma (2012) to assess the possibilities of feeding a growing world population in the future - and preferably with an affluent diet containing various sources of animal protein - while using the current food production methods. Feeding 47 billion people with an affluent diet is technically possible, but only if all the suitable land for agriculture would be used, including nature areas, and high amounts of external inputs such as fertilizer and irrigation are used. From a more realistic scenario by Koning et al. (2008) it was concluded that it would only be possible to feed 8-10 billion people. The latter scenario takes into account that yield gaps – the difference between potential crop yields and the actual yields - cannot be closed completely, the agricultural area can only be increased in a couple of countries and a further expansion of irrigated land is limited to a 50% increase (Koning et al., 2008).

Capture of wild seafood has approached its boundaries. In 2010, the total amount of captured wild seafood - mainly marine fish - was 88.6 Mt (FAO, 2010). Wild fish capture has stagnated for the past thirty years (FAO, 2013; Subasinghe, 2014), and is not likely to increase much further (Merino et al., 2012). The current capture levels can only be maintained or slightly increased by 6% if fish resources are managed sustainably (Merino et al., 2012).

Aquaculture has become an important 'alternative' source to wild fish, with potential to meet the growing demand for seafood (Cao et al., 2013). Although some forms of aquaculture were already developed centuries ago, the major increase in production took place after the 1950s (Cao et al., 2013). By 2010, the aquaculture production of fish, crustaceans and molluscs had grown to nearly 60 Mt (FAO, 2010). The growth of aquaculture is expected to overtake capture fisheries in total production within a number of years (FAO, 2014e). However, aquaculture species depend – like any other production animal – on feed inputs and the rearing of carnivorous fish still depends to a large extend on the fishmeal and fish oil made from wild pelagic fish (Merino et al., 2012).

Given the high demand for feed ingredients required to produce animal protein by traditional livestock species it is also being suggested that we should be using more efficient types of animals such as insects (van Huis et al., 2013). Insects are poikilothermic and do no need to convert feed into heat to maintain their body temperature and are considered as potential candidates to efficiently convert feed into edible animal protein (van Huis et al., 2013). Farming of insects for food or feed (Pieterse and Pretorius, 2013; Veldkamp et al., 2012) is still in its infancy and largely negligible in terms of their current contribution to global food production.

1.1 Problem formulation

How are we going to use our resources optimally to produce enough food and feed? In this thesis, the focus will be on the requirements of animal protein production, because of the associated environmental impacts and the claim on natural resources through the use of feed.

de Vries and de Boer (2010) argue that little attention has been paid so far, to reducing the environmental impacts – and natural resource claims - of food production by choosing the protein products with the lowest impacts and claims. Environmental impacts can be reduced by choosing more environmentally-friendly livestock products in a diet. In order to make well-informed decisions on which product to choose (beef, pork, chicken, milk or eggs) a consistent assessment of the environmental impact is required. Such an assessment requires a quantification of the emissions and resource use during the entire life cycle of that product. de Vries and de Boer (2010) reviewed 16 studies that used the life cycle assessment (LCA) method and were suitable for comparison. Nijdam et al. (2012) compared 52 LCA studies of animal and vegetal sources of protein. The outcomes of this study – see Figure 1.1 – are however limited to only two environmental impact indicators.

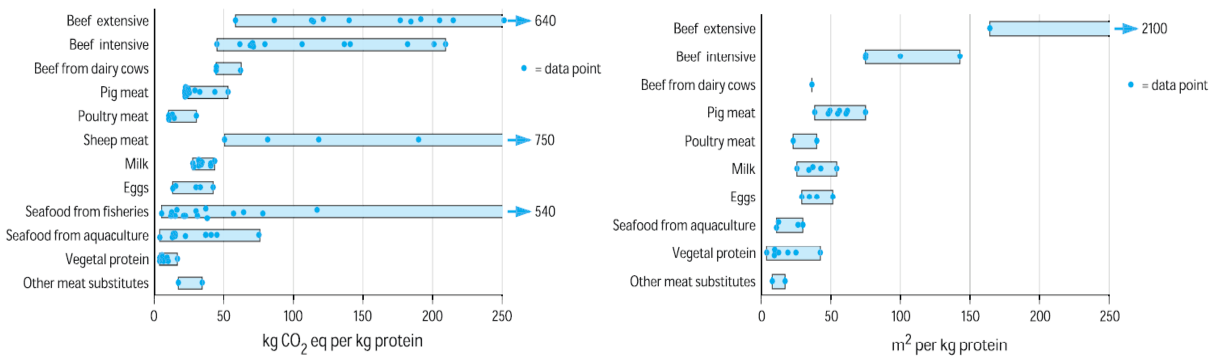


Figure 1.1: Carbon footprints (left) and land use (right) per kilogram of protein. Figures are derived from (Nijdam et al., 2012).

For farmed insects only a life cycle assessment has been performed for the production of mealworms, in which the global warming potential, energy use from fossil fuels, and land use are compared with conventional sources of protein (Oonincx and de Boer, 2012). "The energy use per kg of edible protein for mealworm production is higher than for milk or chicken and similar to pork and beef. However, mealworms, when considered as a human protein source, produce much less GHG's and require much less land, than chickens, pigs, and cattle" (Oonincx and de Boer, 2012). Per kg mass gain mealworms produce only around 1% of the direct GHG emissions of ruminants (Oonincx et al., 2010).

de Vries and de Boer (2010) concluded that their review of livestock products yielded a consistent ranging for land and energy use, and for climate change. However, the interpretation of these LCA results for livestock products, is hindered because results do not include the environmental consequences of competition for resources between humans and animals (de Vries and de Boer, 2010). The diet of commercially raised livestock can contain more than 20 feed ingredients. Some of these feed ingredients – maize, oats – are human-edible and are directly competed for (Wilkinson, 2011). Forage crops – alfalfa - are not suitable for human consumption, but the cultivation of these crops can be considered as being in indirect competition with human food production as the land and fertilizers could be used to grow other human-edible crops. Other sources of feed ingredients are crop residues – straw – or by-products from the food-processing industry – rice middling's – which are to a large extend not suitable for human consumption.

For most people the largest share of their diet consists out of plants. The production of food crops for human consumption can be considered the basis of food production and a minimum claim on natural resources to produce this food is inevitable. There is no competition with human food production when crop residues and by-products originate from crops grown for human consumption. On the contrary, the use of these products as a feed contributes to food production. Although one should keep in mind that continuous removal of crop residues could result in lower soil fertility and hence negatively affect crop productivity.

Which animals protein sources – new or traditional - should we include in our meals that are efficient in transforming the available resources into edible products, have a low environmental impact and at the same time have low competition with human food production?

To provide an answer to the abovementioned questions this MSc thesis has three objectives:

1. Perform a literature review on the developments of aquaculture and insect farming to get an overview of how these products could contribute to increasing animal protein production and lowering the environmental impact and resource claim of human food production.
2. To compare the total environmental impact and resource claims of feed production for animal protein products from aquaculture and insect farming with those of livestock products.
3. To compare the share of competing and non-competing feed sources on the environmental impact and resource claims of animal protein products from livestock, aquaculture and farmed insects.

1.2 Research questions

The problem formulation concluded with the objectives of this MSc thesis and these correspond to the following research questions:

1. How can aquaculture and insect farming contribute to increasing food and protein production?

2. What are the environmental impact and resource claims for the production of protein from aquaculture and insects compared with traditional livestock products?
    2.1 What are the required inputs in terms of land, energy, nitrogen, phosphorus and potassium to produce 1 kg of protein from livestock, aquaculture fish and insects?
    2.2 What are the potential greenhouse gasses, water eutrophication and terrestrial acidification that could result from the production of 1 kg of protein from livestock, aquaculture fish and insects?

3. Which protein products from livestock, aquaculture and insects compete the least with human food production?

3.1 What is the current contribution of livestock, aquaculture, and insect farming to global protein production?
3.2 The production of which feed ingredients in an animal diet are directly and indirectly in competition with human food production?

The first research question is intended to explore how aquaculture and insect farming can contribute to increasing the total food production. What could be obstacles or limitations for the different new products; the availability of resources, production prices or regulations?

The second research question and the corresponding sub-questions are intended to provide an overview of a range of environmental impacts and resource claims that result from the production of traditional sources of animal protein and new types of animals. It is not the aim to look for one product that is best, but instead to point out the strengths and weaknesses of each product. The outputs could help in making informed decisions that – in combination with information on the nutritional quality of each product – could lead to the development of a diet that is both nutritious, diverse, requires fewer resources and results in smaller environmental impacts.

The third research question and corresponding sub-questions are intended to provide an insight into the consequences of producing certain feed ingredients for animal products on the availability of resources. Resources that could be preserved for future generations or that could have be used to provide food for the estimated 805 million people (FAO, 2014b) currently undernourished. The outputs could help to refocus current animal production systems on reducing their competition for resources and to aim for making more efficient use of the resources that are already being deployed in the necessary parts of food production.

Chapter 2: Development of aquaculture and insect farming

This chapter is meant to provide some background information on production developments, prospects and the most important constraints of the aquaculture and insect farming sectors.

2.1 Aquaculture

In 1960, the global output from marine and inland capture fisheries was estimated to be 33.9 Mt[2]. It has increased to 91.3 Mt by 2012 (FAO, 2014e). During the last three decades, the landings from capture fisheries have stabilised at around 90 Mt. The amount of capture fish could increase only by around 5% (FAO, 2014e). At the moment 9.9% of the assessed fish stocks worldwide are under fished, 61.3% of the fish stocks are fully fished and the remaining 28.8% is already over-exploited beyond the maximum sustainable yield (FAO, 2014e). Between 1960 and 2012, aquaculture production increased enormously from 1.6 Mt to 66.6 Mt and will become a more important source of consumed seafood than capture fisheries by the year 2015. Together capture fisheries and aquaculture provide an estimated 17% of the global population's intake of animal protein (FAO, 2014e).

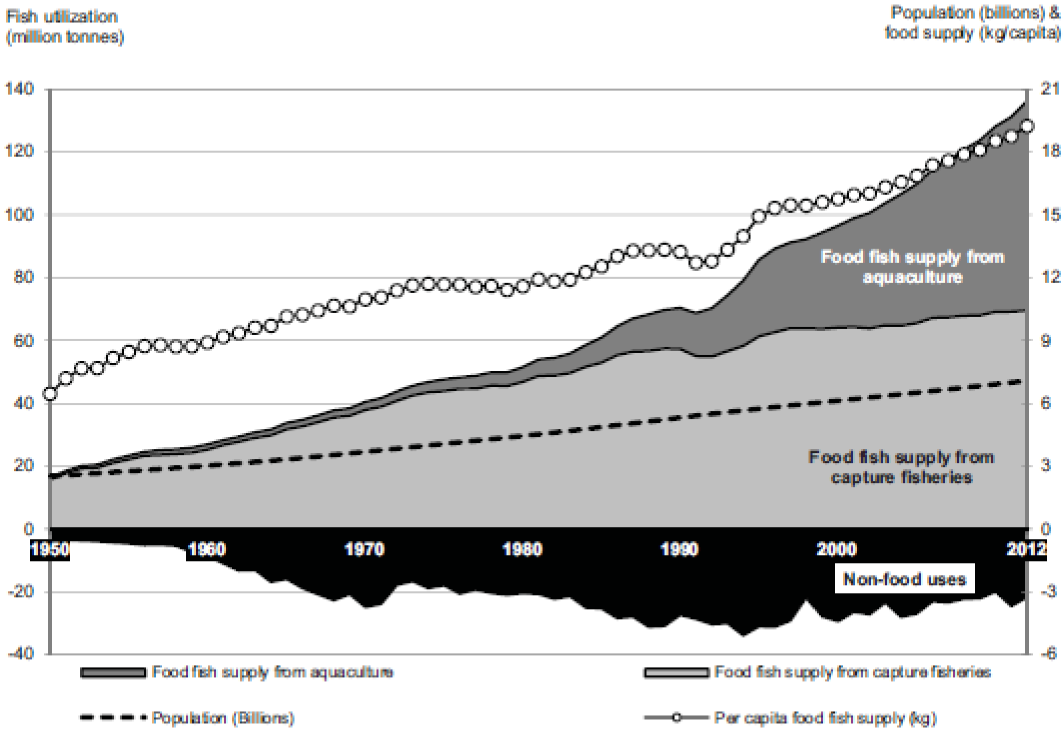


Figure 2.1: World fish utilization and supply. Figure derived from (FAO, 2014c).

2.1.1 Aquaculture species and production methods

In total, there are 567 aquaculture species registered in the FAO statistics (FAO, 2014e). Finfish makes up the largest group with 354 species. The group of molluscs – mussels and bivalves – consists of 102 species. Crustaceans – shrimps and prawns – consists of 59 species. Among the registered species, there are 15 species of reptiles and

[2] Measured in fresh weight.

amphibians, and 37 marine and freshwater algae. Studies on the reproduction of aquaculture species have led to the development of hatchery and nursery technologies (FAO, 2014e), which enabled the rapid expansion of aquaculture production since the 1950s. The number of farmed aquatic species still continues to grow and as the potential of each species becomes better known this opens up new possibilities to increase global food production further.

Aquaculture production systems range from near natural systems to very intensive systems. Production takes place in natural water bodies as well as in artificially created basins. Some of the species depend on naturally occurring phytoplankton in the water for their feed. Other species depend on either plant or animal based ingredients or a combination of the two.

The Asia-Pacific region is by far the most important production area with nearly 90% of global production taking place here (FAO, 2014e). The growth of aquaculture has started to slow down after decades with global annual growth rates of more than 8%. Between 2000 and 2012 the annual growth rate was reduced to 6.2%. The growth of aquaculture production in many countries was mainly driven by area expansion - the introduction of fish in existing water bodies (Subasinghe, 2014). Subasinghe (2014) argues that global aquaculture production might need to increase threefold during 2010-2030 to meet the growing demand for seafood products. With the current trends in aquaculture growth rates in most countries, only a doubling of the aquaculture production would be achieved. In some of the major aquaculture countries, the reduced availability of suitable land and water is lowering growth rates. To sustain further growth of aquaculture production in these countries an intensification of the current systems is required (FAO, 2014e).

Intensification of aquaculture systems with higher densities of animals could lead to the development of diseases and local environmental pollution – through effluents - that affects the productivity of the system. Aquaculture production has suffered in recent years from diseases in some countries – "salmon in Chile, oysters in Europe, and marine shrimp farming in several countries in Asia, South America and Africa" (Subasinghe, 2014). Further growth of the production of certain species could depend on their susceptibility to disease outbreaks and environmental pollution.

The intensity of a system is related to the stocking density. Natural and extensive systems have low stocking densities and the species obtain their food from naturally occurring phytoplankton. In order to maintain medium stocking densities, the fertility of the system – i.e. phytoplankton availability - needs to be enriched through fertilization and sometimes through the supply of small amounts of feed. Intensive systems with high stocking densities are more dependent on the use of aqua feeds.

In 2012, the global production of non-fed inland aquaculture species was 7.1 Mt - mainly filter-feeding carps (FAO, 2014e). This corresponds to 10.7% of the global aquaculture production. These non-fed species should be considered as extremely useful production systems as they avoid any environmental impacts and resource claims from feed production. While non-fed inland aquaculture already exists for centuries the production levels are considered insufficient to provide enough fish to comply with the growing demand. Providing additional feed is a prerequisite, to maintaining high stocking densities as the natural capacity of ponds and rivers to provide feed, is insufficient. Within the aquaculture sector, the fed freshwater finfish supply the largest amount of seafood for consumption. In 2012, this subsector produced more than 30 Mt of fish. This corresponds to more than 45% of global aquaculture production. The fed inland aquaculture consists of both herbivorous and omnivorous species and the percentage of species that receive commercial aqua feed is increasing (Tacon et al., 2011). In most small-scale and low-tech aquaculture systems, fish are fed locally available ingredients. In the more advanced systems fish are fed with commercial aqua feeds that contain all of the required nutritional components. The use of aqua feeds results in higher growth rates. Between 1995 and 2010 the use of commercial aqua feeds increased from 70% to 85% of the total aqua feed use (Tacon et al., 2011).

In 2012, the global production of non-fed marine species – mostly bivalves – was 13.4 Mt (FAO, 2014e). This corresponds to 20.1% of the global aquaculture production. Bivalves – e.g. clams, oysters and mussels – are filter feeders that derive their food from phytoplankton. Throughout the world, they are found in both fresh and salt water habitats. The vast majority of commercially important aquaculture species are saltwater species.

In 2012, the mariculture production of finfish was about 6.7 Mt (FAO, 2014d). This corresponds to 10.1% of the global aquaculture production. Nearly all mariculture – the cultivation of marine species – is inshore, but there is an impetus to look for new production areas away from land based and near coast systems. This search for new production areas is driven by water quality problems, competition for space and a perception of underutilization of the oceans for food production. Furthermore, there is a negative public perception towards environmental and aesthetic impacts caused by mariculture (McDaid Kapetsky et al., 2013).

Schnettler (2014) argues that the utilization of genetic technologies could be beneficial in increasing the efficiency and productivity of aquaculture. "Roughly 8.2% of the global aquaculture production is derived from species that have been domesticated or undergone selective breeding programs. These breeding programs have the potential to increase productivity through improving growth rates and disease resistance" (Schnettler, 2014).

2.1.2 Aqua feed

Most of the feed ingredients used to produce commercial aqua feed are also used in livestock and poultry sectors. In 2010, less than 4% of total feed produced was used as aqua feed. The costs of global commodities are dictated less by demand from the aqua feed sector than by the demand from other animal feed sectors. The aqua feed sector only has a small impact on the availability of grains and oilseeds (Hardy, 2010). However, there are two exceptions: fishmeal and fish oil. While it was not uncommon to include fishmeal in pig and poultry feed a couple of decades ago, now fishmeal and fish oil are almost exclusively used in the aquaculture sector (Hardy, 2010). The demand for fishmeal and fish oil has already exceeded the annual supply.

In 2012, 21.7 Mt of global captured fish was used for non-food uses such as fishmeal and fish oil (FAO, 2014e). Only indirectly as a feed ingredient this captured fish contributes to food production. Fishmeal and fish oil can be produced from whole fish, fish remains or other fish by-products. Some of these whole fish – e.g. anchoveta - are suitable for human consumption, others are not (preferred). Fishmeal prices fluctuate as a result of fluctuations in annual landings (FAO, 2014e). In the long term, fishmeal prices have increased from around US$600 per tonne in January 2003 to US$1919 per tonne in

January 2013. Rising fishmeal prices resulted in more fish by-products being processed into fishmeal instead of being discarded. However, this could result in lower quality feed. "With increasing recovery and utilization of seafood processing waste, global production of fishmeal and fish oil could increase by 15-20%" (Hardy, 2010). In 2012 about 35% of the world's fishmeal production was obtained from fish residues (FAO, 2014e).

Due to the high prices of fishmeal, producers of aqua feed are looking for alternative ingredients to substitute fishmeal. Soybean meal – the most widely available substitute – has risen in price partly due to the increased use in the aqua feed sector (FAO, 2014e). The demand for protein-rich feed ingredients is starting to have an effect on the price and availability of ingredients that were previously only used in other livestock sectors. The average share of fishmeal in aqua feed is projected to decline from 24.6% in 1995 to a mere 4.9% by 2020 (Tacon et al., 2011). The mean percentage of fishmeal in the aqua feed of herbivorous fish – fed carps and tilapias - is expected to decline from 10% to 1% between 1995-2020 (Tacon et al., 2011). For carnivorous fish – salmon, trout, marine fishes – the percentage is expected to decline from 40-50% to 12% between 1995 and 2020 (Tacon et al., 2011). Fishmeal is now increasingly used as a strategic ingredient during specific development stages to reduce mortality and improve feed efficiency (FAO, 2014e).

A number of high-value carnivorous fish species require a minimum amount of fish oil in the diet for their growth (FAO, 2014e). A growing demand for these high-value species– e.g. salmon – as food is also increasing the demand for fish oil. In combination with an increased demand for fish oil as a nutritional supplement for humans, prices have increased from around US$600 per tonne in January 2003 to US$2400 in January 2013 (FAO, 2014e).

"Fish oil in aqua feeds should be - and in many cases is - optimized to ensure that the long-chain omega-3 fatty acids end up in the final product, and are not metabolized by the fish during growth. In nature, marine microalgae are the main producers of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) and these valuable fatty acids are accumulated in the captured fish. Freshwater fish like carp seem better able than their marine relatives to elongate short-chain omega-3 fatty acids into EPA and DHA" (FAO, 2014e). Increasing the production of carps would be an efficient way to supply people with essential fatty acids, especially in areas where these fishes are already common in the diet.

The global usage of fish oil was estimated to be 463.000 tonnes in 1995 from where it is expected to increase further to 908.000 tonnes by 2020. The total fish oil usage in aqua feed will be dominated by the demand from aquaculture sectors with carnivorous fish species. However, only 75.6% of the fish oil is used to feed 18.4% of the total fed aquaculture production. (Tacon et al., 2011)

Because of the growing aquaculture production and the levelling-off of fish meal production, prices have increased and have led to an increased interest in substituting fish meal with plant-based protein-rich ingredients. Some ingredients that have increased in importance in aqua feed are soybean meal, corn gluten meal, cottonseed meal, wheat gluten meal and lupin kernel meal. A number of plant-based oil products included in aqua feed to replace fish oil are soybean oil, rapeseed oil and sunflower oil (Tacon et al., 2011). High-protein concentrates produced from soybeans, grains or oilseeds are the most promising alternative feed ingredients for aqua feed at the moment (Hardy, 2010).

Besides the increased use of plant-based protein and oil sources, there is also use of by-products from livestock production such as poultry by-product meal, hydrolysed feather meal, blood meal and animal fats. Some of these can be used without restrictions to feed fish (Tacon et al., 2011). However, most of these ingredients - whether plant-based or animal-based – are in some way or another inferior to fishmeal and fish oil in terms of their nutritional value (Hardy, 2010; Tacon et al., 2011). Hardy (2010) warns "insufficient information on the nutritional requirements of major farmed species in the formulation of aqua feeds is also a driver for the use of alternatives to fishmeal and fish oil". This could result in lower growth rates and higher feed conversion ratios. Replacing fishmeal and fish oil with plant-based alternatives that are not properly digested could negatively affect the water quality through increased excretion (Hardy, 2010).

"The increased demand for aqua feed is expected to drive the development of new feed sources and products and is also expected to lead to a change in the species we culture and methods we use for production" (Gjedrem et al., 2012). The substitution of fishmeal and fish oil in aqua feeds by vegetal sources will lead to changes in the kind of resource claims such as land use and fertilizer use. These are trade-offs that should be studied further.

2.2 Insects

Entomophagy – the eating of insects – is common practice in most parts of the world. These insects are either collected from the wild or farmed under controlled conditions. In this section, only the prospects of insect farming will be discussed, as the capture of insects from the wild will be largely constrained by what can be collected at sustainable levels. The farming of insects will relieve pressure on wild populations, which are already diminishing for some species in various regions (Hanboonsong et al., 2013). Insect farming can contribute to global food production in two ways – either directly as a food product or indirectly as a feed product for livestock and fish.

2.2.1 Insect farming

The concept of insect farming - in which the insects are reared in a designated area and the living conditions and diet are controlled - is a relatively new development (van Huis et al., 2013). Farming of insects can be small scale with a number of basins or large scale in mechanised production systems. While the FAO statistics department collects data on the most important crops and animal products that are produced globally, no data on production of insect farming other than used in apiculture – bees – and sericulture – silkworms - are published. Bees and silkworms have long played an important role in agriculture for the production of valuable products, such as honey and silk. Mass production – defined as producing more than one ton per day (Vantomme et al., 2012) – of other insect species is not yet common practice. Published production data are available in Appendix C.

The first companies involved in insect farming produced insects as pet food or fish bait. "The species most used are crickets (*Gryllodus aigillatus*, *Gryllus bimaculatus* and *Acheta domesticus*), mealworms (*Zophobas morio*, *Alphitobius diaperinus* and *Tenebrio molitor*), locusts (*Locusta migratoria*), sun beetles (*Pachnoda marginata peregrine*), wax moths (*Galleria mellonella*), cockroaches (*Blaptica dubia*) and larvae of the housefly (*Musca domestica*)" (van Huis et al., 2013).

2.2.2 Insects as food

Insects are considered a suitable alternative to meat and fish. The nutritional value of insects is similar to that of beef, and insects contain a lot of healthy, polyunsaturated fatty acids and minerals (van Huis et al., 2013). In the European Union, the European Commission is working on changing the regulations on novel foods, which will include legislation on the farming and selling of insects (FAVV, 2014)." In the European Union 'novel foods' are all food products or ingredients not used for human consumption in significant amounts, before 15 May 1997. New products first require a risk assessment before sales are allowed by the European Commission" (FAVV, 2014). Microbial, chemical, allergies and physical hazards are of concern for food safety. For each insect species, safe production conditions, application of strict hygiene procedures during the production chain and feed choice are necessary to limit these risks. When insect feeds are composed out of animal ingredients a risk assessment needs to be carried out with respect to the transmission of TSE-agents – Transmissible Spongiform Encephalopathy (FAVV, 2014). This is necessary to avoid repeating mistakes that have led to the spread of the bovine version – BSE – and caused serious health problems for both cattle and humans[3] who ate the infected products. The spread of diseases from insects to livestock or humans – zoonosis - are not very likely though (pers. com. with van Itterbeeck, 23-9-2013). It is not yet known when updated regulations on the production and sale of a number of insect species for human consumption purposes could be expected from the European Commission and how it will influence current insect farms.

In September 2014 the Belgian FAVV[4] – Federal Agency for Safety of the Food Chain – has concluded that the consumption of insects is safe, as long as the insects are reared, processed and prepared under hygienic conditions. Insect farmers need to be associated to the FAVV and follow its regulations on insect farming to be allowed for selling their products for human food purposes (FAVV, 2014).

In October 2014 a number of supermarket chains in Belgium and the Netherlands have started with the sale of processed insect products, such as burgers and nuggets. Previously, insects were only available as dried – whole - products in specialty stores or through the internet. Eating of insects has become more accessible with the sales of processed insects in supermarkets. However, production quantities are still small and the sale of insects for human consumption is not yet legalised, but tolerated instead (FAVV, 2014). It is expected that insect farmers will wait for a decision from the European Commission or national government before they will expand production facilities to produce more insects for food.

2.2.3 Insects as feed

The demand for animal products drives the demand for suitable feed ingredients. With large shares of feed ingredients being imported from other parts of the world, a number of companies have looked into the possibility to use cheap, locally sourced ingredients that are nutritious at the same time. Insects are a natural source of feed for fish and the wild relatives of pigs and chickens. Therefore, the farming of insects – e.g. fly larvae, silkworms and mealworms - as feed ingredient in the diets of livestock and aquaculture

[3] The human type of this disease is better known as Creutzfeldt-Jakob.
[4] In Dutch: Federaal Agentschap voor de Veiligheid van de Voedselketen.

fish are now being considered. A number of companies were set-up in recent years (see Appendix C).

However, the main challenge that the use of insects as feed ingredient faces are the existing regulations – in e.g. the EU - on the use of feed ingredients for livestock and aquaculture species. At the time of establishment, possibilities of using insects as a feed ingredient were not taken into account (Koeleman, 2014). Farmed insects are considered farm animals and the same regulations apply to insects. In short this means that feeding protein-rich animal meal to another animal is not allowed, unless there is an evidence base which proves that there are no negative side-effects – e.g. the feed is free of TSE (Anonymous, 2014). The use of insect fat is already allowed for non-ruminants (Koeleman, 2014).

2.2.4 Prospects and constraints

Oonincx and de Boer (2012) concluded that there is still progress to be made for all environmental indicators they looked at in their LCA study on commercial mealworm production. At the moment, the production of these protein sources are still in their infancy, and by improving the diet and rearing conditions the feed conversion ratio could be reduced further. Further improvement of mealworm – and other insect farming systems – by automation, feed optimization and breeding could lead to improved productivity. Insect farming has enormous potential for food production in countries like Thailand where entomophagy is already practiced, as it could contribute to the supply of insects to existing local markets (van Huis et al., 2013). Given the higher and more favorable temperatures for insect farming in tropical regions it is likely that energy use could be lower compared to production in temperate regions. In the Netherlands, the temperatures are below the optimal growing conditions for most insects and, therefore, additional heating is required. In the case of the van de Ven mealworm farm, 34.8% of the total energy use came from gas usage and 21.2% of electricity usage (Oonincx and de Boer, 2012).

Research should focus on reducing the mortality rate as this currently results in inefficiency in the system. Collavo et al. (2005) reared crickets on a dairy cow diet, but as the survival rate after 61 days was only 27.1% they concluded that this diet performed poorly due to a lack of balanced nutrition. A human refuse diet – with fruits and vegetable peels and leftovers, rice and pasta, pork and beef meat, bread, cheese skins and egg yolk – had a survival rate of 47.5%. It is thus possible to improve survival rates.

