SUSFANS DELIVERABLES

SUSFANS Deliverable D5.4

Report on T5.4: Sustainability impacts of potential innovations in the supply chain of livestock and fish, and fruit and vegetables, and sustainable future diets

Deliverable No. D5.4

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Content

Deliverable short summary for use in media

What innovations will help achieve sustainable healthy diets within the EU? Based on stakeholder consultation, we assessed the following innovations on the supply side: eliminate all grains and soy from animal feed and only use feed that cannot be used to produce food for humans and fish sustainably (to reduce the pressure on arable land and fish stocks). On the demand-side, we assessed shifts from animal-source food (ASF) to non-conventional protein (insects, algae) and plant-based food, and reductions in food waste, mainly but not only related to fruit and vegetables.

We assessed in various models exercises how much sustainable animal-source meat, fish, dairy and eggs could be produced in the EU on an annual basis and converted that into an amount of available protein per person per day. Our results demonstrate that livestock reared solely on biomass unsuited for human consumption could provide a significant part of our daily protein need. Livestock fed with by-products, food waste and grass supplies 31 g of protein per person per day: 5 g pork, 20 g dairy, 6 g meat from dairy cattle. Fish contributes an additional 2 g: 1 g is fish from catches, another 1 g is fish from aquaculture, in particular salmon fed with slaughter waste and by-products from fisheries.

This 31 g of protein supply fulfils about 60% of our global protein requirement. Requirements of omega-3 in the form of DHA and EPA are met by about 66% from salmon and captured fish. Collectively livestock and fish fulfil the full vitamin B12 requirement, which is only available in animal, fish products and some non-conventional foods. Calcium requirements are met by about 94%, iron by about 15%, zinc by about 61% and selenium by about 55%.

The additional nutrients that we require can be met by consuming plant-based foods or non-conventional foods such as insects or algae. Our results showed that non-conventional foods contain the complete array of essential nutrients and may be better substitutes for animal-source foods than plant-source foods. Moreover, the production of insects and algae makes efficient use of limited land resources, and if produced with renewable energy, they also offer benefits in terms of greenhouse gas emissions. Fishing sustainably and directing more of the catches to food directly has the potential to almost double food production and the nutritional contribution from EU fisheries.

Our results therefore showed that combining animal-source food from animals that are not fed with human food, with additional non-conventional foods and plant-source food offer great potential to reduce the environmental impact of our food system while safeguarding our nutrient requirements. Reducing food waste further reduces the environmental impact while it simultaneously indirectly stimulates people to increase their fruit and vegetable intake and therefore contributes to healthier diets.

The package of innovations in production and consumption that we assessed provides a transformative yet potentially effective pathway towards achieving sustainable and healthy diets within the EU. Partly, they require a transition towards circularity in the food system and, therefore, a paradigm shift, as our current food industry is built around the linear extract-produce-consume-discard model.

Teaser for social media

The innovation package – feeding animals with products we cannot or do not want to eat, fishing sustainably, replacing the consumption of ASF with non-conventional food and plant-based food, and reducing food waste (especially fruit and vegetables) – provides a pathway towards achieving sustainable healthy diets within the EU.

Abstract

To assess different possible future directions for the EU food system, potential innovations were identified towards achieving sustainable healthy diets within the EU. The innovations focused on two cases, the 'livestock and fish case' and the 'fruit and vegetable case'. For both supply chains there are concerns regarding the current European diet (excessive consumption of livestock and too low consumption of fruit, vegetables and seafood). For animal production, i.e. livestock and seafood, environmental concerns (land use, GHG emissions, fish stock depletion etc.) are particularly pressing. Based on the current production systems and stakeholder consultation, we assessed the following innovations: novel feeding strategies, including use of waste to increase circularity in livestock production, and the potential of non-conventional foods (e.g. insects), as the innovation pathway for animal-based production. For fisheries we assessed fishing sustainably as the future innovation. Innovations for 'the fruit and vegetable case' focussed on increasing people's fruit and vegetable intake by stimulating a reduction of food waste. Our results demonstrate that livestock reared solely on biomass unsuited for human consumption could still provide a significant part of our daily protein need. Livestock feed is therefore largely decoupled from arable land reducing the pressure on arable land to produce food. Livestock fed with by-products, food waste and grass supplies 31 g of protein /(cap*d) (5 g from pork, 20 g from dairy, 6 g from dairy meat). An additional 1 g comes from fisheries and another 1 g from aquaculture (salmon) meat fed with slaughter waste and co-products from fisheries. This supply fulfils about 60% of our protein requirement. Requirements of omega-3 in the form of DHA and EPA are met by about 66% from salmon and captured fish. Collectively livestock and fish fulfil the full vitamin B12, which is only available in animal, fish products and some non-conventional foods. Calcium requirements are met by about 94%, iron by about 15%, zinc by about 61% and selenium by about 55%. The additional nutrients that we require can be met by consuming plant-based foods or non-conventional foods such as insects or algae. Our results showed that non-conventional foods contain the complete array of essential nutrients and may be better substitutes for animal-source foods than plant-source foods. Moreover, future foods are efficient use of limited land resources if substituted for animal-source foods, and if produced with renewable energy, they also offer benefits in terms of greenhouse gas emissions. Fishing sustainably and directing more of the catches to food directly has the potential to almost double food production and the nutritional contribution from EU fisheries. Our results therefore showed that combining animal-source food from animals that are not fed with human food, with additional non-conventional foods and plant-source food offer great potential to reduce the environmental impact of our food system while safeguarding our nutrient requirement. The results from the fruit and vegetable case, furthermore, showed that reducing food waste indeed reduces the environmental impact while it simultaneously indirectly simulates people to increase their fruit and vegetable intake and therefore contributes as well to more healthy diets. Our assessed innovation packages – feeding animals with products we cannot or do not want to eat, fishing sustainably, replacing the

consumption of ASF with non-conventional food and plant-based food, and reducing food waste (especially fruit and vegetables) – provides a pathway towards achieving sustainable healthy diets within the EU.

Objectives of work package 5

Work Package (WP) 5 exist 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. And in D5.4 (this report) 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 of innovation pathways in supply chain case study
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.

Introduction and background

The current global food system is an important driver for the transgression of many of the proposed 'planetary boundaries', i.e. a definition of a safe operating space for humanity to maintain a stable Earth system (Campbell et al., 2017; Heck et al., 2018; Rockström et al., 2009; Steffen et al., 2015). The major environmental pressures associated with the food system are contribution to climate change (Foley et al., 2005), biodiversity loss (Crist et al., 2017), depletion of fresh-water resources (Wada et al., 2010) and the alteration of nitrogen and phosphorus biogeochemical cycles (Leip et al., 2015). The majority of these pressures originates from the consumption of animal-source food (ASF) (Gerber et al., 2013; Leip et al., 2015; Steinfeld et al., 2006). If no measures are taken in the next decades, the effects of these pressures are expected to increase as a result of changes in population numbers and income levels (Springmann et al., 2018).

These environmental considerations combined with the rise in non-communicable diet-related diseases (much related to high red meat consumption), while hunger and micronutrient deficiencies still persist, makes people question: what is the role of ASF in providing Sustainable Food and Nutrition Security (SUSFANS) in the EU? On the one hand, the daily consumption of ASF protein in Europe is above the dietary recommendation but on other hand, ASF supplies humans not only with high quality proteins but also with a set of essential macro and micro-nutrients, such as calcium, iron, vitamin B12, and vitamin A (Mertens et al., 2017). Nevertheless, the general trend in European diets – too high consumption of livestock and too limited consumption of fruit, vegetables and seafood – causes concern for both health and environment. Although fruit and vegetable intake in Europe differs considerably between countries, it generally remains below the recommended level of 400-600 grams per day (SUSFANS D7.1). From a public health perspective, fruits and vegetables are considered to play a key role in providing a diverse and nutritious diet (SUSFANS D5.3); an adequate consumption reduces the risk of certain chronic diseases, including coronary heart diseases, increased blood pressure, metabolic syndrome, type 2 diabetes, and certain types of cancer (Dauchet et al., 2005; Dauchet et al., 2006; He et al., 2007; He et al., 2006; Nishida et al., 2004; WCRF, 2018; WHO and FAO, 2003)

We thus need interventions and innovations to reduce the environmental impact of our food system while securing nutritional requirements. In the literature three general pathways can be identified that suggest different strategies (innovations/interventions): production-side strategies, consumption-side strategies, and circular strategies (Van Zanten et al., 2018) (see D5.2 for more information). Production-side strategies focus on reducing the environmental impact per kg of product produced by e.g. changing composition of livestock feed. Consumption-side strategies focus on changing consumption patterns of humans by reducing or avoiding consumption of ASF and replacing it with plant-based foods, 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 have therefore the potential to both reduce the environmental impact and contribute to healthier diets. The circular strategy focus on improving the circularity of the food system through e.g. improved utilizations of side-streams, and by this avoiding feed-food competition; this strategy lies in between the production and consumption-side strategies.

