SUSFANS Deliverable D5.2

Report on T5.2: case studies

Innovation pathways towards future nutrition security: Innovation pathways towards more sustainable production and consumption in the livestock-fish supply chain and their uptake in the SUSFANS models

SUSFANS DELIVERABLES

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Our current dietary pattern especially animal source food (ASF), has a strong impact on the environment. Furthermore, in Europe, daily consumption of ASF protein is above dietary recommendation, resulting in an increased risk of chronic non-communicable diseases.The aim of this deliverable was to identify innovations that together can result in a pathway towards sustainable nutrition security by combining production-side strategies (reducing the environmental impact per kg of ASF produced), consumption-side strategies (changing consumption patterns of humans by reducing or replacing ASF), and the circular strategie, (focus on improving the circularity of the food system, and avoiding feed-food competition, and lies in between the production and consumption-side strategies). The paper identifies a set of innovations that has the potential to deliver a pathway towards sustainble healthy diets. These innovations comprise: including insects in livestock and fish feed; reducing meat intake and replacing beef with other ASF products including fish, and including novel protein source e.g. in-vitro meat; a circular strategy centred around using products unfit for human consumption in livestock feed. Data is presented that supports the assessment of the impact of these innovation options on the contribution of ASF in a sustainable and healthy diet, using the SUSFANS toolbox. Similar to this the role of captured seafood - fishing at equilibrium (sustainable yields)- in a suitable diet will be assessed.

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Table of Content

Deliverable short summary for use in media

Our current dietary pattern has a strong impact on the environment. Global food production releases more than 25% of anthropogenic greenhouse gases, pollutes terrestrial and aquatic ecosystems and uses about 40% of the earth's terrestrial surface. The majority of this environmental impact originates from the consumption of animal-source food (ASF). In Europe, daily consumption of ASF protein is above dietary recommendation, resulting in an increased risk of chronic non-communicable diseases, e.g. obesity and heart diseases. To strengthen food and nutrition security, the livestock sector is and will continue to be an important part of the puzzle to ensure sustainable nutrition security.

The aim of this deliverable was to identify innovations that together can result in a pathway towards sustainable nutrition security. Those innovations will be assessed within the SUSFANS project (D5.4). The innovation pathway explored in this deliverable, addresses production-side strategies, consumption-side strategies, and circular strategies. Production-side strategies focus on reducing the environmental impact per kg of ASF produced by e.g. changing composition of livestock feed, whereas consumption-side strategies focus on changing consumption patterns of humans by reducing or avoiding consumption of ASF, or shifting from ASF with a higher environmental impact (e.g. beef) to ASF with a lower environmental impact (e.g. pork or chicken). Consumption-side strategies, therefore, have the potential to reduce the environmental impact and contribute to healthier diets. The circular strategy, will focus on improving the circularity of the food system, and avoiding feed-food competition, and lies in between the production and consumption-side strategies. For each strategy (production-, consumption-, circular strategy) innovations were identified in literature. Based on the results of a stakeholder workshop (results discussed in SUSFANS deliverable D5.1) and the literature search performed we propose to focus on the following innovations:

- For the production-side we propose to focus on including insects in livestock and fish feed.
- For the consumption-side we propose to focus on existing measures (such as reducing meat intake and replacing beef with other ASF products including fish) and a novel protein source preferably in-vitro meat.
- For the circular strategy we propose a focus on using products that people do not or cannot eat as livestock feed and assess the role of livestock in a sustainable diet. Similar to this the role of captured seafood - fishing at equilibrium (sustainable yields)- in a suitable diet will be assessed as this is nutritious food that has large potential if managed for long-term sustainability.

If all innovations are assessed a pathway can be identified that leads to sustainable healthy diets.

Teaser for social media

The following innovations can form a pathway towards sustainable healthy diets: production-side strategies - reducing the environmental impact per kg of animal source food by feeding waste-fed insects to livestock; consumption-side strategies - changing consumption patterns of humans by reducing or replacing red meat with conventional protein sources or novel protein sources; and the circular strategies - focus on improving the circularity of the food system by avoiding feed-food competition by using products that people do not or cannot eat as livestock feed and fishing at equilibrium, to assess the role of ASF in sustainable diets.

Background

Context: WP5 objectives

The overall aim of the case studies is to "run" through the entire project, acting as a "proof of concept" for how to develop more sustainable FNS. Work Package 5 exists of three stages, D5.1 describes the general aim of the case studies based on the current situation, D5.2 (livestock and fish case) and D5.3 (fruit and vegetable case) provide a description of the innovation pathways within the case studies. Finally, a work plan how to assess the innovation pathways is described in D5.4. In D5.4 the assessment of the innovations will be performed and reported. Below the different tasks are described.

T5.1: Proof-of-principle of metrics developed

Analysis of flows of material and goods in present food supply chains (i.e. livestock-fish; fruit-vegetables), and testing and further refining the conceptual framework and metrics for the entire supply chains developed in WP1, WP2, WP3 and WP4.

T5.2: Operationalization of innovation pathways in livestock-fish supply chains

Identification and parameterization of innovative sustainability pathways in the livestock-fish supply chain. Innovation pathways in the livestock-fish supply chain will be defined from the production perspective (e.g. using of insects as animal or fish feed), and requires collection of technical data in addition to WP1-WP4 for the adoption by the SUSFANS models. The analysis may be strengthened with data from the private sector.

T5.3: Operationalization of innovation pathways in fruit-vegetable supply chains

Identification and parameterization of innovative sustainability pathways in the fruit-vegetable supply chain. Innovation pathways in the fruit-vegetable supply chain will be developed from the consumers' perspective, and does not require technical data in addition to those collected in WP1-4. The analysis may be strengthened with data from the private sector.

T5.4: Assess sustainability potential of innovation pathways in case study supply chains

Assess the multi-dimensional, and sometimes, conflicting impacts of innovation pathways in supply chains of livestock and fish, and fruit and vegetables in comparison with a business-as-usual scenario (using SUSFANS toolbox, WP9). This will yield insight into future options and limitations of these pathways and, therefore, contribute to science-based decision making regarding sustainable nutrition security in the future.

Outline of D5.2 and link to other Work Packages

D5.1 starts with giving a description of the importance of assessing innovation pathways (within the different case studies) to reach the EU policy goals (the EU policy goals are described in detail in WP1). D5.1 describes how the conceptual framework and metric (developed in WP1) can be used to determine whether or not the policy goals are realized. Furthermore, D5.1 describes very briefly possible innovations for the livestock and fish case study and fruit and vegetable case study, in relation to the results from stakeholder meetings. To test whether or not it is feasible to assess the innovations with the SUSFANS toolbox (WP9) a baseline situations was assessed in D4.7 and D5.1. The aim of D5.2 is to come to an innovation pathway enabling to reach the policy goals. As described in D5.1, innovations can originate from production-side strategies (e.g. reducing the environmental impact per kg of ASF produced) and from consumption-side strategies (e.g. reducing or avoiding consumption of ASF, or shifting from ASF with a higher environmental impact). The results of the stakeholder meetings showed that there was a particular interest in exploring circular food systems. We, therefore, add a third strategy namely the circular strategy. In D5.2 those three strategies (production-side, consumption-side, and circular strategy) will be discussed in detail. Innovations related to production-side strategy focus on feeding strategies (reasoning described in D5.1, background information available in D4.1 and D4.2). Innovation related to consumption-side strategy focus on reducing (red) meat consumption and replacing red meat with other animal-based protein sources or plant-based protein sources (reasoning described in D5.1, background information avalable in D2.1, 2.5, and D2.6). The circular strategy focusses on optimally using leftover streams as this contributes to increasing the circularity of the food system (also concluded in D3.3). For each innovation data from literature relate to the enviornmental impact and the nutritional values are given. This data is needed for the assessment in D5.4 Furthermore, the feasibility of assessing the innovations with the SUSFANS toolbox will be discussed that can form a innovation pathway. In D5.4 this innovation pathway will be assessed.

1 Introduction

The production and consumption of animal-source food (ASF), has re-emerged at the top of the global political agenda, driven by two contemporary challenges. First, in the areas of nutrition, ASF have a clear role in the challenge of reducing the double burden of malnutrition by achieving more balanced diets for a growing and more prosperous human population. For millions of consumers in lower income households, a greater intake of ASF will contribute to raise diet quality and achieve more adequate nutrition; for consumers in the high-income countries, intake of ASF is on average above recommended levels wheras moderate ASF consumption is consistently advocated among the potential strategies for prevention of the major diet-related diseases (NCDs) and are also included in the recent EU strategic health objectives for improvements of health for all and reduction of health inequalities (WHO - Regional Committee for Europe 2014; WHO Regional Office for Europe 2013). Second, ASF features prominently in debates on how to consume in a more environmentally sustainable way. Consumption of ASF generally results in a greater environmental impact than consumption of plant-source food (Hallström et al., 2015). The analytical framework of SUSFANS is designed to assess and compare the impact of alternative strategies for addressing the environmental and nutrition challenges in the EU (Rutten et al. 2016). In particular, this framework is instrumental for assessment of policy and innovation strategies for addressing four major policy goals related to the EU food system: balanced and sufficient diets for EU citizens; reduced environmental impacts; competitive and viable agri-food business; equitable conditions and outcomes (Zurek et al. 2016; Zurek et al. forthcoming).

Environmental and nutrition challenges can be adressed by implementing mitigation strategies on the production-side or consumption-side. Production-side strategies focus on reducing the environmental impact per kg of ASF produced (without having an impact on the consumption patterns), whereas consumption-side strategies focus on changing consumption patterns by reducing or avoiding consumption of ASF, or shifting from ASF with a higher environmental impact (e.g. beef) to ASF with a lower environmental impact (e.g. pork or chicken) (Hallström et al., 2015). A consumption-side strategy will, therefore, also result in healthier diets as the consumption of processed meat is reduced. A third strategy is the circular strategy, which focusses on improving the circularity of the food system, and avoiding feed-food competition, and lies in between the production-side and consumption-side strategies (Schader et al., 2015). Based on the principles of the circular strategy, livestock systems should mainly and optimally use products that humans cannot or will not eat in livestock feed (so called leftover streams), to minimise use of human-edible feed ingredients. Fairlie (2010) refers to “default livestock” where the main function of livestock is to use leftover streams optimally. Livestock that eat only leftovers do not compete with humans for cropland, and also contribute to sustainable nutrition security. However, when livestock are only fed with leftover streams, less ASF can be produced. A strategy based on feeding only leftovers, therefore, requires changes not only on the production-side but also on the consumption-side.

Figure 1, adapted from van Zanten (2016), illustrates the principle of the three strategies (consumption-, production-, and circular strategy). It shows that the consumption of ASF can decrease or increase land use, depending on the percentage of ASF consumed in the diet. Consuming a small amount of ASF is most land efficient (green line). No consumption of ASF (decreasing red line in Fig 1) results in a higher environmental impact of land use compared with a small amount of ASF (Van Kernebeek et al., 2015). In default livestock systems, feed-food competition is minimized and nutrients available are optimized. As soon as the average global consumption of ASF exceeds the threshold line, feed is in competition with food for arable land (increasing red line). After the threshold point the environmental impact of livestock production can be reduced by implementing production-side strategies, which means decreasing the impact per kg product, e.g. by sustainable intensification (yellow arrow). Livestock systems in which feed-food competition is occurring should aim to reduce the impact per kg of ASF. Most production-side studies, therefore, conclude that intensification results in a reduced environmental impact.

In addition to implementing production-side strategies the environmental impact can be reduced also by implementing consumption-side strategies, e.g. reducing the consumption of ASF (blue arrow). Research suggested shifting to low environmental impact ASF products, such as chicken meat (Hallström et al., 2015). Several studies have shown that after the threshold point, chicken meat, eggs, and maybe milk (also implying some beef) have the lowest environmental impact per kg of ASF protein (De Vries and De Boer, 2010).

Each strategy exists of several innovations. Production-side strategies can contain innovations related to feeding and breeding strategies. Consumption-side strategies can contain innovations related to reducing and replacing red meat. Circular strategies can contain innovations related to optimal use of leftovers streams as livestock feed. Each innovation has its own contribution to accomplishing the four policy goals[1]. To accomplish the four policy goals a pathways based on a set of innovations need to be identified. To determine to what extend policy goals will be improved when innovations are implemented, the framework and sustainable metrics developed in D1.1 and D1.2 will be used as described in D5.1. For the assessment of the innovations, which will be done in D5.4, the SUSFANS toolbox will be used.

In this report we will describe the current debate related to each strategy (production-, consumption-, circular strategy) and discuss possible innovations within each strategy that can be applied to reduce the environmental impact and contribute to healthy diets. The SUSFANS toolbox contains data related to the current situation. To be able to assess the innovations in D5.4 with the SUSFANS toolbox, data related to the innovations must be available. In this report we, therefore, describe the available data in literature for each innovation related to the environment and related to the nutritional value of the products. This report ends with a description of innovations that can be assessed with the SUSFANS

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[1] As discribed in D1.1 four plicy goals aer set:
1. Balanced and sufficient diets for EU citizens
2. Reduced environmental impacts of the food system
3. Viable and socially balanced EU agri-food business
4. Contributions to global food and nutrition security

toolbox. Based on this a package of innovation a pathways towards healthy and sustainable diets can be developed.