According to Margot Calis-Oosterwaal from the Dutch branch organisation for insect farmers[5] (pers. com. 25-9-2013) the feed ingredients used in insect farming should be pesticide free – at least insecticide free – as this could lead to high mortality rates. A human refuse diet might not be very suitable as it is not well known if feed ingredients contain residues of pesticides. Commercial insect farmers that produce insects for pet food and human consumption will prefer feed ingredients that are guaranteed pesticide free. As a consequence crop residues and by-products might be less suitable and insect farmers may have to rely on ingredients from certified organic producers.

Large scale adoption of insect farming requires support to farmers similar to that in the livestock and aquaculture sectors. This includes information on disease prevention,

[5] In Dutch VENIK: Vereniging Nederlandse Insectenkwekers

balanced nutrition, rearing facility materials, construction and maintenance, safety instruction for workers, as well as marketing of the end product. Platforms for knowledge exchange are thus required. From 2015 onwards the Journal of Insects as Food and Feed will be published. One of the aims of the journals is to stimulate further environmental impact studies to be carried out. "Environmental impact studies for the production of insect protein are needed to estimate global warming potential, energy use, and land use as are overall life cycle assessments" (http://www.wageningenacademic.com/jiff 12-1-2015). The in 2013 founded International Producers of Insects for Food and Feed (IPIFF) has addressed research on LCAs and nutritional studies of farmed insects as an important aspect of the promotion of insects as food or feed (http://www.ipiff.org/about-us/ 20-11-2014). Sound evidence is required to reveal both the advantages and disadvantages with regard to the sustainability and food security potential of insect farming.

It is necessary to collect data on production quantities of each insect farm in order to keep track of the contributions of insect farming to food and feed production. Since the FAO is promoting entomophagy as an important way to achieve global food and nutrition security (van Huis et al., 2013), they should start working on production data collection. The data should be made available - similar to aquaculture species and other commodities. The IPIFF can also play an important role in the collection of production data.

Chapter 3: Methodology

3.1 Analysed animal production systems and their comparison at the feed-consumption level.

During the last two decades, various LCA studies have been published on the environmental impacts of livestock, aquaculture, and more recently also insects products. These LCA studies differed in methodology, assumptions and the underlying data used for calculation. This hindered the comparison of these analyses with one another. A consistent approach is required to enable a fair comparison between the different protein-rich animal products for their environmental impacts resource claims. And to divide these impacts and claims into shares directly or indirectly in competition with human food production and into shares that are not. The methodology used by de Vries and de Boer (2010) to assess published LCA studies and to determine system boundaries was used as a basis for the present study (Section 3.2). Functional units and impact indicators were determined for the animal production processes. To assess the influence of the allocation method used in multi-output systems, both economic and biophysical allocation methods were included (Section 3.3).

The LCA calculation tool FeedPrint was used for two purposes:

1. For the data sets for environmental impacts and resource claims of feed ingredients production.
2. For detailed lists of feed rations on several livestock products – milk, pork, eggs, chicken and veal – and the associated feed conversion ratios (FCR).

The animal products for which the feed rations and FCR are based on the FeedPrint tool are referred to as model based animal production methods [M]. Beef, aquaculture fish and farmed insects are not included in this tool. Published LCA studies that cover the a detailed list of feed rations and the associated FCR were used instead and are referred to as literature based animal production methods [L]. The underlying data sets for feed ingredients from FeedPrint were used to recalculate the environmental impacts and resource claims of the animal products in the published LCA studies (Table 3.2). In this way the soya that is fed to either chicken, fish or insects is based on the same production methods. In this study the assessment of the animal products is only carried out for the feed-consumption level. The feed-consumption level covers the total amount of feed that is consumed in an animal production system during a certain time frame with all the associated upstream impacts of feed production included, but does not include impacts caused by the animal husbandry phase. In addition, a range of alternative production methods of milk, pork, eggs, chicken and veal that were modelled till the feed-consumption level using the LCA calculation tool FeedPrint in order to see how this affected FCR and associated environmental impact and resource claims (Sections 3.4 and 3.5). A schematic overview of the methodology is presented in Figure 3.1.

In the present study, FeedPrint version 2013.03 – 18 November 2013 was used to calculate the carbon footprint and other environmental impacts (Table 3.4) of feed raw materials during their complete life cycle. The model takes into account the upstream environmental impacts involved in fertilizer production, crop cultivation, processing and mixing of the feed ingredients and the utilization by the animals (Vellinga et al., 2013). The utilization by the animals in this version can be modelled under a range of management practices – i.e. alternative production methods - for dairy cows, pigs, broilers, laying hens and veal calves that are representative for conventional farming systems in the Netherlands. "The transport and storage between all steps of the production chain are included as well" (Vellinga et al., 2013). The tool has been developed with two objectives in mind:

1. To create an overview the environmental impact from each phase of the feed production chain and utilization (Vellinga et al., 2013).
2. To develop strategies that reduce the environmental impact (Vellinga et al., 2013).

"The calculation tool FeedPrint is intellectual property of Wageningen UR Livestock Research, the underlying database is shared intellectual property of Blonk Milieu Advies and Wageningen UR Livestock Research" (Vellinga et al., 2013).

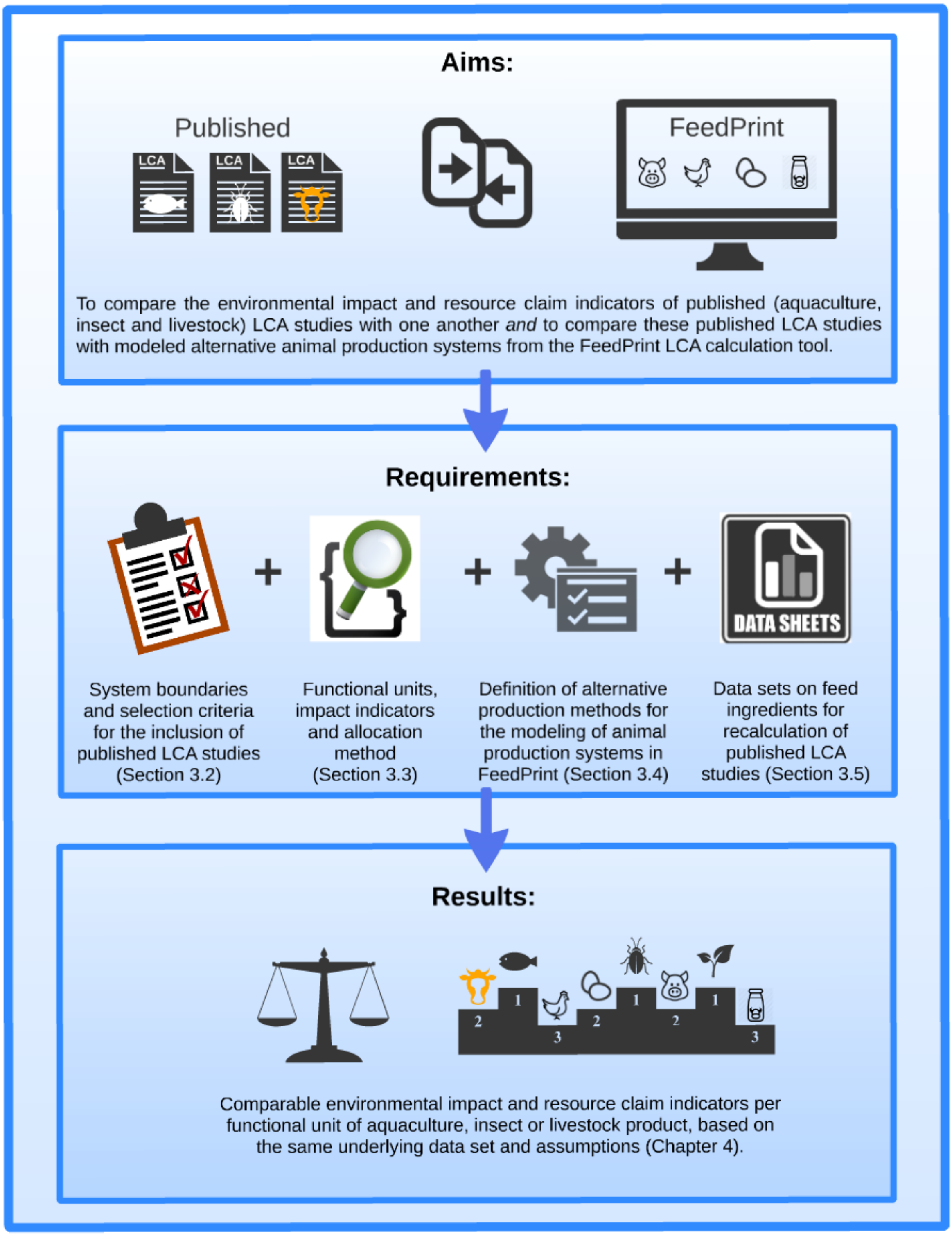


Figure 3.1: Schematic overview of the methodology in the present study.

3.2 Selection of published LCA studies

During the last two decades, various LCA studies have been published on the environmental impacts of animal products. Comparison of these studies is only possible if the same methodologies and system boundaries were applied and if results can be recalculated – e.g. by using the same CO_2-equivalent conversion factors for all studies. The selection criteria in Table 3.1 were used to compare published LCA studies and the modelled alternative production methods in FeedPrint. For a proper comparison, each of the criteria had to be met. See Figure 3.2 for an overview of the system boundaries.

Table 3.1: Selection criteria for using published LCA studies.

	Selection criteria	Explanation
1.	Attributional LCA studies.	Attributional LCA studies evaluate the status quo of an animal product without looking at the possible effects of changing practices.
2.	LCA studies that cover at least a cradle to feed-consumption analysis of the product.	In a complete LCA study the total of environmental impacts and natural resource claims should be allocated to the consumed animal product. However, cradle-to-grave inventories of food products are hard to quantify. The transport, processing, retail and utilization stages result in many uncertainties. Therefore most LCA studies only consider the impact from cradle-to-farm gate. According to Nijdam et al. (2012) feed production, is one of the most important contributors to environmental impact in the life cycle of an animal product. In the present study, the focus is on the impacts caused by the production of animal feed. Animal husbandry – enteric fermentation and housing - was excluded and the comparison was based on the feed-consumption level. The animal husbandry and post-farm gate stages require more detailed information for a cradle-to-grave study.
3.	LCA studies that provide an overview of the amount of each feed ingredient used in the total feed mix.	Quantitative data for each feed ingredient regarding the environmental impact (Table 3.4) was derived from the calculation tool FeedPrint. These datasets were used to recalculate the environmental impact of the different animal products of the published LCAs based on the composition of feed mixes. It was also used to categorize feed ingredients into either competitive or non-competitive with human food production (Section 3.3.2 on feed-food competition).
4.	LCA studies that provide a Feed Conversion Ratio (FCR) of feed mixes used.	The FCR is the amount of feed consumed divided by the amount of live weight (LW) produced. It indicates how efficient an animal in a certain production system is with the amount and quality of feed used.
5.	LCA studies that cover non-organic production systems.	LCA studies of organic products were excluded because present production of crop and animal production is almost entirely non-organic and only a few studies on organic production of livestock products have been published. In addition, insufficient data on organic feed ingredients production and their environmental impacts is available. New animal production systems such as insect farming are not based on organic principles as the farming of insects is only in its infancy.

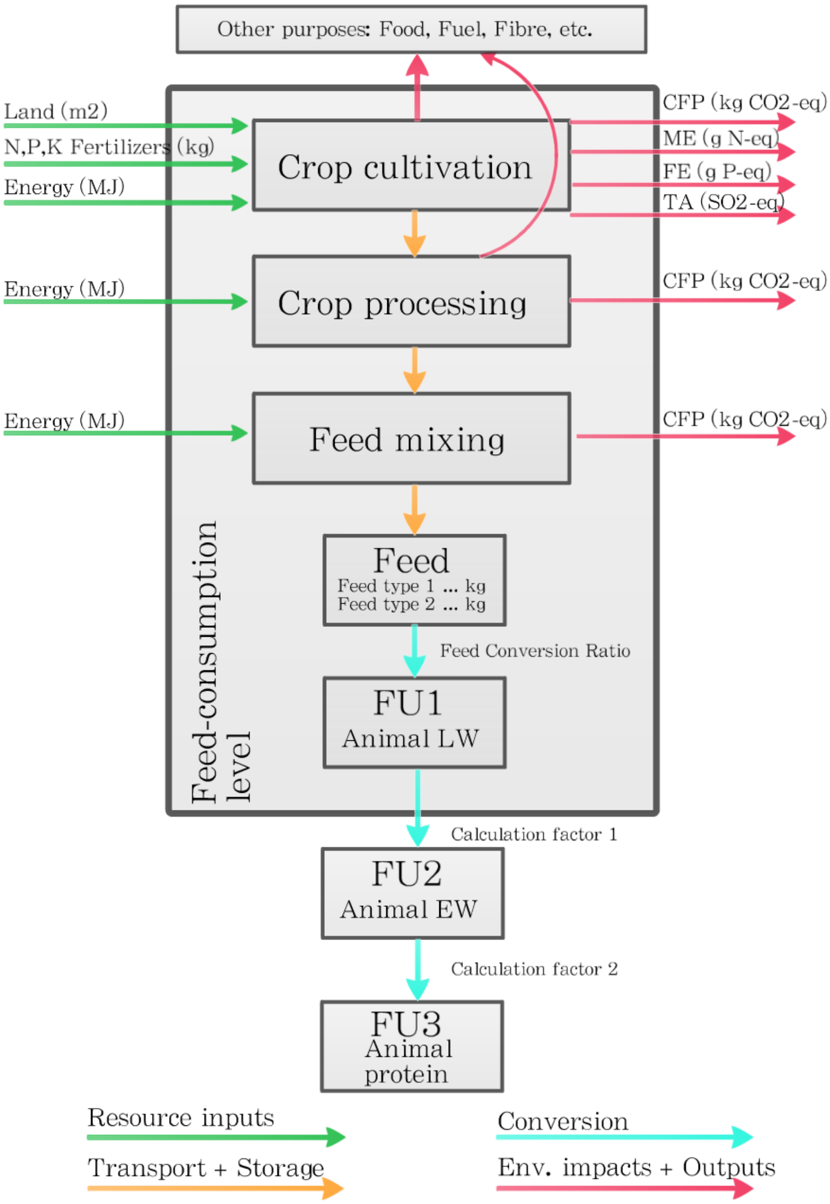


Figure 3.2: Schematic overview of the boundaries and underlying relationships of an animal protein production system at the feed-consumption level – the figure is based on the FeedPrint methodology (Vellinga et al., 2013). Abbreviations used: Carbon Foot Print (CFP), Marine Eutrophication (ME), Freshwater Eutrophication (FE), Terrestrial Acidification (TA), Live Weight (LW), Edible Weight (EW), Functional Unit (FU).

To assess the current potential for the different protein production systems to food production in the long-term, one should look at the most efficient and advanced production systems around the world:

- The livestock production systems in this study only cover OECD countries in which the animals do not have multiple functions – draught power or capital asset – but instead are only kept for the production of animal products (de Vries and de Boer, 2010). It is not clear to what extend the animal production levels in OECD countries can improve further, but it was assumed that the current production levels in these countries are close to its potential. Housing and production methods of pork, chicken and eggs are standardized and, therefore, apply to many OECD countries.
- The FAO estimates that around 567 aquatic species are being cultured (FAO, 2014a). Each of these aquatic species thrives under their preferred conditions. Production mostly takes place where these conditions naturally occur – e.g. warm water in Vietnam for pangasius and cold water in Norway for Salmon – or under controlled conditions anywhere in the world.
- Commercial insect rearing facilities are not common at the moment. Production mostly takes place in OECD countries where conditions are controlled or in tropical countries where the conditions are favourable and small-scale insect farming takes place.

In Table 3.2 an overview is provided with the published LCA studies that were selected based on the abovementioned criteria.

Table 3.2: Overview of selected studies for comparison, with the original environmental impact and resource claim values.

Product	Study	System/ study case	Alterna-tive produc-tion methods	Boun-dary	Country/ region	Functional Unit	GWP or CFP	AP	unit	EP	unit	LU	EU	WD	FFD
							kg CO_2-eq	kg		kg		m^2	MJ	m^3	kg
Livestock															
Beef	Nguyen et al. (2010)	Grazing suckler-cow-calf herd	1	Farm-gate	European Union	Per kg meat (slaughter weight)	27.3	0.210	SO_2-eq	1651	NO_3-eq	42.9	59.2	-	-
Beef	Nguyen et al. (2010)	Intensive rearing dairy bull calf 12 months	1	Farm-gate	European Union	Per kg meat (slaughter weight)	16.0	0.101	SO_2-eq	622	NO_3-eq	16.5	41.3	-	-
Beef	Nguyen et al. (2010)	Intensive rearing dairy bull calf 16 months	1	Farm-gate	European Union	Per kg meat (slaughter weight)	17.9	0.131	SO_2-eq	737	NO_3-eq	16.7	41.7	-	-
Beef	Nguyen et al. (2010)	Intensive rearing dairy bull calf 24 months	1	Farm-gate	European Union	Per kg meat (slaughter weight)	19.9	0.173	SO_2-eq	1140	NO_3-eq	22.7	48.2	-	-
Aquaculture															
Trout	Aubin et al. (2009)	Flow through	1	Farm-gate	France (South-west)	Per 1000 kg live fish weight	2753	19.17	SO_2-eq	65.91	PO_4-eq	-	78,229	52.6	-
Trout (rainbow)	Gronroos et al. (2006)	Cage (marine 80% - inland water 20%)	1	Farm-gate	Finland (Åland islands and Archipelago areas)	Per 10,000 tonnes of ungutted rainbow trout	10,000	21,000	? eq	1,246,000 17,000	PO_4-eq ? eq	-	5,000	-	-
Sea-bass	Aubin et al. (2009)	Cage	1	Farm-gate	Greece	Per 1000 kg live fish weight	3601	25.3	SO_2-eq	108.85	PO_4-eq	-	54,656	48,782.20	-
Turbot	Aubin et al. (2009)	Re-circulating	1	Farm-gate	France (North-west)	Per 1000 kg live fish weight	6017	48.28	SO_2-eq	76.97	PO_4-eq	-	290,986	4.8	-
Salmon	Blonk et al. (2009)	Cage	1	Retail-level	Norway and Scotland	Per kg retail weight	2.2	-	-	-	-	2.5	38	-	-
Salmon	Winther et al. (2009)	Cage	1	Farm-gate	Norway	Per kg live weight	2.0								
Pangasius	Blonk et al. (2009)	Pond/Regular production	1	Retail-level	Vietnam	Per kg retail weight	3.0	-	-	-	-	5.3	31	-	-
Pangasius	Blonk et al. (2009)	Pond/Trace program	1	Retail-level	Vietnam	Per kg retail weight	2.7	-	-	-	-	5.2	28	-	-
Pangasius	Bosma et al. (2009)	Pond	12	Farm-gate	Vietnam (Mekong delta)	Per ton of live weight	8,930	459	m^2	40	PO_4-eq	-	13,200	-	-
Pangasius	Huysveld et al. (2013)	Pond	1	Farm-gate	Vietnam (Mekong delta)	Per tonne live weight	-	-	-	-	-	-	305,000		7,300
Carp and Tilapia	Mungkung et al. (2013)	Cage (feed 2)	2	Farm-gate	Indonesia (Cirata reservoir)	Per tonne fresh fish	1727	13.6	SO_2-eq	98	PO_4-eq	1585	28,645	877	-

Product	Study	System/ study case	Alterna-tive produc-tion methods	Boun-dary	Country/ region	Functional Unit	GWP or CFP	AP	unit	EP	unit	LU	EU	WD	FFD
							kg CO_2-eq	kg		kg		m^2	MJ	m^3	kg
Carp and Tilapia	Mungkung et al. (2013)	Cage (feed 3)	2	Farm-gate	Indonesia (Cirata reservoir)	Per tonne fresh fish	1762	12.9	SO_2-eq	80	PO_4-eq	1648	36,662	711	
Carp and Tilapia	Mungkung et al. (2013)	Cage (feed 4)	2	Farm-gate	Indonesia (Cirata reservoir)	Per tonne fresh fish	1925	12.3	SO_2-eq	79	PO_4-eq	1603	32,188	729	
Carp and Tilapia	Mungkung et al. (2013)	Cage	2	Farm-gate	Indonesia (Cirata reservoir)	Per tonne fresh fish	2025	15.9	SO_2-eq	146	PO_4-eq	1839	32,945	1121	
Tilapia	Pelletier and Tyedmers (2010)	Lake based	1	Farm-gate	Indonesia	Per tonne live weight	1,520	20,200	SO_2-eq	47.8	PO_4-eq		18,200		
Tilapia	Pelletier and Tyedmers (2010)	Pond based	1	Farm-gate	Indonesia	Per tonne live weight	2,100	23,800	SO_2-eq	45.7	PO_4-eq		26,500		
Insects															
Crickets [A]	Collavo et al. (2005)	Small-scale farming	1	Feed-consump-tion level	Italy	Per 1000 kg									
Meal-worms [B]	Oonincx and de Boer (2012)	Climate-controlled-rearing facility	1	Farm-gate	The Netherlands	Per kg fresh product	2.65					3.56	33.68		
						Per kg edible protein	14					18	173		

GWP = Global Warming Potential ; CFP = Carbon Foot Print; AP = Acidification Potential; EP = Eutrophication Potential; LU = Land Use; EU = Energy Use; WD = water dependence; FFD = Fossil Fuel Depletion.

Alternative production methods refer to the number of different management practices for which the corresponding feed conversion ratios was provided. The original results for each indicator that was mentioned in the published study are included in the table.

[A] : Only the dairy cow diet was included in the present study. For the other three diets no FCR was mentioned.

[B] : this study does not fully comply with selection criteria 3. For industrial competitive protection, the exact composition of the diet is not disclosed. The study is included here because the environmental impacts were calculated based on the same dataset as used in the present study. Because the study used economic allocation, it can only be compared with this allocation method.

3.3 Comparison of LCA studies

To compare products from different animal production systems an identical functional unit (FU) is required (de Vries and de Boer, 2010). The focus of this research is on determining the environmental impact and natural resource claims that are needed to supply the global population with adequate amounts of edible protein. Therefore, the environmental impact and natural resource claims are analysed using three functional units:

- Per kg of animal live weight produced (FU 1)
- Per kg of animal edible weight produced (FU 2)
- Per kg of animal protein produced (FU 3)

In the present study, the focus is on protein production and to express the impacts and claims for FU 3 the other two functional units are required as intermediate steps. Animal products at the feed-consumption level are expressed in live weight (LW). However, for animal products – with the exception of milk, eggs and mealworms – the LW does not resemble all parts that are consumed. For meat products, only a part of the animal is suited for consumption, the so-called edible weight (EW). The fraction of edible weight depends on processing methods and culturally defined values of edible and inedible parts. Milk and eggs, for example, have a high water content compared to meat and to allow for comparison of the nutritional values of the consumed products a conversion to protein in the edible weight was applied. The conversion factors in Table 3.3 were used to calculate kg EW from LW and kg protein in the EW. The edible weight represents the parts of livestock animals that are perceived edible in OECD countries.

Table 3.3: Calculation factors to determine a functional unit. Adapted from de Vries and de Boer (2010).

	Product	Kg edible product/kg live weight	Kg protein/kg edible product
Livestock	Pork	0.53 [A]	0.19 [B]
	Chicken	0.56 [A]	0.19 [B]
	Beef (incl. veal and culled dairy cows)	0.43 [A]	0.19 [B]
	Milk products (excl. butter)	1 [A]	0.03 [A]
	Eggs	1 [A]	0.13 [C]
Aquaculture	Carnivorous fish	0.65 [G]	0.20 [H]
	Omnivorous/herbivorous fish	0.65 [G]	0.18 [H]
Insects	Mealworms	1 [D]	0.197 [D]
	Crickets	0.80 [E]	0.163 [F]

[A] Source: (de Vries and de Boer, 2010)
[B] Sources: (de Vries and de Boer, 2010); (Lawrie and Ledward, 2006)
[C] Sources: (de Vries and de Boer, 2010)); (USDA., 2009)
[D] Source: (Oonincx and de Boer, 2012)
[E] Sources: (van Huis et al., 2013); (Nakagaki and Defoliart, 1991)
[F] Source: (Collavo et al., 2005)
[G] Source: (Smil, 2000).
[H] Sources: (Smil, 2000); NEVO-online.rivm.nl (2014) http://nevo-online.rivm.nlProductDetails.aspx

3.3.1 Environmental impact and resource claim indicators

The environmental impact and resource claim indicators that were used in this study are presented in Table 3.4. Besides the six[6] indicators that are used in FeedPrint another four were added in the present study to assess the efficiency of fertilizers and crude protein use. The indicators are expressed per kg of functional unit and can refer to each of the three functional units mentioned above. For the results only functional unit 3 – per kg animal protein – was used.

Table 3.4: Environmental impact and resource claim indicators.

Indicator	Abbreviation	Expressed in	Type of impact	Indicator used in FeedPrint
Carbon Foot Print	CFP	g CO_2-eq per kg FU	Environmental impact	Yes
Land Use	LU	m^2 $year^{-1}$ per kg FU	Resource claim	Yes
Energy Use	EU	MJ per kg FU	Resource claim	Yes
Marine Eutrophication	ME	g N-eq per kg FU	Environmental impact	Yes
Freshwater Eutrophication	FE	g P-eq per kg FU	Environmental impact	Yes
Terrestrial Acidification	TA	g SO_2-eq per kg FU	Environmental impact	Yes
Nitrogen Fertilizer Use	NFU	g N per kg FU	Resource claim	No
Phosphorus Fertilizer Use	PFU	g P per kg FU	Resource claim	No
Potassium (Kalium) Fertilizer Use	KFU	g K per kg FU	Resource claim	No
Crude Protein Use	CPU	g Crude Protein per kg FU	Resource claim	No

The **Carbon Foot Print** is the combined impact of a product on climate change from greenhouse gasses. The emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were converted into of CO_2-equivalents that have an impact horizon of 100 years. The conversion factor for CO_2-eq is 1 for CO_2, 25 for CH_4 and 298 for N_2O (IPCC, 2007). The greenhouse gas emissions originate from fertilizer production, the burning of fossil fuels during cultivation, feed processing, storage and transport.

Land Use in this study refers to the use of 'agricultural land'. This includes arable land - for food or feed crops - or grasslands (Nijdam et al., 2012) unless otherwise stated. The feed components are sourced from different countries – e.g. soybeans from the United States, Brazil and Argentina (Vellinga et al., 2013) to include some diversity of land quality. Land is the only resource that becomes available for re-use every year as long as it is properly managed. A number of feed ingredients are from perennial crops and, therefore, the indicators are expressed per year. For these perennial crops, an average yield throughout its lifetime was used, thereby correcting for the years that the crop was not yet productive - the establishing phase – and the productive years. In areas where multiple cropping seasons take place in one year, the impacts are allocated to the total yield. For example, two crops of maize are cultivated on a hectare of land in the same

[6] The fossil fuel depletion indicator from FeedPrint was not used in the present study, as this resource claim is already covered by the indicator energy use.

year. If two or more crops are grown on the same land within one year the impact of the products depends on the allocation method that is applied in the study (Section 3.2.3 on Allocation in multi-output systems).

Energy Use represents the required energy input of animal products. Most of the upstream energy use is based on fossil fuels.

Marine and Freshwater Eutrophication indicators were used to provide an insight into what the potentials are for eutrophication of water bodies as a result of nutrient leaching from agriculture. The nutrients originate from the leaching of fertilizers and manure and accumulate over time. Accumulation of nutrients in water bodies could negatively affect the environment once a certain threshold is exceeded.

The **Terrestrial Acidification** indicator was used to provide insight in the potentials of sulphur emissions from SO_2-SO_4 and nitrogen emissions from NOx-HNO_3 or NH_3 to acidification of the soils (Roy et al., 2012). A reduction in the pH-levels of the soil could lead to biodiversity loss – e.g. of vascular plant species (Roy et al., 2012).

The **use of N, P, K fertilizers** is considered in this study because of the importance of these macro-nutrients in crop production and the limited minable resources available - especially of rock phosphate – and the environmental impact of synthetic nitrogen fixation. The amount of fertilizer needed to produce a functional unit of animal product was calculated based on standard fertilizer application rates for specific crops in the main producing countries as used in FeedPrint. For nitrogen, both artificial fertilizers and organic manure application were taken into account. For phosphate and potassium, only the application of artificial fertilizer was calculated. These indicators do not reflect the amount of nutrients that end up in the crops and animals. They only reflect the required external inputs for maintaining the productivity of the system.