During SUSFANS stakeholder meetings, different innovations/interventions were discussed within the light of the three strategies with a focus on two cases: livestock-fish and fruit-vegetables (for more information see SUSFANS D5.1). Stakeholders indicated a preference to focus on the following innovations related to the livestock/fish case:

- **Production strategy**: including insects in feed for livestock and fish.
- **Consumption strategy**: existing measures (e.g. reducing meat intake, replacing beef with other ASF including fish) and introduction of novel protein sources, preferably in-vitro meat.
- **Circular strategy:** feeding products that people currently do not or cannot eat, and assess the role of animals in a sustainable diet considering livestock and aquatic animals (fisheries and aquaculture).

Regarding fruit and vegetables, stakeholders indicated the importance of changing people’s behaviour to increase fruit and vegetable intake. One approach could be the avoidance of food waste – also mentioned as highly important during the stakeholder workshops – as it might target both an increase in fruit and vegetable consumption and reduction of environmental impacts. To understand or even stimulate consumption behaviour, such as increasing the consumption of purchased food instead of wasting it, a wide array of drivers need to be taken into consideration, which relate to the individual (biological, demographics, psychological), the product, the interpersonal, physical environment and policy (SUSFANS D5.3).

The aim of this deliverable was to assess the potential contribution of the proposed innovations the stakeholders expressed interest in to reduce the environmental impact of our food system while securing nutritional requirements. The report is structured as follows: Chapter 3 focuses on the environmental potential of changing diets; Chapter 4 assesses the environmental potential of avoiding feed-food competition; Chapter 5 assesses the potential of a change in consumption behaviour in which we assume that less food – especially fruit and vegetables – are wasted, by using the SUSFANS toolbox (SUSFANS D1.4, WP9, WP10). Each innovation/intervention is compared with the current situation (also referred to as business as usual (BAU)). Finally, Chapter 6, discusses the implications of these innovations at a broader perspective including potential trade-offs. The use of insects as feed is not addressed in a specific chapter, but the environmental impact of insects compared to different foods is assessed in Chapter 3. In addition, in Appendix A, the environmental impact of insect is compared with conventional feed ingredients from plant origin.

Innovation pathway: changing diets

In this chapter we first describe the environmental potential of reducing the consumption of ASF in our current diets based on the current literature (chapter 3.1), and second we assess the environmental potential of future foods as alternatives for ASF while maintaining the intake of essential macro- and micronutrients (Chapter 3.2).

This section is based on HHE Van Zanten, M Herrero, O van Hal, E Röös, A Muller, T Garnett, PJ Gerber, C Schader, IJM De Boer (2018) Defining a land boundary for sustainable livestock consumption. Global Change Biology 24, 4185-4194.

Reducing the consumption of animal source food

Direct consumption of human edible plant products by humans is environmentally more efficient than consumption of ASF produced by animals fed with these plant products (Foley et al., 2011; Godfray et al., 2010). Globally, monogastric livestock species (pigs and poultry) consume on average about 3 to 5.5 kg of human edible protein to produce one kg of ASF (Wilkinson, 2011). Considering that the global livestock sector uses around half of all plant proteins and one-third of all plant calories (Cassidy et al., 2013), global food supply is in fact negatively affected by ASF production.

As a consequence, an increasing body of studies have assessed the environmental potential of altering our diets (so called consumption-side studies). They suggest that – to reduce food system environmental impacts – eating less or no ASF is priority. Poore and Nemecek, (2018), for example, present a comprehensive overview of the environmental impact of food production and highlight the major contribution of farm animals. They suggest that a diet excluding animal-source food (ASF), hence a vegan diet, has most transformative potential to reduce these environmental impacts. Such so called consumption studies calculate dietary footprints by summing the environmental impact of all food products consumed, preferably on an annual basis (Aleksandrowicz et al., 2016; Hallström et al., 2015). In this calculation, the environmental impact of each consumed product, for example milk, is determined by multiplying the amount of product (in kg) with the footprint per kg of that food product (e.g. milk). This implies that dietary footprints rely on the footprint of individual food products. Figure 3.1, shows the relation between ASF content (in grams of animal protein) and land use or GHG emissions.

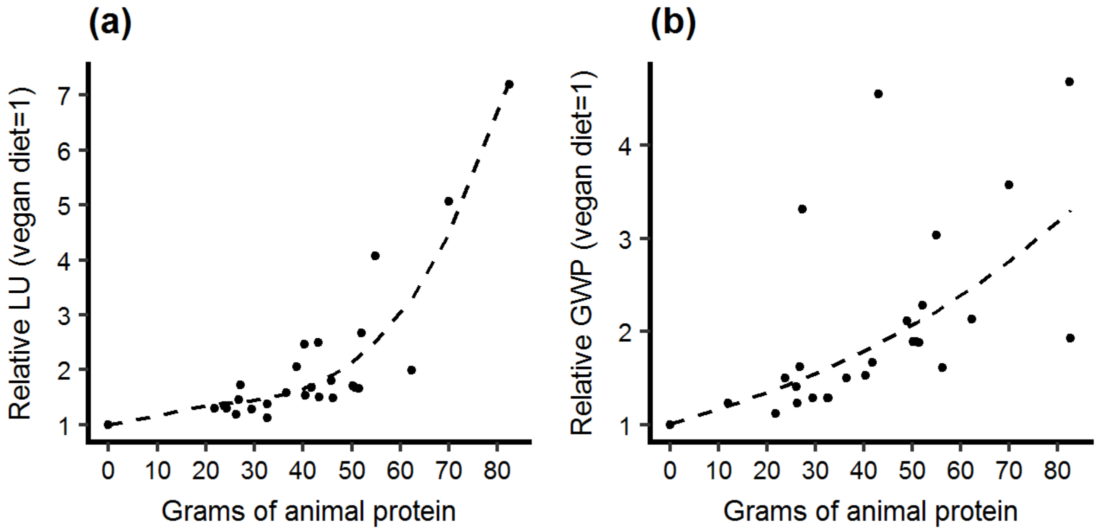


Figure 3.1a. Relative reduction in land use per g of protein from animal source food (ASF) (polynomial fit; adjusted R2 of 0.85; P-value <0.00); Figure 3.1b. Relative reduction in global warmnig potential (GWP) per g of protein from ASF (exponential fit, adjusted R square 0.61;P-value <0.00). Each dot represents a dietary scenario derived from peer reviewed studies assessing the environmental impact of different diets based on footprint approaches that do not account for systemic aspects. Adapted from Van Zanten et al. (2018)

Consumption-side studies (e.g. Poore and Nemecek (2018)) are based on footprint studies (i.e. attributional life cycle assessments) that do not encompass the full complexity of the food system and, therefore, do not account for important features such as feed-food competition (feeding farm animals with grains that we can consume directly) (Van Zanten et al., 2018). As a result, consumption studies advice to eat meat or eggs produced by poultry fed with grains, instead of milk or meat from low-yielding ruminants that are only grass-fed (Hallström et al., 2015). Footprints used in consumption studies also ignore linkages within the food system between, for example, sugar and beet-pulp or between milk and beef, which explains why shifting to a vegetarian or ultimately a vegan diet has most environmental benefits (Aleksandrowicz et al., 2016; Hallström et al., 2015). The footprint of a vegetarian diet including milk products, therefore, ignores the environmental impact associated to the production of meat from culled milking cows and surplus calves, or assumes that this meat is consumed by non-vegetarian people in the population. Similarly, if everyone would become vegan, human inedible by-products like sugar beet pulp, currently fed to animals, will not be longer recycled back into the food system. Thus, such footprint assessments are not able to adequately capture environmental benefits of using low-opportunity cost feedstuff (LCF) as livestock feed (Van Zanten et al., 2018). We will further elaborate on this in Chapter 4.