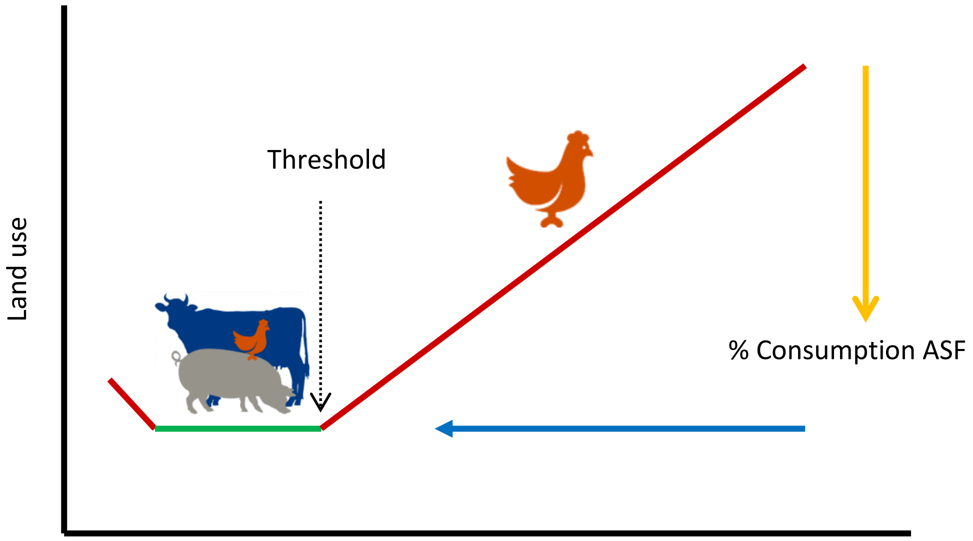

Figure 1. Land use is most efficient when a small amount of animal source food (ASF) is consumed. Land use is less efficient when no ASF is consumed or after the threshold point. Land use can be reduced by production-side strategies, aiming to reduce land use per kg of product (yellow arrow) or by consumption-side strategies, aiming to reduce land use by changing consumption patterns (blue arrow).

2 Production-side strategies

Production-side strategies focus on increasing or maintaining the production volume to meet demand for ASF while increasing efficiency (decrease environmental impact per kg of ASF) and focus on technical innovations and managerial improvements (Garnett, 2014). Background infornation on the production-side is provided in D4.1 and D4.2.

2.1 Livestock and seafood production: innovations

As mentioned in D5.1, looking at the production chain of ASF, differences in environmental impact between pork, chicken, and beef can be seen. Those differences can be explained in part by differences in feed efficiency, reproduction rate, and enteric CH_4 emission (Garnett, 2009; De Vries and De Boer, 2010). Feed production and utilization of feed has the largest impact on greenhouse gas (GHG) emissions and land use (LU) (De Vries and De Boer, 2010; Gerber et al., 2013). About half (47%) of all GHG emissions produced globally by the livestock sector are related to feed production (Gerber et al., 2013). In Europe, the contribution of feed production to emissions from ASF relevant for air and soil quality has been estimated at ca 53% and the contribution of feed production to Global Warming at 66% (Leip et al., 2015). Impact of ASF to water quality is virtually all caused by feed production, including grazing.

For seafood, overall important innovation pathways on the production-side comprise of better management of a) feed (replacing marine-based ingredients, minimize feed use by farming efficient feed converters or species not requiring feed at all), b) farm (minimize emissions, etc.) and c) fisheries (optimized exploitation level, target species, fishing practice). For farmed seafood, feed demand is dominating in terms of contribution to GHG emissions (Ziegler et al., 2016) and it has been identified that feed innovation that allows for minimized competition of resources and reduce dependence on fisheries is imperative for seafood to add to the global food system (Troell et al., 2014; Merino et al., 2012). Thus, the innovation pathway from the production side of seafood that has the highest overall potential for considerable growth in production volume comprises of enabling sustainable growth for aquaculture through use of different waste streams for feed.

Together with farmed salmon, the most consumed seafood in the EU is wild-caught tuna and cod. Fisheries could vary considerably in terms of environmental pressures depending on e.g. gears used, exploitation level, fleet structure. In terms of GHG emissions, fuel use on fishing vessels generally dominates contribution from wild-caught seafood (Ziegler et al., 2016). Improvement potentials from the production side for wild-caught seafood mainly call for innovation pathways on the fisheries management side. This could be done through promoting best available fishing technology (gear use and fleet characteristics) while respecting the limits of natural production and allow for keeping a fishing pressure that is optimized in terms of catch efficiency (high catch per unit effort) without compromising long-term yield.

As feed production has a large impart on the environment for both livestock and farmed seafood, we mainly focus on production-side strategies related to feed production. Examples of novel feeding strategies for livestock are: food-waste, waste-fed insects as livestock feed (Makkar et al., 2014), and producing algae for bio-diesel production and the protein co-product for livestock feed (Craigie, 2011). Examples of novel feeding strategies for seafood are: replacing conventional feedstock that are based on fisheries and agriculture with insects, algae or microbes.

The focus on novel feeding strategies is in-line with the results of the stakeholder meetings. For livestock production stakeholders addressed the importance of using novel protein sources and feed sources that humans cannot or will not eat. There are several products that humans cannot or will not eat, that are suitable as livestock feed, e.g. co-products, food-waste, and biomass from marginal land. Feeding co-products or food-waste to livestock or seafood or using biomass from marginal lands to feed livestock, further referred to as ‘leftover streams’, are effective options of using resources. By feeding leftovers, an inedible stream for humans can be transformed into high-quality food products, such as meat, milk, and seafood (Elferink et al., 2008; Garnett, 2009). Besides novel feed sources stakeholders were interested in more circular production systems. Meaning e.g. that livestock and crop production are more integrated resulting in food production systems that aim to maximize the number of people to be nourished per ha instead of solely increasing efficiency of the animal itself. Feeding leftover streams to livestock is one way of contributing to more circular production systems.

For seafood production there was a request from stakeholder to assess the potential of fishing at equilibrium, i.e. optimize long-term yield through fishing at maximum sustainable yield *MSY*, another innovation pathway focus on best available management and technology for fishing. Fishing at maximum sustainable yield could be considered as a policy goal; it is an objective of the EU common fisheries policy. However, it is questionable if the models can include this metric as the input values varies between years and stocks of the target species. Seafood from capture fisheries would in that case have to be included as single stocks (not species) rather than in commodity categories (such as pelagics, demersals). Even when fishing at MSY, there will be different environmental impacts depending on gear use and fleet characteristics (Ziegler et al., 2016; Parker and Tyedmers 2015) Mitigation strategies related to the production side can focus on 1) changed feed sources (algae, waste, insects) for livestock and Atlantic salmon (most consumed farmed species in EU today), and 2) towards more circular production systems; and 3) optimized fishing for tuna and cod (most consumed wild-caught seafood in EU today).

Below we decribe the possible innovations related to nove protein sources as feed for livestock and seafood. Furthermore, we will dicuss the possibility of fishing at equilibrium. The circular strategy will be dicussed in chapter 4.

2.2 Novel protein sources

The main protein source used in livestock and aquacuture production are soyean meal and fishmeal. Besides those protein sources there are alternative protein sources such as rapeseed meal, sunflower meal, and peas. The main novel protein sources, however, are insects and algea. These two novel protein sources will, therefore, be dicussed in detail below.

2.2.1 Insects as feed

Recent developments indicate environmental benefits of rearing insects for livestock feed (Van Huis et al., 2013; Sánchez-Muros et al., 2014). Insects have a low feed conversion ratio (kg dry matter feed/kg product) and can be consumed completely, without residual materials as bones or feathers. The nutritional value of insects is high, especially as a protein source for livestock (Veldkamp et al., 2012) and looks promising also for farmed fish such as salmon (Lock et al., 2016). Insect-based feed products, therefore, can replace conventional feed ingredients, like fishmeal or soybean meal (SBM), which are associated with a high environmental impact (Veldkamp et al., 2012; Van Huis et al., 2013). The use of insects may reduce the environmental impact of feed production. In contrast with cultivation of feed crops, production of insects is not necessarily land intensive, especially because insects can turn organic waste streams, such as manure or food-waste, into high-quality insect-based feed products (Veldkamp et al., 2012; Van Huis et al., 2013; Sánchez-Muros et al., 2014). Insects moreover recycle part of the nitrogen (N) and phosphorus (P) in waste streams, thereby indirectly reducing gaseous N-emissions. Environmental benefits of waste-fed insects in feed depend on the type and origin of the waste stream used, the efficiency of converting this waste into insect biomass, and the potential to substitute other dietary ingredients. Altogether, waste-fed insects seem to be a promising feed source and, therefore, can be part of the solution to fulfil the growing demand for animal-source food, within the carrying capacity of the earth.

For livestock, feeding insects may also enhance the welfare as this matches their natural dietary preferences. Recent pilot studies indicate, for example, that BSF larvae are highly attractive to chicken (broilers and laying hens) and stimulate foraging behaviours which are important for welfare. For e.g. salmonids, some insects are also a natural part of their diet. Using soy as replacement for fisheries-based feedstock for salmonids has contributed to poor fish welfare (Francis et al., 2001; De Santis et al., 2015).
Replacing feed ingredient that may potentially harm the animal and negatively affect growth rate, with feedstock that characterises a more natural food item and offers less competition for resources is a very important innovation. So far, insect-based meal is still at the experimental stage in terms of feeding trials, with varied results (Lock et al., 2015).

2.2.1.1 Environmental impact

Van Zanten et al (2015), explored whether the environmental impact of pork production can be reduced using the larvae of the common housefly (*Musca domestica*) grown on poultry manure and food waste. Results showed a trade-off between decreased LU and increased GWP and EU, compared to traditional feed protein sources (Van Zanten et al., 2014). Smetana et al., (2015) found that the environmental performance of the insects highly depends on the source of “waste” used to feed the insects. The lowest environmental impact, therefore, is reached either when insects are fed with low value agri-food products with a relatively high nutritional content for the insects (e.g. distiller´s grains from the brewery industry, municipal bio-waste) or when insects are fed with waste with manure (Smetana et al., 2016). Furthermore, there are also LCA studies available that focus on the potential environmental impacts of bioconversion of food-waste by insect. One study highlights besides the good environmental performance of insect biomass as source of animal feed also the environmental benefits connected to the production of organic fertilizers as a co-product of the bioconversion process (Salomone et al., 2017).

The LCA studies mentioned above differ in terms of goal, functional units and system boundaries which make it difficult to compare them. Nevertheless, based on the conclusions of the LCA studies, we could conclude that using insects has potential to improve the environment. While land use seems to be the best performing impact category compared to other protein sources, energy use is causing the highest environmental impact in most insect LCA studies. The heating system, indispensable in some areas to maintain appropriate temperatures for insect growth, is one of the major contributions to energy use. However, it is worth to realize that this impact is site-specific, considering that the ambient temperature in the production area will determine the amount of heat needed for the insect rearing system.

The drying process required to include larvae as livestock feed, was reported to be one of the most energy consuming processes (Salomone et al., 2017). Nonetheless, innovations can be used such as in the study of Van Zanten et al., (2016), there insects were dried with the heat from a waste incineration facility situated nearby the insect production site (Van Zanten et al., 2014). If insects rearing places are developed, one should, therefore, consider all these facts. Combining renewable energies sources and technological innovations will make insect production systems less energy consuming and, therefore, environmentally sustainable.

As farmed fish in general require lower amounts of feed, due to more efficient feed conversion (Welch et al., 2010), defining the optimized use of feed resources to minimize competition of resources and maximize production of food would be very interesting.

2.2.1.2 Nutritional content as feed

The nutrient content of waste-fed larvae meal (Table 1) was adapted from Van Zanten et al., (2015a), but values were consistent with a literature review of Makkar et al., (2014).

Table 1. Nutrient content (g/kg) of soybean meal (SBM) and rapeseed meal (RSM) based on CVB (2010), and waste-fed larvae meal (a) based on data of a laboratory plant (Van Zanten et al., 2015a) and waste-fed larvae meal (b) based on the average value found in Makkar et al., (2014).

	SBM	**RSM**	**Larvae meal (a)**	**Larvae meal (b)**
Dry matter	87.3	87.3	88.0	-
Crude protein	46.4	33.5	47.9	50.4 ± 5.3
Crude fat	1.9	2.6	24.2	-
Crude fibre	3.7	12.0	6.4	5.7 ± 2.4
Ash	6.5	6.7	6.2	10.1 ± 3.3
Phosphorus	0.6	1.1	9.5	16.0 ±5.5
Calcium	0.3	0.7	8.5	4.7 ± 1.7
Lysine (g/16gN)	6.2	5.5	6.8	6.1 ± 0.9
Methionine (g/16gN)	1.4	2.0	2.4	2.2 ± 0.8

2.2.2 Algae as feed

In chapter 3 the use of algae as feed and food is combined as the production process is similar and algae are currently mainly used as food source..

2.3 Fishing at equilibrium

For seafood production there was a request from stakeholder to assess the potential of fishing at equilibrium, i.e. optimize long-term yield through fishing at maximum sustainable yield MSY. Seafood from capture fisheries represents the only large-scale food production based on a wild resource. It is sometimes argued that fisheries is a good alternative to produce food with less impacts and resource use than many land-based protein production systems, as fisheries do not require inputs like feeds, fertilizers or pesticides. However, there are limits to natural production, and many stocks are overexploited and thus produce less than optimal.

During history of exploitation, fisheries have severely depleted predatory fish (Christensen et al., 2003), caused collapse of major fish stocks (Pinsky et al., 2011), severely impacted seafloor structure and function (Tillin et al., 2006) and caused biodiversity loss of target and non-target species (Dulvy et al., 2003; Lewison et al., 2004).

Seafood production from capture fisheries has not increased for decades. According to the latest estimates (2013), roughly 31% of the stocks were fished at unsustainable exploitation levels; 58% were fully fished whereas 11% under-utilized (FAO 2016). There are even indications of declining global catches (Pauly and Zeller 2016). From a sustained ecosystem production capacity perspective, there are both indications of that current global fisheries are exceeding sustainable exploitation levels (Coll et al., 2008) and that there is room for expansion in production volume up to 20% if properly managed. There are also room for improvement in terms of use of seafood resources to direct consumption versus feed (Cashion et al 2017).

Today, around 2500 species (or groups of species) are fished for, based on FAO landing statistics. Present global seafood production volume is based on 49% from marine capture fisheries, 7% from inland capture fisheries and 44% from aquaculture (marine and freshwater).

When wild-caught seafood is fished within the species or stocks production capacity, it can be seen as fishing at equilibrium. This fishing pressure could be set at different levels; in the EU Common Fisheries Policy, the target is Maximum Sustainable Yield. In North-East Atlantic waters, 25 stocks were fished at MSY in 2013, whereas only 12 in the Mediterranean (EU 2014). This situation has improved over time, and it should also be noticed that it may vary between years based on natural fluctuations and political negotiations exceeding the science-based quota. Other areas of the world has other management objectives, such as Maximum Economic Yield in Australia, allowing for less fishing pressure but also better profits and less environmental impacts (Marchal et al., 2016; Farmery et al., 2014).