The **Crude Protein Use** indicator reflects on the amount of crude protein that is present in feed ingredients and is required to produce a kg of animal protein. The crude protein in feed ingredients is in most cases derived from plant biomass of which some are not suited for human consumption. By taking into account the protein that are derived from feed ingredients that are not suited for human consumption (Section 3.3.2 on Feed-Food competition) and the ones that are, it is possible to say if an animal product has a positive or a negative effect on the availability of consumable protein for humans. The composition of amino acids in the protein and the digestibility of both the feed ingredients and the animal products is not covered in this study.

3.3.2 Feed-Food competition

When expressing the claims on resources for the production of livestock products a distinction should be made between feed ingredients that are in competition with human food production and feed ingredients that are not. Wilkinson (2011) re-defined efficiency of feed use by livestock as edible FCR in which the feed ration is divided into a share of human-edible and non-edible feed ingredients. Although this addresses the diversity of feed ingredients and the direct competition between humans and animals, the indirect competition for resources required to produce food are not taken into account. Smil (2013) distinguishes four categories of feed ingredients: main products, crop residues, processing by-products, and feedstuff of animal origin. In the present study, three categories were added: grass – from natural grasslands – food waste and additives. An animal feed ingredient is in direct competition with human food production when it is human-edible. Indirectly it is in competition if the land on which this ingredient is produced is suitable for the cultivation of (other) edible food crops. A feed ingredient is not considered as being in competition with human food production if the land is not suited due to unfavourable climatic conditions, soils or slopes. A feed ingredient that is not human-edible and which originates as a co-product from a food production process in which the main product is used for food is not considered to be competitive with human food production. Land, energy and fertilizer resources allocated to the co-product are not freely available to produce another product instead. For instance, the production of cereals and the co-product straw are related.

It is a rather arbitrary task to categorize crop residues, by-products, feedstuff of animal origin and food waste into suitable or non-suitable for human consumption. What is considered edible or not differs between people, cultures, religions, and locations.

Main products, such as concentrates and fodder crops are in competition with human food production (Table 3.5). They could either have been eaten directly by humans or the resources required for production could have been used to produce another edible crop. Processing by-products were considered not suitable for human consumption if they are not used as common ingredients in the food industry. Peelings from kitchens are also considered processing by-products of food production and preparation. Edible by-products suited for human consumption are in category one. Animal feedstuff from wild caught animals can be in competition with human food production if species are used that are suitable for human consumption. In the present study, it was assumed that feedstuff of wild caught animals is not from species suitable for human consumption. More detailed information is required to assess, for instance, the share of edible fish species in fishmeal. 35% of fishmeal consists of processing by-products and it is expected that this share will increase further in the future (FAO, 2014e).

Table 3.5: Categories of animal feed ingredients and their competition with human food production.

Category		Examples	Competition with human food production
1	Main products	Concentrate grains, palm oil, grass cultivated on land suitable for cropping	Yes
2	Crop residues	Straw	No
3	Processing by-products	Rice middling's, rapeseed meal, peelings	No
4	Feedstuff of animal origin	Blood, whey, fishmeal	Yes/No [A]
5	Natural grass	Grass from natural grasslands	No
6	Food waste	Discarded leftovers, fruits and vegetables	No [B]
7	Additives	Salt, chalk	No

[A] Depends on the origin of the product.

[B] Environmental impacts and resource claims should be allocated to the phase during which the food waste occurs, not to food waste that is used as a feed ingredient.

Crop residues and grass were considered not suitable for human consumption. Grass from natural grassland – e.g. in areas that are too wet[7] or too dry for other crops - is not in competition with human food production. On the contrary, using grass from natural

[7] Peat soils in the Netherlands.

grasslands as feed ingredient increases the potential of food production in these areas, because it is often the only way to transform inedible plant biomass into an edible food product. For the inedible crop residues and by-products counts the same.

Commercial animal diets include additives such as chalk, salt and premixes to enhance growth and health. These additives are not negligible as for their energy use and associated greenhouse gas emissions during production.

Food waste is a product that has been discarded – either on purpose or accidently - and is not regarded safe or acceptable for human consumption anymore. Food that is wasted can be considered as being in competition with human food production because it was a suitable food product before being expired and required resources for production. These resources could have been used to produce food elsewhere or in the future. However, the use of food waste is not considered as being in competition with food production, because the use of food waste as feed ingredients for animals could off-set the need for the production of other feed ingredients that are in competition with human food production. How the environmental impacts and resource claims are allocated to food waste products that are used as feed ingredients is discussed in section 3.3.3. See Figure 3.3 for a schematic overview of the role of the seven categories of feed ingredients in food production.

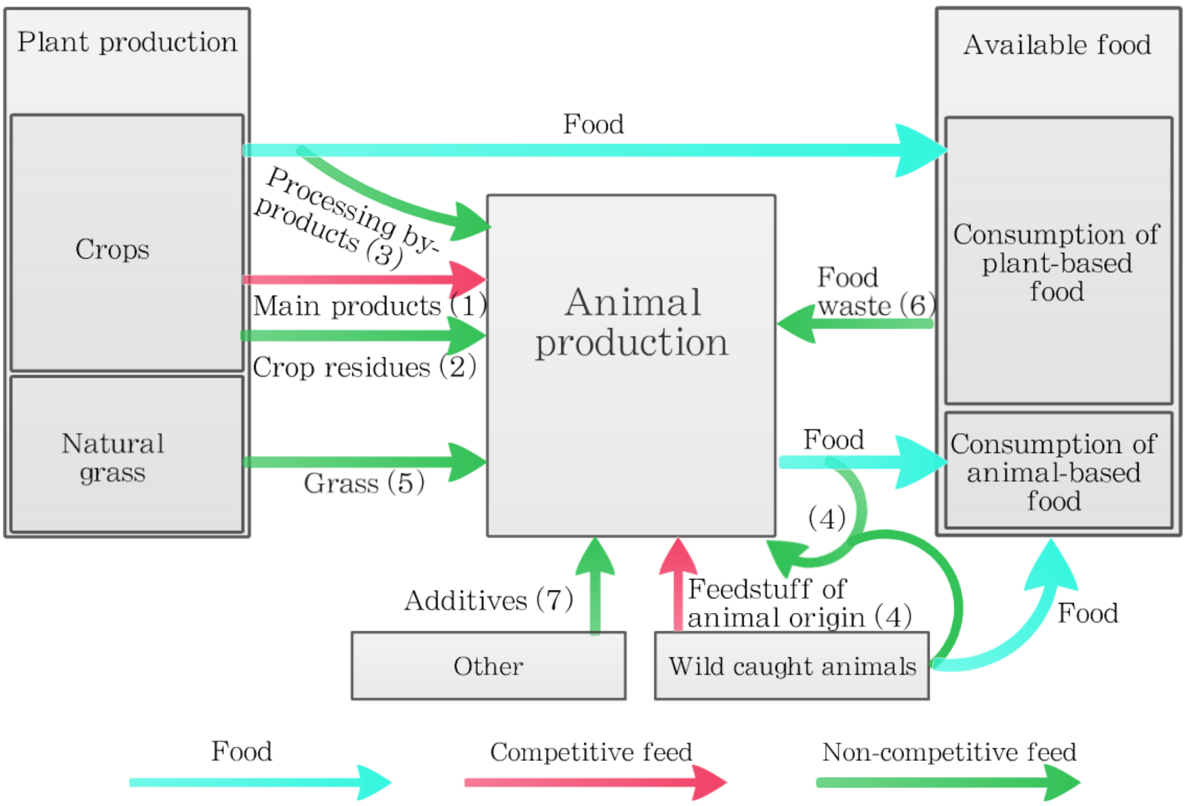


Figure 3.3: Schematic overview of food production with seven categories of feed ingredients used in animal production.

3.3.3 Allocation in multi-output systems

Multi-output systems pose a challenge in LCA studies because they demand a decision on how the environmental burdens are divided over two or more products that are produced in the same process. "The decision of the right method used is critical, as results can hinge on the allocation rule applied" (Pelletier and Tyedmers, 2011). Three main allocation methods exist (de Vries and de Boer, 2010; ISO, 2006):

- Economic allocation; the environmental impact of a production system or process is allocated to its multiple outputs based on market information (e.g. relative economic value).
- Physical allocation; the environmental impact of a production system or process is allocated to its multiple outputs based on the relative mass or on underlying biophysical properties (e.g. caloric energy).
- Systems expansion; the environmental impact of a production system or process is not allocated to its multiple outputs, but instead allocation is avoided by expanding the system to include an alternative way of producing the co-products. It includes comparisons of how a product could be produced using different production strategies.

LCA results based on different allocation methods cannot be compared directly (de Vries and de Boer, 2010; Thomassen et al., 2008). de Vries and de Boer (2010) use economic allocation because most LCA studies apply this method. However, Pelletier and Tyedmers (2011) argue that allocation based on market information – economic allocation – fails to communicate environmentally meaningful information. LCA studies are carried out because it is recognized that market signals are not sufficient in managing the environmental dimensions of human activities within a finite biosphere (Pelletier and Tyedmers, 2011). The allocation method used should be in line with the broader objectives of the LCA. For the present study, it means that the outcomes of the LCA should help in making decisions on how to produce a minimum quality and quantity of calories[8] for the global population within the boundaries of the biosphere. The need to produce this minimum quality and quantity of calories is seen by Pelletier and Tyedmers (2011) as the causal force behind economic activities related to food production and, therefore, a multitude of biophysical variables are much more relevant than the profit motive that is used in economic allocation.

Another argument against the use of economic allocation is the fluctuation of economic values with time and place (Pelletier and Tyedmers, 2011). The use of economic allocation could also be a serious obstacle when trying to improve the sustainability of a product based on the outcomes of an LCA. For example, a by-product has a low environmental impact because of its low relative value with respect to the main product. This by-product - a suitable feed ingredient - was found to be a possible candidate to lower the environmental impact of an animal feed by using a higher percentage of it in the feed mix. But if an increased interest in the by-product leads to a higher relative price with respect to the main-product, then also more environmental impact should be allocated to the by-product and less to the main-product. As a result, the reduction of the environmental impact of the animal feed mix is less than what was intended and in some

[8] A share of the required calories are derived from protein and a share of the protein are used for growth and maintenance of the human body, thus when talking about a minimum quality and quantity of calories protein are included.

cases the overall environmental impact of the animal feed mix could increase. This would make it very hard to find good strategies to achieve environmental objectives.

Pelletier and Tyedmers (2011) propose a biophysical approach for allocation. A physical property, such as mass, is certainly a somewhat crude common denominator for these relationships. "There are, however, a range of other physical and chemical properties that might be chosen as allocation criteria, which simultaneously reflect both the biophysical nature of the process and the causative impetus provided by specific human needs. This is particularly true if the allocation criterion and functional unit (the physical quantity of the product or service system to which impact assessment results are related) are defined according to the same biophysical currency" (Pelletier and Tyedmers, 2011).

Instead of choosing one method of allocation over another, both an economic and biophysical allocation method were used for feed ingredients and compared in the present study. Economic allocation (EA) and gross energy allocation (GEA) factors from FeedPrint dataset were used for feed ingredients. For most feed ingredients used in the present study, data was available to allocate environmental impacts or resource claims to multiple outputs either on an economic basis or a biophysical basis.

In order to complete the full life cycle analysis of a product, the same allocation method as used for feed ingredients should be used for animal products. Dairy and laying hen production systems produce at least two types of edible products. In these farming systems, milk and eggs are the main edible products and the meat from the culled animals are considered edible by-products. The FeedPrint calculation tool only allowed for economic allocation to be applied in this situation as gross energy data was not yet included in the tool. More detailed information on the economic values and biophysical properties of the main and by-products from animal production systems are required. Not only for livestock, but also for aquaculture species and insects. Instead of applying allocation here, the environmental impacts and resource claims were expressed for a kg of milk or eggs produced and the associated meat that is produced is within these impacts and claims. For example, 50 grams of meat are associated with the production of 1 kg of eggs. Both products can be converted to edible weight and protein using the calculation factors in Table 3.3.

Food waste products are a special group for allocation. If food waste can still be used as a feed ingredient this should be encouraged because valuable nutrients can still be used. For the waste product, we need to take into account all the environmental impacts and resources associated with its production. That would mean that using waste products as a feed ingredient can have an impact on the eventual performance of the animal product. However, we need to take into account who is the one to blame for the impact. The one who makes use of the waste product or the one who was responsible for letting a good product turn into waste? I would argue that the latter is to blame for the environmental impact and resource claim has the responsibility to avoid wasting food in the future. As a consequence, only the impacts from transport and processing phases need to be allocated to this feed ingredient. Food waste is thus a low impact feed ingredient to use, but not to produce. Using food waste as a feed ingredient could thus be an option for - especially pig, chicken and insect - farming systems to reduce the environmental impact of their animal products.

3.4 Definition of alternative production methods in FeedPrint

A number of alternative production methods were selected for the animal products that were modelled using the calculation tool FeedPrint. The animal race, gender, slaughter weight and the feeding strategy can be selected in the calculation tool, which results in a specific feed conversion ratio that is associated with that production method. This is illustrated in Figure 3.4 for laying hens. In FeedPrint there are two types of laying hens one can choose from and the number of laying days can be varied from 350 days to 450.

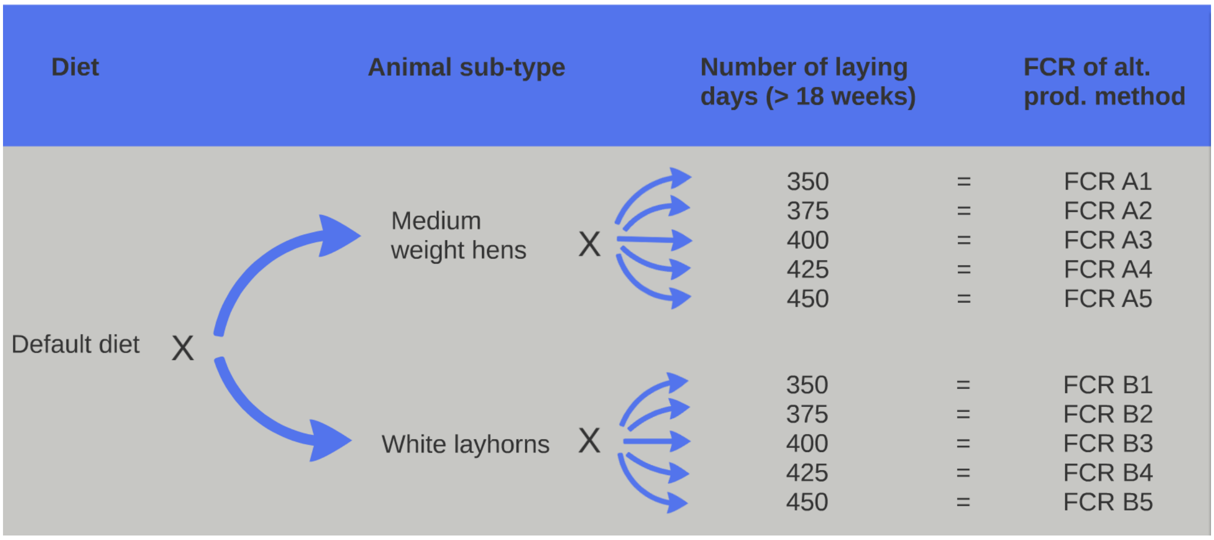


Figure 3.4: Possible alternative production methods and corresponding feed conversion ratios for laying hens with one – default – diet.

The variables that can be selected to model alternative production methods – of pig, chicken, eggs and veal - in FeedPrint can be found in Table 3.5A. In Appendix A, the alternative production methods that were selected for each of the modelled animal products are presented with the corresponding feed conversion ratios.

Assessing the alternative production methods provides information about the range of impacts that can be observed for a particular animal product and what trade-offs result from a change in production strategy.

Table 3.5A: Overview of farm types and variables used for the modelling of the animal products with the FeedPrint calculation tool.

Farm type	Animals and products	Management variables	Variants
Pig farm	Breeding sows: • Piglets • Culled sows	Litter size	Min. 8
			Max. 20
	Fattening pigs • Pork meat	Sub-type of animals	Barrows and gilts
			Boars and gilts
		Feeding strategy	Ad libitum feeding
			Portion feeding
			Combination of ad libitum and portion feeding
		Slaughter weight (kg live weight)	Min. 100
			Max. 130
Poultry farm	Laying hens • Eggs • Culled laying hens	Sub-type of animals	Medium weight hens
			White layhorns
		Number of laying days (>18 weeks)	Min. 350
			Max. 450

Veal calf farm	Broilers: • Chicken meat	Sub-type of animals	Standard broilers
			Slow growing broilers
			Heavy broilers
		Type of growth curve	Flat curve
			Convex curve
		Slaughter weight (kg live weight)	Min. 1.6 or 3
			Max. 2.2 or 3.5
	Milk-fed veal calves: • White veal meat	Sub-type of animal	Black and white
			Red and white
			Croise
			Extra meat
		Gender	Bull calves
			Heifer calves
		Length of fattening period (weeks)	Min. 22
			Max. 30
	Rosé veal calves • Rosé veal meat	Sub-type of animal	Poddy calf
			Weaner calf
		Slaughter weight (kg live weight)	Min. 300
			Max. 400

Four grazing strategies can be selected in FeedPrint for dairy farms and additional compound feed can be provided from 1000 to 3000 kg per cow per year (see Table 3.5B). In the present study compound feed levels of 1000, 1500, 2000, 2500 and 3000 kg were selected for each of the four grazing strategies. The composition of the compound feed is the same for all grazing strategies. However the share of compound feed and grass in the diet is different for each alternative production method. Unlike the other animal products that were modelled with FeedPrint there is no default diet for dairy cows.

Table 3.5B: Overview of farm types and variables used for the modelling of the animal products with the FeedPrint calculation tool.

Farm type	Animals and products	Grazing strategy	Management variables	Variants
Dairy farm	Dairy cattle: • Milk • Calves • Culled dairy cows	Grazing during day and night	Compound feed supplied (kg/cow/year)	Min. 1000 Max. 3000
		Grazing during day		
		Zero grazing		
		Summer feeding [A]		

[A]: Summer feeding is a zero-grazing system in which the cows are not fed any fresh grass. Throughout the year, the cows receive the same diet – with a constant quality – in order to avoid fluctuations in milk production levels as a result of changes in the diet.

3.5 Datasets on the production of feed ingredients in FeedPrint

The diet of farm animals can be composed out of more than 200 feed components, 150 by-products and 25 types of roughage. For all ingredients, the upstream impacts have been identified. This data was used also for the recalculation of the published LCA studies. Data on feed ingredients from FeedPrint was transferred to MS Excel. For each animal product covered in this study – both model based and literature based – the feed ingredients used in the diet were selected and the fraction of each ingredient in the total diet was indicated. The environmental impacts and resource claim per animal live weight were based on the combination of the individual feed ingredients times the associated feed conversion ratio. The calculation factors as mentioned in Table 3.3. were used to express the impacts and claims per kg of protein.

Default diets in FeedPrint were used to calculate the impacts of pigs, broilers, eggs and veal. See Appendix A for these default diets. The default diet – for each animal type – represents a realistic composition of suitable feed ingredients that could be used by farmers. “The diet is composed of various feed ingredients and depends on the animal type and the production goal. The nutritional quality of the feed ingredients is based on the standard values of the Dutch feed list of the ‘Centraal Veevoeder Bureau’ (CVB-list). Digestibility, energy contents, protein contents and minerals are in this list. An average nutritional quality of the feed is calculated as a weighted average of all feed ingredients. The nutritional models of the animals simulate feed intake and calculate growth rates of young animals and production rates of milk and eggs for dairy cows and laying hens, respectively” (Vellinga et al., 2013). Diets inadequate in nutritional composition cannot be modelled.

There are many suitable diets that can be selected manually in FeedPrint. The scope of the modelled alternative animal production methods from FeedPrint in the present study is to assess the variability in feed conversion ratios that can originate through different management practices when only one type of diet is used - i.e. default diet from FeedPrint. Comparing different suitable diets for an animal production system is beyond the scope of this study.

An example – from FeedPrint - of a feed mix used for feeding laying hens is presented in Figure 3.5. For each ingredient, the upstream impacts of transport, crop cultivation inputs and machine work, processing, additives production and the feed mill phases are included. In Figure 3.6 the cultivation inputs are presented for the production of wheat as a feed ingredient in the Netherlands, which represents 10% of the wheat used in the feed mix. The rest of the wheat in this example comes from Germany (35%), France (30%) and the United Kingdom (25%). The underlying data for each crop in FeedPrint is based on average production and input levels in main producing countries.

When multiple products are the result of a feed production process, the allocation within the tool can be based on:

- Economic allocation (EA) – *used in present study*
- Mass balance allocation (MBA)
- Gross energy allocation (GEA) – *used in present study*

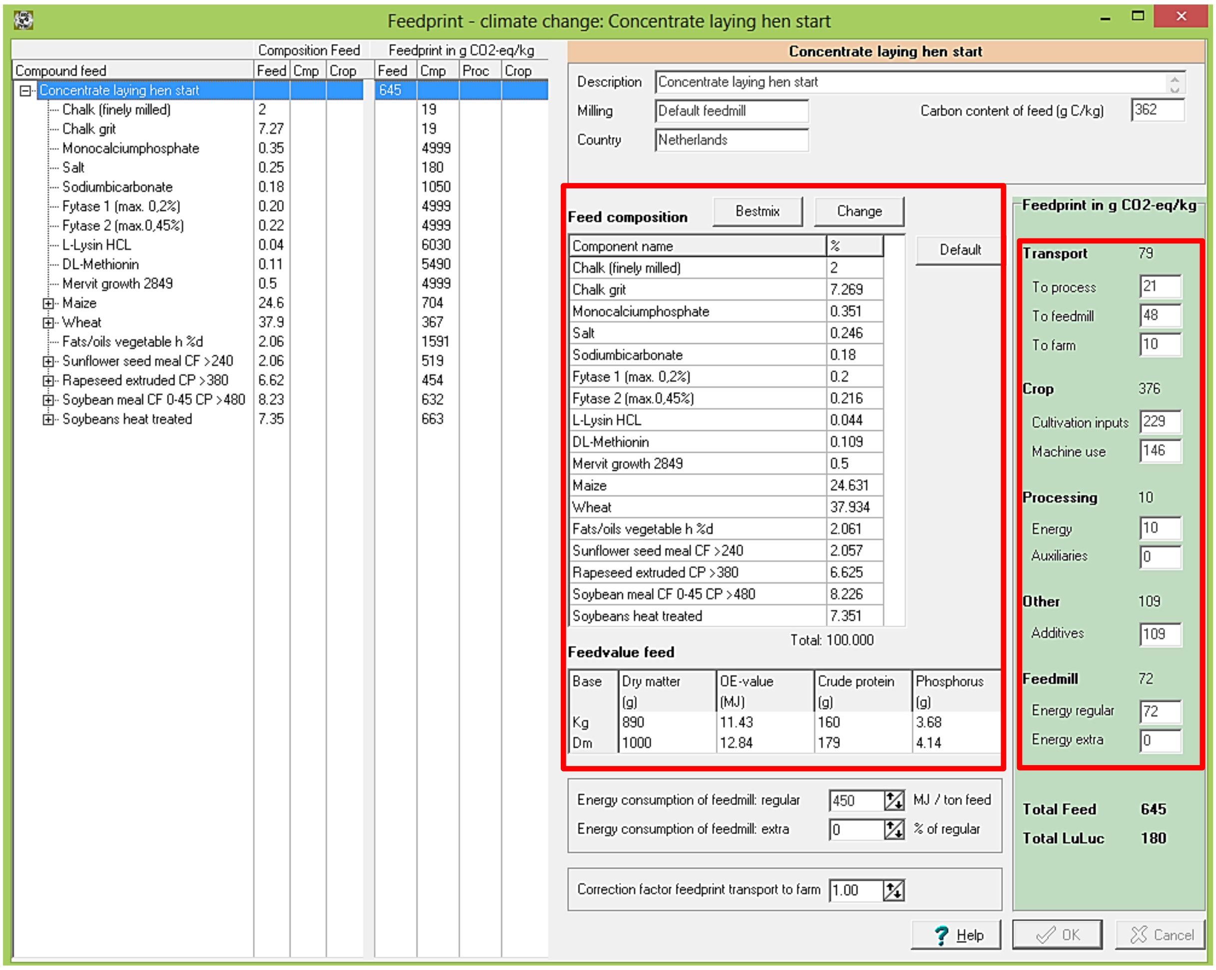


Figure 3.5: Overview of feed ingredients used to mix Concentrate laying hen start.

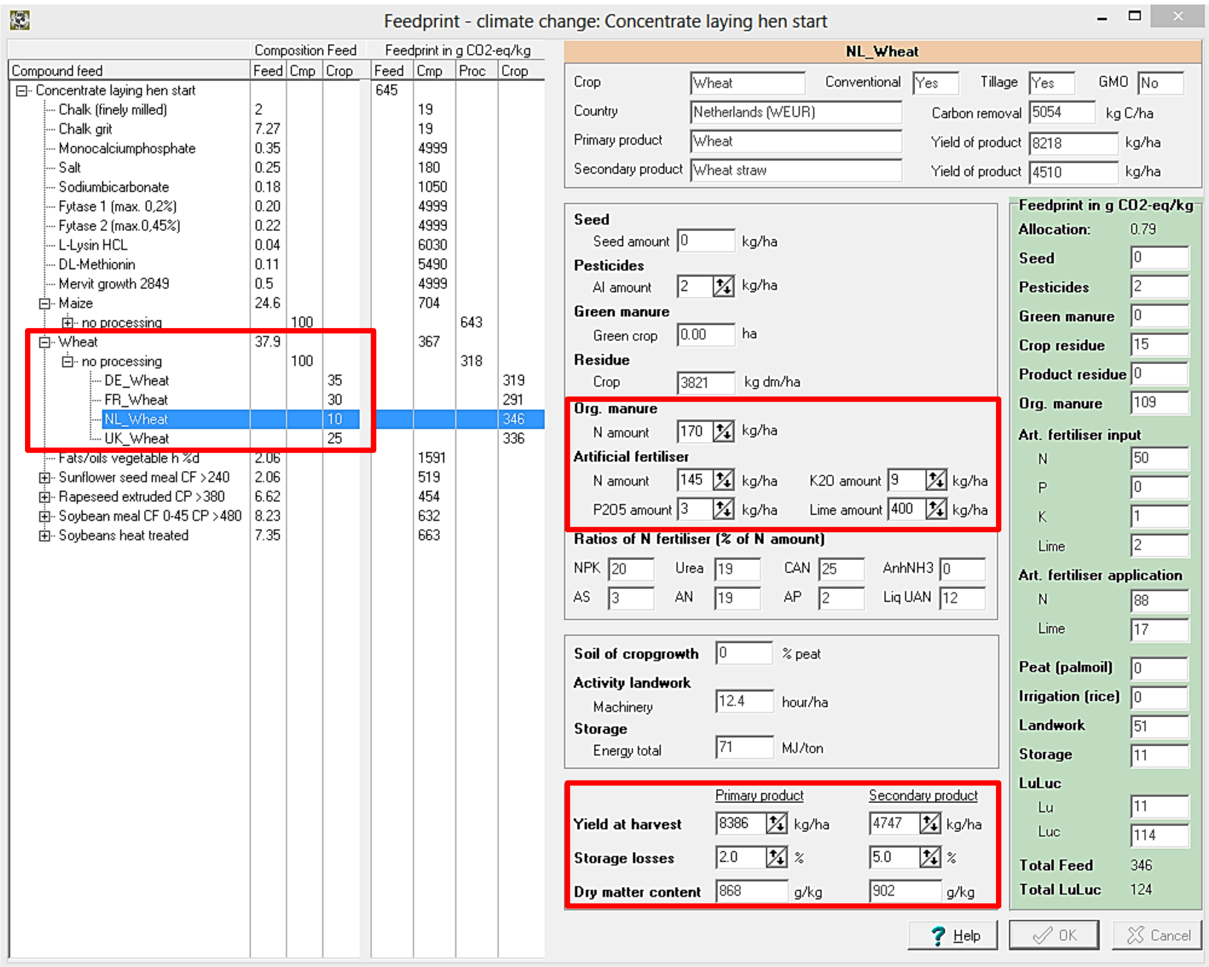


Figure 3.6: Overview of cultivation inputs for producing wheat as a feed ingredient in the Netherlands.