Non-conventional foods

This chapter is based on A Parodi, A Leip, IJM De Boer, PM Slegers, F Ziegler, EHM Temme, M Herrero, H Tuomisto, H Valin, CE Van Middelaar, JJA Van Loon, HHE Van Zanten (2018) The potential of future foods for sustainable and healthy diets. Nature Sustainability, 1: 782–789. The work of this paper was financed by the SUSFANS project.

In search for a planet-friendly diet, the main focus has been on eating more plant-source foods, and eating no or less animal-source foods, while the potential of non-conventional foods has been underexplored.

Non-conventional food sources that are increasingly gaining global attention due to their rich nutritional composition – which can be comparable or even superior to conventional-animal source foods – and their low impact on the environment. These foods include terrestrial sources such as insects, cultured meat also known as "lab-grown meat", and fungal mycelia called "mycoprotein", and aquatic sources such as seaweed, microalgae, and forms of non-fed aquaculture such as mussels. In SUSFANS D5.2 most of these future foods were described in detail. The aim of this work was to assess the environmental potential of non-conventional foods and their nutritional composition and compare them with conventional ASF, plant-source foods and seafood. The following section contains a brief description of each food, followed by the results and conclusion related to their nutritional performance and the environmental impact. Information about the materials and methods is available in Parodi et al., 2018. (Note: the assessment related to the conventional ASF and plant-source foods is derived from the partial equilibrium agri-economic model CAPRI[1] and represent the BAU case).

Introduction to non-conventional foods

Insects

Humans, throughout the world and along its existence, have been consuming insects as regular source of nutritious food. 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). For years, edible insects have been mainly obtained from the wild, which means that they were scarcely obtained from production systems. Nowadays, the focus is to mass-produce them in insect farms. This has implied new challenges such as the generation of biological knowledge on each farmed species and the selection of adequate diets and optimal densities for mass production. The insect industry is growing and many brands are already selling insect-based foods around the world (Bugs feed 2015).

[1] Common Agricultural Policy Regionalized Impact Modelling System, https://www.capri-model.org/

Mycoprotein

The term Mycoprotein refers to microbial proteins produced from microscopic fungi. A well-established mycoprotein product for human consumption derives from the mycelium of *Fusarium venenatum* (Wiebe 2002). Mycoproteins are produced through a fermentation process in 150 000 L pressure-cycle reactors using a continuous flow process with air lift fermentation technology (Finnigan et al. 2017). The process starts inoculating *Fusarium venenatum* into a defined medium made from glucose, ammonium and supplemented with biotin, at 28-30 C and pH 6.0 (Wiebe 2002). Each 6 hours, testing for mycotoxins and potentially harmful contaminants is carried out. At the end of the grow cycle, the biomass is then heat-treated, centrifuged, mixed with other ingredients and frozen to achieve the desirable meat texture (Finnigan et al. 2017). Different foods are made from mycoproteins, most of them commercialized under the brand Quorn.

Cultured-meat

Cultured meat, also called lab-grown meat, is a product based on growing cells from animals origin without the need of the organisms from which the cells are derived (Fayaz Bhat & Fayaz 2010). The technology to produce cultured meat is derived from medical tissue engineering. The process starts isolating myosatellite cells from a small piece of cow muscle through a combination of mechanical and enzymatic disruption. Myosatellite cells in the damaged muscle will start to form myoblasts. These myoblasts are then multiplied using a nutrient-rich fluid called "medium". Current research efforts are focusing on finding serum-free mediums, as the existing mediums are supplemented with a percentage of serum derived from calf blood (Post 2018). Once a sufficient number of cells is reached (trillions), cells are separated and packed in a temporarily supporting gel. Myoblasts will merge to form myotubes which then will form muscle fibres. After 3 weeks, muscle fibres of 2-3 cm long but less than 1 mm in diameter can be harvested. With around 10 000 muscle fibres, a 100 g hamburger can be made (Post 2018).

Seaweed

Macro-algae or seaweeds have been part of the human diet since thousands of years. For hundreds of years seaweeds were obtained through the harvesting of wild seaweed stocks, but nowadays that situation have changed. In 2018, the FAO reported that 96.5% of the total aquatic plant production (mainly seaweed) came from aquaculture and only the 3.5% were wild-collected (FAO 2018c). 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 (39%), Philippines (4.7%) and the South Korea (4.5%), produce most of the seaweed present in the market (FAO 2018c). 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. Seaweed are popular for use in soups and to wrap sushi. The most widely cultivated species for human consumption include Japanese kelp (*Laminaria japonica*), Eucheuma seaweeds, elkhorn sea moss (*Kappaphycus alvarezii*) and wakame (*Undaria pinnatifida*) (FAO 2018c). South Korea, China and Japan have highest daily intake of aquatic plants per capita, with 61g, 26g and 9 g respectively (FAO 2017; MHLW 2014).

Microalgae and cyanobacteria

Microalgae are microscopic algae (eukaryotic) that live in either fresh or marine water bodies. Cyanobacteria, also known as "blue-green algae", are a phylum of bacteria (prokaryote) capable of obtaining energy through photosynthesis. Nowadays, the microalgae Chlorella and the cyanobacteria Spirulina are the main species produced, and widely commercialized as dietary supplements for food and feed (García et al. 2017). Nonetheless, there are other species which cultivation is mainly destined to the extraction of isolated compounds that are added to different foods and feeds in order to improve their nutritional value. For example, microalgae-derived 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).

Mussels

Mussels are filtering organisms that fed on phytoplankton and organic matter in a wide variety of aquatic habitats. As they obtain their nutrients from the sea or brackish waters, no feed inputs are needed for their farming. For this reason, mussels are seen as a low-impact seafood. Mussel culture starts with the collection of mussel seeds. These seeds can be collected from natural areas or from a collector placed in strategic areas. The collectors (usually ropes) are then collected and transferred to mussel farms which vary in rearing techniques (vertical ropes, wood stakes or plots located in shallow waters). In Europe, mussel farming is the shellfish farming activity with the highest production volumes (EC, 2013). China and the European Union are the biggest mussel producers, followed by Chile and New Zealand.

Nutritional composition of non-conventional foods

Raw non-conventional foods are nutritious. Mixed, they contain high levels of four essential amino acids (i.e., lysine, methionine, threonine and tryptophan) that are in limited amounts available in some plant-source foods (Figure 3.2). In addition, they contain high levels of minerals. Calcium, for instance, is abundant in the sugar kelp and in the black soldier fly larvae. Iron, can be found in most non-conventional foods, especially in chlorella and spirulina. Chlorella contains such high iron levels that its intake should be limited to avoid exceeding the upper intake levels for iron. Zinc, also appears in non-conventional foods, such as sugar kelp, and in all insect species and mussels, at levels that are comparable to or higher than in beef. In relation to vitamins, non-conventional foods such as spirulina reach vitamin A concentrations up to 20 times higher than eggs, the ASF that is richest in vitamin A. Vitamin B12, which is absent in all plant-source foods, is found in large amounts in all aquatic non-conventional foods and in black soldier fly larvae. Lastly, the two omega-3 fatty acids, EPA and DHA, which in nature are mainly synthesized by microalgae and cyanobacteria and then are bio accumulated through the trophic chain in seafood, are well-represented among aquatic non-conventional foods. Altogether, it is concluded that non-conventional foods contain essential nutrients for human nutrition and could be replacers of animal-source foods for the provisioning of essential nutrients.