At this point, it is still uncertain to which level of detail seafood will be included in the models and thus the SUSFANS conceptual framework. It is therefore uncertain at this point what can be assessed in terms of fishing at an equilibrium.

2.3.1.1 Environmental aspects

Even if fish are caught at an equilibrium, fuel use and other environmental impacts such as impact on seafloor habitats and threatened species, varies with the targeted species and fishing gear used (Ziegler et al., 2016).

3 Consumption-side strategies

As stated in D5.1 the production of ASF has a high environmental impact and, furthermore, a high intake of ASF can result in human health issues. Eating less or no ASF is an often suggested solution to reduce the environmental impact of the human diet (Garnett, 2011; Hallström et al., 2015). Furthermore, shifting the type of ASF e.g. from ruminant meat to monogastric meat, is also often offered as a strategy to reduce the environmental impact of human diets (Hallström et al., 2015). Consumption-side strategies, focussing on changes in human diet patterns, therefore, can reduce both environmental problems and health issues (Garnett, 2011; Schader et al., 2015).

Furthermore, while consumption of terrestrial ASF is considered being too high, many European and other countries recommend their citizens to consume more seafood, because of their beneficial nutritional profile (Thurstan and Roberts 2014). Seafood also serves as an important source of minerals (including calcium, iodine, zinc, iron and selenium), contain all essential amino acids, provides essential fats (e.g. long-chain omega-3 fatty acids) and vitamins (D, A and B). There are also reported benefits such as improved brain function. However, it is also important to be aware that there are also health risks connected to certain types of seafood due to content of heavy metals, organochlorine contaminants or pesticide residues originating in agricultural feed inputs.

3.1 Reducing the consumption of red meat

There are several options to reduce meat consumption e.g. reduced portion size, meat free days (‘meatless Monday’, flexitarianism etc), mixed source (meat+non-meat, dilute the meat), increase the price of meat products. Results of D2.1 showed that reducing red meat consumption is one of the most feasible strategies from a consumer perspective, as this not necessarily requires consumers to change the composition of their meal. Strategies, therefore, where consumption of unsustainable products is reduced appears to be an important pathway to reduce the environmental impact of one’s diet (Garnett, 2011; Hallstrom et al., 2015).

We performed a literature search and found three literature reviews related to the environmental impact of diets: Heller et al., (2013); Hallstrom et al., (2015) and Aleksandrowicz et al., (2016). The studies included in these reviews generally compared a reference diet with different diets e.g. vegan, vegetarian, balanced energy intake, healthy guidelines, Mediterranean, new Nordic diet, or pescatarian. There were no studies that assessed a reduction in meat intake of the reference diet while the remaining ingredients in the reference diet remained intact, or the diet composition changed or meat was replaced with other protein sources. Nevertheless, in general you can see a trend in the amount of meat included in these diets, from vegan diets with no ASF, to vegetarian, to healthy diets, to Mediterranean to the reference scenario. In general it can be concluded that the reduction in environmental impact proportionally reduced with the magnitude of ASF reduction (Aleksandrowicz et al., 2016). Furthermore, the results of Aleksandrowicz et al., (2016) also showed that dietary shifts yielded modest benefits in all-cause mortality risk. Based on those literature reviews we, therefore, can conclude reducing meat consumption is a promising strategy to reduce the environmental impact and contribute to healthy diets.

However, although reducing meat seems to be a promising strategy one should be aware that most studies assessed the impact per diet. Each diet fulfils certain requirements mainly protein or calories intake but generally not all dietary requirements were considered. As meat provides, besides protein and calories also essential nutrients with a high bio-availability (.e.g iron, calcium, thiamine, vitamin B12, and Zn), simply reducing ASF in European diets might, therefore, result in other health problems. An assessment about the potential of reducing red meat, therefore, should consider also other nutritional aspects of ASF.

3.2 Replacing red meat with other protein sources

Mitigation strategies related replacing red meat with other protein sources can focus on, 1) replacing beef-based-protein with animal (pork/chicken) based-protein 2) replacing animal-based-proteins with plant-based-proteins, 3) replacing animal-based-protein with seafood-based-proteins, or 4) replacing animal-based-proteins with alternative protein sources. The results of D2.1, D2.5, and D2.6 showed that consumers were most open to animal-based-proteins (cheese, fish and eggs) as an alternative to meat, followed by plant-based alternatives. Consumers are the least open to new types of products, like insects or in vitro-meat as an alternative to regular meat.

The three literature reviews (Heller et al., 2013; Hallstrom et al., 2015; Aleksandrowicz et al., 2016) also included studies in which meat was replaced with other protein sources: ruminant replaced by monogastric meat; ruminant meat replaced by mongastric and no dairy; meat partially replaced by plant-based food; meat partially replaced by dairy products; meat partially replaced by mixed food; meat and dairy replaced by plant-based food. Similar to 3.1, it can be concluded that the reduction in environmental impact proportionally reduced withthe magnitude of ASF reduction (Aleksandrowicz et al., 2016). Also similar to 3.1, diets met calories requirements and/or protein requirements, but did not consider other nutritional aspects of ASF. Furthermore, replacement of meat, in studies included in reviews, was based on conventional protein sources, such as pork-based-proteins or plant-based-proteins, and only sporadically fish was included. Alternative proteins - e.g. in-vitro meat, insects, algae - were not considered. Although consumers are less willing to replace meat with alternative protein sources, it might be a good innovation to reduce the environmental impact and might contribute to healthy diets in the future. We, therefore, explored this possibility in literature. Below we zoom-in per alternative protein sources it environmental impact and the nutritional content, this data can be used for a potential assessment in D5.4. We did not zoom-in related to the replacement of red meat with orther ASF or with plan-based-protein as data about the enviornmental impact and the nutrtional data is avaliable from databases such as eco-invent (environmental data) and USDA (nutritional data).

3.2.1 Replace red meat with fish

Seafood in balanced and sufficient diets deserves a special note. At present, seafood accounts for approximately 17% of the global population's intake of animal protein and nearly 7% of all protein consumed (FAO 2016). As EU consumers don't have a protein deficiency, merely addressing seafood as a protein source is misleading. Seafood also serves as an important source of minerals (including calcium, iodine, zinc, iron and selenium), contain all essential amino acids, provides essential fats (e.g. long-chain omega-3 fatty acids) and vitamins (D, A and B). There are also reported benefits such as improved brain function. Furthermore, the global fisheries resource is highly skewed towards utilization by a limited number of mainly developed countries (Swartz et al., 2010); the full effect on food security for countries with undernourished citizens is currently debated (Smith et al., 2010; Brunner et al., 2012; Golden et al., 2016; Black et al., 2013; Crona et al., 2016).

While consumption of terrestrial ASF is considered being too high, many European and other countries recommend their citizens to consume more seafood (Thurstan and Roberts 2014), because of their beneficial nutritional profile. However, it is also important to be aware that there are also health risks connected to certain types of seafood due to content of heavy metals, organochlorine contaminants or pesticide residues originating in agricultural feed inputs.

European consumers tend to choose mainly wild-caught seafood (such as tuna and cod) and low variety of farmed fish (mainly salmon). From a positive side, these systems are generally in the lower range in terms of energy use and greenhouse gas emissions compared to land-based animal production systems; eating less red meat and more seafood (farmed salmon, cod and tuna) has the potential to contribute to improved FNS. However, the production systems even for these three species are truly diverse and choosing the most low-impact production systems also within seafood products represents an important improvement option.

The range in impacts (and thereby potential improvement options) is even wider if we look beyond the most common species. There is thus also another innovation pathway related to seafood that requires a change in seafood consumption habits. Increased direct consumption of low-impact seafood otherwise destined for feed, such as herring and by-products, is one innovation pathway. Another one is replacing traditional salmon production with more low-impact seafood types like mussels and carps.

Mitigation strategies related changes in human diet patterns can focus on replacing terrestrial animal-based-protein with seafood-based-proteins. Consumers in many countries are advised to eat seafood two to three times per week, related to assumed health benefits of a safe seafood-rich diet. Depending on what will be included in the models (metrics and aggregation of species), one innovation could be to meet the dietary advice of seafood without increasing consumption of animal-based proteins, which would imply reducing consumption of land-based animal protein accordingly.

3.2.1.1 Environmental aspects

The limits of natural production much be acknowledged. About 55% of the seafood consumed in the EU is imported and, from a global perspective, there are only few fish stocks that could tolerate increased fishing pressure. There is thus little room to expand fisheries. Aquaculture is the fastest-growing animal production sector in the world and bridges the gap between limited supply from fisheries and increasing seafood demand from consumers. Aquaculture, however, is not independent from fisheries, since many forms of aquaculture rely on the input of marine feeds. Whether or not replacing conventional ASF with seafood, therefore, results in an improved environmental impact have to be explored. It also depends on which ASF product that is replaced, and with which seafood product.

3.2.2 Replace red meat with in-vitro meat

One innovations related to meat alternatives is cultured meat, in vitro-meat, or synthetic meat. All these terms refer to the same product which is based on growing cells from animal or plant origins without the organisms from which the cells are derived (Fayaz Bhat and Fayaz 2010). In 2013, the first cultured beef hamburger produced by a team of Dutch scientists was eaten in London and cost €250 000 (Jha 2013). The technology for large-scale production of cultured meat is still at research stage, and its proponents estimate that in less than 5 years, the cultured meat will be commercially available in the market (culturedbeef.org n.d.).

The first step to produce cultured meat is to take a small samples of fresh muscle obtained from a living animal. Using a combination of mechanical and enzymatic disruption, satellite cells are separated from the all other muscle components. These satellite cells, which have the capacity to give rise to other satellite cells or myoblasts (Kadi et al., 2005), are then propagated using a right culture medium and growing conditions. To produce the first beef cultured hamburger, the medium included relatively high concentrations of fetal bovine serum, however new medium options without animal products are part of the research agenda (Post 2014). Once a sufficient number of cells is reached, the cells are separated into groups of 1.5 million cells and each batch is submerged in a collagen gel displayed in a culture dish around a central hub of agarose gel (Post 2012). After 3 weeks, millions of these cells will self-organize into a donut-shape muscle fibers of 1 mm and will be ready to be harvested. For a 85 g hamburger, 10 000 of these 1 mm muscle strips were needed (Post 2012). Further information related to tissue engineering techniques can be found in the literature (Edelman et al., 2005; Sharma et al., 2015; Fayaz Bhat and Fayaz 2010)

3.2.2.1 Environmental aspects

Cultured meat is often proposed as a more environmental friendly way to produce meat. At the moment, all LCA studies related to the use of cultured meat are, however, based on hypothetical scenarios as large scale production of cultured meat is not yet current practice. However, such studies are important in order to evaluate the possible environmental impact of mass production of cultured meat compared to alternative food sources. The first study that evaluated the environmental impacts of cultured meat production was performed in 2011 by Tuomisto and Texteira de Matos (2011). Using several assumptions, this study found that in comparison with conventional European meat, cultured meat reduced EU with 7-45% (with the exception of chicken), reduced GWP with 78-96%, reduced water use with 82-96% and reduced LU with 99%. Despite all the assumptions and, therefore, the high uncertainty of the results, this study showed that from an environmental perspective, cultured meat has great potential compared to conventional meat products (Tuomisto and Texteira de Mattos 2011). Four years after the publication of the first cultured meat LCA, two other studies on this topic have been published. Using Chinese Hamster ovary cells, Mattick et al., (2015) got 3 times higher GWP values and 20 times higher LU values than found in the first LCA study. Also EU was higher. Mattick et al., (2015) considered additional inputs and processes that were not included in the study of Tuomisto and Texteira de Matos (2011). The additional inputs and processes were: scaffold material, facility energy, deionization of water, bioreactor cleaning and energy to maintain the cell culture temperature.

The results of Mattick et al.,(2015) showed that cultured meat required more EU than most conventional livestock products (beef, pork, poultry) and depending on the production conditions. In terms of GWP, cultured meat had higher values than poultry and pork, but lower than beef, and regarding LU, cultured meat still performed better than the other meat sources (Mattick et al., 2015). Another study that performed a cradle-to-plate LCA on different meat substitutes (dairy-based, gluten-based, insect-based, soybean-based, etc.) found that cultured meat will not improve the environmental impact as a meat replacer (Smetana et al., 2015). When the GWP, EU and LU values obtained in this study are compared to those obtained by an LCA review of different animal products (De Vries and De Boer, 2010), cultured beef perform worse than all animal products in terms of GWP and EU, and better in LU.

Overall we can conclude that cultured meat will reduce LU but due to high EU GWP is relatively high compared to conventional meat sources. Nevertheless, in the future EU might come from renewable sources of energy or other technical innovations instead of fossil fuels. Land, however, is a resource that eventually will become scarce. In this context, cultured meat could have the potential to enhance environmental sustainability.

3.2.2.2 Nutritional aspects

The production of cultured meat is still at a research stage, and therefore, no information is available related to the nutritional composition of this product.

3.2.3 Replace red meat with insects

Humans, throughout the world and along its existence, have been consuming insects as regular source of nutritious food. First direct evidence of insect consumption dates back to 7500 years ago, when early American Indians consumed termites, adult and larva beetles (Elias 2010). The natural existence of insects in patches, clumps and swarms, together with the development of mass collection techniques by old human societies made it attractive to consume insects(Madsen and Schmitt 1998). Remnants of such ancient behaviours might be still used by actual societies that manipulate the natural environment in order to increase the efficiency in the collection of insects (Itterbeeck and Van Huis 2012).

Nowadays, is estimated that more than 2000 insect species are consumed worldwide as food (Jongema 2015) by at least 2 billion people, mainly from Asia, Africa and Latin America (van Huis et al., 2013). The most consumed insect groups are beetle larvae (31%), caterpillars (18%), wasps, bees and ants (15%), crickets, grasshoppers and locusts (14%), true bugs (11%), termites (3%) and others (9%) (Jongema 2015).