The following information from the cultivation inputs was used to calculate the environmental impact and resource claim indicators that are not automatically generated by FeedPrint as environmental indicators (Table 3.4):

- N amount applied with organic manure (kg/ha)
- N amount applied with artificial fertilizers (kg/ha)
- P_2O_5 amount applied with artificial fertilizers (kg/ha)
- K_2O amount applied with artificial fertilizers (kg/ha)
- primary yield of product (kg/ha), including storage losses
- secondary yield of product (kg/ha), including storage losses

In addition to the data on feed ingredients, FeedPrint also provided the following outputs that were used for further calculations of the modelled animal production systems in the present study:

- Amount of feed required in kg per animal per year (Figure 3.7)
- Amount of animal product produced in kg live weight per animal per year (Figure 3.7)
- The environmental impact and resource claims per kg feed and kg live weight (Figures 3.8 and 3.9)

The feed conversion ratio (FCR) that is used in FeedPrint represents the economic feed conversion ratio (EFCR), only the feed that is used during the production or fattening phase is taken into account. In order to cover the full feed requirements of an animal throughout its life, also the feed requirements of young calves, piglets and pullets were taken into account as much as possible. Breeding sows provide the piglets for the pig fattening phase, dairy cows provide the calves for the veal or beef production phases, while the pullets that are supplied to the laying hen farms were based on a slow growing broiler system. See Appendix A for the alternative production methods that were used to supply the young animals.

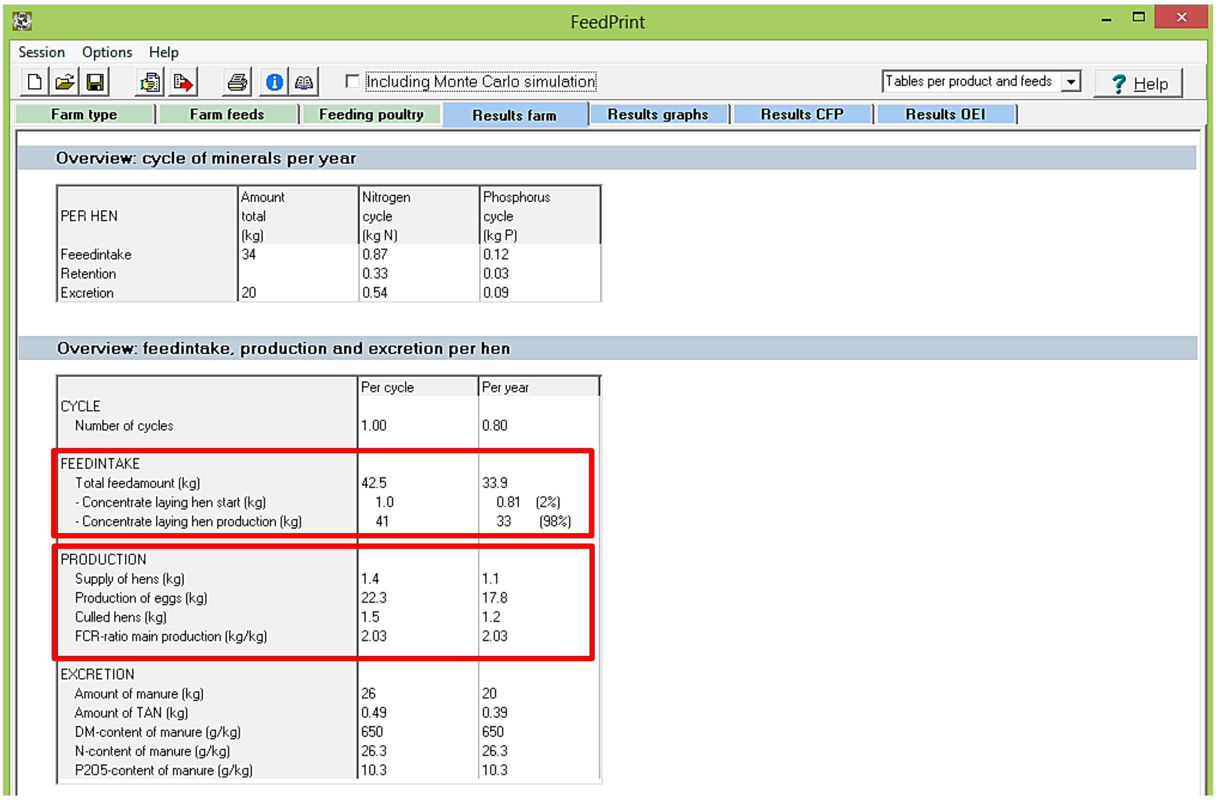
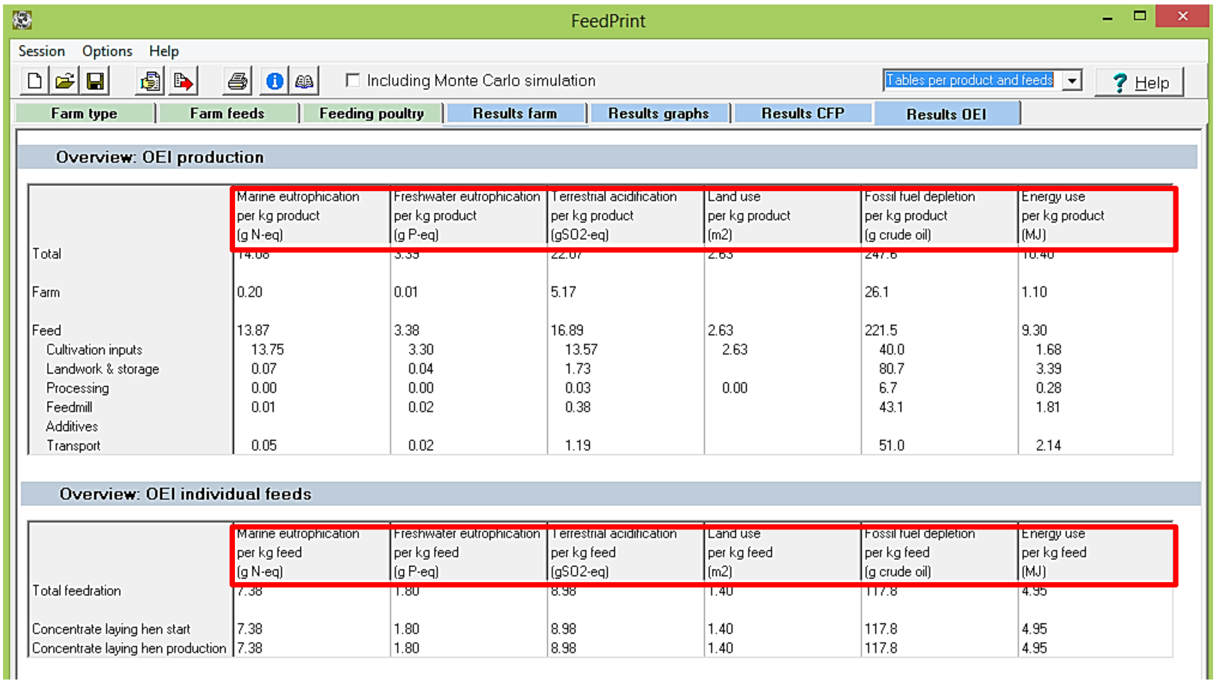


Figure 3.7: Overview of the feed intake, production and manure excretion per hen.



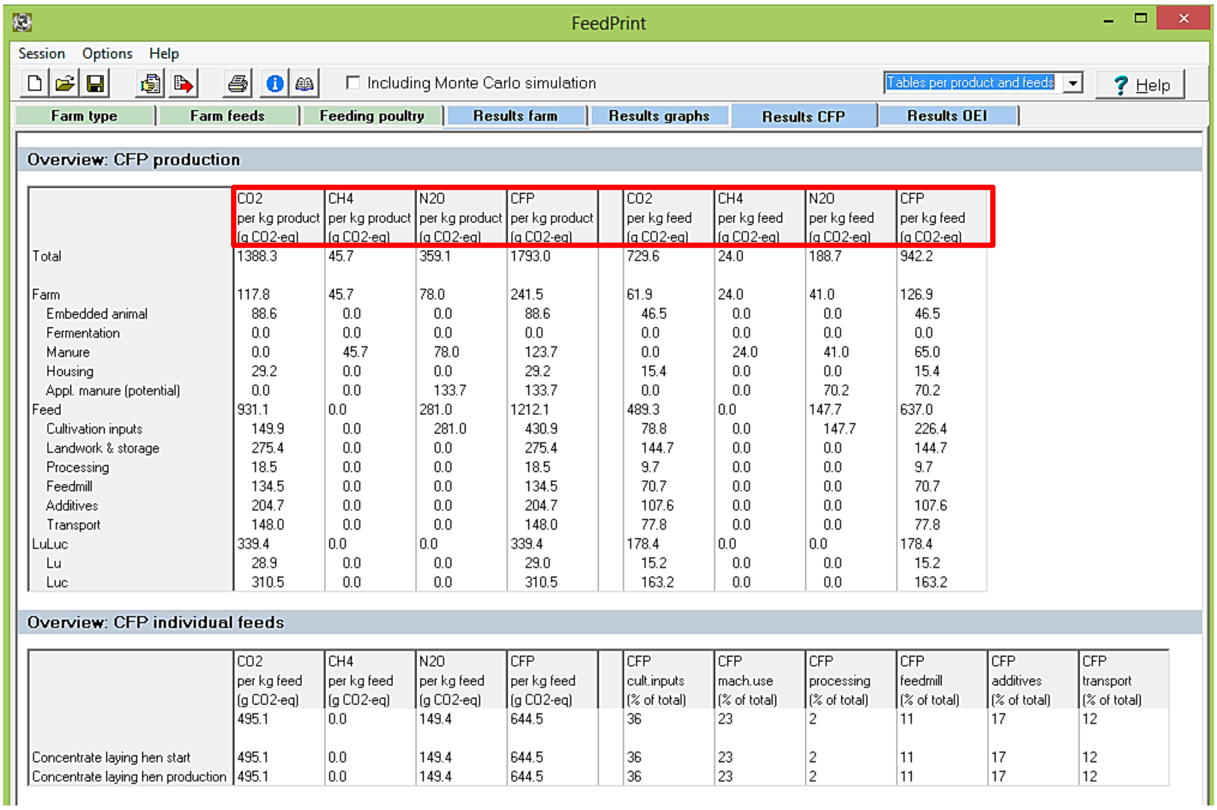
Overview: OEI production

	Marine eutrophication per kg product (g N-eq)	Freshwater eutrophication per kg product (g P-eq)	Terrestrial acidification per kg product (gSO2-eq)	Land use per kg product (m2)	Fossil fuel depletion per kg product (g crude oil)	Energy use per kg product (MJ)
Total	14.08	3.39	22.07	2.63	247.6	10.40
Farm	0.20	0.01	5.17		26.1	1.10
Feed	13.87	3.38	16.89	2.63	221.5	9.30
Cultivation inputs	13.75	3.30	13.57	2.63	40.0	1.68
Landwork & storage	0.07	0.04	1.73		80.7	3.39
Processing	0.00	0.00	0.03	0.00	6.7	0.28
Feedmill	0.01	0.02	0.38		43.1	1.81
Additives						
Transport	0.05	0.02	1.19		51.0	2.14

Overview: OEI individual feeds

	Marine eutrophication per kg feed (g N-eq)	Freshwater eutrophication per kg feed (g P-eq)	Terrestrial acidification per kg feed (gSO2-eq)	Land use per kg feed (m2)	Fossil fuel depletion per kg feed (g crude oil)	Energy use per kg feed (MJ)
Total feedration	7.38	1.80	8.98	1.40	117.8	4.95
Concentrate laying hen start	7.38	1.80	8.98	1.40	117.8	4.95
Concentrate laying hen production	7.38	1.80	8.98	1.40	117.8	4.95

Figure 3.8: Environmental impact indicators at the feed and farm level.



Overview: CFP production

	CO2 per kg product (g CO2-eq)	CH4 per kg product (g CO2-eq)	N2O per kg product (g CO2-eq)	CFP per kg product (g CO2-eq)	CO2 per kg feed (g CO2-eq)	CH4 per kg feed (g CO2-eq)	N2O per kg feed (g CO2-eq)	CFP per kg feed (g CO2-eq)
Total	1388.3	45.7	359.1	1793.0	729.6	24.0	188.7	942.2
Farm	117.8	45.7	78.0	241.5	61.9	24.0	41.0	126.9
Embedded animal	88.6	0.0	0.0	88.6	46.5	0.0	0.0	46.5
Fermentation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Manure	0.0	45.7	78.0	123.7	0.0	24.0	41.0	65.0
Housing	29.2	0.0	0.0	29.2	15.4	0.0	0.0	15.4
Appl. manure (potential)	0.0	0.0	133.7	133.7	0.0	0.0	70.2	70.2
Feed	931.1	0.0	281.0	1212.1	489.3	0.0	147.7	637.0
Cultivation inputs	149.9	0.0	281.0	430.9	78.8	0.0	147.7	226.4
Landwork & storage	275.4	0.0	0.0	275.4	144.7	0.0	0.0	144.7
Processing	18.5	0.0	0.0	18.5	9.7	0.0	0.0	9.7
Feedmill	134.5	0.0	0.0	134.5	70.7	0.0	0.0	70.7
Additives	204.7	0.0	0.0	204.7	107.6	0.0	0.0	107.6
Transport	148.0	0.0	0.0	148.0	77.8	0.0	0.0	77.8
LuLuc	339.4	0.0	0.0	339.4	178.4	0.0	0.0	178.4
Lu	28.9	0.0	0.0	29.0	15.2	0.0	0.0	15.2
Luc	310.5	0.0	0.0	310.5	163.2	0.0	0.0	163.2

Overview: CFP individual feeds

	CO2 per kg feed (g CO2-eq)	CH4 per kg feed (g CO2-eq)	N2O per kg feed (g CO2-eq)	CFP per kg feed (g CO2-eq)	CFP cult.inputs (% of total)	CFP mach.use (% of total)	CFP processing (% of total)	CFP feedmill (% of total)	CFP additives (% of total)	CFP transport (% of total)
	495.1	0.0	149.4	644.5	36	23	2	11	17	12
Concentrate laying hen start	495.1	0.0	149.4	644.5	36	23	2	11	17	12
Concentrate laying hen production	495.1	0.0	149.4	644.5	36	23	2	11	17	12

Figure 3.9: Greenhouse gas emissions at the feed and farm level.

Chapter 4: Results

All comparisons are made per kg of animal protein at the feed-consumption level. First a comparison is made between the different animal protein products from recalculated published studies and the modelled animal products. Also, the impact of the economic and gross energy allocation method on the outcomes are assessed. Secondly, the most efficient production method in terms of total land use for each of the alternative production methods for beef, pigs and pangasius are compared. Thirdly, the most efficient pig, broiler, salmon, pangasius and cricket production methods are compared with the most efficient beef production method for multiple-indicator performance. Beef was chosen here because it has the largest environmental impacts and resource claims. A more nuanced approach is proposed in the last section, not only the total impact of each indicator is compared but also the competition with human food production through the use of certain feed ingredients.

4.1 Allocation methods

The gross energy allocation (GEA) instead of economic allocation (EA) leads to both higher and lower outcomes for the land use claim indicator (see Figure 4.1). The observed values for EA are lower than those observed for GEA for milk (7-10 m^2), pangasius (4-6 m^2), carp+tilapia (6-8 m^2) and tilapia (7 m^2). The observed values for EA are higher than those observed for GEA for pigs (9-15 m^2). These differences are the result of the combined effect of small differences in land use allocation of the feed ingredients used.

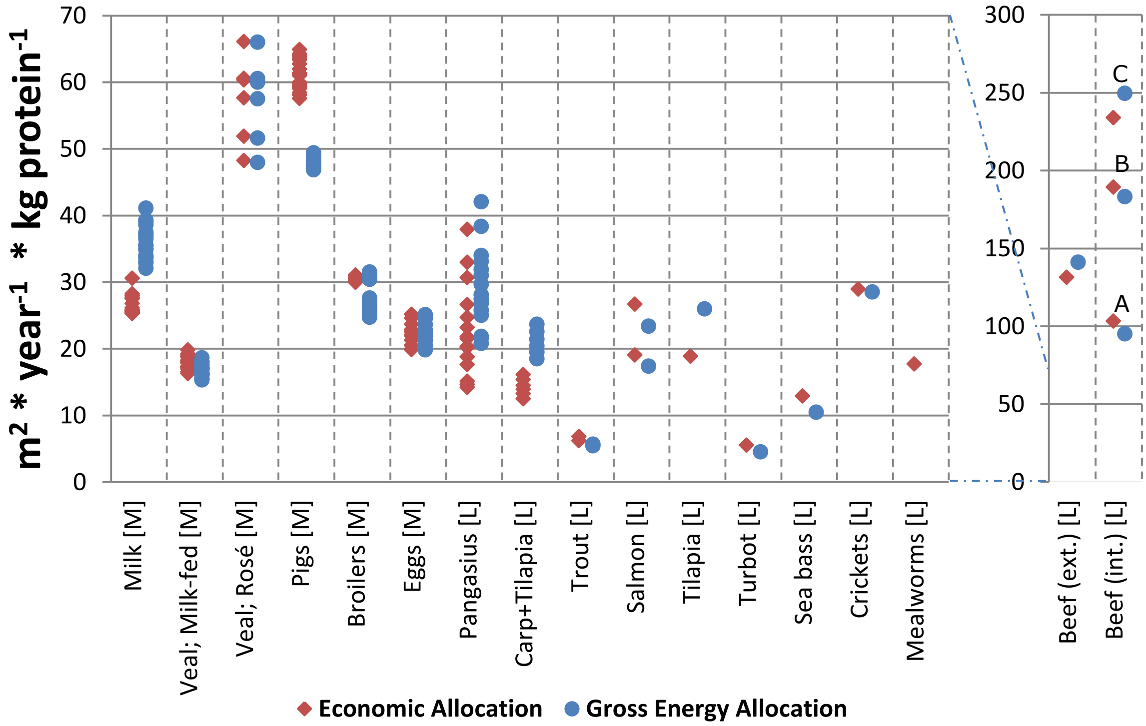


Figure 4.1: Comparison of economic (red) and gross energy (blue) allocation methods for the annual land requirements of animal products in m^2 per kg protein at the feed-consumption level. [M] = model based animal production methods; [L] = literature based animal production methods. Mealworm gross energy allocation is excluded, because details of feed composition were not provided in the original study. Attention: the y-axis on the right has a larger scale. Ext. = extensive; Int.= intensive; A = 12, B = 16, C = 24 months.

Regardless of the allocation method, the highest land use claim per kg of protein is observed for beef production. The extensive beef system is less efficient than the intensive beef system A in which the bull calves are slaughtered at 12 months. The intensive beef systems B and C in which the bull calves are slaughtered at 16 and 24 months respectively are less efficient than the extensive beef system.

Also milk-fed and rosé veal are fed formulated diets to stimulate growth. Milk-fed veal is slaughtered after 22-30 weeks and rosé veal is slaughtered after 35-45 weeks of fattening. The land use claim increases with age of slaughtering. Milk-fed veal is fed residues from the milk-processing industry - such as whey powder - with a low land use claim.

The land use claim for feed production is, in general, low for aquaculture species, with the lowest values observed for turbot and trout. Pangasius has similar results as milk, broilers and eggs. The insects covered in this study are also at the lower end of the land use spectrum. The land use claim of crickets is similar to that of broilers and mealworms have a similar claim as eggs.

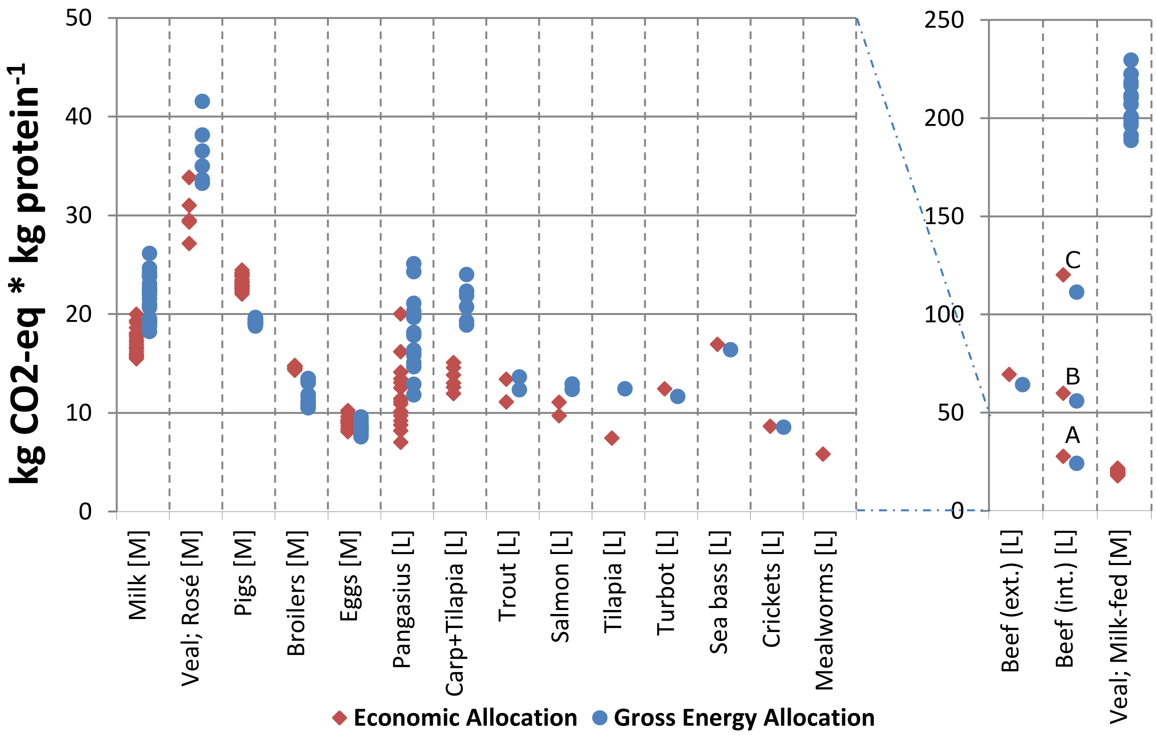


Figure 4.2: Comparison of economic (red) and gross energy (blue) allocation methods for the carbon foot print of animal products in kg $CO_{2\text{-eq}}$ per kg protein at the feed-consumption level. [M] = model based animal production methods; [L] = literature based animal production methods. Mealworm gross energy allocation is excluded, because details of feed composition were not provided in the original study. Attention: the y-axis on the right has a larger scale. Ext. = extensive; Int.= intensive; A = 12, B = 16, C = 24 months.

The use of gross energy allocation instead of economic allocation leads to both higher and lower outcomes for the carbon footprint indicator (see Figure 4.2). The observed values for EA are lower than those observed for GEA for milk (2-6 kg $CO_{2\text{-eq}}$), rosé veal (7-9 kg $CO_{2\text{-eq}}$) pangasius (5 kg $CO_{2\text{-eq}}$), carp+tilapia (7-9 kg $CO_{2\text{-eq}}$), tilapia (5 kg $CO_{2\text{-eq}}$) and milk-fed veal (171-208 kg $CO_{2\text{-eq}}$). The observed values for EA are higher than those observed for GEA for pigs (3-4 kg $CO_{2\text{-eq}}$). These differences are the result of the combined effect of small differences in $CO_{2\text{-eq}}$ allocation of the feed ingredients used.

The production of milk-fed veal has the highest carbon footprint 189-230 kg $CO_{2\text{-eq}}$ per kg of protein when gross energy allocation is applied, while the values for economic allocation are only 19-22 kg $CO_{2\text{-eq}}$ per kg of protein. This difference can be traced back to the use of whey powder in the feed. Whey powder – a by-product from cheese making – does not receive any of the carbon footprint of milk production when economic allocation is applied, unlike for gross energy allocation. Once whey is dried and concentrated the carbon footprint per kg is 681 g $CO_{2\text{-eq}}$ for EA and 18217 g $CO_{2\text{-eq}}$ for GEA.

Most of the aquaculture products are similar in carbon footprint impacts with broilers and eggs. With economic allocation, the carbon footprint of aquaculture species ranges from 7.0 kg $CO_{2\text{-eq}}$ per kg protein for tilapia to 20 kg $CO_{2\text{-eq}}$ per kg protein for pangasius. With gross energy allocation, the carbon footprint of aquaculture species ranges from 12 kg $CO_{2\text{-eq}}$ per kg protein for turbot to 25 kg $CO_{2\text{-eq}}$ per kg protein for pangasius. Crickets have a similar carbon footprint to eggs. With economic allocation mealworms have the lowest impact of just 5.8 kg $CO_{2\text{-eq}}$ per kg protein.

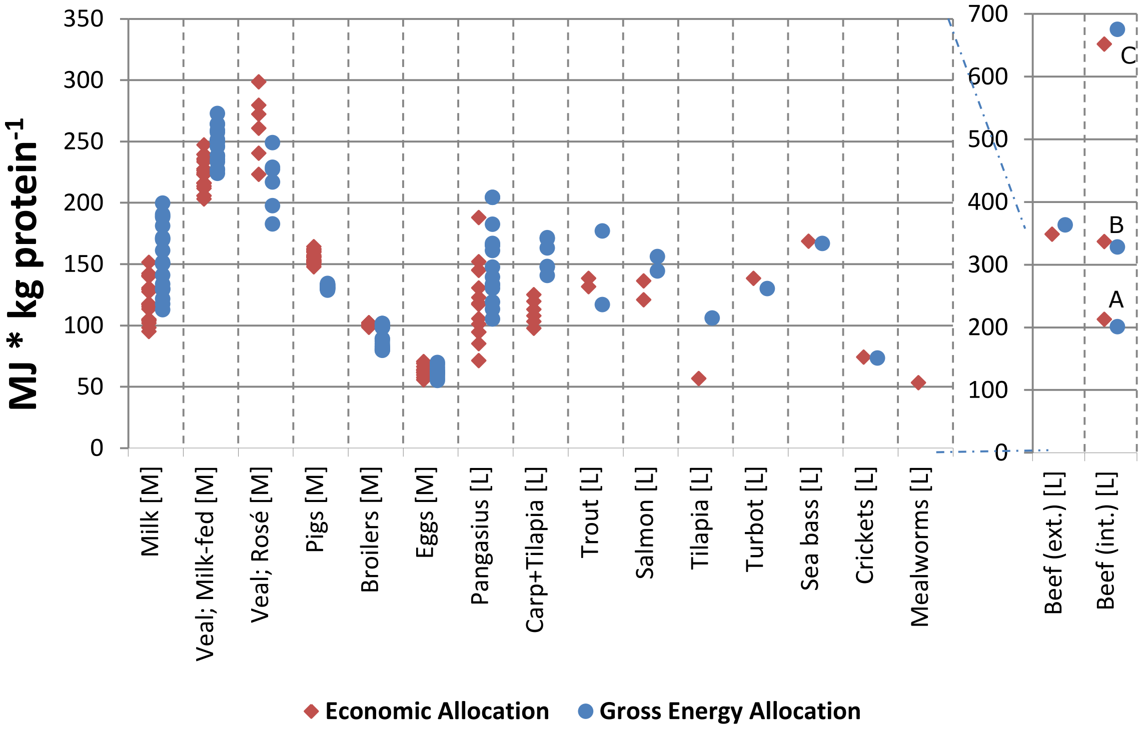


Figure 4.3: Comparison of economic (red) and gross energy (blue) allocation methods for the energy requirement of animal products in MJ per kg protein at the feed-consumption level. [M] = model based animal production methods; [L] = literature based animal production methods. Mealworm gross energy allocation is excluded, because details of feed composition were not provided in the original study. Attention: the y-axis on the right has a larger scale. Ext. = extensive; Int.= intensive; A = 12, B = 16, C = 24 months.

The use of gross energy allocation instead of economic allocation leads to both higher and lower outcomes for the energy use indicator (see Figure 4.2). The observed values for EA are lower than those observed for GEA for milk (18-49 MJ), milk-fed veal (21-26

MJ), pangasius (16-34 MJ), carp+tilapia (43-51 MJ) and tilapia (49 MJ). The observed values for EA are higher than those observed for GEA for pigs (17-28 MJ) and rosé veal (40-50 MJ). These differences are the result of the combined effect of small differences in energy allocation of the feed ingredients that were used.

With economic allocation, the five most efficient animal products in terms of MJ energy use per kg protein are eggs (56 MJ), tilapia (57 MJ), pangasius (71 MJ), crickets (73 MJ) and milk (95 MJ). With gross energy allocation the top five would be eggs (55 MJ), crickets (73 MJ), broilers (80 MJ), pangasius (105 MJ) and tilapia (106 MJ).

In the next sections the comparisons between the different animal protein products will be based on gross energy allocation only.

4.2 Alternative production methods

In this section the alternative production methods – as described in Appendix A and B – are compared for beef, pigs and pangasius in order to assess which production method results in the lowest total land use and how the different types of feed ingredient categories contribute to the total land use claim. These three animal protein products were included as examples of the - sometimes limited - variation that can be observed between alternative production methods of an animal product.