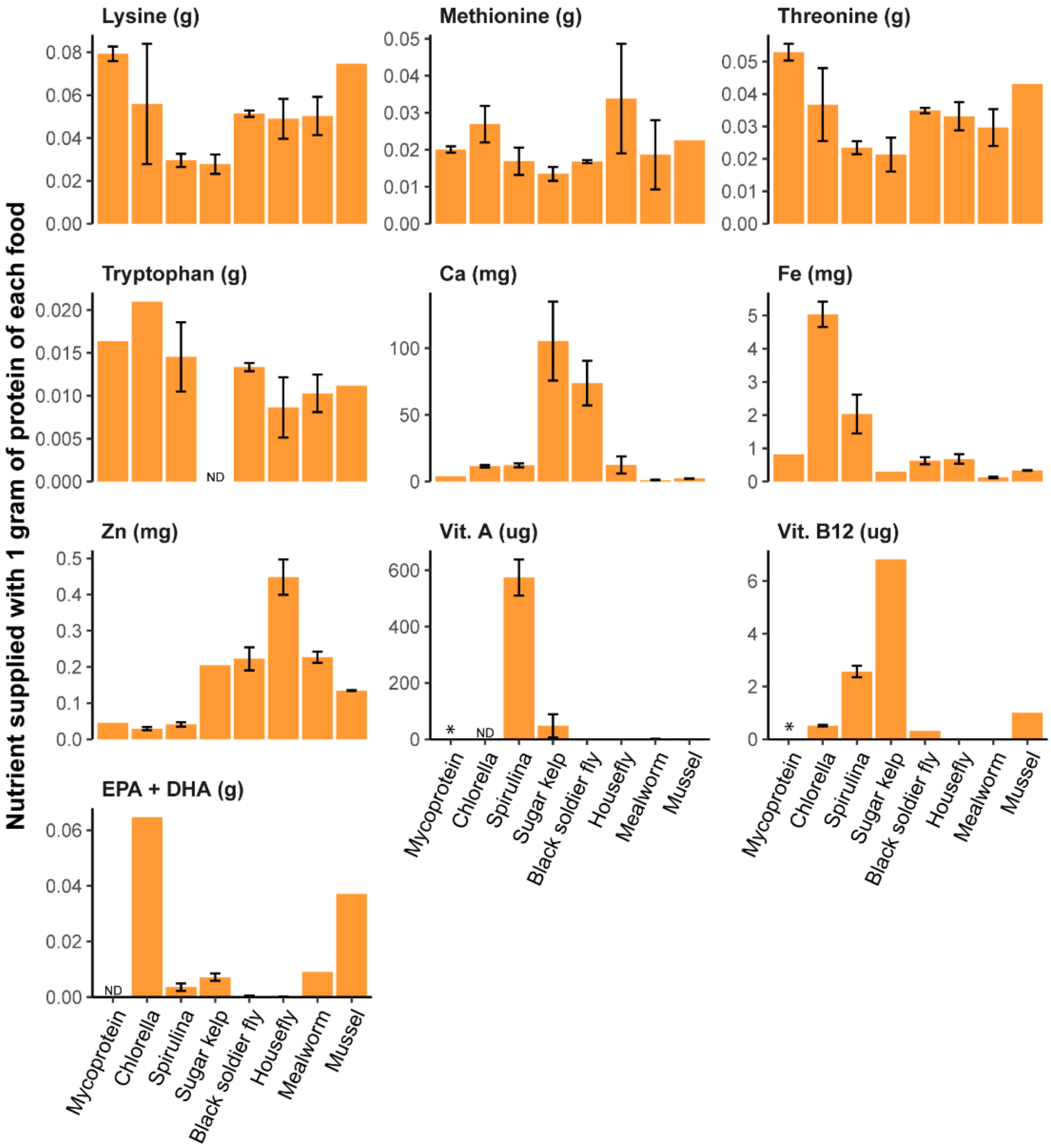


*Figure 3.2. Nutrient content per gram of protein for each non-conventional food, excluding cultured meat (lack of data). Mean value (bars) & standard error (error bars) * nutrient absent, ND no data for that nutrient/food. Adapted from Parodi et al. 2018.*

Environmental impact of non-conventional foods

The production of essential nutrients via non-conventional foods require substantially less land than the production of those nutrients via ASF per unit of nutrient derived from a raw food (Parodi et al., 2018). GHG emissions of most non-conventional foods were also lower than most GHG-intensive ASF (i.e., beef, pork, chicken and tilapia) but in many cases similar to eggs and milk per unit of nutrient. GHG emissions of non-conventional foods could be even further reduced if renewable energy sources are used, given that most of the GHG emissions mainly result from using fossil fuels for energy-intensive processes. Factors contributing to a better environmental performance of non-conventional foods compared to ASF are higher nutrient use efficiencies, capacity to produce mainly edible biomass, lower resource use given that many of these foods can be produced with just few inputs, and their capacity to be produced using leftover streams (Parodi et al. 2018).

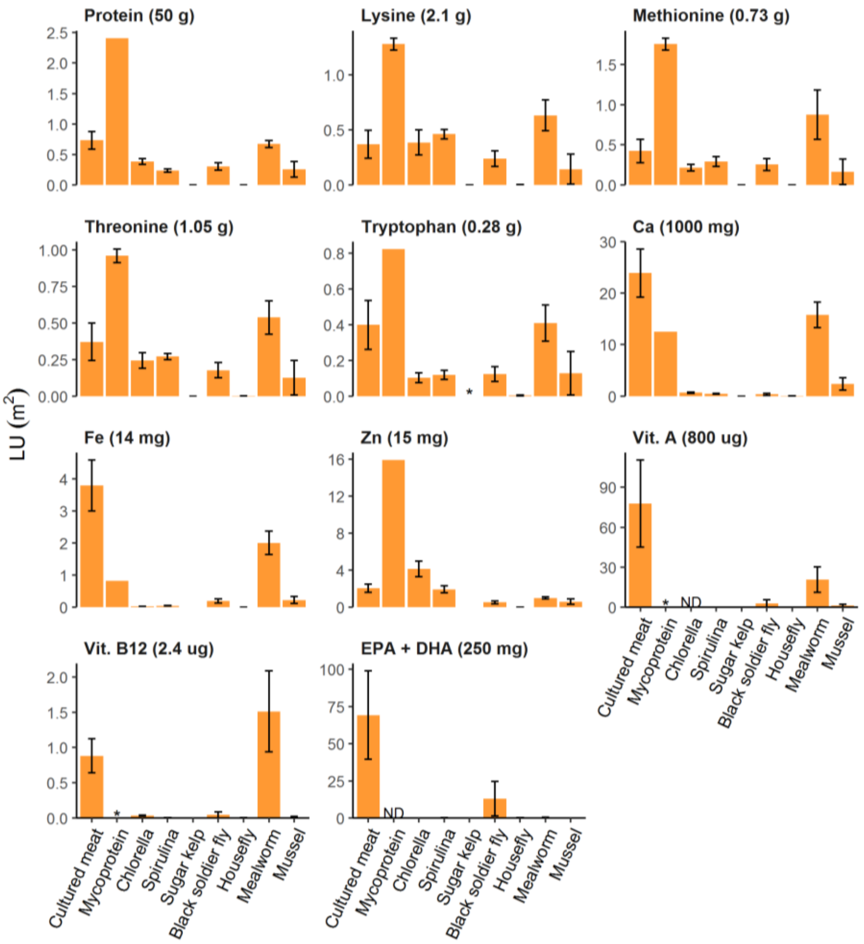


*Figure 3.3. Land use to fulfil daily recommended intake of nutrients through each non-conventional food; mean value (bars) & standard error (error bars) Nutritional value cultured meat assumed similar to other meat types. * nutrient absent, ND no data for that nutrient/food. Adapted from Parodi et al. 2018.*

Figure 3.3 and 3.4 show the land use and GHG emissions to produce the daily recommended intake of each nutrient with each non-conventional food. The land use of aquatic non-conventional foods such as seaweed is nearly zero, given that most of the production process takes place on the sea. Mussels, depending on the farming technique, will require no land or just minimum amounts of land in intertidal coastal areas (Aubin et al. 2018; Buck et al. 2010). However, for mussels, no extra land is needed to produce their feed, as they obtain their nutrients from the seawater. Chlorella and Spirulina can be produced in brackish or saline water areas unsuitable for crop production (Cho et al. 2007; Sandeep et al. 2013;). The production method (e.g., open ponds or photobioreactors), and productivities, will influence the land use of these foods (Smetana et al. 2017). For terrestrial non-conventional foods, most of the land use requirements are associated to the types of feedstock used. The land use for insect larvae, for instance, is mainly driven by the diet fed to the insects. Insect larvae fed with diets made of cereals and vegetables will have a higher land use of diets compared to insects fed with organic waste streams such as food waste, given that the land use impacts of the organic waste streams are mainly attributed to the initial human-edible product (Oonincx & De Boer 2012; Van Zanten et al. 2014). Hypothetical studies on large-scale cultured meat production systems show that the land required to produce cultured meat is associated to the types of inputs used for cell cultivation. For instance, the land required to produce cultured meat could be reduced by about 30% if we fed cultured cells with cyanobacteria instead of crops (Tuomisto & Texteira de Mattos 2011; Tuomisto et al. 2014). The land use requirements for mycoprotein are associated to the raw materials needed for the elaboration of glucose, which is used as a carbon source in the fermentation process.