Even though the Western World have benefit from different ecosystems services provided by insects, such us pollination, honeybee, cochineal, silk, pest control, etc. (van Huis et al., 2013), insects have been usually seen as pests (Van Lenteren 2006). The negative perception of insects is reflected in the way how entomophagy is perceived by western societies. In general insects are seen as a “primitive” form of food acquisition or as “poor man’s diet” (van Huis and Dunkel 2017). Nonetheless, in the last years this picture changed as the interest for insects as source of food is increasing in different disciplines of science, governments, private institutions and society.

Several reasons are making western countries interested in using insects as source of food and feed. In contrast to chicken, pork and beef, which edible weight are 55%, 55% and 40% respectively (Flachowsky 2002; Smil 2002), most part of insect biomass is edible (Oonincx et al., 2015; Oonincx and de Boer 2012). Moreover, it is commonly mentioned that the feed conversion ratio (FCR) of insects is higher in relation to traditional animal sources probably because insects do not have to invest metabolic energy for maintaining a constant body temperature (van Huis 2011). However, it is important to realize that such high FCRs can vary between insect species and are only reachable when a suitable diet - especially rich in N- is provided (Oonyncx el al., 2015). Additionally, insects can be fed and grown using organic side-streams, such as animal manure (Roffeis et al., 2015; Van Zanten et al., 2014) or food waste (Komakech et al., 2015; Salomone et al., 2017; Smetana et al., 2016), thus helping to close nutrient gaps and at the same time transform waste into edible protein. All these reasons have fed the widespread claim that insects are a more sustainable source of protein than other animal sources, and in the last years a growing number of LCA studies have been published to test this claims.

3.2.3.1 Environmental impact

The first LCA study of insect production for human consumption, was performed by Oonincx and de Boer (2012). They evaluated the environmental performance of mealworm (*Tenebrio molitor*), finding that when expressed per kg of protein, mealworms perform better than milk, pork, chicken and beef in terms of GWP potential (kg CO_2-eq) and LU (m^2). Nevertheless, EU (MJ) of mealworm production per kg of protein is higher than for milk and chicken, similar to pork and lower for beef (Oonincx and de Boer 2012). Two other studies (ref Smetana et al., (2015; 2016) came to a similar conclusion as Oonincx and de Boer (2012) and concluded that insect-based meat substitutes are more sustainable from an environmental perspective than other meat substitutes (myco-based, dairy-based, gluten-based, etc.) and then chicken meat, which is often considered as the meat source with the lowest environmental impact (Smetana et al., 2015, 2016).

3.2.3.2 Nutritional content

Several studies have covered the nutritional aspects of insects as a source of human food and feed. In general, insects are often considered as a nutritious source of food, especially for its high protein content and other valuable micro-nutrients. However, it is important to realize that with more than 2000 edible insect species consumed during different development stages, the nutritional content can vary significantly (van Huis et al., 2013). Different factors such as gender, type of diet, temperature, stage of development (Finke and Oonincx 2014), as well as processing factors and the way how the insect is cooked, can influence in the nutritional value of edible insects.

Proteins and amino acids

The protein content of edible insects is highly variable (Rumpold and Schlüter 2013). As can be seen in Fig 2, the percentage of protein between species can range from 5% to almost 80%. Even in the same insect order (e.g. Orthoptera), huge variation can be found. Nonetheless, considering that the average protein content of all insect orders evaluated by Rumpold and Schlüter (2013) is 49%, and that eight of nine insect orders evaluated have species with a protein content higher than 60%, indicates that in general insects contain a high protein content. Regarding, the quality of insect proteins for human consumption no studies were found in literature, but some exist for animals. It is known that the removal of the chitin increases the protein quality by increasing the protein digestibility, net protein utilization, amino acid availability and other factors (Ozimek et al., 1985) in rats. Moreover, feed trial studies found good protein quality and growing performance in rats and broilers (Finke, DeFoliart, and Benevenga 1989; Hwangbo et al., 2009) after feeding them with insects.

Usually, plant proteins are deficient in the essential amino acids lysine, tryptophan and threonine (van Huis et al., 2013). Studies covering the amino acid profile of different insect species (Finke 2002, 2015; Rumpold and Schlüter 2013) have reported the content of those amino acids in significant amounts for different insect species. Moreover, most of the insect orders covered by Rumpold and Schlüter (2013) meet the essential amino acid requirements recommended by the World Health Organization (WHO 2007).

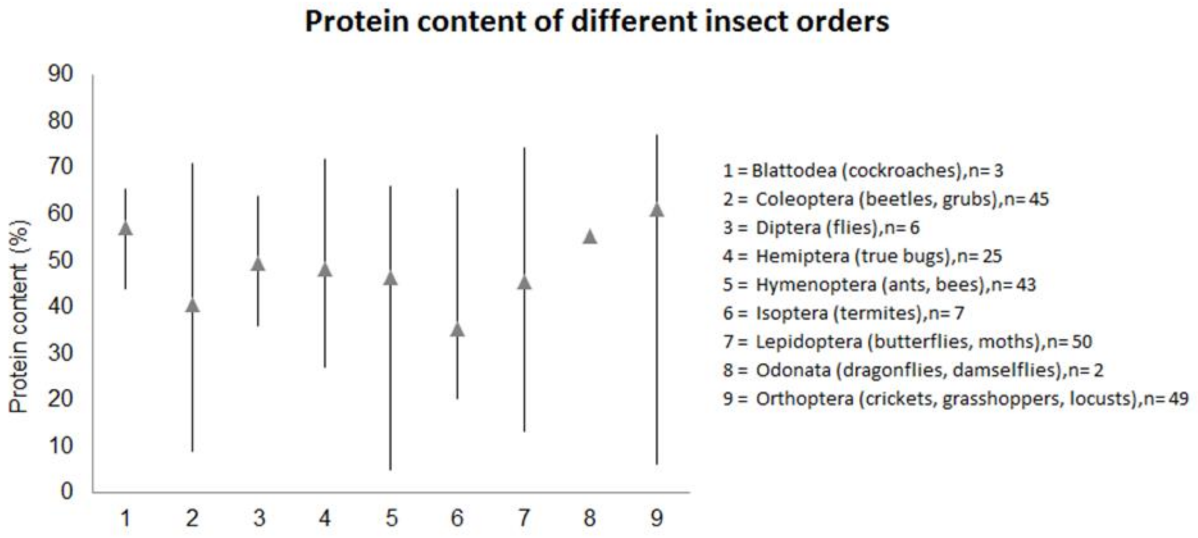

Figure 2. Protein content of different insect orders. Triangles indicate the average value in each content. Adapted from Rumpold and Schlüter (2013).

Fat and fatty acids

After proteins, fat is the second largest macronutrient of edible insects (Rumpold and Schlüter 2013). Different species from the Orthoptera, Lepidoptera, Hemiptera and Coleptera orders contain fat contents higher than 70% (on dry weight basis), which makes them not only a great source of energy (Ramos-Elorduy 1997), but also a great source of polyunsaturated fatty acids (PUFA), monounsaturated fatty acids (MUFA) and saturated fatty acids (SFA). For detailed information check (Finke 2015; van Huis et al., 2013; Rumpold and Schlüter 2013; Womeni et al., 2009). If compared to fish and poultry, insects have a similar fatty acid content in their degree of unsaturation, but are higher in PUFAs (DeFoliart 1991). Furthermore, Womeni et al., (2009) reported that the proportion of PUFA/SFA content found in different insects is above the amount needed to maintain desirable levels of cholesterol. Thus, insects being a great source of different types of fatty acids, have the potential to contribute to the healthy development of infants and children (e.g. omega-3 and omega-6) and to reduce the prevalence of cardiovascular diseases due to the hypocholesterolemic effect of some fatty acids on human health (Mensink and Katan 1989).

Minerals

Studies show that insect contain different minerals, including iron and zinc, which are commonly deficient in some developing countries. Wild insects show variations in the mineral composition between seasons (Finke, Sunde, and DeFoliart 1984; Studier and Sevick 1992) and between populations of the same area, so it seems that mineral composition largely depends on the food sources of the insect (Oonincx et al., 2010). It is reported that different edible insects contain equal or higher iron contents than beef. For example, the mopane caterpillar (Gonimbresia belina) contains 31 mg of iron per 100 g (Bukkens 2005), and the locust Locusta migratoria, depending on the diet given can contain between 8 to 20 mg per 100 g (Oonincx et al., 2010). Rumpold and Schlüter (2013) found that only 10 of 82 species analysed, fulfilled the daily amount of iron needed by an adult person if 100 g dry insects are consumed. Nevertheless, the same authors conclude that because it is unknown until what extent iron from insects is bioavailable, the claim that insect can solve the iron deficiency problems cannot be yet confirmed. Zinc, another mineral that if is not consumed in the required amounts can lead to severe health problems like retardation, immune syndromes, etc. (WHO 2007), is well represented among insect orders (Finke 2002; van Huis and Dunkel 2017; Longvah, Mangthya, and Ramulu 2011; Rumpold and Schlüter 2013; Yang et al., 2014). For this mineral, insects could be consumed as a food supplement in order to satisfy the amounts needed.

It is also worth to mention that insects have high phosphorus content and low calcium and potassium content, e.g. with 100 g of dry insects, the minimum daily requirements are not fulfilled (Rumpold and Schlüter 2013).

Vitamins

Even though it has been suggested that the feed given to insects can determine the vitamin content of edible insects (Pennino, Dierenfeld, and Behler 2007), the wide variation in vitamin content along species makes necessary to select specific insect species for the vitamins of desire (Rumpold and Schlüter 2013). Thus, insects can be considered as a good sources of most B vitamins (except B3 and B1) folic acid (grasshoppers, crickets and locust) and poor sources of vitamins A, D and E (Rumpold and Schlüter 2013). For detailed information see (Finke and Oonincx 2014; Rumpold and Schlüter 2013).

3.2.4 Replacing red meat with algae

3.2.4.1 Macro-algae

Macro-algae or seaweeds have been part of the human diet since thousands of years. First evidences of its use goes back to 14 000 years in the coastal areas of Chile, where early South Americans use it as source of food and medicine (Dillehay et al., 2008). In Asia, seaweeds were part of the diet of ancient inhabitants of the Japanese archipelago and Chinese main lands (Nisizawa ' et al., 1987; Chapman and Chapman 1980). For hundreds of years these resources were obtained through the harvesting of wild seaweed stocks, but nowadays that situation have changed. In 2015, the FAO reported that 95% of the total aquatic plant production (mainly seaweed) came from Aquaculture (FAO 2015). The actual production of seaweed is highly dominated by Asian countries which produce 96.5% of the worldwide seaweed biomass. Within Asia, China (48%), Indonesia (38%), Philippines (5.8%) and the South Korea (4.1%), produce most of the seaweed present in the market (FAO 2017b).

The FAO estimated that 38% of the farmed seaweed production was consumed directly as a food product (FAO 2014). This percentage would be higher if food and beverage products containing hydrocolloids extracted from algae (agar, alginates, carrageenans) were also included (Wells et al., 2016). Other authors estimate that 66% of the Algae production is used as a source of human food (Taelman et al., 2015). Seaweeds are embedded in the daily diet of Asian countries. South Korea, China and Japan have highest daily intake of aquatic plants per capita, with 61g, 26g and 9 g respectively (FAO 2017a; MHLW 2014). For decades the brown algae *Laminaria japonica* used to be the most cultivated algae in the world. Nevertheless, since 2010 the Indonesian seaweed farming sector increased significantly and due to this trend a couple of red algae belonging to the Euchema species (*Kappaphycus alvarezii and Eucheuma spp.*) have overpassed the production of the Japanese kelp *Laminaria japonica* (FAO 2014). These species are mainly produced as raw materials for the food and polymer industries (Rebours et al., 2014).

The macronutrients and diverse bioactive compounds present in seaweeds, can have beneficial effects in digestive and cardiovascular health (Rajapakse and Kim 2011; Bocanegra et al., 2009) and can enhance the physical fitness through bioactive compounds with anticoagulant, antiviral, anti-oxidative, anticancer and inmunomodulating activities (Wijesekara et al., 2011). Nonetheless, it is also important to mention that seaweeds take up and bio-accumulate heavy metals and toxic minerals, resulting in safety issues when used as food or feed. Heavy metals and toxic minerals accumulated by seaweeds include cadmium, cooper, zinc, mercury, arsenic, etc. (Bocanegra et al., 2009; Maehre et al., 2014). The concentration of toxic minerals depend on the environment were seaweeds are grown (Holdt and Kraan 2011).

Even though there is no data available about the amount of seaweed used as animal feed, seaweeds have been used for centuries as animal feed for monogastric and ruminants (Evans and Critchley 2014). Using kelp meal as a source of energy (above of 10% of DM intake) can lead to reduced growth performance due to the low digestibility of complex carbohydrates. Nevertheless, when low levels of kelp meal are included in the diet ration (<2% of DM intake), a potent prebiotic activity is observed, leading to an improvement of stress resistance, better immunity and less production of Greenhouse gas emissions due to favourable changes in gastrointestinal flora (Evans and Critchley 2014). For this reasons, seaweed meal made from the algae *Ascophyllum nodosum, Fucus spp., Laminaria spp., and Macrocystis spp*. are principally used as a vitamin and mineral supplements (Craigie 2011).

For seafood algae are particularly interesting as alternative sources for long-chain omega-3-fatty acids in aquafeeds to replace fish oil. Given the expected continued growth of aquaculture, aquaculture needs to become independent of capture fisheries, whose production is limited. Still, to maintain the health benefits of eating seafood, the level of omega-3-fatty acids needs to be maintained. Therefore, various forms of farming of micro- and macroalgae (both photosynthetic and heterotrophic) have emerged, producing algae oils rich in omega-3-fatty acids. While these do not exert any pressure on wild fish stocks, it is important to optimise how these oils are produced to avoid trade-offs between different environmental impacts as far as possible.

3.2.4.1.1 Environmental aspects

The lack of additional feeds or fertilizers in most coastal seaweed production systems, combined with the low level of habitat modification compared to other aquaculture systems (e.g. shrimps, fish), have created the perception of seaweed farming as the most environmental friendly type of aquaculture.