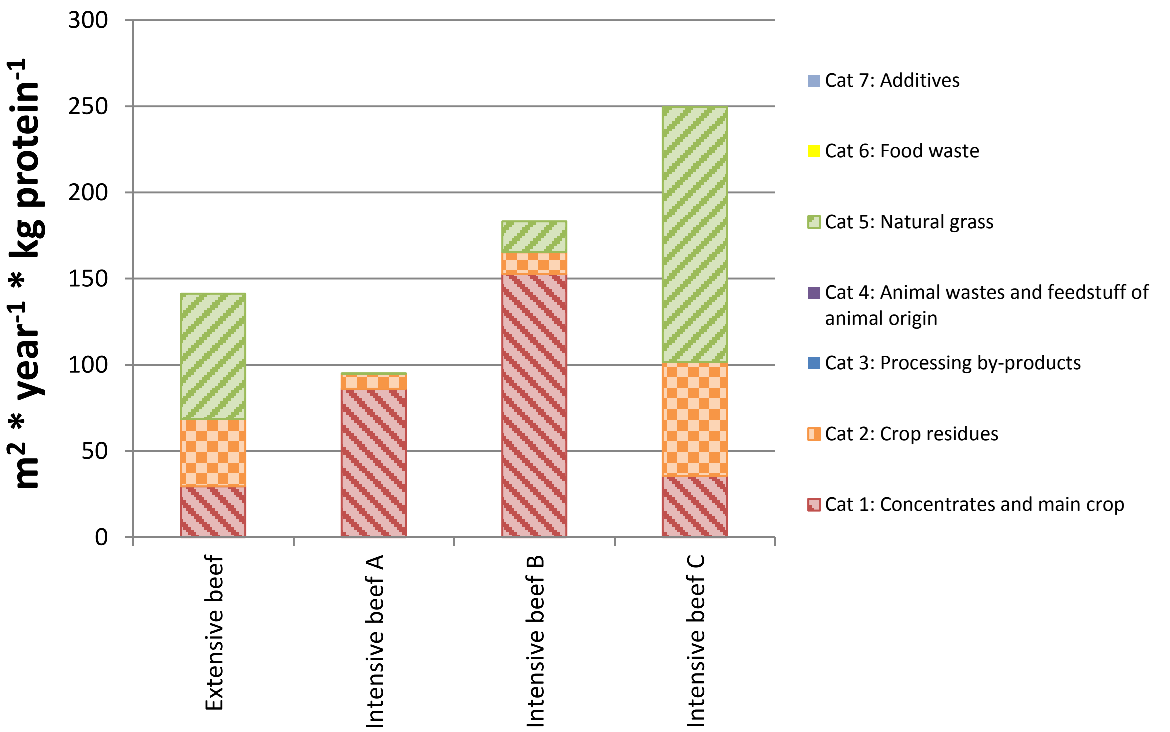


Figure 4.4: Annual land use of different – published - beef production methods in m² per year per kg protein at the feed-consumption level. Intensively produced beef is slaughtered after: A = 12 months; B = 16 months; C = 24 months. Allocation method: Gross Energy.

The total annual land use of beef ranges from 95-250 m^2 per kg protein (see Figure 4.4). Intensively raised dairy bull calves slaughtered at 12 months (A) have the lowest land use claim. This method claims 95 m^2 of land per year for the production of feed, of which 86 m^2 required for the cultivation of cereals, soy meal, and maize silage (category 1). This production method is compared to other animal products in section 4.3 below.

Intensively raised dairy bull calves that are slaughtered after 24 months (C) do not receive any soy meal or maize silage, but are fed with large quantities of grass silage instead. Extensively raised suckler-calf-cow herds – in which young calves replace the older animals in the herd – require 141 m^2 per year with around 50% grassland.

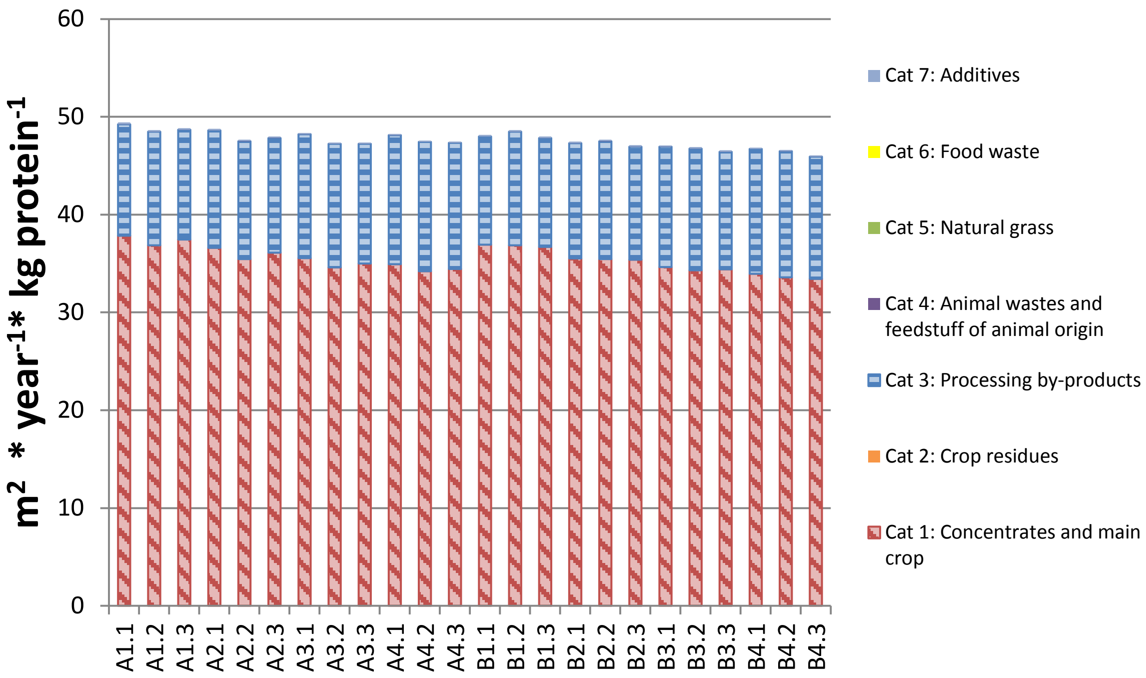


Figure 4.5: Annual land use of alternative – modelled - pig production methods in m^2 per kg protein at the feed-consumption level. Allocation method: Gross Energy.

The annual land use claim for alternative pig production methods included in this study ranges from 47-50 m^2 per kg protein (see Figure 4.5). The variants that can be selected in FeedPrint only result in small variation in production efficiencies between the different alternative production methods. The alternative production methods are all based on piglets from a breeding sow with 13 life born piglets. The production method in which boars and gilts receive a combination of ad libitum and portion feeding, and in which the pigs are slaughtered at 130 kg (B4.3) has the lowest total annual land use claim for feed cultivation. Under this production method 33 m^2 is required for the cultivation of concentrates and other main crops. This production method is used for further comparison with other animal products in section 4.3 below.

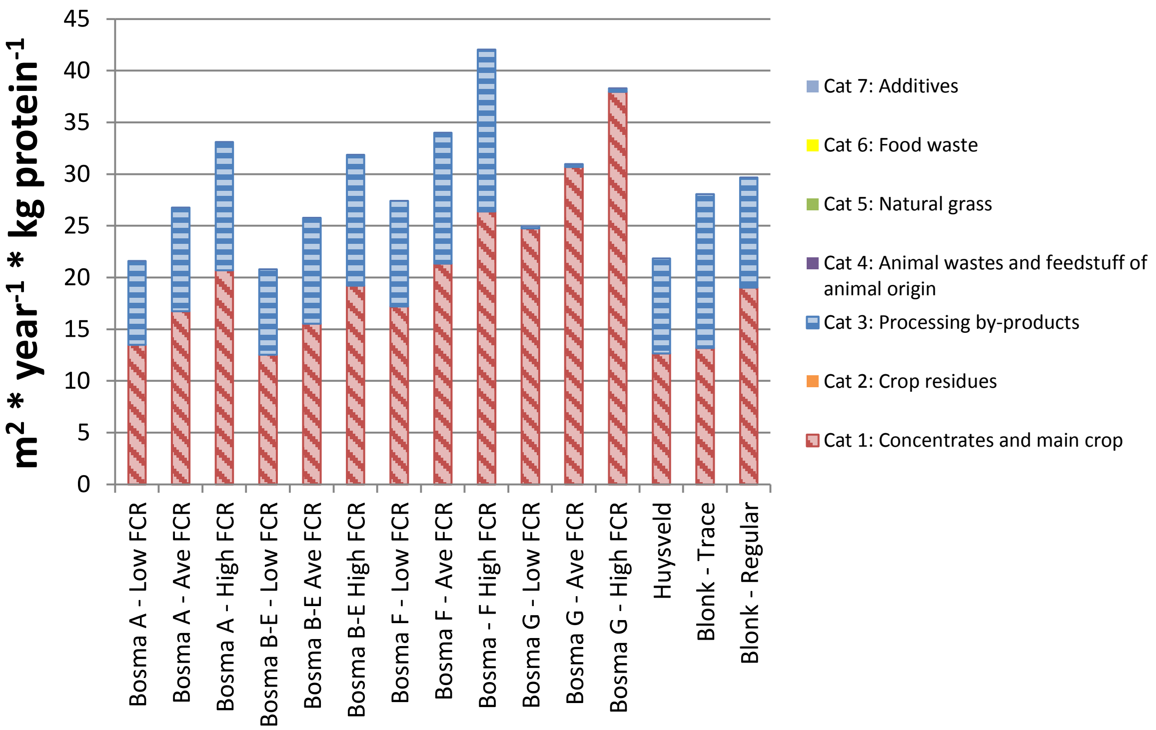


Figure 4.6: Annual land use of alternative – published - pangasius production methods in m^2 per kg protein at the feed-consumption level. Allocation method: Gross Energy.

The annual land use claim for alternative pangasius production methods included in this study ranges from 21-42 m^2 per kg protein (see Figure 4.6). There is variation in production efficiencies between the different alternative production methods. The pangasius production system described by Bosma et al. (2009) with feed types B-E and the low FCR has the lowest total land use. This production method will be compared with other animal products in sections 4.3 and 4.4 below. This production method only requires 13 m^2 of land for the cultivation of concentrates and other main crops per kg of protein. That is three times less than the 38 m^2 observed for pangasius with feed type G and a high FCR. The fishmeal content in feed type B-E was 12.8% and fish oil was 1.9%, but these feed ingredients do not have any land use claim.

4.3 Multiple-indicator performance

In this section, a number of animal protein products are compared with beef protein for their relative environmental impacts and resource claims (see Figure 4.7). The first comparison is of beef with pigs and broilers. The second comparison is between beef and two popular aquaculture species – salmon and pangasius, respectively a carnivorous and an omnivorous species. The third comparison is between beef and farmed crickets. For each animal protein product, the production method was chosen that resulted in the lowest total land use. The other indicators are based on the same production method, although it does not necessarily have to result in the lowest impact for that indicator.

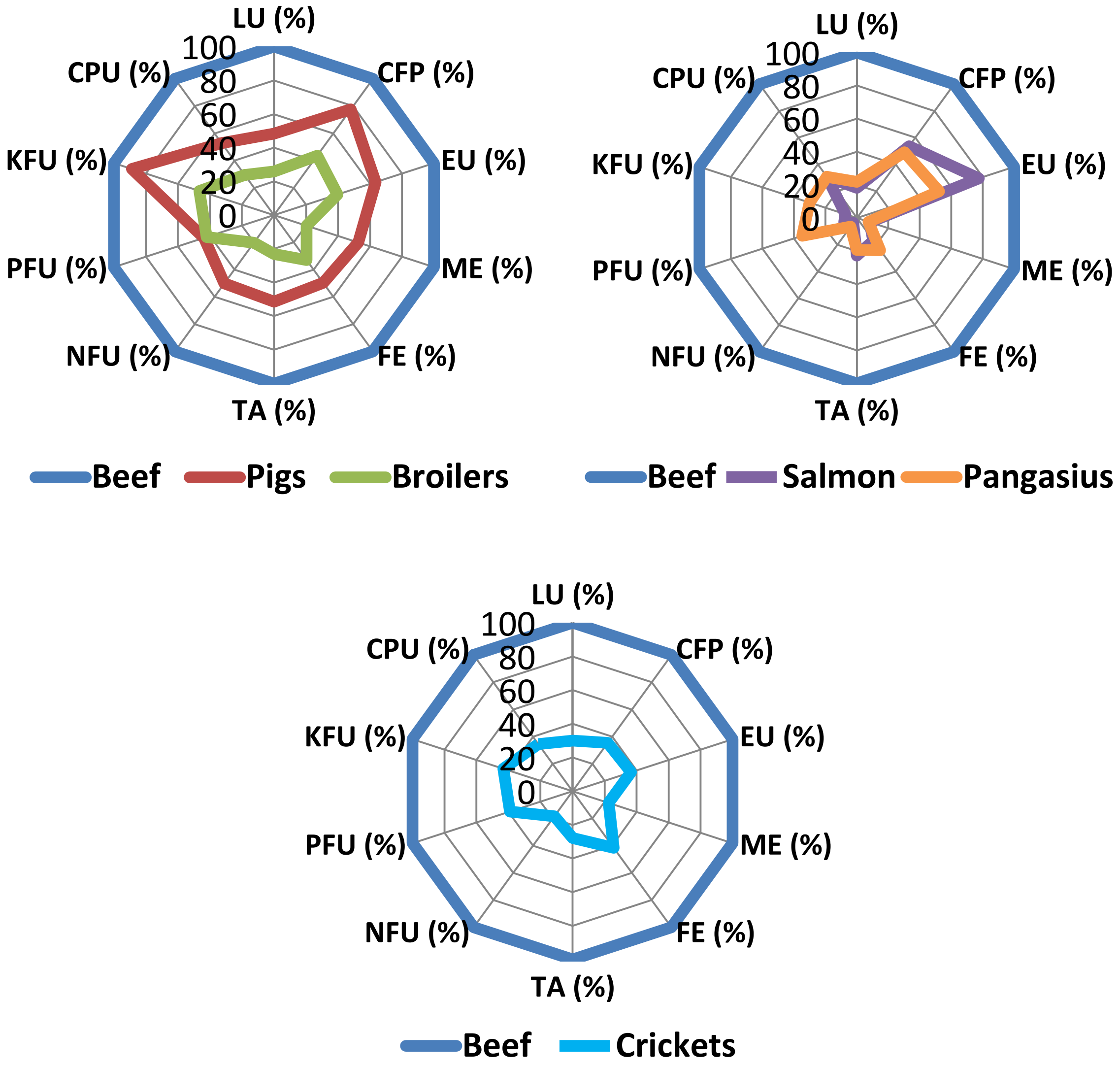


Figure 4.7: Comparison of ten environmental impact or resource claim indicators related to the production of beef protein with that of pigs, broilers, salmon, pangasius and crickets at the feed-consumption level. Indicators are compared per kg protein, with the highest product set at 100%. For each animal protein product the alternative production method with the lowest total land use was selected. Abbreviations: LU = land use; CFP = carbon footprint; EU = energy use; ME = marine eutrophication; FE = freshwater eutrophication; TA = terrestrial acidification; NFU = nitrogen fertilizer use; PFU = phosphorus fertilizer use; KFU = potassium fertilizer use; CPU = crude protein use. Allocation method: Gross Energy.

Land use: The total annual land use occupied for the production of feed can be up to 82% lower for salmon when compared with beef. pangasius, broilers and crickets all can reduce the total annual land use with more than 70%. Pigs have a higher land use requirement than the other products, but still there is a reduction possible of 52%.

Carbon foot print: During the production of feed for crickets, 65% fewer emissions take place than for beef. Broilers, salmon, and pangasius have around 50% less emission than beef while pigs only results in 22% fewer emissions.

Energy use: The production of feed for crickets requires up to 64% less energy when compared to beef. Broilers have a slightly higher energy demand, but the difference with beef is still 60%. Salmon production only had a 22% lower energy use compared to beef.

Marine and **freshwater eutrophication**: The production of feed for pangasius can result in 93% lower marine eutrophication potential and 76% lower freshwater eutrophication potential than for beef. For salmon, these levels are comparable to pangasius with 92% lower potential for marine eutrophication and 83% lower for freshwater eutrophication. Pigs result in 47% lower marine eutrophication and 50% lower freshwater eutrophication than beef.

Terrestrial acidification: The production of feed for broilers, salmon and pangasius can result in around 80% lower terrestrial acidification than would originate from the feed production of beef. Feed production for crickets could result in a 72% lower impact and for pigs it could be 49% less than for beef.

N, P, K fertilizer use: The production of feed for salmon requires 96%, 92% and 93% less fertilizers for respectively N, P and K than for the production of feed for beef. Crickets and broilers have roughly the same fertilizer requirements for the feed, which are ca. 80% (N), 60% (P) and 55% (K) lower than beef. The reduction of K fertilizer for pig feed production is only 11% lower than that of beef.

Crude protein use: Broilers, salmon, and pangasius require 70% fewer crude protein in their diet to produce a kg of protein than beef. Crickets are slightly less efficient with a 65% lower requirement. Pigs require only half (47%) of the crude protein than beef does for the production of a kg of protein.

4.4 Feed-food competition

Animals are fed a large variety of feed ingredients. The type of ingredients that are used determine to what extent the animal product that humans can eventually consume is in competition with other forms of human food production – for example the production of edible plant proteins. Unlike most published LCA studies, a more nuanced approach is used here to present resource claims through the use of feed ingredients in both a competitive and a non-competitive share[9]. In this section the consequences of feed-food competition are presented for the following indicators: land use, carbon footprint, phosphorus fertilizer use and crude protein use. Land use and carbon footprint are common indicators in most published LCA studies. The three fertilizer types that are considered in the present study all have similar results in terms of feed-food competition and P fertilizer use was highlighted here as it is an important fertilizer with limited minable resources. Crude protein use was included to highlight the origin of the crude protein in animal feed and its conversion efficiency into animal protein.

For most of the animal products included in this study the land use claim comes from feed ingredients that are in competition with human food production (see Figure 4.8). Milk and extensive reared beef are the exceptions as most of their claim on land use come from natural grassland. Dairy cows are supplemented with processing by-products and concentrates. Extensively produced beef is supplemented with crop residues and

[9] Since one cannot compete for environmental impacts that originate from the production of feed ingredients, the word competition is replaced here by the word avoidance. Environmental impacts are divided into avoidable and unavoidable impacts, in which the avoidable impacts originate from the use of feed ingredients that are in competition with human food production.

concentrates. Although extensive beef production depends to a large extent on land that is not in competition with human food production, still the amount of land that is in competition is 30 m^2. Only Pigs (33 m^2) and intensively produced beef (86 m^2) require more land that is in competition with human food production. Milk-fed veal has a low land use impact due to the high inclusion of whey powder, to which no land use allocation is made.

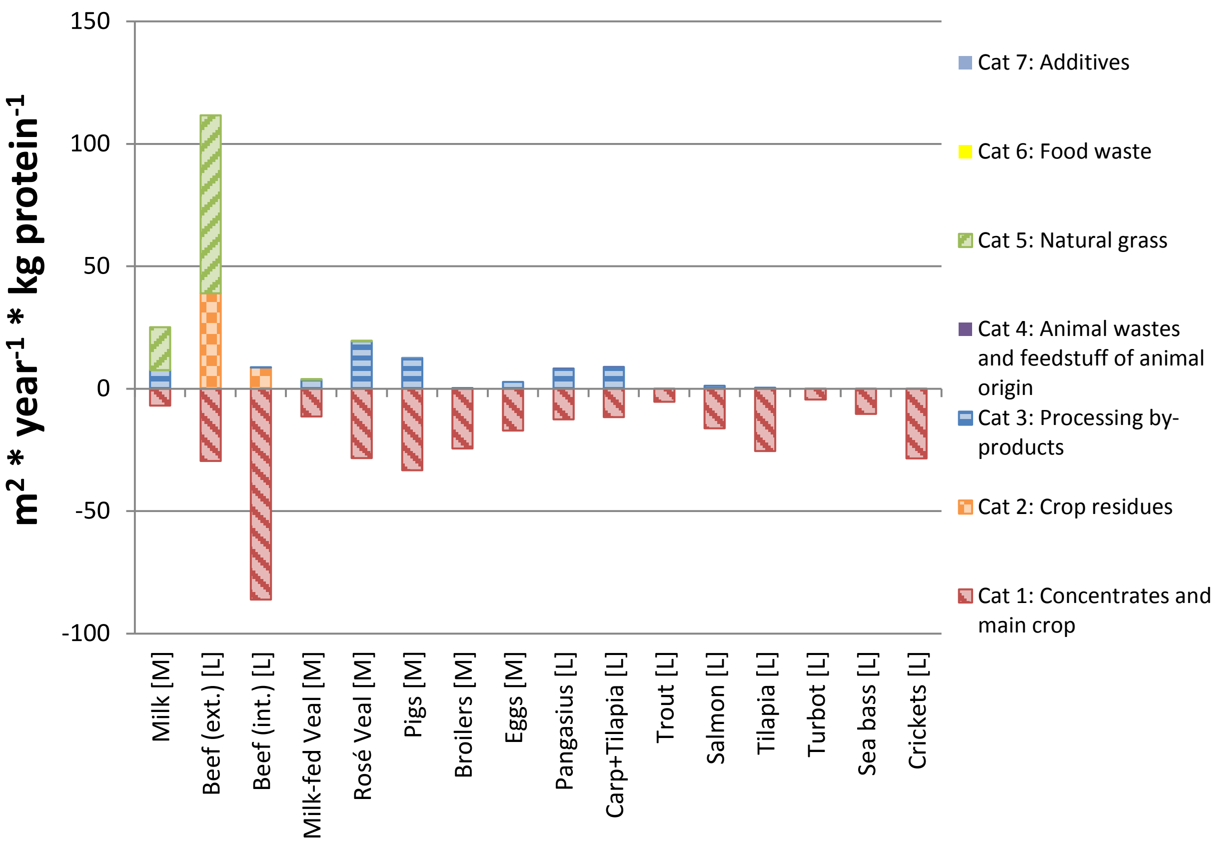


Figure 4.8: Comparison of the required annual land use and competition with human food production of animal products in m^2 per kg protein. For each animal protein product the alternative production method with the lowest total land use was selected. Competitive feed ingredients are presented as negative values. [M] = model based animal production methods; [L] = literature based animal production methods. Allocation method: Gross Energy.

Animal products with the smallest land use claim in competition with human food production are turbot (4.5 m^2) followed by trout (5.4 m^2). However, the low competitive land use claims of these products are due to the high levels of fishmeal and fish oil included in their diet, which do not have any land use claim. Fishmeal content in the diet of rainbow trout is 64.5%; trout has 45% fishmeal and 24% fish oil; turbot 63.5% fishmeal and 5% fish oil. Other carnivorous species fish species have smaller shares of fishmeal and fish oil in their diet while having more vegetal ingredients that are in competition with human food production. Even the most efficient carp+tilapia system covered in this study was fed 17% fishmeal and 3% fish oil. Tilapia has the highest land use claim of all aquaculture species. As the diet of tilapia contains only 3% fishmeal and 2% fish oil, the dependence on products that are in competition for land with human food production is high.

Crickets covered in this study were fed concentrates and other feed ingredients that are in competition with human food production (29 m^2). These crickets are slightly less competitive to extensively produced beef (30 m^2) and slightly more competitive than broilers (25 m^2).

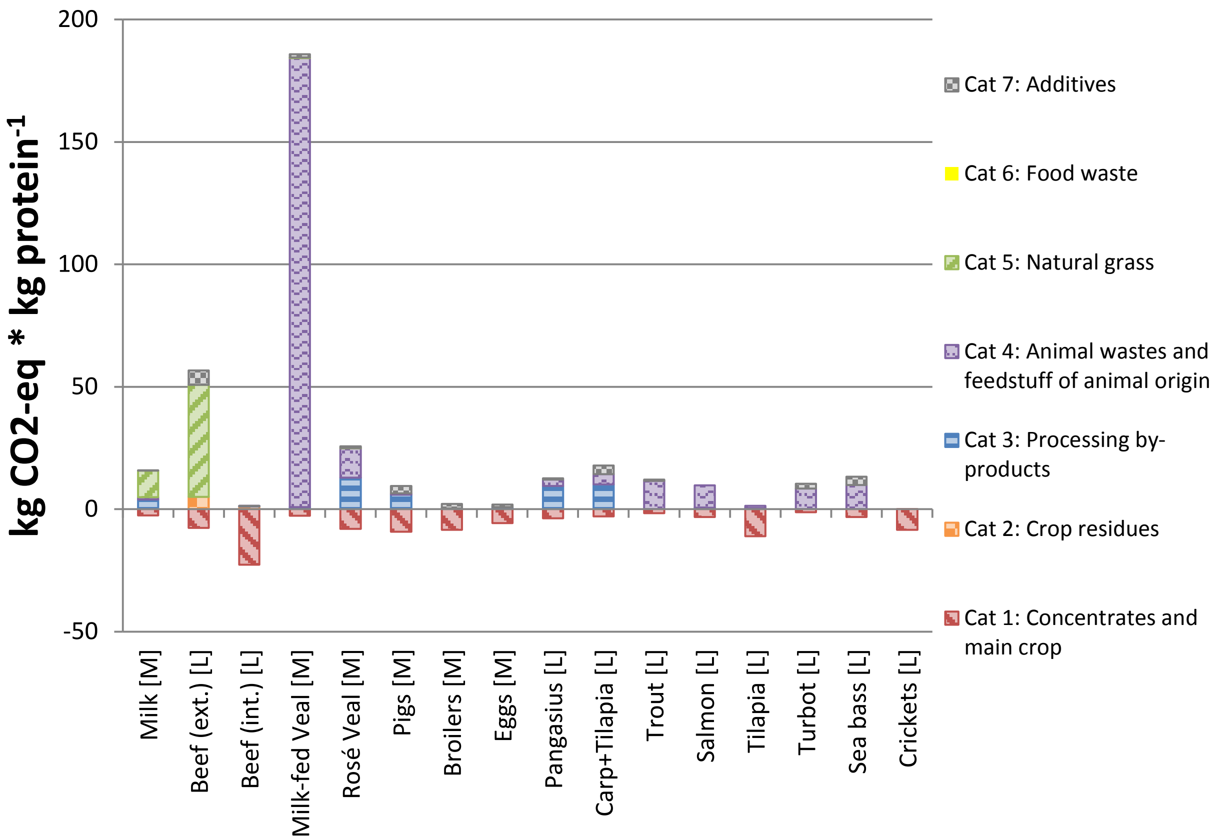


Figure 4.9: Comparison of the carbon foot print and competition with human food production of animal products in kg $CO_{2\text{-eq}}$ per kg protein. For each animal protein product the alternative production method with the lowest total land use was selected. Avoidable feed ingredients are presented as negative values. [M] = model based animal production methods; [L] = literature based animal production methods. Allocation method: Gross Energy.

Milk-fed veal has the largest total CFP (see Figure 4.9), but most of the emissions originate from whey, through the process of cheese-making. As long as the process of cheese-making itself is not avoided the emissions allocated to whey will remain and are thus unavoidable. Milk-fed veal causes only 2.8 kg $CO_{2\text{-eq}}$ through the use of concentrates that are avoidable.

Intensively produced beef result in the highest amount of avoidable CFP with 23 kg $CO_{2\text{-eq}}$ through the choice of concentrates and main crops in the diet. Extensively reared beef has only 7.8 kg $CO_{2\text{-eq}}$ of avoidable emissions while the remaining emissions originate from useful exploitation of – for humans - non-competitive crop residues and natural grasslands.

For the remaining protein products, 1.7 kg $CO_{2\text{-eq}}$ for trout is the lowest avoidable CFP and 11 kg $CO_{2\text{-eq}}$ for tilapia the highest. Tilapia, crickets, broilers and eggs have the highest levels of avoidable CFP. Carnivorous aquaculture species – trout, salmon, turbot and sea bass – have low levels of avoidable CFP as most of the emissions originate through fishmeal and fish oil.