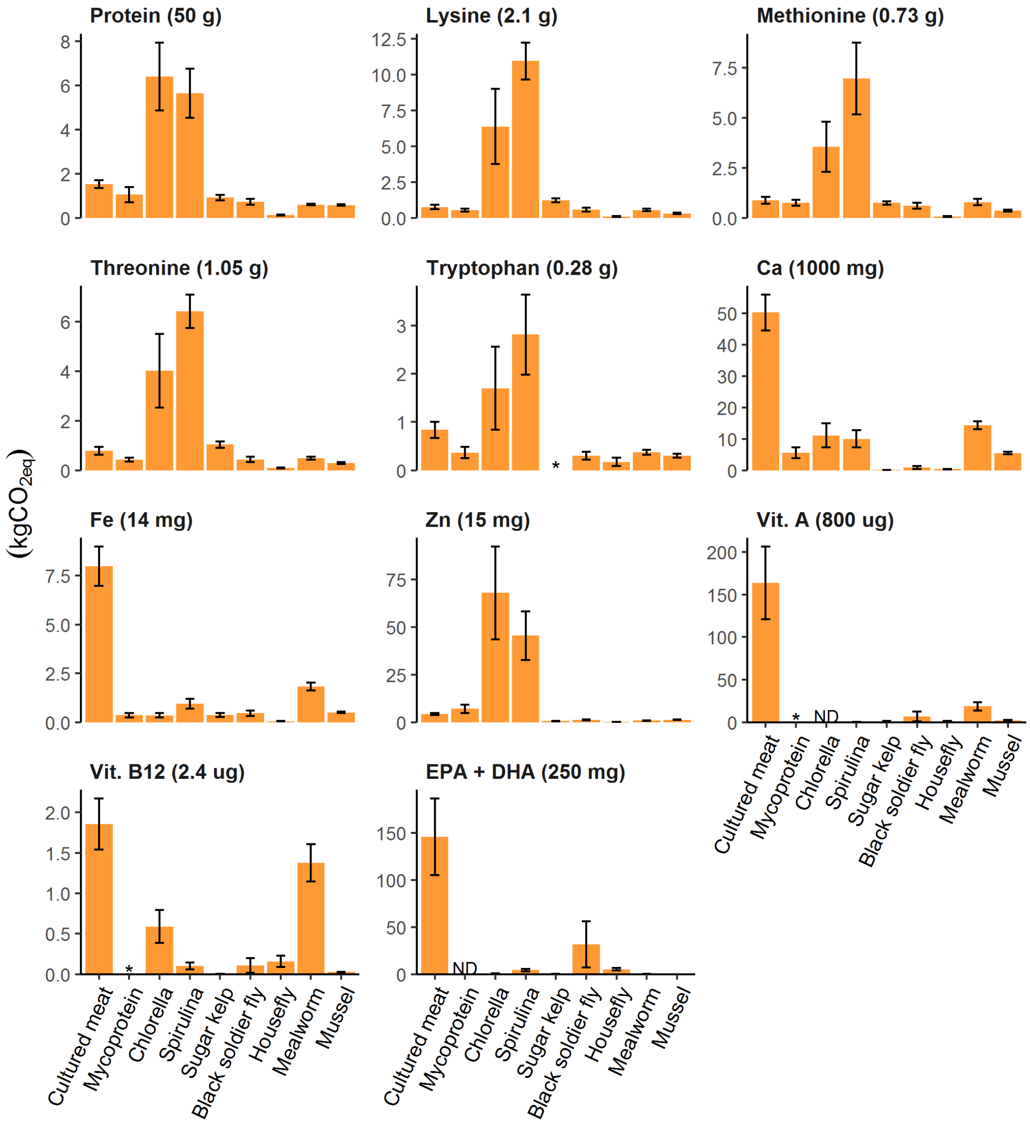


*Figure 3.4. Greenhouse gas emissions to fulfil daily recommended intake of nutrients through each non-conventional food; mean value (bars) & standard error (error bars) Nutritional value cultured meat assumed similar to other meat types. * nutrient absent, ND no data for that nutrient/food. Adapted from Parodi et al. 2018.*

GHG emissions of non-conventional foods are mainly associated to high energy-consuming processes and the current use of fossil energy sources for those processes. To obtain microalgae or cyanobacteria powder, for instance, dewatering and drying (both high-energy demanding processes) are needed (Parodi et al. 2018). For seaweed, most of the GHG emissions occur during to the cultivation phase and are mainly driven by the types of materials composing the cultivation lines, and the drying process (Seghetta et al. 2016). To produce mycoprotein, energy is required to maintain constant temperatures during the fermentation process, as well as for other processes such as heat treatments, centrifugation and freezing (Wiebe 2004). In insect production systems, GHG emissions are mainly caused by the use of gas and electricity for heating the rearing environment in temperate climates, drying the larvae and feed production (Oonincx & De Boer 2012; Salomone et al. 2017; Smetana et al. 2016; Van Zanten et al. 2014). For cultured meat, GHG emissions are mainly linked to the production of the medium to grow the muscle cells, the energy needed during the cleaning phase, (Mattick et al. 2015) and the need to keep constant temperatures during the cell cultivation process (Tuomisto & Texteira de Mattos 2011).

It is important to highlight that as it happens with most foods the environmental impact of producing non-conventional foods goes beyond the assessment of land use and greenhouse gas emissions. Future research should aim to assess all non-conventional foods with the full set of metrics developed in WP1, i.e. covering diets, environment, competitiveness and equity impacts, using the SUSFANS toolbox from WP9. Nevertheless, at this point data is lacking to allow such a comprehensive analysis. Furthermore, additional biodiversity-related indicators should be designed and used to evaluate the possible consequences that the eventual escape of insects from production facilities (Berggren et al. 2019) or the introduction of new diseases to marine environments, could have on local biodiversity.

Innovation pathway: avoiding feed-food competition

In Chapter 3.1 we explained that according to most consumption-side studies, switching to vegan diets is the way to move forward to reduce the environmental impact of human diets. However, a recent study published in Global Change Biology (Van Zanten et al., 2018) shows that animals reared under the circular food systems concept can contribute significantly to ensure the provisioning of essential nutrients to human diets, while at the same time reducing the environmental impact of the entire food system. These farm animals then would not consume human-edible biomass, such as grains, but convert biomass that we cannot or do not want to eat, into valuable food, manure and ecosystem services (Figure 4.1). Biomass that we cannot or do not want to eat consists of biomass from grassland and leftovers. Leftovers include crop residues left over from harvesting of food crops, co-products left over from industrial processing of plant-source and animal-source food, and losses and waste in the food system. By converting these leftover streams, livestock recycle nutrients back into the food system that otherwise would have been lost in food production. Under this concept, the competition for land for feed or food would, therefore, be minimized and compared to no animal-source food, including some animal-source food in the human diet could free up about one quarter of global arable land (Van Zanten et al., 2018).

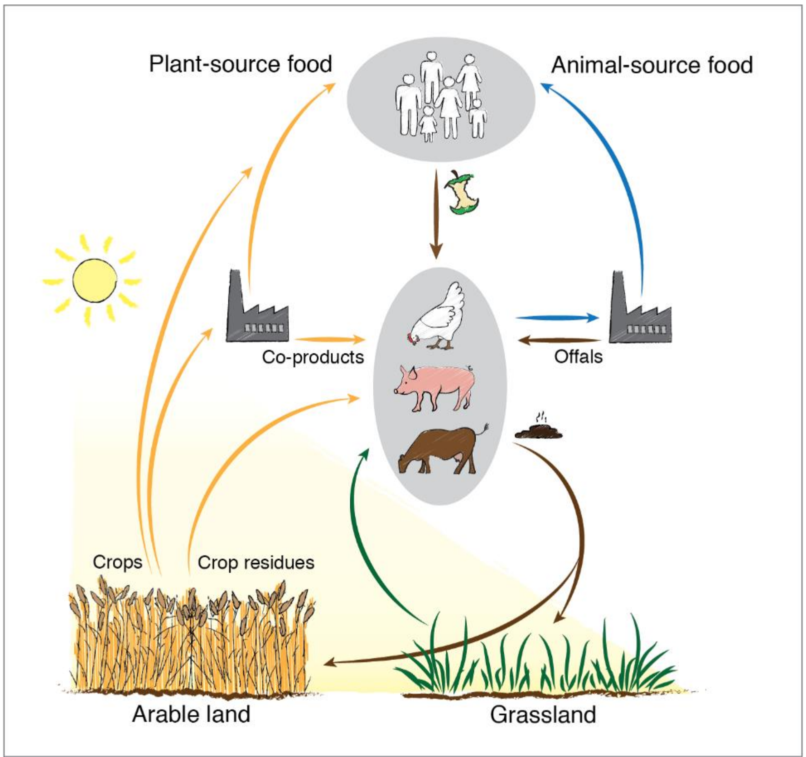


Figure 4.1. The role of animals in a circular food system. Livestock convert biomass that we cannot or do not want to eat into valuable products, such as animal-source food and manure. Adapted from Van Zanten et al. (2018).