The environmental impacts of seaweed aquaculture and wild collection will depend on the culture and harvest methods used. Environmental impacts include positive and negative effect on biodiversity and community assemblage, disease outbreaks, reduction of the genetic diversity of native seaweeds, nutrient depletion in coastal areas, contamination with pesticides, etc. (Cottier-Cook et al., 2016; Zemke-White and Smith 2003). Seaweeds can provide shelter and a suitable habitat for different fish and invertebrate species. For instance, in Hawaii, a higher biodiversity index was found in seaweed farming areas than in the surrounding areas (Russell 1983). However, seaweed species can affect negatively other species as well. Sea grasses can be negatively affected through mechanical removal for site preparation (Zemke-White and Smith 2003) or through interspecific competition with the farmed seaweed (Eklöf et al., 2006). As well, phytoplankton biomass could be reduced in the vicinity of the production area (Aldridge et al., 2012), and thus ecosystem cascading effects could occur.The ice, ice disease, caused by a combination of stress conditions and infection by certain bacteria, have attacked *Eucheuma/Kappaphycus* seaweeds leading to a dramatic declines of the productivity (Cottier-Cook et al., 2016; Valderrama et al., 2013; Danielo Largo B. 2002). It is unknown until what extent seaweed cultures facilitate the spread of ice-ice or epiphyte infestations, and even more important, what are the consequences of these diseases in the marine ecosystems. It has been reported that in order to overcome problems associated with nutrient depletion and pathogens, some seaweed producers use fertilizers and chemicals for control and prevention of diseases (Phillips 1990). The environmental impacts of these practices are missing in the literature.

Integrated multi-tropic aquaculture (IMTA) have the potential to enhance the environmental sustainability of seaweed production systems. IMTA systems have been used in China and Korea for many years, combining the production of seaweed, abalone and sea cucumber (Cottier-Cook et al., 2016). In Europe, IMTA systems have been proposed in the German North sea for farming seaweeds and mussels in off-shore wind farms (Buck et al., 2010). The efficient nutrient cycle that characterizes these integrated systems should be considered for future seaweed farming production projects.

Only a few studies are available in literature that explored the environmental impacts of seaweed production using a life cycle approach. Two studies focussed on seaweed as a source of energy for biofuel (Alvarado-Morales et al., 2013) and biogas (Langlois et al., 2012) production. One study used the regenerative circular economy approach combining ethanol production, proteins production for animal feed and fertilizer production (Seghetta et al., 2016). The other study evaluated the environmental impacts related to seaweed as a source of food, feed and hydrocolloids (Taelman et al., 2015). The last study found that the environmental impacts related to the production of Saccharina latissimi in Ireland and France are highly associated with the use of fossil fuels and electricity production. Compared to the footprint of micro-algae and different crops such as sugar beet, potatoes and maize, seaweed production in North West Europe (particularly in Ireland) seem to be resource-efficient (Taelman et al., 2015).

3.2.4.1.2 Nutritional aspects

The nutritional composition of seaweed will depend on several factors such as species, place, atmospheric conditions, seasonality nutrient availability, water flow, etc. In general it can be stated that seaweeds are a rich source of minerals (iodine, calcium), fibre, vitamins (including B12) and bioactive compounds that have positive health effects in humans and animals (Bocanegra et al., 2009; Burtin 2003; Macartain et al., 2007).

Proteins and amino acids

Generally, the protein content in seaweeds is low but it has a good amino acid profile. The protein content is lower than 15% (dry weight) for most brown seaweed species, with the exception of *Undaria pinnatifida* which can reach 24% of dry weight (Fleurence 1999). On average, red and green seaweeds can have a protein contents between 10 to 30% (dry weight). In some cases, like *Palmaria palmate* and *Porphyra tenera*, the protein content can reach 35% and 47% of the dry weight respectively (Fleurence 1999). However, it is important to consider that studies that used the 6.25 N-Protein conversion factor to calculate the amount of protein based on total N, may have overestimated the protein content of seaweeds. Seaweeds contain high amounts of N that is not bound to proteins. For this reason, and in order to avoid overestimations, an average N-Protein conversion factor of 4.92 has been suggested (Lourenço et al., 2002). Another alternative is to calculate the protein contents as the sum of individual amino acid residues following acidic hydrolysis (Maclean et al., 2003). With this method, it was found that the protein content from brown, red and green seaweeds varied from 11% to 23.1% (Lourenço et al., 2002). In Norway this method was used for different seaweed species and the protein content found varied between 3% and 15% (Maehre et al., 2014). The same study found that the chemical score of the amino acids ranged between 0.75 and 1 and concluded that red, brown and green seaweed species are able to cover the human requirements for Essential Amino Acids (EEA) and can be a better source of proteins and EAA than corn, rice or wheat.

The low protein content of seaweeds compared to traditional sources of animal feed protein, such as soy, makes substitution not feasible. However, seaweeds contain significant amounts of methionine, which is limiting in soy. For this reason, seaweeds have been proposed as a supplement to soy in fish aquaculture (Maehre et al., 2014), but its application could be extended to other animals.

Fat and fatty acids

The fatty acid content of seaweeds have been explored and reviewed in the literature. (Barbosa et al., 2017; Sánchez-Machado et al., 2004; Macartain et al., 2007; Burtin 2003; Bocanegra et al., 2009; Norziah and Ching 2000; Maehre et al., 2014; Wells et al., 2016). Seaweeds usually contain a low percentage of lipid components (<5% DM). Even though values are low, they are usually higher than those of most vegetables, which generally have lipid content lower than 1% (Bocanegra et al., 2009; Balboa et al., 2013). Seaweed fatty acids, contain, a high amounts of polyunsaturated fatty acids (PUFA) (Sánchez-Machado et al., 2004) which are essential for animal and human health (Cottin et al., 2011; Broadhurst et al., 2002). Both classes of PUFA, omega-3 (ω3) and omega-6 (ω6), can be found in seaweeds with an optimal ω6/ω3 ratio balance (Sánchez-Machado et al., 2004; Balboa et al., 2013). Essential fatty acids (EFAs) such as ecosapentaenoic acid (EPA; 20:5 n-3) and docosahenoic acid (DHA; 22:6 n-3), have as precursors to α-linolenic acid (ALA; 18:3 n-3) and docosapentaenoic acid (22:5 n-3). Long chain ω3 acids like EPA and DHA have important roles preventing cardiovascular diseases (Simopoulos 2008) and are crucial components for the correct functioning of the brain, nervous system (Sinclair et al., 2007) and mental health (Murakami et al., 2010). Considering that humans and different animal species cannot convert ALA to EPA and DHA at required amounts (Wells et al., 2016), the ingestion of these EFAs through the diet is crucial. The content of EPA in some red seaweed species, such as Palmaria palmate, represents 50% of the total fatty acid content (van Ginneken et al., 2011), and in brown seaweed varies between 20 and 25% (McHugh 2003). This numbers suggest that seaweeds can represent a potential source of these long chain ω3 acids (van Ginneken et al., 2011), especially in a context where the future fish oil supply, nowadays the main commercial source of long chain ω3 acids (Ryckebosch et al., 2014), and is of limited natural production (Budge et al., 2010) and today puts a high pressure on wild fish stocks for fish oil (Tacon and Metian 2015). As stated earlier, microalgae can also represent an alternative source for these substances.

Minerals

Seaweeds obtain a vast diversity of minerals from the marine environment including calcium, iron, sodium, potassium, magnesium, cooper, zinc, etc. The amounts of some minerals ishigher in seaweeds than in different plant and animal foods (Macartain et al., 2007; Ruperez 2002). For this reason, edible brown and red seaweeds have been suggested as a food supplement to meet the recommended daily intake of (Ruperez 2002). Even though the bioavailability of some minerals might be reduced due to mineral- polysaccharides interactions (Burtin 2003), the amount of available iron was found to comparable to different iron-fortified foods (Yang et al., 2014). Furthermore, seaweeds can be a source of iodine, an essential mineral (De Benoist et al., n.d.). However, it is important to consider which seaweed species are as iodine supplement for human or animal diets, given that the amounts of iodine in some seaweed species can be 10 to 1400 times higher than the mean iodine amounts found in fish (Maehre et al., 2014), exceeding the tolerable iodine limit for humans (Fordyce 2003).

Vitamins

The large exposure of seaweeds to direct sunlight in an aqueous media, have resulted in many forms of antioxidants, vitamins and protective pigments (Macartain et al., 2007). Seaweeds are known to be a good source of B complex vitamins, including vitamin B12 which is usually absent or poorly represented in most plant sources (Burtin 2003; Macartain et al., 2007; Wells et al., 2016). In addition, the bioavailability of vitamin B12 derived from seaweed appeared to e high (Fumio Watanabe et al., 1999). It is also important to consider that there are edible seaweeds that contained none or only traces of vitamin B12 (Watanabe 2007).

Seaweeds are also a good source of vitamin C, which is important to strength the immune defence system, control the absorption of iron and to form conjunctive and bonny tissues (Burtin 2003). With vitamin C levels ranging between 50 to 300 mg/100 g of DM, green and brown seaweeds contain higher levels of vitamin C than red algae (10 – 80 mg /100 g of DM) (Bocanegra et al., 2009). A 8 g per-portion of fresh Porphyra umbilicalis (nori), provides 9 mg of vitamin C, representing 15% of the recommended daily intake (Macartain et al., 2007). Moreover, different pigments such as chlorophylls, carotenoids and phycobilliproteins are present in seaweeds and act as sources of vitamin A and vitamin E (van den Burg et al., n.d.). In Chile, the levels of β -carotene found in the seaweeds can exceed the amounts measured in carrots and the levels of α-tocopherol (biologically active form of vitamin E) can equal those levels found in rich vitamin E plants (Ortiz et al., 2009; Wells et al., 2016).

Seaweeds are a potential source of vitamins for human and animals. However, besides B12, there is still high uncertainty about the bioavailability of vitamins.

3.2.4.2 Micro-algae

First evidences of micro-algae use for human consumption goes back to 2000 years ago when indigenous societies from Mexico, Africa and Asia harvested microalgae (Spirulina and Nostoc spp) from natural populations to be consumed as a source of food (Borowitzka 2013). In 1850 the German scientist Ferdinand Cohn, motivated by studying the natural history of microalgae, performed the first attempts of microalgae cultivation using the chlorophyte Haematociccus pluvialis (Cohn 1850). Later on, modern microalgae culture took place during 1890 with Chlorella and subsequent studies deepened on the nutritional requirements for cultivation and physiological aspects (Borowitzka 2013).

During 1940 and 1950, the high lipid content of microalgae was discovered and the idea of using it as a source of food or to produce fuels arsed. Nevertheless, after World War II the need for liquid fuel alternatives was no longer a problem, and the attention turned on microalgae as a protein and food source (Borowitzka 2013). The research done in USA, Germany, and Japan during the 1950s and 1960s, allowed the implementation of the first commercial Chlorella farms in Japan during the early 1960s and Arthrospira (Spirulina) in Mexico during the early 1970s. This farm produced microalgae as a source of healthy and nutritional food and feed. In the next years, other plants started to operate in the USA, Thailand, Australia and Israel. The main products of this farm were food/feed supplements but also some components such as b-carotene and Astaxanthin started to drive the production of other microalgae species like Dunaliella salina and Haematococcus pluvialis (Borowitzka 2013).

In the last decade, the development of new production systems, together with advances in microalgae biotechnology for the extraction of other high-value nutrients (phycobilins, fatty acids, sterols, polyhydroxyalkonates and polysaccharides) (Borowitzka 2013), have changed the attention again on microalgae not only as a source of food/feed, but also as a source for high-value nutrients, ethanol, pharmaceuticals and biodiesel (Enzing et al., 2014).

Microalgae are currently produced using different cultivation systems. Roughly, systems can be classified in open systems and closed systems. Open systems consist in ponds, usually with a depthless below 30 cm. At large-scale production facilities, the circulation of water, nutrients and microalgae is done either using a mechanical arm (for Centre-pivot ponds) or a paddle wheel (raceway ponds). The main weaknesses of open systems are low volumetric productivity due to the low algae concentration (0.1 to 0.5 g L), high risk of contamination (algal predators, parasitic algae, other algae species), elevated consumption of water and high dependency to climatic and environmental conditions (Enzing et al., 2014). Due to lower construction, maintenance and operational costs, open systems are the mostly used system for large scale commercial micro-algae production (Enzing et al., 2014), with dried-micro algae as the main output (Vigani et al., 2015). On the other hand, closed systems, usually called photobioreactors, prevent contact between the algae and the environment through the use of tubes, bags, flat panels, etc. These structures can be installed outdoors or indoors to allow more controlled conditions (temperature, light, etc.). Minimal contamination risk, better cultivation conditions (temperature, pH, etc.), less water use and higher productivity are some of the benefits of this systems. Initial investment and operation costs are much higher than those for open ponds, and for this reason closed systems are mainly used for the production of high value molecules extracted from micro algae (Vigani et al., 2015).

Nowadays, 80% of the total microalgae biomass used for food is dried and sold as dietary supplements for food and feed. The actual percentage use as animal feed is unknown, but in 2006, it was estimated that 30% of the total microalgae was used for animal feed applications (Becker 2007). The main species produced are Spirulina (5000ton/year dry weight) and Chlorella (2000 ton/year dry weight) (Enzing et al., 2014). The other 20% of algae biomass is destined to the extraction of isolated compounds that are added to different foods and feeds in order to improve their nutritional value. For example, the microalgae omega-3, docosahexaenoic acid - DHA is found on 99% of all commercial baby food in USA (Eckelberry 2011). In animal feed, the pigment astaxanthin is largely used for obtaining the pink coloration on salmon aquaculture (Hemaiswarya et al., 2011). Other high-value compounds include, antioxidants (e.g. ß-carotene), fatty acids (e.g. eicosapentaenoic acid – EPA), etc. (Vigani et al., 2015). For a detailed list of products check Enzing et al., 2014 and Gouveia et al., 2008a. Biomass leftovers after the extraction of high-value compounds could be used in the production of animal feed, however such markets don’t exist yet (Vigani et al., 2015).