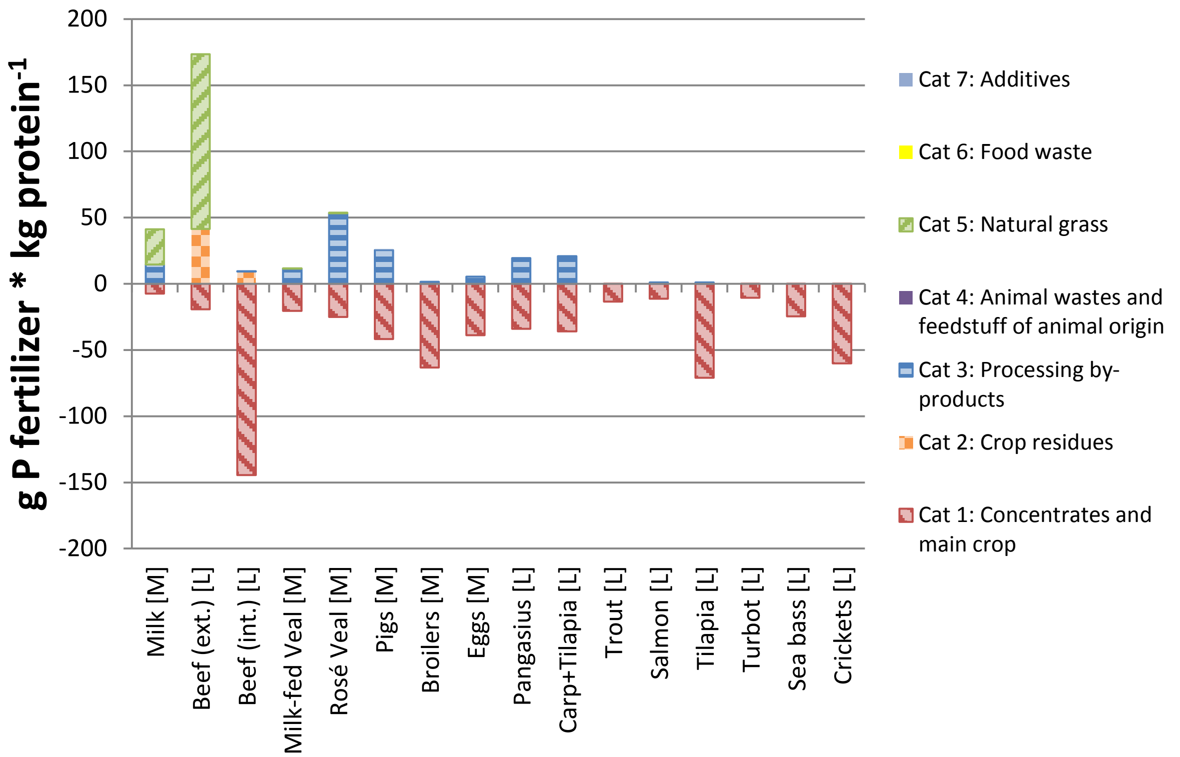


Figure 4.10: Comparison of the Phosphorus fertilizer use and competition with human food production of animal products in g P per kg protein. For each animal protein product the alternative production method with the lowest total land use was selected. Competitive feed ingredients are presented as negative values. [M] = model based animal production methods; [L] = literature based animal production methods. Allocation method: Gross Energy.

The use of phosphorus fertilizer - derived from minable, but finite phosphorus resources - is compared for the production of animal protein products (see Figure 4.10). P fertilizer that is applied to natural grasslands could be considered as being in competition with human food production, however the application of fertilizers to natural grasslands here is considered as necessary to avoid mineral depletion and to maintain grassland productivity[10].

Intensively reared beef requires 145 g P fertilizer per kg of protein that is in competition with human food production. Also, tilapia (71 g P fertilizer), broilers (63 g P fertilizer) and crickets (60 g P fertilizer) have high competitive P fertilizer requirements. The lowest competitive use of P fertilizer is for milk (8.1 g P fertilizer). Another 21 g P fertilizer is allocated to milk production through the use of processing by-products and 20 g P fertilizer through natural grassland. Extensively produced beef requires 193 g P fertilizer, but only 19 g P fertilizer is used to fertilize concentrates and main crops that are in competition with human food production.

[10] The natural grasslands here are assumed to be on peat soils in the Netherlands.

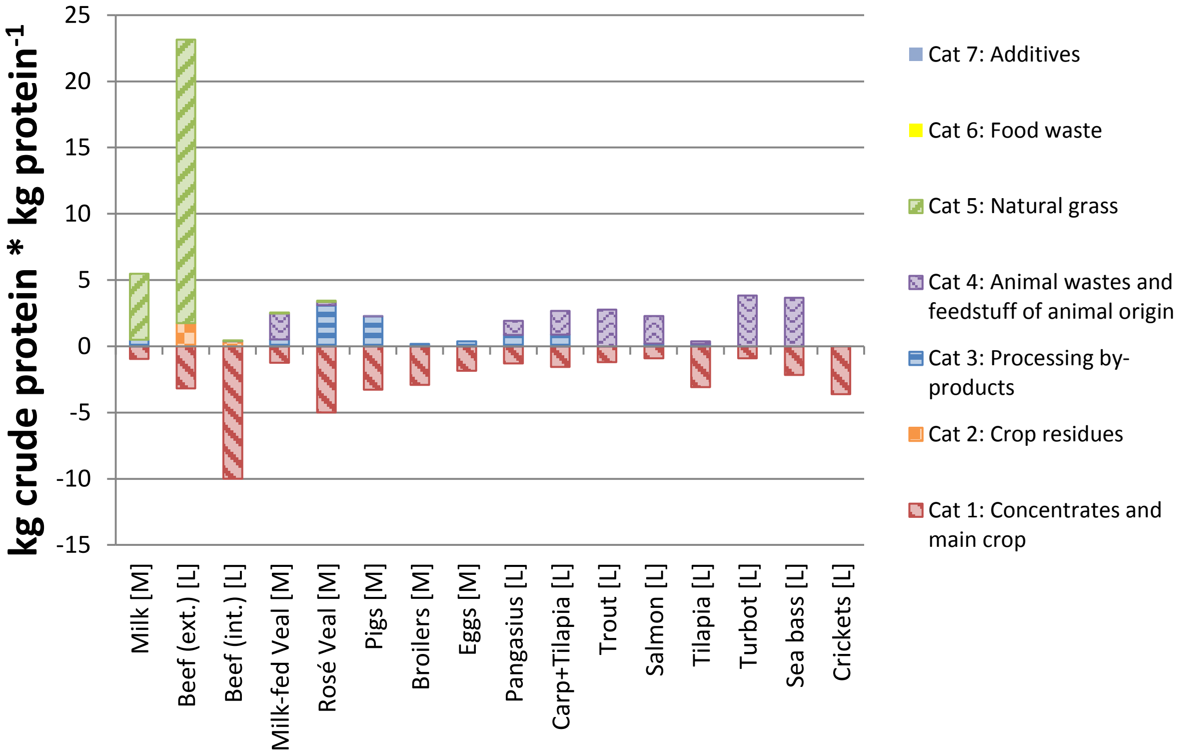


Figure 4.11: Comparison of the crude protein use efficiency and competition with human food production of animal products in kg crude protein per kg protein. For each animal protein product the alternative production method with the lowest total land use was selected. Competitive feed ingredients are presented as negative values. [M] = model based animal production methods; [L] = literature based animal production methods. Allocation method: Gross Energy.

The most efficient production method, of converting crude protein from the feed into animal protein, is observed for eggs with 2.21 kg CP per kg protein of which 1.83 kg comes from competitive feed ingredients (see Figure 4.11). However, lower levels of competitive feed ingredients are observed for carp+tilapia (1.56 kg CP), pangasius (1.28 kg CP), milk-fed veal (1.22 kg CP), trout (1.19 kg CP), milk (0.95 kg CP), turbot (0.90 kg CP) and salmon (0.89 kg CP). All of these products depend only for a limited extent on protein from concentrates and main crops. The least efficient way, of producing a kg of edible animal protein, is observed for intensively produced beef, which requires 10.00 kg of CP from competitive feed ingredients. Extensively produced beef requires only 3.17 kg of CP from competitive feed ingredients and another 1.76 kg CP and 21.40 kg CP are provided through non-competitive crop residues and grass respectively.

Chapter 5: Discussion

In Figure 5.1 an overview is provided of the development of the world's most important sources of animal protein between 1961 and 2011. Global production levels of beef – bovine - protein increased by 0.10 Mt per year since 2000. Since 2000 global protein production levels have increased annually by 0.36 Mt for poultry, 0.31 Mt for aquaculture, 0.40 Mt for milk, 0.19 Mt for pork and 0.11 Mt for eggs. With the exception of mutton and goat, eggs, and aquaculture, all these protein products have already surpassed beef in total quantity. Unfortunately, it is not possible to disaggregate the animal protein products that are added annually in shares fed with competitive and non-competitive feed ingredients. The share of non-competitive feed ingredients in the total feed will be 'diluted' if higher quantities of competitive ingredients than non-competitive ingredients are added annually. An animal protein product could thus become more competitive with human food production than it is at the moment.

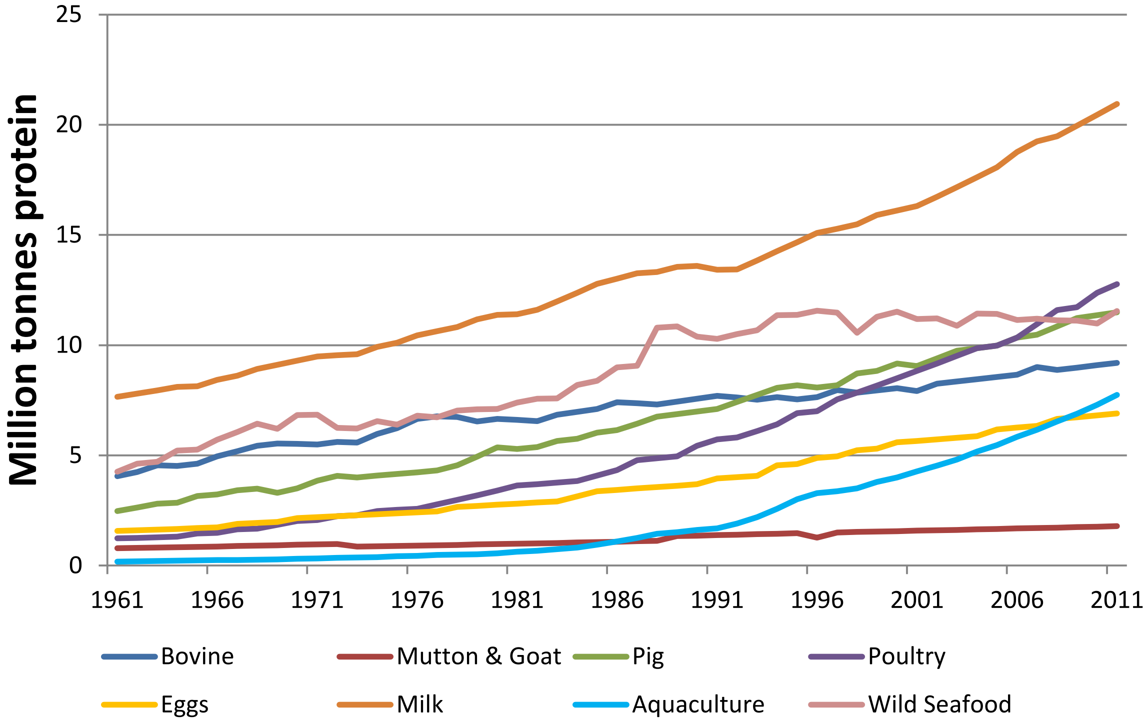


Figure 5.1: World animal protein supply by type, 1961-2011.
Source: FAOSTAT http://faostat3.fao.org/download/FB/CL/E (Checked on 2-2-2015). Wild seafood data is not corrected for fishmeal use.

This raises the question whether or not it is necessary to stimulate the production of certain types of animal protein at the expense of others in order to produce more[11] animal protein with the same – or even lower – amounts of environmental impacts and resource claims. And if it is deemed necessary, how this production should take place without compromising the possibilities to produce other food sources, both now and in the longer term future.

[11] Sufficient to provide the global population with adequate amounts of animal protein that are beneficial to human health.

5.1 Towards a food strategy?

The Scientific Council for Government Policy (WRR[12]) in the Netherlands advised the government to adopt a food strategy – instead of an agricultural strategy - that takes into account the connections between agricultural production, processing, distribution and consumption. They argue it is necessary to base food production on the requirements for a healthy diet, all within the limits of the resources that are available and the environmental impacts that are acceptable. "Such a strategy requires a clear formulation of the decisions that have to be made. A consequence of the differences of interest by stakeholders is that it is always required to make choices and it is important to be honest about the fact that choices have to be made. For a number of product groups, this could imply that the production should be reduced. Both the environment and the human health will benefit from a substantial shift of animal products towards plant-based products. For certain sectors, such a shift will have economic consequences. But, these difficult decisions are part of a food strategy" (Knottnerus et al., 2014).

The approach suggested by Knottnerus et al. (2014) would be a step in the right direction, given the environmental challenges and – in some cases uncertain - amounts of resources available for the current and future global food production. Although a country like the Netherlands can tackle a number of the local environmental problems and develop strategies to maintain resource availability in the future, it will depend on cooperation with other countries to implement effective policies. In a number of other countries – Finland, the United Kingdom, Canada and Australia – reports have been published by government advisors who propose a national food strategy as well (Knottnerus et al., 2014). Certain aspects of the food strategy are likely to be more effective if neighbouring countries introduce the same regulations – e.g. consumers might travel to neighbouring countries for shopping if the price of meat in their country is raised with the purpose of lowering its consumption. It is necessary to offer alternatives to those who will be harmed by the decisions of a food strategy – e.g. by assisting intensive beef farmers with knowledge and capital to convert their businesses into insect farms to maintain employment opportunities.

5.2 Recommendations

Based on this study I would advocate that it is possible to reduce the area of land required for animal feed that will be in competition with direct human food production. If we consider the production systems from section 4.4 then a substitution of intensively produced beef protein by other animal products would already result in considerable reductions in competitive land use. Substitution by pork or chicken would easily result in a reduction of competitive land use of 61% and 72%, respectively. The potential of farmed crickets would be similar to that of pork. Since cricket farming is still in its infancy, it is likely that both the production efficiency and the composition of the diet can be adjusted to produce insect protein not only lower in total land use, but also in competitive land use. A substitution of intensively produced beef by milk or eggs could free up, respectively, 92% and 80% of land for the cultivation of other crops. The small additional quantities of meat from dairy cows and laying hens are not taken into account here. Replacing intensively produced beef with aquaculture products is also promising, but the reduction of competitive land use depends on the species and feed ingredients

[12] In Dutch: Wetenschappelijke Raad voor het Regeringsbeleid

used. Substitution of beef produced on natural grassland for instance cannot be considered a viable option to make more resources available. Furthermore, it should be taken into account that the land use claim of aquaculture species could increase in the upcoming years as fishmeal and fish oil in aqua feeds are gradually being replaced by vegetal sources.

The land, fertilizer and crude protein use in this study are the most suitable indicators for exploring the potential of choosing for different animal products in order to reduce natural resource claims. The claims of these resources occur at the crop cultivation stage and do not increase any further after this stage. On the other hand still a significant share of the – carbon footprint and eutrophication - indicators impact can occur after the feed-consumption stage. This hinders the interpretation of the results of these indicators in the present study.

If one is looking for animal products with the lowest impact for a certain indicator, he or she should be aware that the allocation method could influence which product comes out best. It is, therefore, important to take into account which feed ingredients differ strongly between allocation methods. For instance whey powder, which comprises an important part of the diet of milk-fed veal, has a carbon footprint that is nearly 27 times higher when gross energy allocation is used instead of economic allocation. With economic allocation whey powder is almost considered a feed ingredient that is free of any environmental impact and all burdens originating from milk production are allocated to cheese. When the relative value of whey powder increases due to higher demand more impact will be allocated to it. Does this then really reflect the underlying processes if the production system itself remains unchanged? Although economic allocation was used in most of the published LCA studies included in the present study, I agree with Pelletier and Tyedmers (2011) that economic allocation fails to communicate environmentally meaningful information. In addition, market signals are not sufficient in managing the environmental dimensions related to food production as economic incentives are – sometimes - the cause of unsustainable practices. Therefore, I consider the use of a bio-physical allocation method as proposed by Pelletier and Tyedmers (2011) to be more suitable for this type of assessments.

In the present study, only a small number of animal production systems were assessed and compared, which limits the possibilities to draw hard conclusions on what would be a suitable food strategy. It is necessary that more information on different product life cycles is combined in order to better understand the implications on environmental impacts and resource claims of changes in the production of the most important animal protein sources in the upcoming decades. Efforts by – to name just a few – (de Vries and de Boer, 2010), (Oonincx and de Boer, 2012), (Nijdam et al., 2012), (Smil, 2013) and the developers of the FeedPrint calculation tool help us to increase our understanding of the requirements and consequences of our global food system better and are, therefore, much appreciated. However, to increase our understanding further, more LCA studies – that use harmonized methodologies – are required that cover a wider variety of innovative adaptations in livestock, aquaculture and insect production methods and various feed compositions. For example: pigs and chickens that are fed mostly non-competitive feed ingredients; aquaculture fish with stepwise substitution of fishmeal and fish oil shares in the diet by vegetal sources or insects; current cricket farming practices in Thailand; insects that are fed grass from natural grasslands as an alternative to ruminants; a larger variety of edible insects species that are fed on a wide range of feed ingredients. The aquaculture and insect species that are deemed most promising should be included in FeedPrint-like calculation tools as this would allow farmers to base the feed composition on more than just price and nutritional values. In addition, potentially promising feed ingredients based on algae, seaweeds, duckweed and insects should be covered in LCA studies and included in these calculation tools as well, in order to assess their potential as substitutes for other feed ingredients.

5.3 Limitations and uncertainties of present study

No uncertainty levels are included for the results of this study. FeedPrint provides the option to perform a Monte Carlo simulation. For a poultry farm with broilers slaughtered at 1.9 kg and fed the default FeedPrint diet a standard deviation in production of 0.58 kg is given[13]. However, the Monte Carlo simulation is limited to the carbon footprint indicator only and it appears that there are still a number of mistakes in the FeedPrint version used in this study. For broilers the standard deviations for total carbon footprint are 100 times larger with 500 simulations than for 150 simulations.

The factors for converting live weight to edible and protein were assumed constant for each type of animal product. However, it is likely that an animal slaughtered at a later age has a higher share of edible weight than those slaughtered earlier. This could influence outcomes. The conversion factors used for aquaculture species were estimated based on literature data and are not species specific. Given the high values used for edible weight, this could lead to overestimation.

In the present study, the focus was on the production of protein while animal-based products are also important suppliers of other nutrients such as essential fats, calcium, zinc, and iron. The reason, for, not including these nutrients as functional units in this study, is a lack of information on the availability of nutrients in specific types of fish and insects. It is assumed that feed composition plays an important role in the eventual nutrient composition of animal products. Additional product quality information should, therefore, be added to LCA studies to create a link to the feed and the nutritional value of the animal product.

An important indicator not included in the present study is water use. This indicator was not included in the FeedPrint crop data. Combining the data from FeedPrint with those of virtual water (Falkenmark and Rockström, 2006) would be an elaborate task with lots of uncertainties. If the water use indicator would be included in future studies it is important to pay attention to ‘blue’ water – from rivers, lakes and aquifers – that is used for irrigation. ‘Blue’ water is an important natural resource for which one can determine how much is used and where. This is especially of interest in areas that – could - experience water scarcity.

[13] N=500 simulations.

Chapter 6: Conclusions

In the introduction, three main questions were raised. In this concluding chapter, I will briefly conclude on each of these questions.

How can aquaculture and insect farming contribute to increasing food and protein production? Based on the literature review of chapter 2, I would conclude that stocking densities need to increase and more aqua feed is required to accommodate an increase in the contribution of aquaculture to food and protein production. Important to global protein production are the low-value herbivorous species such as carp and tilapia. The growth in production of economically important carnivorous and omnivorous species will be constrained by the availability of fishmeal and fish oil. Due to high prices, these feed ingredients are increasingly being replaced by vegetal sources. However, this could result in lower feed conversion efficiencies and an increased demand for feed ingredients now used in other livestock sectors. The availability and affordability of suitable feed ingredients will be an important factor in determining aquaculture growth.

The main challenge insect farming currently faces is regulation (chapter 2). Before farmed insects can enter the market there needs to be sufficient evidence that they are save for use in both food and feed. It could still take a couple of years before insect farming starts to take off and farmed insects can be considered important supplier of global protein. Insects - fed on waste streams – has the potential to become an important feed ingredient in the fast growing aquaculture and poultry sectors. The collection of production data of insect farmers would allow for a better understanding of the contribution of this new sector to food and protein supply.

What are the environmental impact and resource claims for the production of protein from aquaculture and insects compared with traditional livestock products? Based on the results of this study (chapter 4) I would conclude that per kg of animal protein, the production of feed for aquaculture species and farmed insects have a similarly low land use claim as milk, broilers, and eggs. The land use claim is lower than pork, rosé veal and much lower than both intensively and extensively produced beef. The carbon footprint of feed production for most of the aquaculture species and farmed insects is similar to the low values observed for broilers and eggs. A number of aquaculture species have somewhat higher carbon footprint, similar to milk and pigs. Veal and beef production systems score poorest for this indicator.

Which protein products from livestock, aquaculture and insects compete the least with human food production? No straightforward answer can be given to this question, as this depends on the indicator. Based on the results of this study (chapter 4) I would conclude that milk produced by cows grazing on natural grassland, and trout, turbot and salmon have the least competition with human food production in terms of land and fertilizer use. Carnivorous and omnivorous fish obtain an important share of their crude protein from fishmeal, an ingredient with no claims on land and fertilizers. The production of protein by crickets and tilapia results in more competitive land use claim, similar to broilers and extensively produced beef. In this study, protein from intensively produced beef is most competitive with human food production.

The competition for resources by animal protein production can be reduced by basing its production largely on non-competitive feed ingredients such as grass from natural grassland, crop residues, processing by-products and food waste. The use of animal types best suited to convert these non-competitive feed ingredients into edible products should be promoted. More research needs to be carried out in order to compare insect protein production with livestock and aquaculture. One of the focus points should be to explore the use underutilized non-competitive feed ingredients by insects. The use of competitive feed ingredients should be limited to the use as strategic ingredients, which help to balance the diet composition and are beneficial in the conversion process to animal protein. It is recommended to study possible trade-offs that could occur from changes in diet composition on the overall sustainability performance of an animal product. In addition, attention is still required to minimize environmental impact during the feed production chain, transport phases, as well as the emissions from enteric fermentation and losses from manure.

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List of abbreviations

AD	Anno Domini
AP	Acidification Potential
BSE	Bovine Spongiform Encephalopathy
CFP	Carbon Foot Print
CH_4	Methane
$CO_{2\text{-eq}}$	Carbon dioxide equivalents
CPU	Crude Protein Use
CVB	Centraal Veevoeder Bureau = Central Bureau for Livestock Feed
DHA	Docosahexaenoic Acid
EA	Economic Allocation
EFCR	Economic Feed Conversion Ratio
EP	Eutrophication Potential
EPA	Eicosapentaenoic Acid
EU	Energy Use
EW	Edible Weight
FAO	Food and Agricultural Organization of the United Nations
FAVV	Federaal Agentschap voor de Veiligheid van de Voedselketen = Federal Agency for the Safety of the Food Chain
FCR	Feed Conversion Ratio
FE	Freshwater Eutrophication
FFD	Fossil Fuel Depletion
FU	Functional Unit
GEA	Gross Energy Allocation
IPCC	Intergovernmental Panel on Climate Change
IPIFF	International Producers of Insects for Food and Feed
ISO	International Organization for Standardization
K	Potassium
KFU	Potassium Fertilizer Use
LCA	Life Cycle Assessment
LU	Land Use
LW	Live Weight
MBA	Mass Balance Allocation
ME	Marine Eutrophication
MJ	Mega Joules
MSc	Master of Science
Mt	Million tonnes
N	Nitrogen
N_2O	Nitrous oxide
NFU	Nitrogen Fertilizer Use
OECD	Organization for Economic Co-operation and Development
P	Phosphorus
PFU	Phosphorus Fertilizer Use
TA	Terrestrial Acidification
TSE	Transmissible Spongiform Encephalopathy
UN	United Nations
US$	United States Dollar
Wageningen UR	Wageningen University and Research Centre
WD	Water Dependence
WRR	Wetenschappelijke Raad voor Regeringsbeleid = Scientific Council for Government Policy

Appendix A – Modelled animal production systems

The FeedPrint calculation tool allows for the selection of several alternative production strategies in which animal races, gender, slaughter weight and a number of feeding strategies can be selected for the different animal types. In the present study the range of feed conversion ratios (FCR) resulting from the default diets were explored for each animal type by changing the management variables. For each animal production system the – default FeedPrint - diet is provided in this appendix. The feed diet can be changed and optimized, but is beyond the scope of this study.

The share of each feed ingredient in the feed mix is based on the fresh weight of the different ingredients at the time of feed processing.

Dairy

Table 1: Dairy farm – Codes for alternative production methods.

Grazing strategy	Compound feed: Amount of concentrate, excl. young stock (kg/cow/year) on a base of 90% dm)				
	1000	1500	2000	2500	3000
Grazing during day and night	A1	A2	A3	A4	A5
Grazing during day	B1	B2	B3	B4	B5
Zero grazing	C1	C2	C3	C4	C5
Summer feeding	D1	D2	D3	D4	D5

Table 2: Dairy - Feed mix composition (default diet).

Feed 1 composition **Milkpowder dairy calves**	**Feed Mix (%)**	**Category**
Magnesiumoxide	1.00	7
Premix Veal 45	1.00	7
Wheat feed flour CF 0-35	2.00	1
Wheat gluten meal	7.00	1
Milk powder skimmed	30.00	4
Whey powder	22.00	4
Whey powder, delactosed ASH 0-210	3.00	4
Fat filled whey powder	34.00	4
Total	100	
Feed 2 composition **Concentrate dairy standard**	**Feed Mix (%)**	**Category**
Salt	0.13	7
Maize glutenfeed CP 200-230	18.53	1
Wheat middlings	7.34	3
Triticale	1.25	1
Palm kernel expeller CF 0-180	15.00	1
Soybean hulls CF 320-360	15.00	3
Coconut expeller CFAT >100	10.00	3
Vinasse Sugarbeet CP 0-250	4.00	3
Citrus pulp dried	25.00	3
Sugarcane molasses SUG >475	3.00	3
Milk powder whole	0.75	4
Total	100	
Feed 3 composition **Concentrate dairy protein rich**	**Feed Mix (%)**	**Category**
Chalk (finely milled)	1.38	7
Maize glutenfeed CP 200-230	37.00	1
Wheat middlings	0.75	3
Soybean meal Mervobest	7.56	1
Palm kernel expeller CF 0-180	15.00	3

Soybean hulls CF 320-360	5.00	3
Coconut expeller CFAT >100	10.00	3
Vinasse Sugarbeet CP 0-250	4.00	3
Citrus pulp dried	15.56	3
Sugarcane molasses SUG >475	3.00	3
Milk powder whole	0.75	4
Total	100	
Feed 4 composition		
Concentrate dairy extra protein	**Feed Mix (%)**	**Category**
Chalk (finely milled)	1.43	7
Salt	0.73	7
Soybean meal Mervobest	14.00	1
Palm kernel expeller CF 0-180	15.00	3
Rapeseed extruded CP 0-380	12.59	3
Soybean meal CF 45-70 CP 0-450	32.00	1
Coconut expeller CFAT >100	10.00	3
Vinasse Sugarbeet CP 0-250	4.00	3
Citrus pulp dried	6.50	3
Sugarcane molasses SUG >475	3.00	3
Milk powder whole	0.75	4
Total	100	
Feed 5 composition		
Roughage - grass	**Feed Mix (%)**	**Category**
Grass fresh April normal yield	4.00	5
Grass fresh May normal yield	16.00	5
Grass fresh June normal yield	16.00	5
Grass fresh July normal yield	16.00	5
Grass fresh August normal yield	16.00	5
Grass fresh September normal yield	16.00	5
Grass fresh October normal yield	16.00	5
Total	100	
Feed 6 composition		
Roughage – grass silage	**Feed Mix (%)**	**Category**
Grass silage May 3500	40.00	5
Grass silage June 3500	25.00	5
Grass silage July-Aug 3000	25.00	5
Grass silage Sept-Oct 3000	10.00	5
Total	100	
Feed 7 composition		
Roughage – Maize silage	**Feed Mix (%)**	**Category**
Maize silage DM 0-240	25.00	1
Maize silage DM 240-280	25.00	1
Maize silage DM 280-320	25.00	1
Maize silage DM 320	25.00	1
Total	100	

Table 3: Dairy - Total feed composition (default diet) and corresponding FCR.