The availability of biomass from grassland and leftovers (referred to as low-opportunity-cost feed (LCF)) for animals will, to a large extent, determine the boundaries for animal production and consumption. (Van Zanten et al., 2018) demonstrated that farm animals raised solely on those biomass streams could provide a significant, non-negligible part (9-23g/per capita) of our daily protein needs (~50-60 g/per capita).

To summarize, previous studies, reviewed by Van Zanten et al. (2018), showed that livestock fed primarily on low-opportunity-cost feed (LCF) contribute to a resource efficient food system, as they provide valuable nutrients without competing for resources with food production. To our knowledge, however, no scientific study so far explored the allocation question: which leftovers are available where, and to what livestock and fish should we feed them in order to maximize the production of default ASF. Besides the livestock and aquaculture sector, capture fisheries can also provide low-opportunity-costs ASF. In this chapter we first assess the allocation question (Chapter 4.1), second assess the potential nutritional contribution from captured fisheries (Chapter 4.2), and last assess the potential nutritional contribution from aquaculture (Chapter 4.3).

Livestock fed on leftovers

This chapter is based on van O Hal, IJM De Boer, A Muller, S De Vries, K-H Erb, C Schader, WJJ Gerrits and HHE van Zanten (2019) Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. Journal of Cleaner Production, 219: 485-496. The work of this paper was financed by the SUSFANS project.

In this chapter we addressed the allocation question "what LCF should we feed to which livestock to maximise livestock's contribution (in terms of protein supply) to the food system". As livestock species vary in their ability to digest specific feeds (Preston, 1986), we (in the article of van Hal et al. (2019)) hypothesize that such optimal use of available LCF requires various livestock systems. Ruminants are, for example, specifically adapted to feed on grass and other grazing resources. Additionally, maximising animal protein supply from available LCF, may require livestock with a reduced productivity (regarding daily growth or yield) compared to conventional livestock systems. Conventional livestock, requires a nutrient dense feed to fulfil their high nutrient requirement – related to high productivity – within their feed intake capacity. Low productive livestock, with a reduced nutrient requirement, may be better adapted to value LCF which often have a low nutrition density (Zijlstra and Beltranena, 2013).

In this chapter published in van Hal et al. (2019) we aim to identify the combination of livestock systems, differing in production level, that optimally converts LCF available in the EU-28 into animal protein. As livestock also provide other valuable nutrients besides protein, we also estimated how much the produced animal protein contributes to the daily recommended intake of vitamin-D, vitamin B12, calcium, iron, zinc, and selenium (Macdiarmid et al., 2012; Mertens et al., 2017)). Besides estimating the potential contribution to food supply of livestock fed on the LCF available in the EU-28, our approach unravels how animals can efficiently use such LCF. Adapting current farm practices to consider these insights may improve the efficiency of the entire food system.

Material and methods

Van Hal et al., 2019 assessed the optimal use of LCF available in the EU-28, using an optimisation model in General Algebraic Modelling System (GAMS) version 24.2., based on the system illustrated in Figure 4.2. The model maximises human digestible protein (HDP) output by converting the available LCF in the EU-28 (input to the model) into valuable ASF (output of the model), using a combination of livestock systems of various productivity levels.

The output of ASF is restricted by LCF availability, the nutritional value of each LCF as feed ingredient for each livestock system, and the nutritional requirements of each livestock system. The latter two are quantified using the nutritional system of the Dutch animal feed board (CVB, 2012). This nutritional system provides animal specific net nutrient content for a wide range of feed products and methods to calculate nutrient requirements for a range of livestock systems based on their productivity.

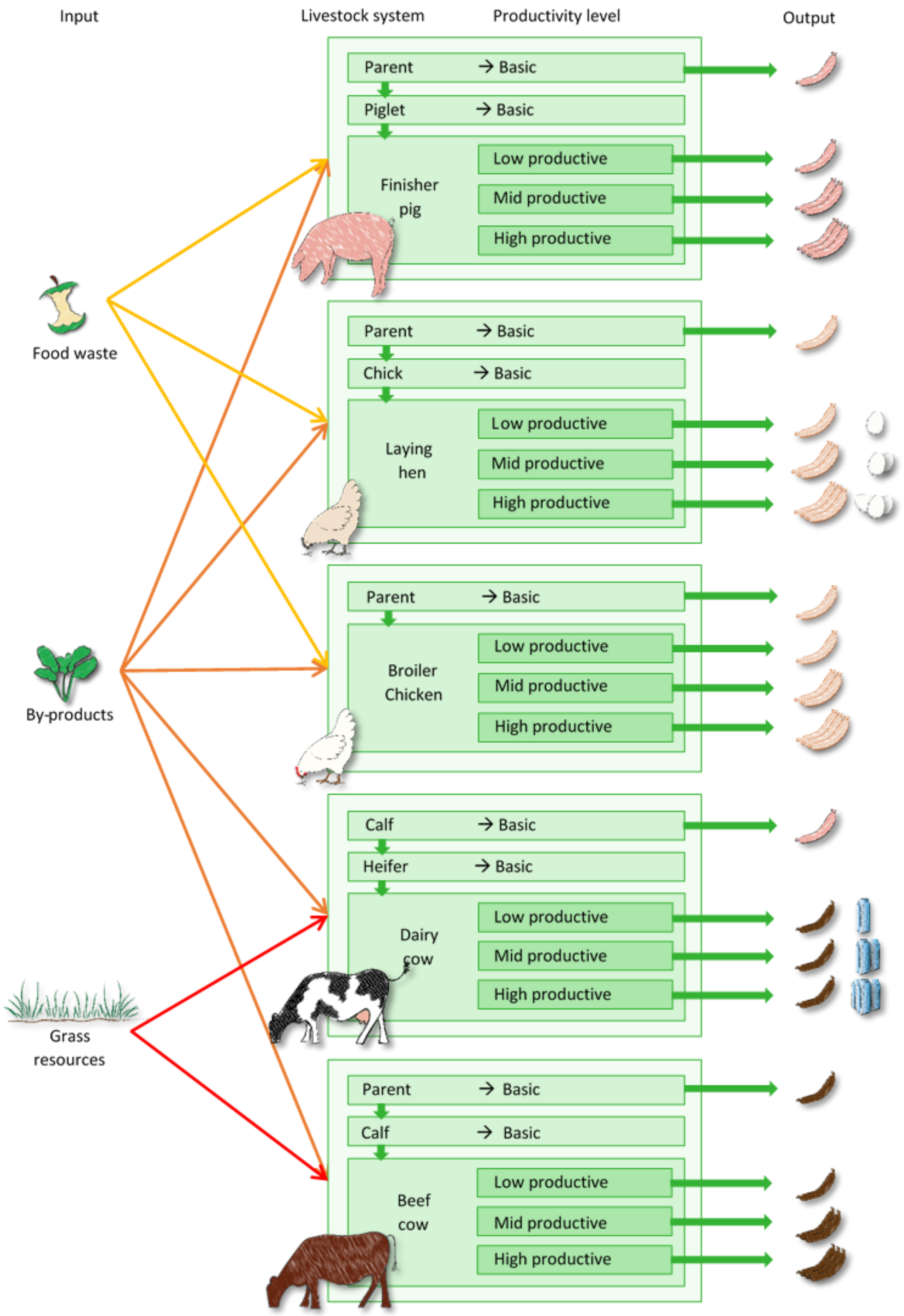


Figure 4.2. Definition of the livestock systems (pig, laying hen, broiler, dairy cattle & beef cattle) varying in productivity (low, mid, and high), including their inputs (low-opportunity-cost feeds; food waste, food by-products & grass resources) and outputs (animal products; milk, meat & eggs). Adapted from van Hal et al. (2019).