It has been hypothesized that the main reason why microalgae are not used as a mainstream protein source but as a supplement, relates to its dark green colour, the slightly fishy smell and the high production costs (Becker 2007). Furthermore, with the actual production volumes, microalgae is not yet able to significantly contribute to the reduction of the food and feed insecurity worldwide (Vigani et al., 2015). In order to make microalgae competitive with other agricultural commodities, dramatic reduction of costs and higher production volumes will be needed (Vigani et al., 2015).

Moreover, micro-algae high oil content (Chisti 2007), combined with the fact that it can be cultivated on land unsuitable for agricultural production (Gouveia et al., 2008a), got the attention of the biofuel industry. Biofuels derived from microalgae are called third generation biofuels, and according to some authors seems to be the only possible feedstock to completely replace fossil fuels (Milano et al., 2016). Nevertheless, biofuels derived from microalgae still face some technical and economic challenges that make it not yet economically feasible and comparable to fossil fuels in terms of production costs (Milano et al., 2016).

3.2.4.2.1 Environmental aspects

Even though during the last decades microalgae research increased its popularity in a broad scope of topics (nutritional, pharmaceutical, production technologies, etc.), less attention was given to the environmental aspects of microalgae production. Recently, the biofuel sector had produced different studies in which the environmental impacts of microalgae production and processing are compared to other crops for biofuel production using an LCA (Zaimes and Khanna 2014; Gnansounou and Kenthorai Raman 2016; Sills et al., 2013; Shirvani et al., 2011; Batan et al., 2010; Manganaro and Lawal 2016). Moreover, recent reviews have covered the environmental impacts in large scale cultivation systems and some mitigation strategies (Usher et al., 2014; Smith et al., 2010).

Most of the LCA studies on microalgae use functional units and impact categories related to the energy sector. Examples of these functional units are: Energy on Return Investment (EROI), 1 British Thermal Unit (BTU) and 1 MJ Fuel. Results are usually very variable (Sills et al., 2013) and presented in a context of comparison with other fuel sources. Furthermore, it has been revealed that the choice of technological route (dewatering, drying, lipid extraction technologies), coproduct option (animal feed, anaerobic digestion and combine heat power) and allocation scheme (based on displacement, economic or energy) can have huge significant impacts on the GWP of biodiesel algae systems (Gnansounou and Kenthorai Raman 2016). For all these reasons, it is not easy to interpret the results of these LCA in a food/feed context.

Only a few LCA studies mentioned the use of microalgae as animal feed as a coproduct of biodiesel production. One of these studies found that the process that most contributed to CO_2 emissions (in order of importance) when expressed by 1 million BTU was the heat for drying wet biomass to be sold as animal feed (99.5 kg of CO_2e). However, the electricity used for drying can be used from more renewable sources (wind) making the footprint of algae meal more comparable to soymeal (Taelman et al., 2015).

The impacts of large scale cultivation of microalgae on the atmosphere are diverse. Although microalgae produce CO_2 via respiration, CO_2 is also fixated through algae photosynthesis (Usher et al., 2014). Using several assumptions, Walsh et al., (2015) found that if microalgae are used as a feedstock LU will be decreased with 2 billion hectares of land. Moreover, methane emissions coming from anaerobic decomposition can be reduced if microalgae systems are well managed with constant aeration in the water ponds. In relation to N_2O emissions, literature shows that N_2O emissions are very low under oxic conditions, but can increase under anoxic conditions (Fagerstone et al., 2011).

Water use is an important impact category for microalgae production. Open systems have a higher water use than closed systems because photobioreactors limit the amount of water that evaporates. Depending on the local climate, an open system can yearly use, 0.48 m^3 - 2.28 m^3 in 1 m^2 (Benoit Guieysse et al., 2013). In biofuel terms, microalgae systems have a lower water footprint than biodiesels produced from soy and sugar cane (Usher et al., 2014). It is unknown that this trend is the same when expressed per kg or dry product or per kg of protein.

A positive environmental impact of microalgae cultivation is related to the treatment of wastewater. Human wastewater can be an important source of nutrients such as N and P (Duncan 2003), which can cause severe problems of eutrophication (Correll 1998). Microalgae require N and P for its metabolism and for this reason have been proposed as a way to recover the N and P from wastewater and thus contribute to alleviate eutrophication problems (Usher et al., 2014). Furthermore, it has been found that microalgae can also be used to remove pesticides from agricultural waste waters (Butler et al., 1975) and to bio remediate polluted environments (Subashchandrabose et al., 2013).

3.2.4.2.2 Nutritional aspects

Microalgae nowadays are consumed by humans not only directly as a supplement rich in nutrients, but also in different red foods as a nutrients to enhance the nutritional value of food products (Spolaore et al., 2006). In addition to its use in human nutrition, microalgae are used in animal diets mainly as a feed supplement. Its application in feed rations have shown to produced different favourable effects such as improved immune response, improved gut function, probiotic colonization stimulation, improved feed conversion, reproductive performance and weight control, and even better external appearance (Gouveia et al., 2008b).

Proteins

With protein contents varying from 48% to 61% (Becker 2013) of dry matter, Chlorella and Spirulina, can be considered as high protein sources. The protein content of these microalgae is even higher than those for traditional animal protein sources such as eggs, beef and milk, which contain 47%, 43% and 26% of protein (dry matter), respectively. In addition, microalgae amino acid content, proportion and availability is comparable to other sources such as eggs and soy (Becker 2007). However, it is important to realize that with the exception of Spirulina, microalgae cell wall is thick and non-digestible for humans and other non-ruminants (Chronakis and Madsen 2011). As a consequence, the Net Protein Utilization (NPU) values for microalgae can be 35 to 57% lower than other sources like casein or egg (Becker 2007). In this context, post-harvest treatments can play an important role in improving the digestibility of these proteins and therefore the NPU. For example, drum-drying can increase the NPU of *Chlorella* compared to air drying from 31.4% to. 68%. Other study with Chlorella found that ultrasonic drying showed a higher crude protein digestibility in rats than spray-dried algae and electroporated algae (Janczyk et al., 2005). Hence, it is important to consider that processing techniques can have an impact on the nutritional quality and digestibility of algae proteins (Becker 2007; Chronakis and Madsen 2011; Becker 2013). In the case of *Spirulina*, its cell wall can be degraded by proteolytic enzymes of monogastrics and therefore can be digested without the need of physical or chemical rupture (Becker 2013). Anyway, other factors such as nitrogen supply, light intensity and quality, climate, mineral concentration and the age of the cells can influence the protein content of microalgae (Chronakis and Madsen 2011). For detailed information about the functional properties of *Spirulina and Chlorella* proteins, check (Chronakis and Madsen 2011).

Lipids

The average lipid content of microalgae generally varies from 1% to 40% (Becker 2013). The lipid content of *Chlorella* vulgaris range from 14-22% and that for Spirulina from 4-9% (% of dry mater) (Becker 2007). Besides the influence of environmental factors in this variation, the availability of certain nutrients seems to have an effect on the total lipid content of cultured microalgae. For instance, extreme lipids content of 85% (dry weight) have been recorded under conditions of nitrogen starvation (Becker 2013). Studying the effect of different nitrogen regimes on lipid content and growth parameters, Piorreck et al., (2014) concluded that green algae (e.g. *Chlorella*), can be manipulated in mass cultures to yield a biomass with desired fatty acid composition (Piorreck et al., 1984).

Some microalgae synthetize fatty acids of particular interest. For example, commercial *Spirulina* tablets from Turkey and China contained 30-48% of PUFAs (n-3 and n-6) (Diraman et al., 2009). Moreover, it has been proved that *Spirulina* is a rich source of g-linolenic acid (GLA) and like *Chlorella vulgaris*, contain other essential omega 3 fatty acids like Alpha linolenic acid (ALA), eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA) (Tokuşoglu and uunal 2003; Diraman et al., 2009). These long PUFA with more than 18 carbons, cannot be synthesized by higher plant and animals (Gouveia et al., 2008b), and are naturally supplied by microalgae to whole food chains (Pulz and Gross 2004).

Different microalgae species such as *Nannochloropsis*, *Phaeodactylum*, *Nitzschia* are being grown commercially to produce EPA. For DHA, the species cultivated are *Shizochrytiu*, and *Cryptocodinium* (Enzing et al., 2014). Nowadays the main commercial source of these fatty acids is fish oil (Becker 2013) extracted from wild catches. If in the following years the production volumes of these microalgae species are increased, microalgae not only can get a better position in the market, but also could help to alleviate the depletion of marine resources due to overfishing (Pauly and Zeller 2016).

Minerals

Microalgae have the capacity to bioaccumulate minerals under different conditions of temperatures, pH, salinity, etc.(FAO. Fisheries 2008). This characteristic can be used for bioremediation applications like detoxify arsenic from water and food (FAO. Fisheries 2008), but also to supply a rich array of minerals to humans and animals. These minerals include: Potassium (K), Calcium (Ca), Iron (Fe), etc. For instance, studies have found that *Spirulina platens*is contain all essential minerals (FAO. Fisheries 2008) and in particular have a high K content (1413.0 mg/100 g dry weight) (Tokuşoglu and uunal 2003). *Chlorella vulgaris* is a good source of P (1761.5 mg/100 g dry weight) and *Isochrisis galbana* an important source of Ca (1081.0 mg/100 g dry weight) (Tokuşoglu and uunal 2003). In fish aquaculture, the incorporation of powdered marine microalgae in the diet, can almost replace the mineral mixtures commonly used (Fabregas and Herrero 1986). In commercial broilers, Venkataraman et al., (1994) replaced fish meal, vitamins and minerals with *Spirulina* and found that weight gain, protein utilization and meat quality was not negatively affected (Venkataraman et al., 1994). In other experiments with heat-stressed broilers, it was found that supplementation of *Chlorella* at high rates, increased the levels of Fe, Mn and Se in the plasma content, reducing heat-stressed (Moradi kor et al., 2016). This is particularly relevant considering that heat stress increase mineral excretion (Smith and Teeter 1987). It shows that some microalgae species have the potential be used as a feed source that contributes with the nutritional status of the animals and at the same time enhancing their health.

Vitamins

Microalgae biomass represents a valuable source of various essential vitamins. The amounts of vitamins A, B1, B2, B6 and Niacin were found to be in most cases much higher in microalgae than in spinach or beef liver, both considered good sources of vitamins (Becker 2013). Other vitamins such as vitamin K, vitamin E can be also found in most microalgae (Becker 2013).

It is known that the drying method can affect negatively the concentrations of certain heat unstable vitamins such as vitamins B1, B2, B3 and C (Becker 2013).

The occurrence of B12 in microalgae, specially *Spirulina*, have been a matter of debate. Commercially, *Spirulina* is marketed as a good source of vitamin B12, however this claim is discussed within the scientific community. Two intrinsic factor vitamin B12 analogues have been characterized: pseudo-vitamin B12 and vitamin B12. In *Spirulina*, the factor pseudo-vitamin B12 represent 83% of the overall vitamin B12 and the remaining 17% is composed by the factor vitamin B12 (Watanabe et al., 1999). Pseudo-vitamin B12 is hardly absorbed in mammalian intestines (Watanabe 2007) and there are evidences that *Spirulina* vitamin B12 might not be bioavailable in mammals (Watanabe et al., 1999). For these reasons, some authors have strongly suggested that *Spirulina* is not suitable for use as a vitamin B12 source (Watanabe et al., 1999; Watanabe 2007; Becker 2013).

3.2.5 Mycoprotein

The discovery of mycoproteins is the result of the British company Rank Hovis McDougall, that was motivated to solve food security problems around the world and, therefore, explored ways to convert abundant carbohydrate sources into a protein source. First trials consisted on spraying different fields with surplus starch with the intention to select organisms capable of using this starch as a substrate. Around 1967 the filamentous fungus *Fusarium venenatum* (PTA 2684) was selected. After 20 years of research in protein content, toxin production, suitable growth and morphology, the commercialization of mycroprotein products started in 1985 in the UK under the brand “Quorn” and in 1991 in other European countries (Wiebe 2004)

Mycoprotein can be defined as the “microbial protein produced from microscopic fungi” (Castrillo and Ugalde 2004), however in this text the term mycoprotein will be used to refer to the microbial protein derived from the mycelium of *Fusarium venenatum*. Mycoproteins are produced through a fermentation process, very similar to beer. However, while for beer the solids of the fermentation process are discarded, for mycoprotein the solids are the valuable product and the liquids are the leftovers. The fermentation process takes place in 150 000 L pressure-cycle reactors using a continuous flow process with air lift fermentation technology (Finnigan et al., 2017). Mycoproteins are produced using a defined medium made from glucose, ammonium and supplemented with biotin, at 28-30 C and pH 6.0. These conditions enable the production of 300 to 350 kg biomass h-1 (Wiebe 2004). Glucose levels are maintained at such conditions that fungus can grow at its maximum rate with biomass concentrations of 10 to 15 g L-1 (Wiebe and Trinci 1991). Each 6 hours, testing for mycotoxins and potentially harmful contaminants is carried out. To avoid the appearance of branched colonial mutants that can change the texture of the final product, cultivation beyond 100 generations (around 400 hours) is avoided (Castrillo and Ugalde 2004), but periods above 200 h are necessary to have consistent units costs of production (Trilli 2007).

The biomass produced, then passes through a 68 °C heat treatment to reduce the RNA content to levels below 2% (dry weight). This process is important, given that in humans, the purine bases of nucleic acids are metabolized to insoluble uric acid that can lead to health disorders like kidney and gall stones (Ahangi et al., 2008). Following the RNA treatment, the biomass is heated up to 95 °C using steam heating. The biomass is centrifuged and the outcome is a paste 20% solid-paste called mycoprotein (Wiebe 2004). Besides removing the liquid content, centrifugation also removes the mononucleotides that were released during the RNA reduction treatment (Wiebe 2002). This paste is then mixed with other ingredients such as egg albumen, roasted barley, malt extract, calcium and water. The mix is frozen to -18 °C for the creation of the desirable meat texture (Finnigan et al., 2017). Different foods are made from mycoproteins, most of them commercialized under the brand Quorn.