Alternative production method	**Share of feed mix in total feed composition (%)**							***FCR***
	Feed 1	*Feed 2*	*Feed 3*	*Feed 4*	*Feed 5*	*Feed 6*	*Feed 7*	
A1	0.06	3.45	0.06	0.72	55.82	23.71	16.17	3.79
A2	0.06	5.20	0.06	0.92	54.46	23.37	15.92	3.28
A3	0.06	7.34	0.06	0.75	53.11	23.01	15.66	3.14
A4	0.06	9.53	0.06	0.55	51.75	22.65	15.40	3.02
A5	0.06	11.71	0.05	0.38	50.38	22.28	15.13	2.92
B1	0.07	3.37	0.18	0.87	46.77	24.81	23.92	3.62
B2	0.07	5.24	0.24	0.99	45.29	24.46	23.70	3.18
B3	0.07	7.54	0.21	0.79	43.84	24.09	23.47	3.04
B4	0.07	9.87	0.17	0.57	42.36	23.72	23.23	2.92
B5	0.07	12.17	0.14	0.40	40.88	23.34	23.00	2.80

C1	0.06	2.93	0.25	0.88	56.72	21.34	17.82	3.69
C2	0.06	4.79	0.28	0.87	55.37	21.02	17.61	3.38
C3	0.06	6.91	0.25	0.66	54.03	20.70	17.39	3.23
C4	0.06	9.04	0.22	0.47	52.68	20.37	17.17	3.10
C5	0.06	11.13	0.19	0.33	51.31	20.03	16.94	2.99
D1	0.06	3.27	0.01	0.65	60.63	27.51	7.88	4.15
D2	0.06	4.85	0.01	0.83	59.41	27.21	7.62	3.60
D3	0.06	6.78	0.01	0.69	58.21	26.91	7.34	3.45
D4	0.06	8.76	0.01	0.51	57.00	26.59	7.06	3.32
D5	0.06	10.72	0.01	0.36	55.78	26.28	6.78	3.21

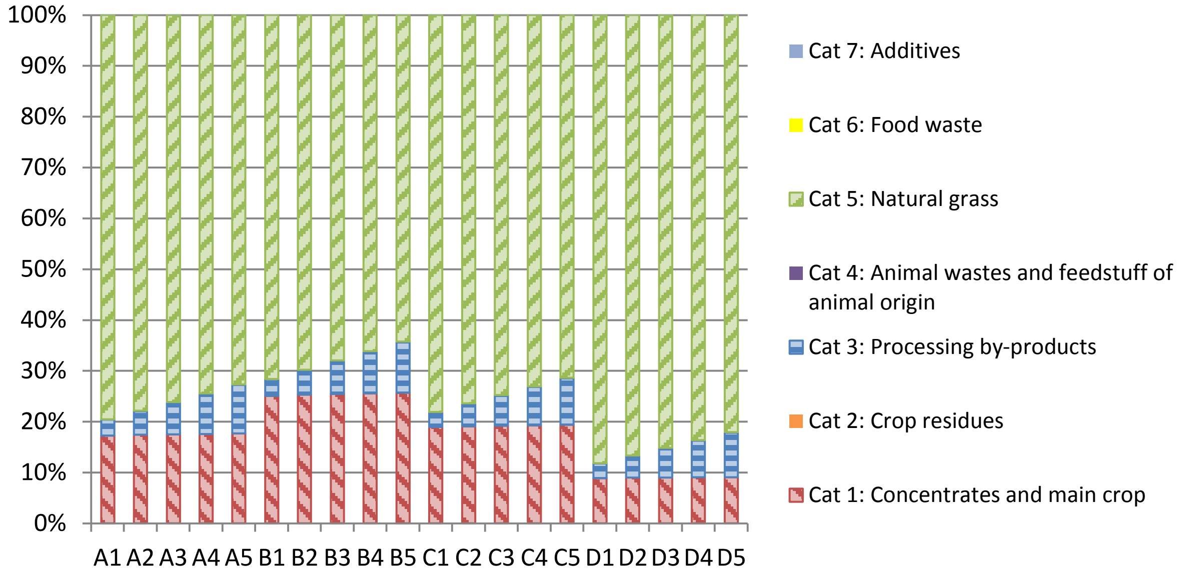

Figure 1: Dairy – share of each feed ingredient category in the total diet on a weight basis. A = grazing during day and night; B = grazing during day; C = zero grazing; D = summerfeeding. See Table 1 for codes of alternative production methods.

Calves are a necessary by-product of milk production. In the present study it was assumed that 1% of the feed required for dairy cows is required for the growth of calves. In the present study the calves that are supplied to veal and beef production systems are assumed to come from alternative production method B2 for dairy cows. The 1% of feed required for the calves from the dairy system is added to the environmental impacts and resource claims that occur in the different veal or beef production methods.

Pigs

Table 4: Pig fattening farm – Codes for alternative production methods.

Sub-type of animal	**Feeding strategy**	**Slaughter weight (kg live weight)**			
		100	110	120	130
Barrows and gilts	*Ad libitum feeding*	A1.1	A2.1	A3.1	A4.1
	Portion feeding	A1.2	A2.2	A3.2	A4.2
	Combination of ad libitum and portion feeding	A1.3	A2.3	A3.3	A4.3
Boars and gilts	*Ad libitum feeding*	B1.1	B2.1	B3.1	B4.1
	Portion feeding	B1.2	B2.2	B3.2	B4.2
	Combination of ad libitum and portion feeding	B1.3	B2.3	B3.3	B4.3

Ratio of feed input / main product live weight output (*italics*)

Table 5: Pigs – Feed mix composition (default diet).

Feed 1 composition Concentrate pig starting	Feed Mix (%)	Category
Soy protein concentrate	1.69	1
Chalk (finely milled)	1.26	7
Monocalciumphosphate	0.24	7
Salt	0.23	7
Sodiumbicarbonate	0.08	7
Fytase 1 m2346 (max 0.2%)	0.20	7
Fytase 2 m2346 (max 0.45%)	0.45	7
L-Lysin HCL	0.41	7
L-Threonin	0.12	7
L-Tryptophane	0.02	7
DL-Methionin	0.09	7
Barley	20.00	1
Rye	5.00	1
Wheat	30.88	1
Wheat middlings	6.96	3
Bread meal	3.00	3
Triticale	5.00	1
Rapeseed expeller	3.00	3
Rapeseed extruded CP >380	3.00	3
Soybean meal CF 0-45 CP >480	11.97	1
Sugarcane molasses SUG >475	4.00	3
Fat from animals, bovine	2.00	4
Mervit starter	0.40	7
Total	100	
Feed 2 composition **Concentrate pigs fattening**	**Feed Mix (%)**	**Category**
Rye	5.00	1
Soybean meal CF 0-45 CP >480	1.31	3
Soy protein concentrate	2.00	1
Chalk (finely milled)	0.91	7
Salt	0.31	7
Fytase 1 m2346 (max 0.2%)	0.20	7
Fytase 2 m2346 (max 0.45%)	0.27	7
L-Lysin HCL	0.31	7
L-Threonin	0.06	7
DL-Methionin	0.03	7
Barley	13.99	1
Wheat	31.61	1
Wheat middlings	12.62	3
Bread meal	2.00	3
Triticale	5.00	1
Palm kernel expeller CF 0-180	3.00	3
Rapeseed expeller	7.50	3
Rapeseed extruded CP 0-380	7.50	3
Sugarcane molasses SUG >475	4.00	3
Fat from animals, bovine	2.00	4
Mervit starter	0.40	7
Total	100	

Table 6: Pig fattening – Total feed composition (default diet) and corresponding FCR.

Alternative production method	Share of feed mix in total feed composition (%)		FCR
	Feed 1	*Feed 2*	
A1.1	30.00	70.00	2.84
A1.2	25.00	75.00	2.79
A1.3	30.00	70.00	2.80
A2.1	26.00	74.00	2.91
A2.2	22.00	78.00	2.85
A2.3	26.00	74.00	2.85
A3.1	22.00	78.00	2.99
A3.2	19.00	81.00	2.92
A3.3	23.00	77.00	2.91
A4.1	20.00	80.00	3.07
A4.2	17.00	83.00	3.02
A4.3	20.00	80.00	3.00
B1.1	29.00	71.00	2.73
B1.2	25.00	75.00	2.79
B1.3	28.00	72.00	2.73
B2.1	24.00	76.00	2.81
B2.2	22.00	78.00	2.85
B2.3	25.00	75.00	2.78
B3.1	21.00	79.00	2.88
B3.2	19.00	81.00	2.88
B3.3	22.00	78.00	2.84
B4.1	19.00	81.00	2.95
B4.2	17.00	83.00	2.95
B4.3	19.00	81.00	2.90

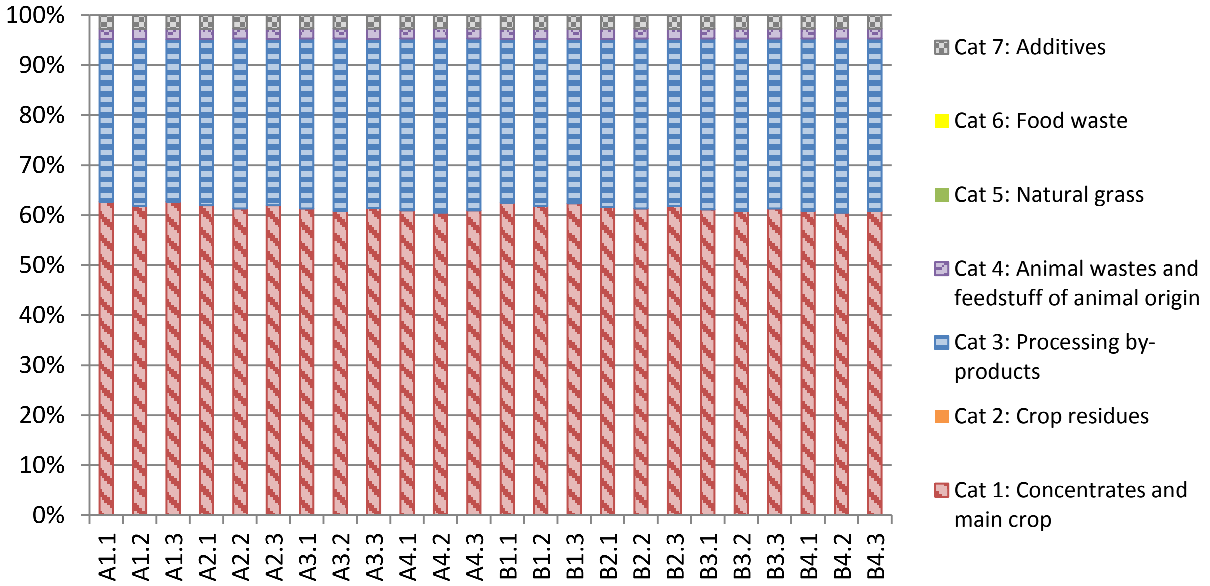

Figure 2: Pig fattening – share of each feed ingredient category in the total diet on a weight basis. A = barrows and gilts; B = boars and gilts. Xx.1 = ad libitum feeding; Xx.2 = portion feeding; Xx.3 = combination of ad libitum and portion feeding.

Breeding Sows

Table 7: Breeding sow farm – Codes for alternative production methods.

	Litter size per year (piglets born alive)						
	8	*9*	*10*	*11*	*12*	*13*	*14*
Breeding sows	A8	A9	A10	A11	A12	A13	A14

Table 8: Sows – Feed mix composition (default diet).

Feed 1 composition **Concentrate gilt**	**Feed Mix (%)**	**Category**
Chalk (finely milled)	0.97	7
Monocalciumphosphate	0.18	7
Salt	0.26	7
Sodiumbicarbonate	0.11	7
Fytase 1 m2346 (max 0.2%)	0.20	7
Fytase 2 m2346 (max 0.45%)	0.45	7
L-Lysin HCL	0.32	7
L-Threonin	0.06	7
DL-Methionin	0.02	7
Maize	8.80	1
Barley	19.49	1
Wheat	40.00	1
Sunflower seed meal CF >240	10.00	3
Rapeseed extruded CP >380	3.00	3
Soybean meal CF 0-45 CP >480	5.88	1
Soybean hulls CF 320-360	0.87	3
Sugarbeet pulp SUG 0-100	5.00	3
Sugarcane molasses SUG >475	2.00	3
Fat from animals, bovine	2.00	4
Mervit starter	0.40	7
Total	100	
Feed 2 composition **Concentrate sow gestation**	**Feed Mix (%)**	**Category**
Chalk (finely milled)	1.34	7
Monocalciumphosphate	0.69	7
Salt	0.18	7
Sodiumbicarbonate	0.23	7
Fytase 1 (max 0.2%)	0.20	7
L-Lysin HCL	0.19	7
L-Threonin	0.04	7
L-Tryptophane	0.01	7
DL-Methionin	0.21	7
Maize	40.00	1
Wheat	23.92	1
Fats/oils vegetable h%d	5.57	1
Soybean meal CF 0-45 CP >480	25.33	1
Std vealcalf premix 5 g/kg	0.50	7
Rovabio Excel AP	0.01	7
Potato protien ASH 0-10	1.58	3
Total	100	
Feed 3 composition **Concentrate sow lactation**	**Feed Mix (%)**	**Category**
Chalk (finely milled)	1.34	7
Monocalciumphosphate	0.69	7
Salt	0.18	7
Sodiumbicarbonate	0.23	7
Fytase 1 (max 0.2%)	0.20	7

L-Lysin HCL	0.19	7
L-Threonin	0.04	7
L-Tryptophane	0.01	7
DL-Methionin	0.21	7
Maize	40.00	1
Wheat	23.92	1
Fats/oils vegetable h%d	5.57	1
Soybean meal CF 0-45 CP >480	25.33	1
Std vealcalf premix 5 g/kg	0.50	7
Rovabio Excel AP	0.01	7
Potato protien ASH 0-10	1.58	3
Total	100	

Feed 4 composition **Concentrate piglet growing**	**Feed Mix (%)**	**Category**
Fytase 2 m2346 (max 0.45%)	1.34	7
Premix Dairy 31	0.69	7
Sugarbeet pulp SUG 100-150	0.18	3
Sunflower seed dehulled	0.23	1
Lupins fat 0-70 CP >335	0.20	1
Malt culms CP 0-200	0.19	3
Meat bone meal CFAT > 100, bovine	0.04	4
Meat bone meal CFAT > 100, porcine	0.01	4
L-Lysin HCL	0.21	7
Meat meal CFAT 0-100, poultry	40.00	4
Grass fresh August normal yield	23.92	5
Lucerne meal CP 140-160	5.57	1
Sunflower seed partly dehulled	25.33	1
Vinasse Sugarbeet CP 0-250	0.50	3
Sugarbeet fresh	0.01	1
Sodiumbicarbonate	1.58	7
Total	100	

Table 9: Sows – Total feed composition (default diet) and corresponding FCR.

Alternative production method	**Share of feed in total feed composition (%)**				**Allocation**		**FCR**	
	Feed 1	*Feed 2*	*Feed 3*	*Feed 4*	*Sows*	*Piglets*	*Sows*	*Piglets*
A8	1.00	34.00	19.00	46.00	0.09	0.91	2.47	4.83
A9	1.23	32.31	18.47	48.00	0.08	0.92	2.30	4.54
A10	1.00	31.00	18.00	50.00	0.07	0.93	2.10	4.34
A11	1.00	35.00	20.00	44.00	0.07	0.93	1.88	3.51
A12	1.00	33.00	19.00	47.00	0.06	0.94	1.70	3.43
A13	1.00	32.00	18.00	49.00	0.06	0.94	1.78	3.33
A14	1.13	30.29	17.19	51.40	0.05	0.95	1.56	3.28

Allocation of sows and piglets is based on mass allocation.

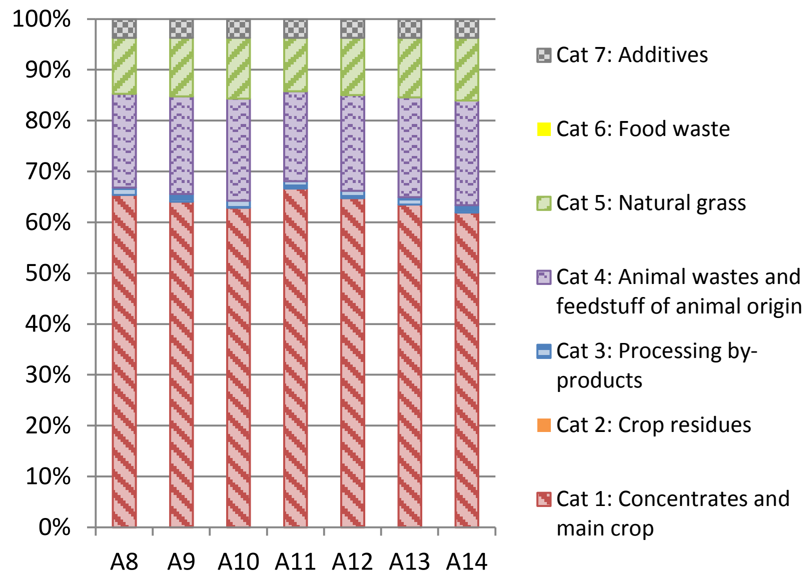

Figure 3: Breeding sows – share of each feed ingredient category in the total diet on a weight basis.

In the present study it was assumed that breeding sows farrow 2.3 times per year and get on average 13 live born piglets. 94% of the feed impacts are allocated to the piglets (based on FeedPrint).

Laying hens

Table 10: Laying hen farm – Codes for alternative production methods.

Type of laying hens	Number of laying days (>18 weeks)				
	350	*375*	*400*	*425*	*450*
Medium weight hens	A1	A2	A3	A4	A5
White layhorns	B1	B2	B3	B4	B5

Table 11: Laying hens – Feed mix composition (default diet).

Feed composition **Concentrate laying hen start + production**	**Feed Mix (%)**	**Category**
Chalk (finely milled)	2.00	7
Chalk grit	7.27	7
Monocalciumphosphate	0.35	7
Salt	0.25	7
Sodiumbicarbonate	0.18	7
Fytase 1 (max 0.2%)	0.20	7
Fytase 2 (max 0.45%)	0.22	7
L-Lysin HCL	0.04	7
DL-Methionin	0.11	7
Mervit growth 2849	0.50	7
Maize	24.63	1
Wheat	37.93	1
Fats/oils vegetable h%d	2.06	1
Sunflower seed meal CF >240	2.06	3
Rapeseed extruded CP >380	6.63	3
Soybean meal CF 0-45 CP >480	8.23	1
Soybeans heat treated	7.35	1
Total	100	

Table 12: Laying hens – Total feed composition (default diet) and corresponding FCR.

Alternative production method	FCR
A1	1.96
A2	2.03
A3	2.09
A4	2.17
A5	2.23
B1	1.75
B2	1.80
B3	1.87
B4	1.92
B5	1.97

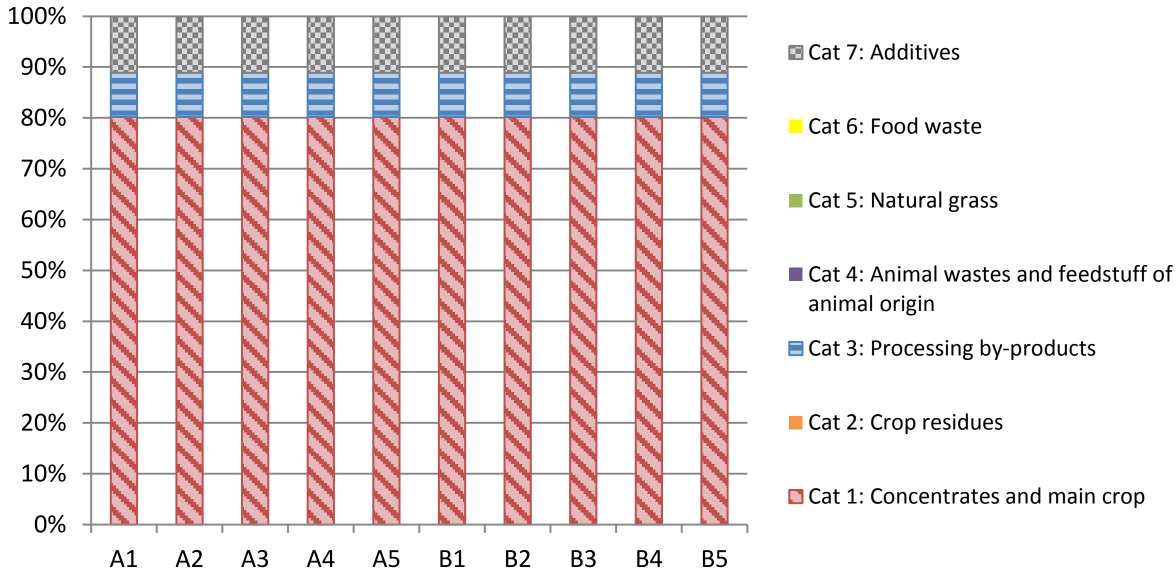

Figure 4: Laying hens – share of each feed ingredient category in the total diet on a weight basis. A = medium weight hens; B = white layhorns.

Broilers

Table 13: Broiler farm – Codes for alternative production methods.

Type of broilers	Type of growth curve	Bodyweight at slaughtering (kg live weight)			
		1.6	*1.8*	*2.0*	*2.2*
Standard broiler	*Flat curve*	A1.1	A2.1	A3.1	A4.1
	Convex curve	A1.2	A2.2	A3.2	A4.2
Slow growing broilers	*Flat curve*	B1.1	B2.1	B3.1	B4.1
	Convex curve	B1.2	B2.2	B3.2	B4.2
		Bodyweight at slaughtering (kg live weight)			
		3	*3.25*	*3.5*	
Heavy broilers	*Convex curve*	C1	C2	C3	

Table 14: Broilers – Feed mix composition (default diet).

Feed 1 composition Concentrate broiler starting	Feed Mix (%)	Category
Chalk (finely milled)	1.68	7
Monocalciumphosphate	0.95	7
Salt	0.18	7
Sodiumbicarbonate	0.27	7
Fytase 1 (max 0.2%)	0.20	7
Fytase 2 (max 0.45%)	0.45	7
L-Lysin HCL	0.19	7
L-Threonin	0.07	7
DL-Methionin	0.27	7
Maize	50.00	1
Wheat	4.12	1
Fats/oils vegetable h%d	2.44	1
Soybean meal CF 0-45 CP >480	36.11	1
Std vealcalf premix 5 g/kg	0.50	7
Rovabio Excel AP	0.01	7
L-Valin	0.05	7
Fat from animals, bovine	2.50	4
Total	100	
Feed 2 composition **Concentrate broiler growing**	**Feed Mix (%)**	**Category**
Chalk (finely milled)	1.34	7
Monocalciumphosphate	0.69	7
Salt	0.18	7
Sodiumbicarbonate	0.23	7
Fytase 1 (max 0.2%)	0.20	7
L-Lysin HCL	0.19	7
L-Threonin	0.04	7
L-Tryptophane	0.01	7
DL-Methionin	0.21	7
Maize	40.00	1
Wheat	23.92	1
Fats/oils vegetable h%d	5.57	1
Soybean meal CF 0-45 CP >480	25.33	1
Std vealcalf premix 5 g/kg	0.50	7
Rovabio Excel AP	0.01	7
Potato protein ASH 0-10	1.58	3
Total	100	
Feed 3 Composition **Concentrate broiler fattening**	**Feed Mix (%)**	**Category**
Chalk (finely milled)	1.34	7
Monocalciumphosphate	0.69	7
Salt	0.18	7
Sodiumbicarbonate	0.23	7
Fytase 1 (max 0.2%)	0.20	7
L-Lysin HCL	0.19	7
L-Threonin	0.04	7
L-Tryptophane	0.01	7
DL-Methionin	0.21	7
Maize	40.00	1
Wheat	23.92	1
Fats/oils vegetable h%d	5.57	1
Soybean meal CF 0-45 CP >480	25.33	1
Std vealcalf premix 5 g/kg	0.50	7
Rovabio Excel AP	0.01	7
Potato protien ASH 0-10	1.58	3
Total	100	

Table 15: Broilers – Total feed composition (default diet) and corresponding FCR.

Alternative production method	Share of feed in total feed composition (%)			FCR
	Feed 1	*Feed 2*	*Feed 3*	
A1.1	10.00	66.00	24.00	1.71
A1.2	11.00	59.00	30.00	1.74
A2.1	10.00	66.00	24.00	1.71
A2.2	11.00	59.00	30.00	1.74
A3.1	9.00	59.00	31.00	1.73
A3.2	10.00	54.00	37.00	1.76
A4.1	8.00	52.00	40.00	1.83
A4.2	9.00	49.00	42.00	1.77
B1.1	28.00	48.00	24.00	2.04
B1.2	28.00	48.00	24.00	2.04
B2.1	28.00	48.00	24.00	2.04
B2.2	28.00	48.00	24.00	2.04
B3.1	25.00	46.00	29.00	2.10
B3.2	25.00	46.00	29.00	2.10
B4.1	22.00	41.00	36.00	2.15
B4.2	22.00	41.00	36.00	2.15
C1	26.00	55.00	19.00	1.81
C2	23.00	56.00	21.00	1.86
C3	22.00	56.00	23.00	1.85

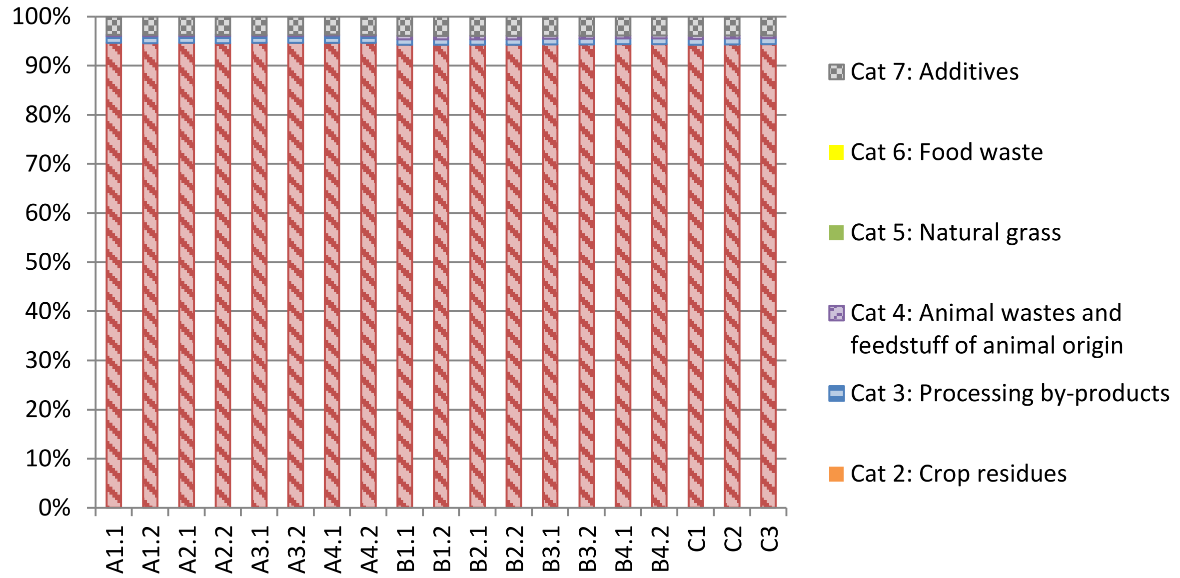

Figure 5: Broilers – share of each feed ingredient category in the total diet on a weight basis. A = standard broilers; B = slow growing broilers; C = Heavy broilers; Xx.1 = flat grow curve; Xx.2 = convex growth curve.

Egg production has two phases. In the first phase pullets are raised from 0.04 kg to 1.4 kg in 18 weeks. After 18 weeks the second phase starts till the laying hens are culled. It is assumed that young hens in the first phase need about the same amount of feed that is given to slow growing broilers that are slaughtered at 1.6 kg. In this case the feed would be given over a longer period of time, i.e. 18 weeks instead of the 8 weeks normally used to fatten slow growing broilers.

Milk-fed veal calves

Table 16: Milk-fed veal calf farm – Codes for alternative production methods.

Sub-type of animal	Gender	Length of fattening period (weeks)		
		22	*26*	*30*
Black and white	*Bull calves*	A1.1	A1.2	A1.3
	Heifer calves	A2.1	A2.2	A2.3
Red and white	*Bull calves*	B1.1	B1.2	B1.3
	Heifer calves	B2.1	B2.2	B2.3
Croise	*Bull calves*	C1.1	C1.2	C1.3
	Heifer calves	C2.1	C2.2	C2.3
Extra meat	*Bull calves*	D1.1	D1.2	D1.3
	Heifer calves	D2.1	D2.2	D2.3

Table 17: Milk-fed veal – Feed mix composition (default diet).

Feed 1 composition **Calf milk replacer milkveal starting**	**Feed Mix (%)**	**Category**
Magnesiumoxide	1.00	7
Premix Veal 45	1.00	7
Wheat gluten meal	5.00	1
Fats/oils vegetable h%d	5.00	1
Fat from animals, bovine	6.00	4
Fat from animals, porcine	7.00	4
Whey powder	45.00	4
Whey powder, delactosed ASH 0-210	11.00	4
Soy protein concentrate	7.00	1
WPC60 (dry)	12.00	4
Total	100	
Feed 2 composition **Calf milk replacer milkveal fattening**	**Feed Mix (%)**	**Category**
Magnesiumoxide	1.00	7
Premix Veal 45	1.00	7
Wheat gluten meal	3.00	1
Fats/oils vegetable h%d	5.00	1
Fat from animals, bovine	9.00	4
Fat from animals, porcine	5.00	4
Whey powder	57.00	4
Whey powder, delactosed ASH 0-210	11.00	4
Soybean meal CF 45-70 CP 0-450	6.00	1
WPC60 (dry)	2.00	4
Total	100	
Feed 3 composition **Concentrate milk replacement mix**	**Feed Mix (%)**	**Category**
Magnesiumoxide	2.00	7
Premix Veal 45	2.00	7
Maize	30.00	1
Maize gluten meal	6.00	1
Barley feed meal high grade	30.00	1
Lupins fat 0-70 CP >335	30.00	1
Total	100	
Feed 4 composition **Roughage – maize silage**	**Feed Mix (%)**	**Category**
Maize silage DM 0-240	25.00	1
Maize silage DM 240-280	25.00	1
Maize silage DM 280-320	25.00	1
Maize silage DM 320	25.00	1
Total	100	

Table 16: Milk-fed veal – Total feed composition (default diet) and corresponding FCR.