LCF included in the model consisted of plant based food leftovers (food waste and food processing by-products) related to current food consumption in the EU-28 (according to FAO's food balance sheets) and currently available grazing resources in the EU-28. While food processing by-products consider undesired outputs along food production chain, food waste considers products intended for human consumption wasted in retail or during consumption. Wasted food in each country was combined into one waste stream of which 35% was assumed available as livestock feed. This amount of food waste used as livestock feed is currently achieved in Japan, where the safe use of food waste as animal feed is legal and stimulated (Zu Ermgassen et al., 2016). As feeding ruminants with food waste is associated with high health risks (Salemdeeb et al., 2017), food waste was only fed to monogastric animals in undried form. Availability of grass resources in the EU-28, distributed over three classes based on vegetation type (i.e. managed grassland, natural grassland & shrub land), was collected from Plutzar et al. (2016). Although it is controversial to consider grass resources from managed land – suitable for food crop production – a leftover stream, they were included, assuming conversion of grassland to cropland is undesired due to the associated carbon losses (Gerber et al., 2013). The range in nutrient content of each vegetation type – obtained from literature – was assumed to be normally distributed (16% low, 68% mid & 16% high quality) over the biomass available in each class. While food waste and grazing resources were assumed local resources to be used in the country of origin, co-products could be used anywhere in the EU-28.

The model contains the five most common livestock systems in the EU-28 (pig, laying hen, broiler, dairy cattle, beef cattle) under three productivity levels (low, mid, high). Each livestock system includes the entire life cycle and, therefore, consists of non-food-producing animals (i.e. parent and young stock) and food-producing animals (i.e. fattening pig). As the environmental impact of each livestock system to a large extent relates to food-producing animals (Reckmann et al., 2012), only their productivity level was varied. The performance of the high productive animals was based on the Dutch livestock sector, while their nutrient requirement was calculated using the nutritional system of the Dutch animal feed board (CVB, 2012). This system also enabled calculation of the nutrient requirements for low and mid producing animals. The production details of each livestock system and productivity and the assumptions behind these data can be found in van Hal et al. (2019).

The assumptions made to simulate this hypothetical future food system, may have significant impact on the results. A sensitivity analysis was therefore performed to assess how the most relevant assumptions influenced protein supply by livestock fed only with LCF, and the livestock systems selected for this production. In this sensitivity analysis the baseline optimisation was compared with alternative optimisation: 1) allow only for high productive animals; 2) exclude food waste; 3) exclude managed grasslands; 4) assume that the range of (vegetation specific) nutrient content of the grazing resources – found in literature – was distributed uniformly (33% for each low, mid and high quality) and 5) require the ratio of protein originating from each type of ASF (milk, eggs and meat) to match the current ratio of ASF in the average European diet.

Results & Discussion

Optimal conversion of available LCF in the EU requires 56 million low-productive pigs, 9.5 million high-productive laying hens, and 30 million low-productive dairy cows. Besides abolishment of beef and broilers farming, this requires 78% less pigs and 98% less laying hens, but 9% more dairy cattle than current EU livestock. The model selecting these production systems follows from dairy cattle's and laying hens' high production efficiency (De Vries and de Boer, 2010), cattle's ability to value grazing resources, and pigs' ability to value low quality food leftovers. Almost all food waste was fed to pigs, as well as most oil seed by-products (Figure 4.3; Optimal conversion). In countries where the nutrient density of waste was highest, however, this food waste – supplemented with food by-products – was fed to laying hens. While most of the available food by-products were fed to dairy cattle, their diet consisted mainly of grazing resources (Figure 4.4; Optimal conversion).

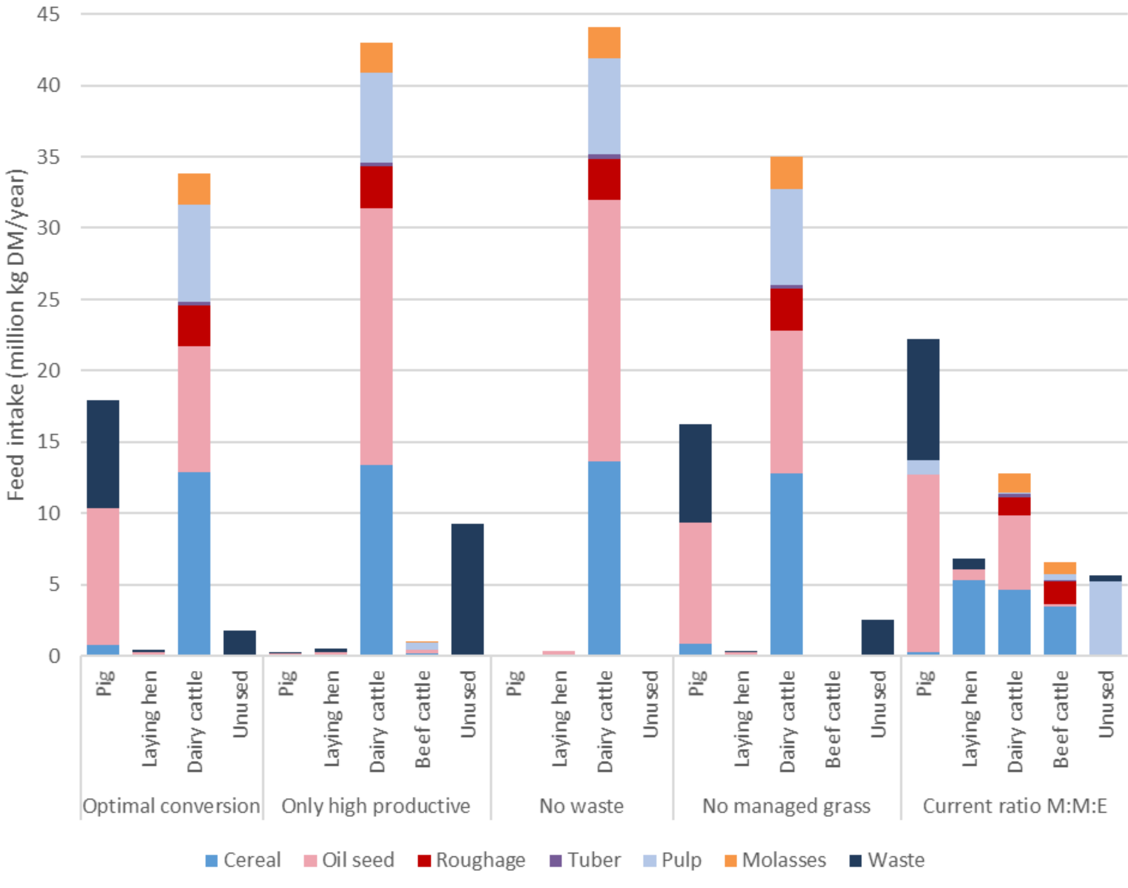


Figure 4.3. Proposed allocation of available food leftovers (by-products and waste; classification see van Hal et al. (2019)) in the EU over the selected livestock systems (pig, laying hen, broiler, dairy, beef) under optimal use of available LCF and alternative optimisations of the sensitivity analysis (M:M:E = Milk:Meat:Eggs). Adapted from van Hal et al. (2019).

Such optimal use of LCF supplies 27 g pork, 610 g dairy (fresh milk equivalents), 33 g beef meat from dairy cattle and one g egg per capita per day; 160g less meat, 40 g less dairy and 31 g less egg compared to current EU ASF supply (FAO, 2017). Together this ASF supplies 31 g HDP/(cap*d) – 5 from pork, 20 from dairy, 6 g dairy cattle meat – 19 g less then currently consumed on average in the EU (Figure 4.5). Additionally, this ASF supplies a range of valuable micronutrients. While for all considered nutrients the supply is reduced, the large share of dairy still meets 93% of our calcium requirements. Our vitamin B-12 supply – which we obtain solely through ASF – was met for 80%, meaning supplementation of this nutrient would be needed.