In 2010, the patent that Marlow Foods had to produce mycoproteins expired in all EU countries (Bouckley 2011). Up to our knowledge, no other companies are producing mycoproteins as a primary source of proteins for human food. There is no scientific literature related to the use of mycoproteins in as animal feed, however in online portals, mycoproteins (not necessarily from Fusarium venenatum) are offered as animal feed for chicken and pigs (Alibaba.com). The use of microorganisms as a direct feeding source for farmed seafood has been called “one of the shortest, cheapest, and most sustainable ways to produce food for humans” (Martínez-Córdova et al., 2016), and if grown on residual streams, such as the forest industry as has been explored for tilapia (Alriksson et al 2014), competition of feed resources can be minimized, as has been pointed out as vital for aquaculture growth (Troell et al., 2014). Promising feeding trials using yeast have also been performed for salmonids (Øverland et al., 2013).

3.2.5.1 Environmental aspects

The environmental impacts related to mycoprotein production have been explored by different studies. In 2009, the Dutch Vegetarian Association and Blonk consultants evaluated the environmental consequences of substituting vegetable proteins by animal proteins in Dutch diets. Using an LCA, they found that one kilogram of Quorn emitted 2.6 kg CO_2-eq., consumed 38 MJ and used 1.2 m^2 of land per year. In terms of GWP, the environmental impact was lower than cheese and Valess (another meat substitute made from skim milk), but higher than eggs, milk and other meat substitutes like tofu, tempeh, etc. However, from a LU perspective, the performance of Quorn was one of the best, being much lower than eggs and very close to milk and soymilk (Blonk, et al,. 2008; Blonk, et al., 2008). The study also highlighted the large contribution of ammonium production to EU and GWP (Blonk, et al., 2008).

In 2010, an LCA was performed by Marlow Foods and De Montfort University in order to test the hypothesis that growing mycoprotein and converting it to Quorn foods was environmentally more benign than the equivalent process for animal protein. They found per 1 kg of mince Quorn a GWP of 6.840 kg of CO_2-eq, EU 50,614 MJ, and water use 2.885 m^3 (Finnigan et al., 2010). Mycoprotein production was responsible for 45.5% of the CO_2-eq, while Quorn processing was responsible for the other 54.5%. For EU, the production of mycoprotein consumed 70% of the total energy, while processing only 30%. In 2011, another LCA on different meat and meat alternatives was published (Head et al., 2011). In this study, Quorn performed better than all animal meats and meat substitutes in terms of GWP (2.40 kg CO_2-eq per kg of Quorn) and LU (0.41 m^2). The GWP and LU values were 91% and 99% lower than beef, respectively (Head et al., 2011). Smetana (2015) published an LCA on meat substitutes with a cradle-to plate approach and included mycoprotein as one of the cases. The results expressed per kg of product showed a GWP of 5.5-6.16 kg CO_2-eq, energy use of 60-76.8 MJ and LU of 0.79-0.84 m^2. In this study, 14 other impact categories were explored, and the single-score comparison (grouping the 17 impact categories into a single value) placed mycoproteins with a slightly higher environmental impacts than the other meat substitutes (dairy-based, gluten-based, insect-based and soymeal-based) and chicken meat (Smetana et al., 2015). Last but not least, Finnigan et al., (2017) showed the results of a carbon foot print assessment for Quorn products done by an independent certification provided by the Carbon Trust. The cradle to gate results showed that for 1 kg of mycoprotein, 1.6 kg CO_2 eq were emitted, while for 1 kg of frozen mince (international markets), the emissions were 2.4 kg CO_2 eq. (Finnigan et al., 2017).

These results showed that the environmental impact of mycoprotein is variable between studies. Results and contribution to food supply are affected from the used of egg in texturizing the end product Quorn, which may be substituted through innovation in the production system, and which feedstock the microbe is cultured on (residual streams or based on crop). Nonetheless, environmentally, mycoprotein seem to be a good alternative protein source compared to traditional meat products.

3.2.5.2 Nutritional aspects

Nutritionally, mycoprotein can offer a good combination of nutrients including high protein content, the presence of nine essential amino acids, low-energy and high-fiber, a fat content largely composed by polyunsaturated fatty acids and some vitamins.

Proteins

The protein content of *Fusarium venenatum* is approximately 44% on a dry matter basis (Wiebe 2002). Quorn mycoprotein have been reported to have Protein Efficiency values (proportion of nitrogen retained when the protein under test is compared with that retained by a reference protein) of 75% with respect to egg albumin, and can reach 100% if 0.2% methionine is supplemented (Wiebe 2002). The Protein Digestibility-Corrected Amino Acids Score (PDCAAS) for micoprotein is 0.99. If mycotoxins are constantly monitored to not exceed the limits, mycoprotein could be consumed continuously as the main protein source without any adverse effect (Wiebe 2002). In relation to the amino acid content, nearly 80% of the total fungal nitrogen is made by essential amino acids. The amino acid composition is very similar to eggs, but with less concentrations of methionine (Marlow Foods 2008). An study made with humans found that the biological value of mycoprotein was almost equal to the one for skimmed milk (84% vs 85%), while Net Protein Utilization was a bit lower (65% vs 80%).

Fatty acids

Mycoprotein contain low saturated fatty acids and high mono and polyunsaturated fatty acids. Fat content is 13% in a dry matter basis (Finnigan et al., 2017). Generally, 40% of the fat is composed by polyunsaturated, 11% monounsaturated and 11% saturated fatty acids. In a 100 g of dry mycoprotein it is possible to find 6.9 g of omega-3 fatty acids and 4.3 g of omega-6. Finnigan et al., (2017) show edsome information related to the fatty acid content of mycoproteins, studies covering the whole spectrum of fatty acids of mycoproteins are missing.

Mycoprotein is often considered as healthy source of protein, not only because it is free from cholesterol (Wiebe 2002) but also because its daily consumption can reduce the Low Density Lipoprotein (LDL) cholesterol (Turnbull et al., 1992), cause positive effects on appetite regulation (Bottin and Jeanne 2014) and reduce the glycaemic response (Turnbull and Ward 1995).

Minerals

Mycoprotein is a good source of zinc, phosphorus, manganese, copper, selenium and chromium (Derbyshire and Finnigan 2015) . However, the content of sodium and iron are low compared to read meat (Marlow Foods 2008). Moreover, the small amounts of iron (0.5 mg / 100 g wet weight) are expected to be less bioavailable because its non-haem iron structure (Denny et al., 2008).

Vitamins

Regarding vitamin content, mycoprotein contains Riboflavin (vitamin B12) (Denny et al., 2008; Derbyshire and Finnigan 2015). At less concentration, it also contains other vitamins from the B complex (B1, B2, B3, B5,B6, B9), with the exception of vitamin B12. Vitamins A, C and E are missing from mycoprotein (Marlow Foods 2009), however these could be added during the mixing with the other ingredients for getting the final product.

4 Circular strategy[2]

There are several products that humans cannot or will not eat, but that are suitable as livestock feed, e.g. co-products, food-waste, and biomass from marginal land. Feeding co-products or food-waste to livestock or using biomass from marginal lands to feed livestock, further referred to as 'leftover streams', are effective options of using resources. In D3.3 based on a literature review it was also concluded that using post-farmgate biomass streams offers the opportunities to move into the direction of an agri-food system with low emissions and with closed nutrient circles. By feeding leftovers, an inedible stream for humans can be transformed into high-quality food products, such as meat and milk (Elferink et al., 2008; Garnett, 2009).

Co-products are obtained throughout the harvesting or processing of human food. During the processing of sugar beet, for example, is not only sugar produced, but also beet-pulp and molasses. In such a multiple-output situation, a 'package of products' is produced. As sugar determines the production volume of sugar beets, sugar is defined as the 'determining product', and beet-pulp and molasses are defined as the 'co-products'. The production volume of a co-product, therefore, is driven by the demand for the determining product. If demand for sugar increases, production volume of sugar increases, which automatically increases production volume of beet pulp and molasses. If demand for beet-pulp increases, however, then production volume of beet-pulp will not increase, because volume of beet-pulp is determined by demand for sugar. If demand for beet-pulp increases in a way that beet-pulp becomes the product that economically drives the production process, then beet-pulp will become the determining product and sugar will become the co-product. In this thesis the term 'product-package' refers to the determining product and dependent co-products.

Products that are produced for human consumption, but that are wasted during retail or final consumption are referred to as food-waste in this thesis. The FAO estimated that, during production and consumption of food, about one third is wasted, and that per capita food-wasted by consumers in Europe and North America is about 95-115 kg per year (Gustavsson et al., 2011). High priority for strategies to reduce waste streams, therefore, seems logical. Part of our food-waste, however, is unavoidable. Feeding food-waste to livestock, therefore, can have a major contribution in reducing the environmental impact of the livestock sector (Zu Ermgassen et al., 2016). Food-waste has historically already been used as livestock feed, particularly for pigs (Zu Ermgassen et al., 2016). Pigs eat most foods also consumed by humans and can consume liquefied food, so they are an ideal target species to feed food-waste (Boland et al., 2013). Use of most food-waste as feed, however, is prohibited in many

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[2] The text below originate from the thesis of Van Zanten, 2016: 'Feed sources for livestock: recycling towards a green planet'.

countries, including European countries, because of health and safety problems related to, for example, foot and mouth disease, African swine fever, and Bovine Spongiform Encephalopathy (BSE) (EC regulation 1774/2002). Intermediate innovations, such as feeding waste-fed insect to livestock, therefore, are being explored (Makkar et al., 2014; Van Huis, 2015). Although waste-fed insect are currently banned from livestock feed in the EU, we expect a rapid development of research initiatives and lobbying efforts to use waste-fed insects in the near future (Makkar et al., 2014; Van Huis, 2015). Using co-products and food-waste as livestock feed, therefore, would provide valuable nourishment for livestock and avoid feed-food competition.

Besides co-products and food-waste, biomass from marginal lands can also be used to reduce the impact of the livestock sector on the environment. Marginal land includes areas that are less suitable or even unsuitable for crop production, because of rainfall, temperature or poor terrain limitations. Ruminants play an important role in grazing marginal land, because they can eat hay, silage, and high fibre crop residues that are unsuitable for consumption by humans and monogastrics (Fairly, 2010; Eisler et al., 2014). By doing so, ruminants relieve pressure on arable land, and retrieve otherwise inaccessible nutrients by adding them to the food chain (Fairly, 2010).

Livestock that eat only leftovers do not compete with humans for cropland, and also contribute to sustainable nutrition security. Such a transition requires a change in focus from increasing productivity per animal towards increasing the number of people to be nourished per hectare. This change in focus means making optimal use of leftovers. However, when livestock are only fed with leftover streams, less ASF can be produced. A strategy based on feeding only leftovers, therefore, requires changes not only on the production-side but also on the consumption-side.

4.1 Overview of circular studies[3]

Several recent studies have concluded that using leftover streams is important to reduce the environmental impact of ASF (e.g. Schader et al., 2015), but only four had a circular strategy approach (Elferink et al., 2007; Smil, 2014; Schader et al., 2015; Van Kernebeek et al., 2015) (table 1). In circular strategy studies, arable land is not used or uses only minimally to produce feed, only products that humans cannot or do not want to eat are fed to livestock, and biomass from marginal land is used to feed ruminants (Garnett, 2009).

Elferink et al. (2007) concluded that about 27 g protein originating from pig meat can currently be consumed per person per day. Their calculation considered only available co-products, and did not consider food-waste and biomass from marginal land. Availability of co-products was based on average Dutch consumption of three crops: sugar beets, soybeans, and potatoes, which represent approximately 60 % of the co-products produced from the food industry in the Netherlands. They then calculated that Dutch person consumes on average 43 kg sugar, 18 kg soy oil, and 97 kg potatoes per year. Furthermore, they corrected for the total share of co-products produced in the Netherlands.

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[3] The text below originate from the thesis of Van Zanten, 2016: ‘Feed sources for livestock: recycling towards a green planet’.

Smil (2014) concluded that in total about 200 million tons of meat (carcass weight) can be produced currently, resulting in about 9 g of protein per person per day. He based his calculation on the amount of available co-products, crop-residues, and biomass from grazing land, but he did not include food-waste. He assumed that globally 40 Mt meat can be produced from ruminants feeding on crop-residues, 40 Mt pig meat and 70 Mt chicken meat can be produced from monogastrics feeding on co-products, and 40 Mt meat can be produced from ruminants grazing on grasslands.

Schader et al., (2015) concluded that in 2050 about 26 g of meat, 2 g eggs, and 138 g milk can be consumed per person per day, resulting in protein supply of 9 g per person per day. Their calculation was based on the amount of available co-products and biomass from grazing land, but did not include food-waste. Bottom-up mass flows were used for the calculations, based on data from the Food and Agricultural Organisation on a global scale.

Van Kernebeek et al., (2015) concluded that land use was most efficient if people (up-to a human population of 35 mln) would consume about 7 g of protein from ASF (mainly milk) derived from livestock fed mainly on co-products. Their calculation was mainly based on co-products and marginal land, and hardly on food-waste. They used linear programming to determine minimum land use required to feed the Dutch population.

Table 2. Estimates of protein production from animal source food from livestock production systems that only use feed products that are not in competition with humans: co-products, food-waste, and biomass from marginal land and crop-residues.

	g protein per capita per day	Food-waste	Co-products	Biomass marginal land	Crop-residues	ASF products
Elferink et al., (2007)[a]	27		x			meat
Smil (2014)	9		x	x	x	meat
Schader et al., (2015)	9		x	x		meat, milk, egg
Van Kernebeek et al., (2015)[a]	7		x			meat, milk
Van Zanten et al., (2015)	21	x	x	x		meat, milk

[a] Based on the Dutch situation, other studies are global

The amount of ASF produced in Van Zanten et al., (2016) was higher because they included not only food-waste, but also feed-food crops. The importance of food-waste as livestock feed was also recognised by Zu Ermgassen et al., (2016), who concluded that feeding heat-treated food-waste to livestock can reduce the land use impact of pork production within the EU by 20% (about 1.8 billion hectares of agricultural land). Feeding food-waste to livestock is currently not allowed, and some people question the legal status of food-waste (Zu

Ermgassen et al., 2016). Zu Ermgassen et al., (2016) state that feeding food-waste to livestock can be a safe alternative if food-waste is heat-treated. Such practices are applied commonly in Japan and South Korea, where about 35% of the food-waste is fed to livestock (Zu Ergassen et al., 2016).