Alternative production methods	Share of feed in total feed composition (%)				FCR
	Feed 1	*Feed 2*	*Feed 3*	*Feed 4*	
A1.1	8.00	52.00	10.00	30.00	2.43
A1.2	8.00	52.00	10.00	30.00	2.56
A1.3	8.00	52.00	10.00	30.00	2.68
A2.1	8.00	52.00	10.00	30.00	2.56
A2.2	8.00	52.00	10.00	30.00	2.70
A2.3	8.00	52.00	10.00	30.00	2.84
B1.1	8.00	52.00	10.00	30.00	2.36
B1.2	8.00	52.00	10.00	30.00	2.48
B1.3	8.00	52.00	10.00	30.00	2.60
B2.1	8.00	52.00	10.00	30.00	2.48
B2.2	8.00	52.00	10.00	30.00	2.62
B2.3	8.00	52.00	10.00	30.00	2.75
C1.1	8.00	52.00	10.00	30.00	2.36
C1.2	8.00	52.00	10.00	30.00	2.48
C1.3	8.00	52.00	10.00	30.00	2.60
C2.1	8.00	52.00	10.00	30.00	2.48
C2.2	8.00	52.00	10.00	30.00	2.62
C2.3	8.00	52.00	10.00	30.00	2.75
D1.1	8.00	52.00	10.00	30.00	2.33
D1.2	8.00	52.00	10.00	30.00	2.45
D1.3	8.00	52.00	10.00	30.00	2.57
D2.1	8.00	52.00	10.00	30.00	2.45
D2.2	8.00	52.00	10.00	30.00	2.58
D2.3	8.00	52.00	10.00	30.00	2.71

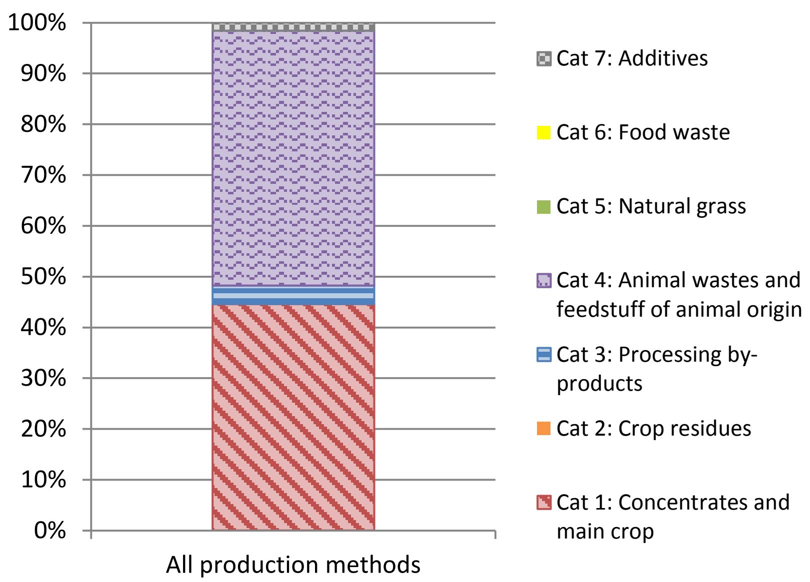

Figure 6: Milk-fed veal – share of each feed ingredient category in the total diet on a weight basis. All production methods had the same diet composition.

Rosé veal calves

Table 17: Rosé veal calf farm – Codes for alternative production methods.

Sub-type of animal	Bodyweight at slaughtering (kg live weight)		
	300	*350*	*400*
Poddy calf	A1	A2	A3
Weaner calf	B1	B2	B3

Table 18: Rosé veal – Feed mix composition (default diet).

Feed 1 composition **Calf milk replacer rose vealcalves**	**Feed Mix (%)**	**Category**
Magnesiumoxide	1.00	7
Premix Veal 45	1.00	7
Wheat feed flour CF 0-35	2.00	1
Wheat gluten meal	7.00	1
Milk powder skimmed	30.00	4
Whey powder	22.00	4
Whey powder, delactosed ASH 0-210	3.00	4
Fat filled whey powder	34.00	4
Total	100	
Feed 2 composition **Concentrate roseveal starting**	**Feed Mix (%)**	**Category**
Magnesiumoxide	2.00	7
Maize	16.00	1
Wheat gluten meal	19.00	1
Lupins fat 0-70 CP >335	3.00	1
Palm kernel meal, solvent extracted	10.00	3
Sunflower seed meal CF 160-200	8.00	3
Rapeseed extruded CP 0-380	5.00	3
Soybean meal CF 0-45 CP >480	14.00	1
Sugarbeet pulp SUG 150-200	19.00	3
Sugarbeet molasses	2.00	3
Vinasse Sugarbeet CP 0-250	2.00	3
Total	100	
Feed 3 composition **Concentrate roseveal growing**	**Feed Mix (%)**	**Category**
Urea	1.00	7
Chalk grit	1.00	7
Rye	12.00	1
Wheat	5.00	1
Wheat gluten meal	11.00	1
Lupins fat 0-70 CP >335	3.00	1
Palm kernel meal, solvent extracted	15.00	3
Rapeseed extruded CP 0-380	5.00	3
Soybean hulls CF 320-360	13.00	3
Sugarbeet pulp SUG 150-200	25.00	3
Sugarbeet molasses	4.00	3
Vinasse Sugarbeet CP 0-250	5.00	3
Total	100	
Feed 4 composition **Concentrate roseveal fattening**	**Feed Mix (%)**	**Category**
Urea	1.00	7
Chalk grit	1.00	7
Rye	12.00	1
Wheat	5.00	1
Wheat gluten meal	11.00	1
Lupins fat 0-70 CP >335	3.00	1
Palm kernel meal, solvent extracted	15.00	3
Rapeseed extruded CP 0-380	5.00	3
Soybean hulls CF 320-360	13.00	3
Sugarbeet pulp SUG 150-200	25.00	3
Sugarbeet molasses	4.00	3
Vinasse Sugarbeet CP 0-250	5.00	3
Total	100	
Feed 5 composition **Roughage – maize silage**	**Feed Mix (%)**	**Category**
Maize silage DM 0-240	25.00	1
Maize silage DM 240-280	25.00	1

Maize silage DM 280-320	25.00	1
Maize silage DM 320	25.00	1
Total	100	

Table 19: Rosé veal – Total feed composition (default diet) and corresponding FCR.

Alternative production methods	Share of feed in total feed composition (%)					FCR
	Feed 1	*Feed 2*	*Feed 3*	*Feed 4*	*Feed 5*	
A1	2.00	4.00	0.00	30.00	64.00	7.08
A2	2.00	3.00	0.00	31.00	64.00	7.73
A3	1.00	3.00	0.00	32.00	64.00	8.46
B1	2.00	5.00	0.00	30.00	64.00	8.52
B2	1.00	3.00	0.00	31.00	64.00	9.00
B3	1.00	3.00	0.00	32.00	64.00	9.64

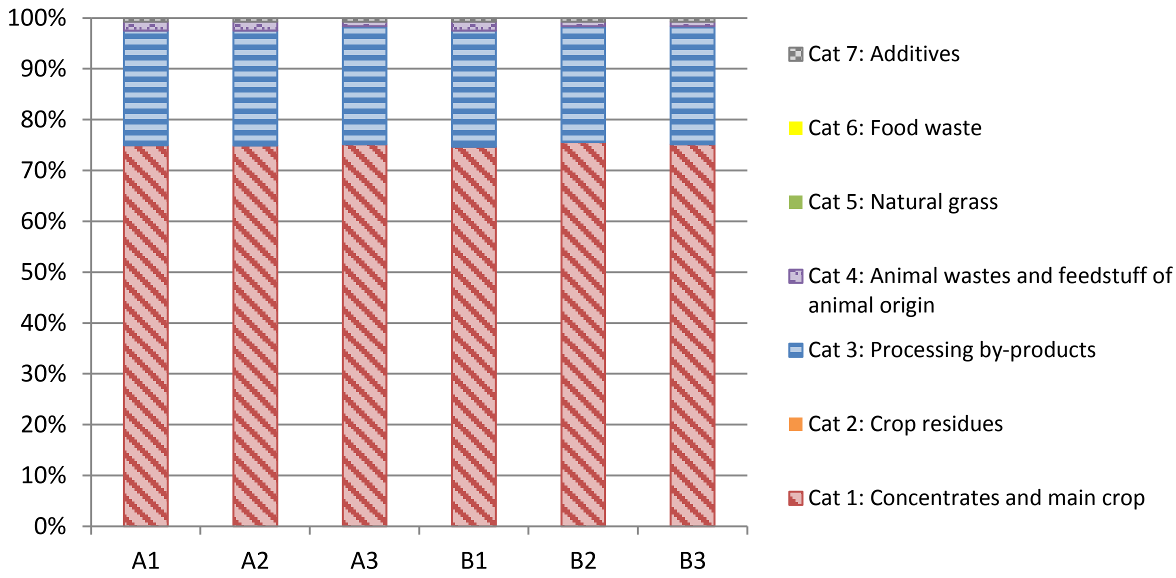

Figure 7: Rosé veal – share of each feed ingredient category in the total diet on a weight basis. A = poddy calves; B = weaner calves; X1 = slaughtered at 300 kg; X2 = sl. at 350 kg; X3 = sl. at 400 kg.

Appendix B - Animal production systems from published LCA studies

A small number of feed ingredients mentioned in the published LCA studies is not included in the FeedPrint dataset. Feed ingredients not listed in the dataset are replaced by a substitute ingredients that were assumed to be suitable. FeedPrint only covers a small number of premixes, which all have the same estimated impact values. More information on the impact of different premixes used in aquaculture is required. In the present study the feed additives mentioned in the published studies were substituted with Premix Veal 45 for the calculations.

Beef

Table 20: Beef – Feed mix composition
Based on Nguyen et al. (2010).

Feed 1 composition **Indoor feeding**	**Feed Mix (%)**	**Category**
Barley	100	1
Total	100	
Feed 2 composition **Indoor feeding**	**Feed Mix (%)**	**Category**
Barley straw	100	2
Total	100	
Feed 3 composition **Indoor feeding**	**Feed Mix (%)**	**Category**
Soybean meal CF 0-45 CP >480	100	1
Total	100	
Feed 4 composition **Indoor feeding**	**Feed Mix (%)**	**Category**
Premix Veal 45	100	7
Total	100	
Feed 5 composition **Grazing**	**Feed Mix (%)**	**Category**
Grass fresh April normal yield	4	5
Grass fresh May normal yield	16	5
Grass fresh June normal yield	16	5
Grass fresh July normal yield	16	5
Grass fresh August normal yield	16	5
Grass fresh September normal yield	16	5
Grass fresh October normal yield	16	5
Total	100	
Feed 6 composition **Indoor feeding**	**Feed Mix (%)**	**Category**
Grass silage May 3500	40	5
Grass silage June 3500	25	5
Grass silage July-Aug 3000	25	5
Grass silage Sept-Oct 3000	10	5
Total	100	
Feed 7 composition **Indoor feeding**	**Feed Mix (%)**	**Category**
Maize silage DM 0-240	25	1
Maize silage DM 240-280	25	1
Maize silage DM 280-320	25	1
Maize silage DM 320	25	1
Total	100	

Table 21: Beef – Total feed composition (Based on Nguyen et al. (2010) and corresponding FCR.

Alternative production method	Share of feed mix in total feed composition							*FCR*
	Feed 1	*Feed 2*	*Feed 3*	*Feed 4*	*Feed 5*	*Feed 6*	*Feed 7*	
Extensive beef production: Grazing suckler-calf-cow herd	3.00	7.20	0.00	0.20	66.10	13.50	10.00	47.49
Intensive beef production: dairy bull calf 12 months	49.00	9.00	8.30	0.00	0.00	0.00	33.60	8.38
Intensive beef production: dairy bull calf 16 months	11.30	3.20	3.10	0.40	0.00	11.30	70.70	34.84
Intensive beef production: dairy bull calf 24 months	3.70	7.60	0.00	0.00	66.30	22.50	0.00	76.19

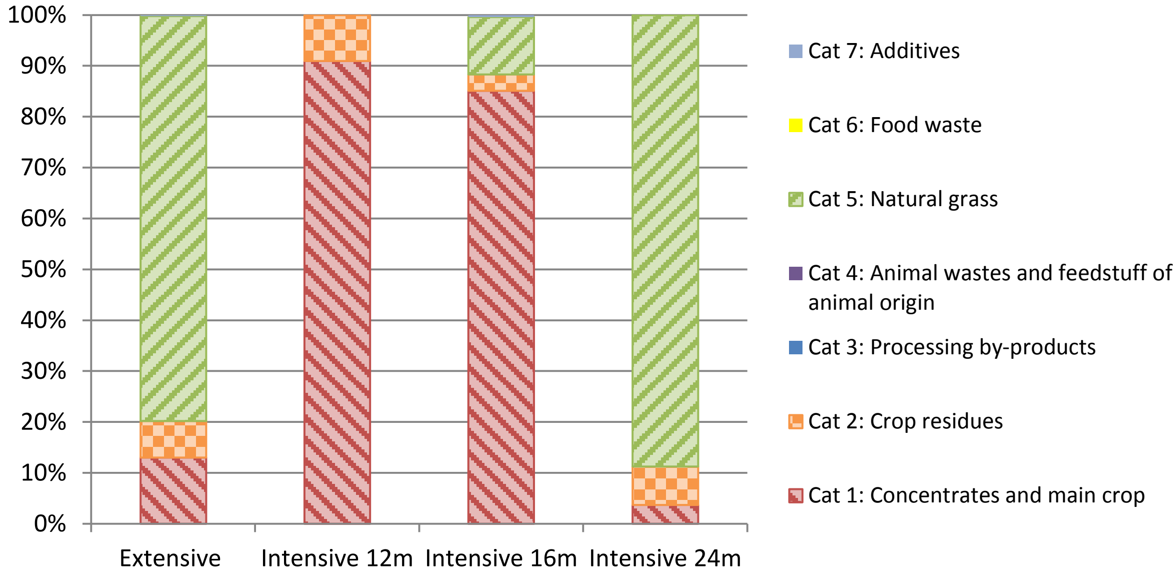

Figure 8: Beef – share of each feed ingredient category in the total diet on a weight basis.

Trout

Table 22: Trout – Feed mix composition

Based on Aubin et al. (2009)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	12.00	1
Fish meal	45.00	4
Fish oil	24.00	4
Wheat	11.10	1
Wheat gluten meal	7.00	1
Premix Veal 45	0.90	7
Total	100	

Trout (rainbow)

Table 23: Rainbow trout – Feed mix composition

Based on Gronroos et al. (2006)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	4.20	1
Fish meal	64.50	4
Wheat feed meal	14.10	1
Premix Veal 45	7.20	7
Maize feed meal	1.70	1
Soy protein concentrate	8.30	1
Total	100	

Sea bass

Table 24: Sea bass – Feed mix composition

Based on Aubin et al. (2009)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	15.00	1
Fish meal	42.00	4
Fish oil	8.00	4
Wheat	22.00	1
Wheat gluten meal	8.00	1
Premix Veal 45	5.00	7
Total	100	

Turbot

Table 25: Turbot – Feed mix composition

Based on Aubin et al. (2009)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	9.50	1
Fish meal	63.50	4
Fish oil	5.00	4
Wheat	13.50	1
Wheat gluten meal	4.50	1
Premix Veal 45	4.00	7
Total	100	

Salmon

Table 26: Salmon – Feed mix composition

Based on Blonk et al. (2009)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	9.00	1
Fish meal	35.00	4
Fish oil	21.00	4
Maize gluten meal	9.00	1
Wheat feed meal	16.00	1
Sunflower oil	10.00	1
Total	100	

Table 27: Salmon– Feed mix composition

Based on Winther et al. (2009)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	13.20	1
Fish meal	45.00	4
Fish oil	15.00	4
Sunflower oil	13.60	1
Wheat	8.00	1
Wheat gluten meal	1.04	1
Sunflower seed meal CF >240	4.40	3
Total	100.24	

Pangasius

Table 28: Pangasius Striped Catfish – Feed mix compositions

	Feed A	Feed B-E	Feed F	Feed E	
Based on Bosma et al. (2009)		Feed Mix (%)			Category
Soybean meal CF 0-45 CP >480	22.50	20.70	35.00	53.00	1
Fish meal	12.00	12.80	8.50	26.00	4
Fish oil	2.00	1.90	0.00	1.00	4

Wheat bran	12.50	13.20	15.00	3.00	1
Rice branmeal, solvent extracted	22.00	21.90	7.50	0.00	3
Tapioca STA 625-675	19.00	18.00	12.50	13.00	1
Rice feed meal ASH 0-90	10.00	10.70	7.00	0.00	3
Coconut copra meal, solvent extracted	0.00	0.00	6.00	0.00	3
Rapeseed extruded CP 0-380	0.00	0.00	8.50	0.00	3
Premix Veal 45	0.00	0.80	0.00	4.00	7
Total	100	100	100	100	

Table 29: Pangasius – Feed mix composition

Based on Huysveld et al. (2013)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	25.00	1
Fish meal	8.00	4
Fish oil	1.00	4
Wheat bran	10.00	3
Rice branmeal, solvent extracted	35.00	3
Premix Veal 45	0.00	7
Wheat	19.00	1
Feather meal hydrolised	2.00	4
Total	100	

Table 30: Pangasius – Feed mix compositions

	Trace	Regular	
Based on Blonk et al. (2009)	Feed Mix (%)		Fraction
Soybean meal CF 0-45 CP >480	30.00	25.00	1
Fish meal	10.00	12.00	4
Fish oil	0.00	1.00	4
Rice branmeal, solvent extracted	35.00	37.00	3
Tapioca STA 625-675	25.00	25.00	1
Total	100	100	

Carp and Tilapia

Table 31: Carp and Tilapia – Feed mix compositions

	Feed 2	Feed 3	Feed 4	
Based on Mungkung et al. (2013)	Feed Mix (%)			Category
Soybean meal CF 0-45 CP >480	22.00	23.00	22.00	1
Fish meal	20.00	17.00	15.00	4
Fish oil	2.00	3.00	5.00	4
Wheat bran	11.00	20.00	30.00	3
Premix Veal 45	5.00	5.00	5.00	7
Maize	10.00	10.00	0.00	1
Rice branmeal, solvent extracted	30.00	22.00	23.00	3
Total	100	100	100	1

Tilapia

Table 32: Tilapia – Feed mix composition

Based on Pelletier and Tyedmers (2010)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	50.00	1
Fish meal	3.00	4
Fish oil	2.00	4
Wheat middlings	32.00	3
Premix Veal 45	4.00	7
Distiller grains and solubles	4.00	3

Maize gluten meal	3.00	1
Palm kernel oil	2.00	1
Total	100	

Overview aquaculture species

Table 33: Feed conversion ratios of aquaculture species in published LCA studies.

Aquaculture production method	FCR		
Trout	1.255		
Rainbow trout	1.255		
Sea bass	1.77		
Turbot	1.23		
Salmon (Blonk)	1.20		
Salmon (Winther)	1.20		
Pang.Str.Catfish (Bosma)	1.50	1.86	2.30
Pangasius (Blonk - regular)	1.80		
Pangasius (Blonk - trace)	1.60		
Pangasius (Huysveld)	1.51		
Carp + Tilapia	1.65	1.91	
Tilapia	1.23		

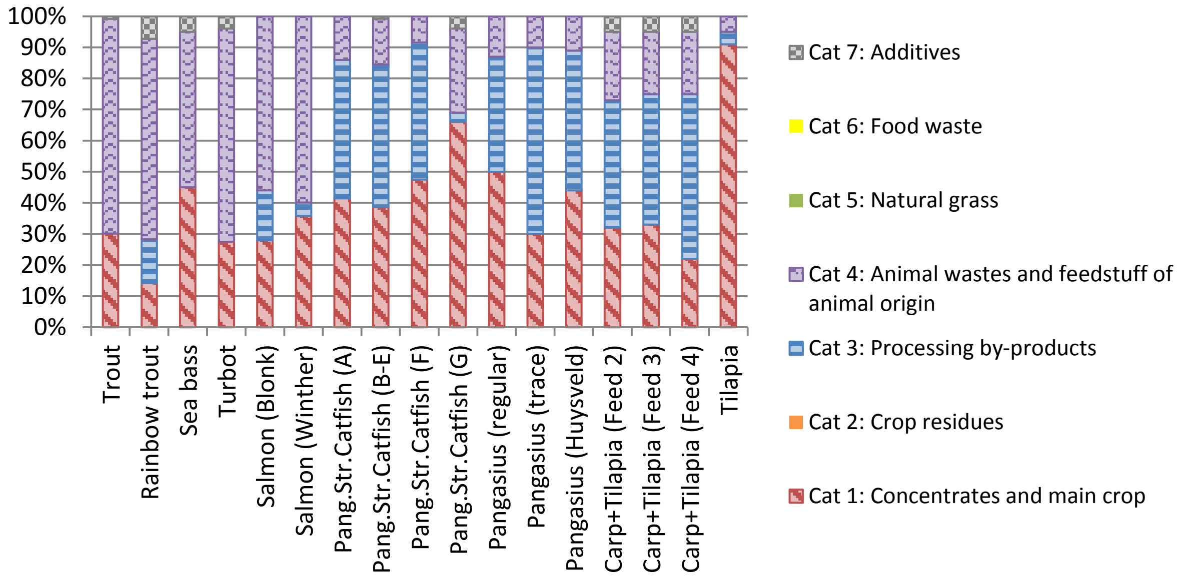

Figure 9: Aquaculture species – share of each feed ingredient category in the total diet on a weight basis.

Crickets

Table 34: Crickets – Feed mix composition

Based on Collavo et al. (2005)	Feed Mix (%)	Category
Soybean meal CF 0-45 CP >480	22.96	1
Lucerne hay	19.87	1
Maize feed flour	16.49	1
Wheat	14.93	1
Maize silage DM 0-240	3.17	1
Maize silage DM 240-280	3.17	1
Maize silage DM 280-320	3.17	1
Maize silage DM 320	3.17	1
Sugarbeet fresh	13.09	1
Total	100	

FCR = 2.78

Appendix C – Farmed insects and production quantities

In this appendix a short overview is provided of known commercial insect farms and published production data.

For the Netherlands it is estimated that there are around 15 'professional' insect farmers of which eight are organised in a branch organisation (pers. com. with Margot Calis-Oosterwaal 25-9-2013; Venik.nl 19-11-2014). A number of insect farms in the Netherlands produce small quantities of mealworms and grasshoppers that are suitable for human consumption. In Belgium there are four insect farmers for which the production of insects for human consumption is tolerated (FAVV, 2014). In Belgium and the Netherlands – as in the rest of the European Union there is no specific legislation for the farming and selling of insects for human consumption. At the moment these practices are tolerated by the governments.

Besides the companies that farm insects for human consumption there are also a number of companies that farm insects for the production of feed ingredients. Very limited data on quantities produced by insect farms are available and even the companies that do rear insects for human consumption do not share their data with one another (pers. com. with Margot Calis-Oosterwaal 25-9-2013). Hereafter, an overview of the published production data of the most common farmed insect species - in both temperate and tropical regions - will be given.

Mealworms
The first[14] published LCA study on a farmed insects was carried out for van de Ven Insecten Kwekerij – a commercial mealworm producer in the Netherlands. The annual production of this company is 83,200 kg of live weight. Two mealworm species (*Tenebrio molitor* and *Zophobas morio*) are produced in equal quantities per year. T. *molitor* has an average dry matter content of 38%, which consists of 53% crude protein. Z. *morio* has an average dry matter content of 43%, which consists of 45% crude protein. The diet consists of fresh carrots, wheat bran, oats, soy, rye and corn supplemented with beer yeast. The exact composition of the grain mix has not been made available for industrial competitive protection reasons. The mealworms species reach the maturation period within 2.5-3.5 months, but most are harvested prior to pupation. (Oonincx and de Boer, 2012)

Crickets
"In Thailand, Viet Nam and Lao People's Democratic Republic two species of crickets are reared for human consumption: the native cricket (*Gryllus bimaculatus*) and the house cricket (*Acheta domesticus*). These crickets are often reared in small rearing facilities" (van Huis et al., 2013). Cricket farming in Thailand started with 22,340 cricket farmers in 1998. In 2011, around 20,000 were still active as cricket farmers. "Cricket farming has developed into a significant animal husbandry sector and is the main source of income for a number of farmers" (Hanboonsong et al., 2013). In 2006 the recorded production was 6,523 tonnes live weight, and between 2007 and 2011 this was around 7,500 tonnes LW. "Commercial high protein animal feed – particularly chicken feed – is widely used in cricket farming" (Hanboonsong et al., 2013). The lifecycle of crickets in these farms is around 45 days till harvest. In the first 20 days a 21% protein feed is used, this is later

[14] And only one at the moment.

replaced by a feed with 14% protein. In the last days before harvest vegetables and leaves are fed to enhance flavour and to reduce costs (Hanboonsong et al., 2013).

Palm weevils

Palm weevil (*Rhynchophorus ferrugineus* Olivier) farming started in 1996 for home consumption by local people. In 2011 – the only year in which data has been recorded – 120 farmers produced 43 tonnes using rearing basins. Palm weevils were either reared on ground palm plants mixed with pig feed – 12% protein – or on palm trunks without additional feed. Production is largely constrained by the availability of specific types of palm and sago species and therefore the production is limited to specific locations (Hanboonsong et al., 2013).

Silk worms

In sericulture the cocoons of silkworm are boiled for extracting the silk, and the pupa can be used either for direct human consumption or used as animal feed. "In China silkworm pupae powder is already used as a feed ingredient" (Vantomme et al., 2012). In 1997 – as a result of a drop in silk market prices – a silk company with at least 4000 silk farmers changed its strategy. Instead of harvesting silk cocoons for the textile industry, the farmers received instructions on how to harvest the cocoons for human consumption. The silkworms are harvested a couple of days before they start to form silk threads (Yhoung-Aree and Viwatpanich, 2005). According to the FAO, the global production of silkworms (reelable) was 563,507 tonnes in 2011 (FAOSTAT Data 12-01-2015). The production of raw silk was 161,436 tonnes in the same year (FAOSTAT Data 12-01-2015). This means that the pupae by-product could contribute around 402,071 tonnes to food and feed production.

Fly larvae

The registration application of MagMeal™ – fly larvae based animal feed – from the AgriProtein company in South Africa has been approved by the South African Department of Agriculture in 2013. This makes AgriProtein the first licensed company in the world able to sell insect protein meal into the animal feed market (Drew and Joseph, 2012). However, current production levels at the demo facility are only 800 kg of dried larvae – 50% protein content – per week (Personal communication with Cameron Richards, 11-9-2013). At the end of 2013 the construction of a commercial factory with a projected daily production of seven tonnes of MagMeal has started (AgriProtein.com, 19-11-2014). Larvae of the common house fly (*Musca domesticus*), black soldier fly (*Hermetia illucens*) and blow fly (*Calliphoridae* spp) are reared on a mixture of fruit and kitchen waste (Personal communication with Cameron Richards, 11-9-2013) and even slaughterhouse waste. In the current demo facility about 25 tonnes of fruit and vegetable waste are required to produce one tonne of larvae protein. In potential 1.5 tonnes of larvae protein would be possible with the same amount of waste.

Around the world a number of companies are developing production processes for mass-rearing of fly larvae on waste streams: Protix Biosystems BV and Jagran BV in the Netherlands, Millibeter in Belgium, Ynsect in France, Hermetia in Germany, Entologics in Brazil, Hangzhou Tianyuan Agricultural Company in China, and EnviroFlight in the Unites States. Although the use of larvae meal as an ingredient in livestock and poultry feed in the Netherlands and European Union is not allowed yet, Protix Biosystems BV has already signed an agreement to deliver 300 tonnes of larvae meal to a feed company. The company is also working together with a Norwegian aquaculture project to develop new aqua feed for salmon http://www.protix.eu/projects/ 12-1-2015) (Lock et al., 2013).

Besides larvae meal also oil can be extracted from the larvae, which can be used as a feed ingredient or biofuel. The digested and non-digested residues can be dried and used as fertilizers. The process also yields small quantities of chitin powder from the exoskeleton of the insects, this can be used in the pharmaceutical and cosmetics industries (Drew and Joseph, 2012).