Furthermore, Van Zanten et al., (2016) included feed-food crops by choosing those food ingredients in the vegan diet whose co-products had a high nutritional value for livestock. Oil production originated from soy cultivation, for example, resulted in the co-product SBM. Compared with other co-products from oil processing, e.g. sunflower meal, SBM has a high nutritional value for livestock. Elferink et al., (2008) also included SBM as a co-product in their calculation and concluded that about 27 g of protein per person per day could be consumed. This conclusion not only has an impact on the final protein production from pork, but also demonstrates the importance of optimizing crop production based on called feed-food crops.

Although using different assumptions, each studies concluded that consuming a small or moderate amount of ASF by humans reduces land use most. At present, the average global consumption of animal protein, however, is about 32 g per person per day. To avoid feed-food competition completely, the total world-wide consumption of ASF must, therefore, be reduced.

All studies, except for Schader et al., (2015), focussed only on land use. Schader et al., (2015), however, also concluded that feeding only co-products and biomass from marginal land to livestock also resulted in a decrease of GHG emissions, EU, N-surplus, P-surplus, pesticide use, water use, and soil erosion potential.

4.2 Innovations within the circular strategy

The studies above clearly demonstrate that livestock can play a role in future nutrition security. It, however, also shows that future research on the role of livestock in sustainable nutrition supply should assess the entire food production system in relation to consumption of ASF. Meaning that livestock production should not focus on increasing efficiency of the animals but on increasing efficiency of the entire food system. The circular strategy, therefore, has the basic assumption that resource use efficiency while fulfilling human nutritional requirements is achieved by maximising the human food output per unit of resource. Therefore, both the direct

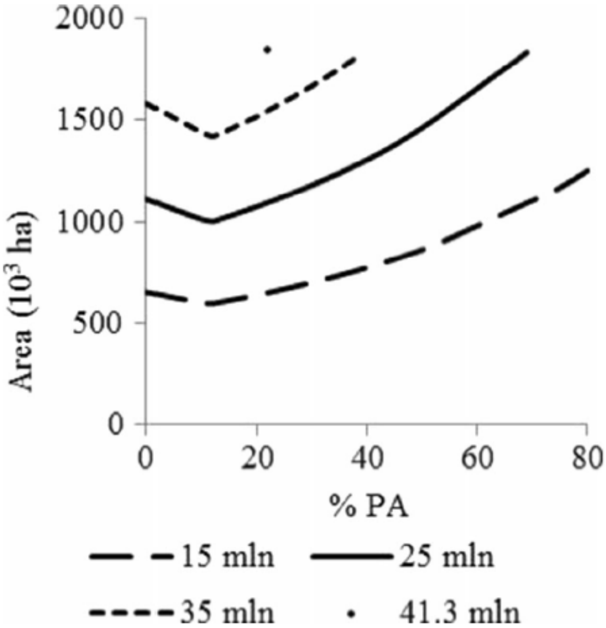

Figure 3. Minimum land (10^3 ha) needed to feed a population varying in size with a diet varying in percentage animal protein (%PA). *mln* million (Van Kernebeek et al.,, 2015)

output (human edible crop product) and the indirect output (animal product produced on leftovers) of production systems should be considered.

Which crops are selected to fulfil human nutritional requirements largely affects the amount of ASF that can be produced from leftover streams, as indicated above by the variation in results of studies assessing the amount of ASF that can be produced solely on leftovers. To analyse which crops would provide the nutrients required by humans most efficiently, both directly or via default livestock production, an optimisation model of the entire food system must be applied. First to introduce such a model were Van Kernebeek et al.,(2015), who used linear programming to assess the minimum amount of land needed to feed a growing population with a diet varying in the percentage of protein derived from ASF. This study indicates that the environmental impact of a diet does not linearly reduce as the amount of ASF in the diet decreases, as assumed in most consumption side studies.

Although the study of Van Kernebeek et al.,(2015) perfectly illustrates the theory of the circular narrative, it contains only a limited number of animal production systems (i.e. milk and pork production systems and it focusses on a very specific Dutch case. Furthermore, as the model includes only energy and protein requirements for the human diet, it may not meet other nutrient requirements for a healthy diet (Garnett, 2009) and, thus, propose unrealistic diets, containing a limited amount of products in large quantities.To get more grip on the actual contribution livestock can make on nutrition security, the novel modelling approach introduced by Van Kernebeek et al.,(2015) should expanded to include animal production systems varying in animal type and productivity, a larger more varying area and to include additional dietary requirements to assure a heathy diet.

For this purpose, we propose a study (for D5.4) that aims to analyse how the available agricultural land in the European Union (EU) should be used to feed the EU population, when aiming to minimise land use. To analyse how the available land in the EU can be optimally used, a model will be developed, based on the approach introduced by Van Kernebeek et al.,(2015). This optimisation model uses Linear Programming (LP) to predict what products the human diet should contain when aiming to minimise land use. The system under study consists of production, processing and consumption of food the EU, where no import and export are considered (Fig 4). The aim of this food production system is to provide the population with the required nutrients.

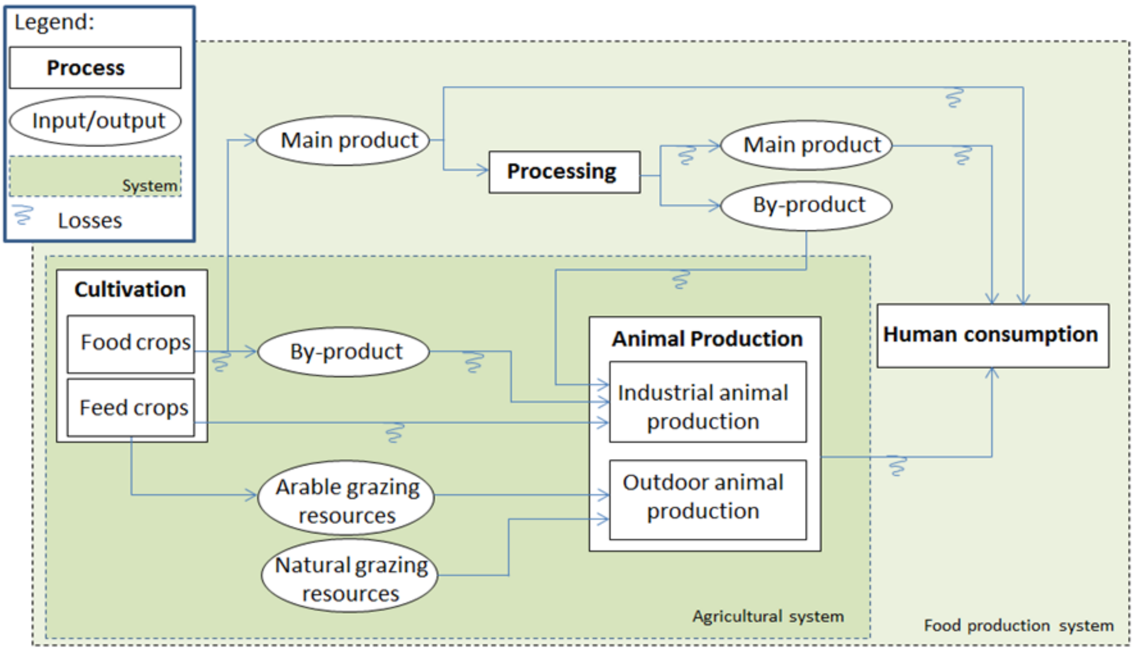

Figure 4. Diagram of the European food production system

The basic structure of the LP-model has the standard form of a linear programming model:

Minimize	$Z=\underline{c}'\underline{x}$
Subject to	$A\underline{x}\geq\underline{b}$
and	$\underline{x}\geq 0$

where $\underline{x}$ = the variable of land use activities; $\underline{c}$ = the vector of land use per unit of activity; A = a matrix of technical coefficients; and $\underline{b}$ = vector of quantitative constraints. The objective function of the model is to minimize land use (Z). The activities in the model are production of plant- and animal-source food. The constraints included in the model relate to fulfilling the nutritional need of the population and the quality and quantity of the available land.

As indicated in (Fig 4) the model consists of three modules, the animal production model, the cultivation module and the human consumption module. Each of the modules will be developed separately and is described below. By combining the three modules, the linear programming model can predict how to fulfil the human nutritional requirements when minimising land use. This will indicate if, and how, ASF can play a role in a land use efficient diet.

Animal production module

The animal module concerns the animal production systems that can be used to convert the available leftover streams into animal products. The module will be designed in such a way that the available default livestock production systems can optimally use the available leftovers. Optimally using the available leftover streams may require various types of production animals, as they differ in their ability to digest the variation in available leftover streams. The previous studies (mentioned above) included only few animal types and only conventional systems in which mainly high productive animals are used, requiring high quality feed. High-productive animals may not be able to optimally use available leftover streams, due to the high nutrient intake required to achieve their high productivity. Especially products with a low nutrient density may not be able to provide the required nutrients within the feed intake capacity. We, therefore, hypothesise that by considering lower productive animals in the assessment, leftover streams may be used more efficiently. To implement the relationship between feed quality and productivity, three archetypes (low, mid and high productivity) with different input-output relations will be implemented for the five main production animal types (dairy, beef, pork, layers and broilers).

Cultivation module

Arable land

The land module contains the available land in the EU and the crops that can be grown on it to fulfil the human nutritional requirements. The module will consider the variation in suitability and productivity of production systems on the available agricultural land due to several factors such as altitude, slope, temperature and precipitation.

Marginal land

Part of agricultural land is marginal land (land not suitable for the production of food crops). We, therefore, want to analyse the potential ASF production on grasslands in the EU excluding grasslands that are currently under cultivation (fertilisers, tillage, irrigation) as these could also be used for food crop production.

Human consumption module

The consumption module contains human nutritional requirements to ensure a healthy diet.

5 Innovation pathway

5.1 Proposed innovations for D5.4

Based on the results of a stakeholder workshop (results discussed in SUSFANS deliverable D5.1) and the literature search performed we propose to focus on the following innovations:

- For the production-side we propose to focus on including insects in livestock and fish feed.
- For the consumption-side we propose to focus on existing measures (such as reducing meat intake and replacing beef with other ASF products including fish) and a novel protein source preferably in-vitro meat.

- For the circular strategy we propose a focus on using products that people do not or cannot eat as livestock feed and assess the role of livestock in a sustainable diet. Similar to this the role of captured seafood - fishing at equilibrium (sustainable yields)- in a suitable diet will be assessed as this is nutritious food that has large potential if managed for long-term sustainability.

If all innovations are assessed a pathway can be identified that leads to sustainable healthy diets.

5.2 SUSFANS toolbox

On 15 and 22 March a virtual coordination meeting took place between WPs case studies (WP5), modelling (WP9), scenarios (WP6) and foresight (WP10) to discuss the road forward for introducing modelling work in the case studies. The feasibility of assessing the proposed innovations with the SUSFANS toolbox was discussed. Below you will find the main findings of this meeting.

5.2.1 Livestock

Production-side - insects as feed: CAPRI, GLOBIOM, and MAGNET can be used. Assessing the use of feed might be feasible but the level of detail of the assessment must be discussed further.

Consumption-side – reducing meat or replacing it with conventional sources or alternative protein sources: CAPRI, GLOBIOM, MAGNET, and SHARP can be used. Assessing a reduction or replacement with conventional protein sources will be feasible. Assessing a replacement of meat with alternative protein sources might be feasible but the level of detail of the assessment must be discussed further.

Circular strategy – use of leftover streams: the Animal Production Systems group from Wageningen University will develop a model to assess this.

5.2.2 Seafood

Seafood is an important part of the food system, but has so far received much less attention in discussions on future food security than land-based animal systems and crop systems. Compared to the baseline, the SUSFANS toolbox intends to make a first step to include seafood in the models, which will be an important contribution.

Production side- insects as feed: it is still uncertain to which level of detail the models will include seafood, but production-side innovations have the highest probability of being able to be addressed e.g. alternative feed sources in aquaculture. This is an innovation that has been pointed out to be critical in order to feed the world with nutritious and less resource-demanding food.

Consumption-side – replace meat with fish: assessing a replacement with seafood will be feasible for the models that will include seafood.

Circular strategy – captured seafood: Another important innovation, although at this point more uncertain if it is feasible to address it within the SUSFANS toolbox due to resolution, is the potential of capture fisheries, which is wild production of nutritious food that has large potential if managed for long-term sustainability.

6 Conclusion

The aim of this deliverable was to identify innovations that together can result in a pathway towards sustainable nutrition security. Those innovations will be assessed within the SUSFANS project (D5.4). The innovation pathway explored in this deliverable, addresses production-side strategies, consumption-side strategies, and circular strategies. Production-side strategies focus on reducing the environmental impact per kg of ASF produced by e.g. changing composition of livestock feed, whereas consumption-side strategies focus on changing consumption patterns of humans by reducing or avoiding consumption of ASF, or shifting from ASF with a higher environmental impact (e.g. beef) to ASF with a lower environmental impact (e.g. pork or chicken). Consumption-side strategies, therefore, have the potential to reduce the environmental impact and contribute to healthier diets. The circular strategy, will focus on improving the circularity of the food system, and avoiding feed-food competition, and lies in between the production and consumption side strategies. For each strategy (production-, consumption-, circular strategy) innovations were identified in literature. Based on the results of a stakeholder workshop (results discussed in SUSFANS deliverable D5.1) and the literature search performed we propose to focus on the following innovations:

- For the production-side we propose to focus on including insects in livestock and fish feed.
- For the consumption-side we propose to focus on existing measures (such as reducing meat intake and replacing beef with other ASF products including fish) and a novel protein source preferably in-vitro meat.
- For the circular strategy we propose a focus on using products that people do not or cannot eat as livestock feed and assess the role of livestock in a sustainable diet. Similar to this the role of captured seafood - fishing at equilibrium (sustainable yields)- in a suitable diet will be assessed as this is nutritious food that has large potential if managed for long-term sustainability.

If all innovations are assessed a pathway can be identified that leads to sustainable healthy diets.

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