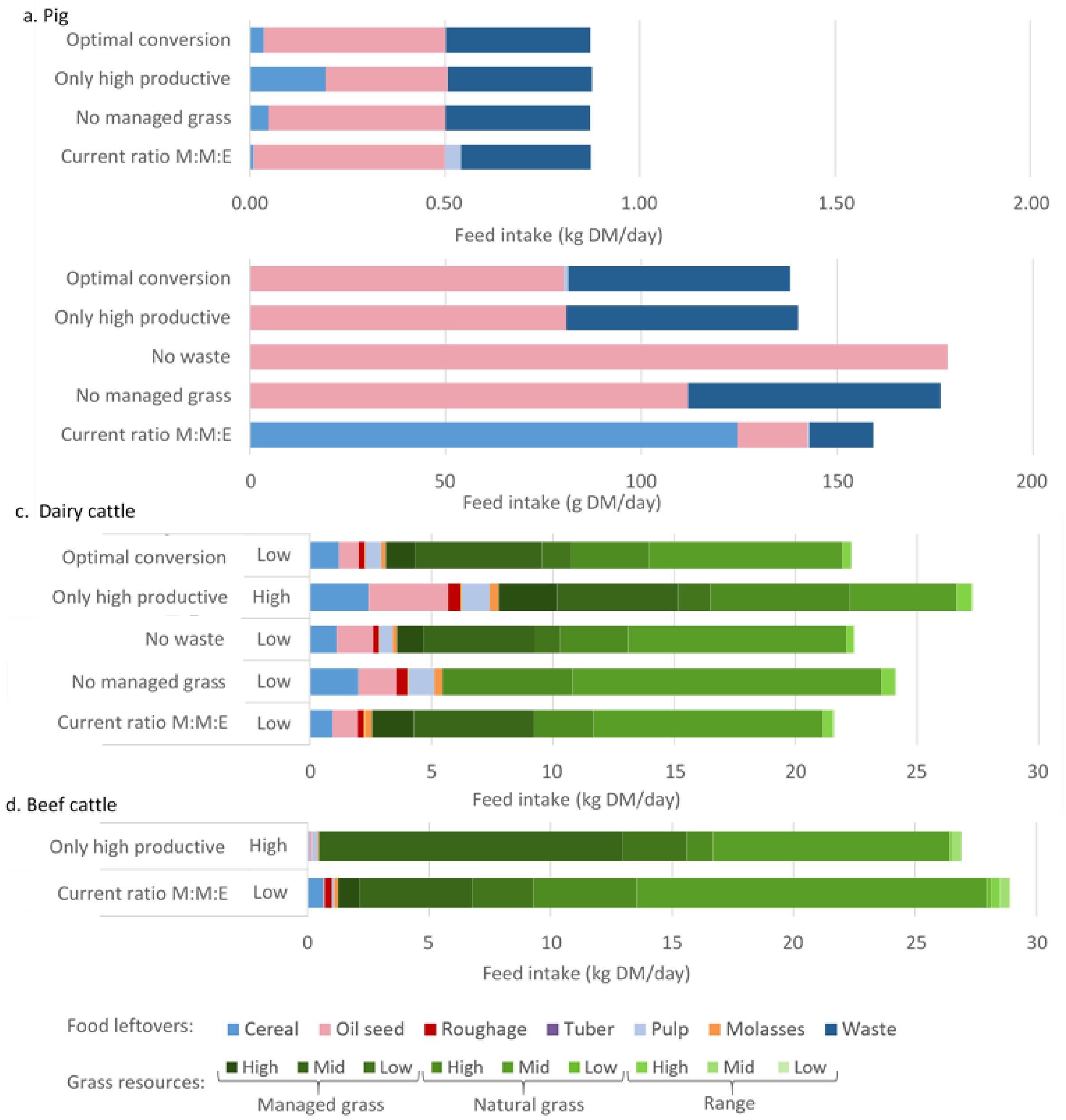


*Figure 4.4. Proposed averaged (EU) diet for each livestock system (a. pig, b. laying hen, c. dairy cattle, d. beef cattle) under the optimal use of food leftovers (classification van Hal et al. (2019)**)** and grass resources**;** and alternative optimisation scenarios of the sensitivity analysis. Expressed per production animal per day including related requirement of non-producing animals. Adapted from (van Hal et al., 2019).*

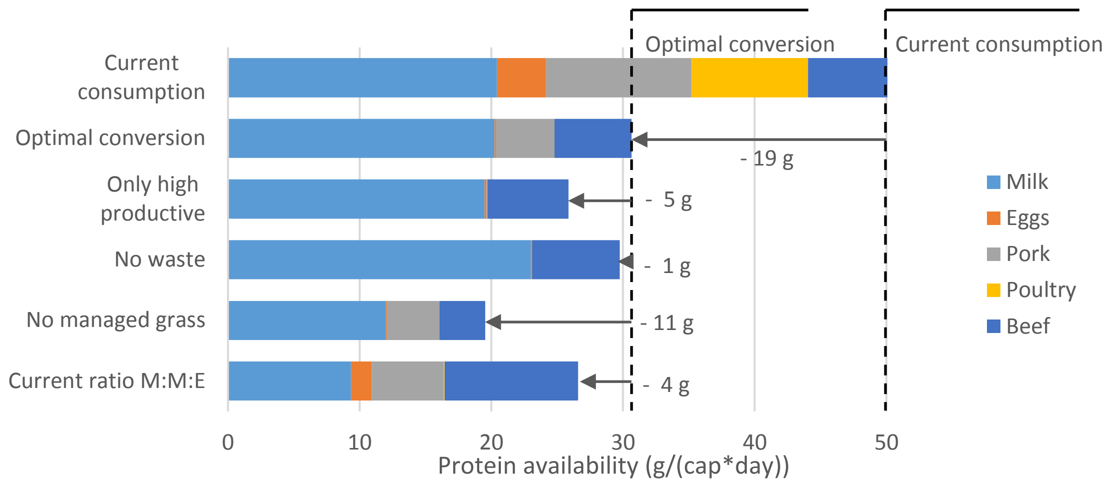


Figure 4.5. Animal human digestible protein (HDP) supply, per EU capita per day, under optimal conversion of LCF compared with current animal HDP consumption, and alternative optimisation scenarios of the sensitivity analysis. Adapted from (van Hal et al., 2019).

The found protein supply of 31 g/(cap*d) of van Hal et al. (2019) is relatively high compared other estimations of the protein supply when feeding only leftovers to livestock (7-30 g/(cap*d)(Van Zanten et al., 2018)). This difference and differences between studies in the review of (Van Zanten et al., 2018) is partly explained by efficiency with which livestock upcycle the available LCF, which is the focus of the study of van Hal et al. (2019). Where previous studies assumed fixed leftovers rations to achieve a fixed (often high) productivity, this model uses leftovers more efficiently by formulating nutritionally adequate rations for those animal production systems that maximised protein output. The results confirm the hypothesis that such efficient use of LCF requires variety of livestock systems & productivity.

Regarding productivity, low productive dairy cattle and pigs were needed to value food waste or leftovers with a low nutrient density such and low quality grass. When restricting the model to only use high productive animals; it was found that high productive pigs were unable to meet their nutrient requirement within their feed intake capacity using food waste, leaving this LCF largely unused (Figure 4.3; Only high productive). Pig numbers where, therefore almost reduced to 0. The high productive cattle used the oil seed-co products previously fed to pigs and grass resources of higher quality to fulfil their higher nutrient requirements (Figure 4.3; Only high productive), but as these resources are limited cattle numbers dropped with more than 30%. Remaining grass of lower quality was used to produce 6 million beef cows (Figure 4.4; Only high productive). All in all, allowing only for high productive animals reduced the supply of animal protein to 26 g/cap/d (Figure 4.5; Only high productive). This reduction in protein supply is relatively small compared to the reduction in livestock numbers. The efficiency benefit, of using low productive animals (resulting in 16% more protein) may, therefore, come with an environmental cost due to greenhouse gas emissions of the high number of dairy cattle.

The high protein availability in Van Hal et al., 2019 compared to literature is, furthermore, explained by differences in the assumed availability and quality of leftovers. van Hal et al. (2019) based the availability of waste and co-products on the affluent European diet, while other studies based them on a healthy vegan diet (Van Zanten et al., 2016) or on current global consumption (Schader et al., 2015). Moreover, many studies excluded food waste as feeding it to livestock is currently not allowed in the EU-28, while van Hal et al. (2019) included it partly (35%) to demonstrate its value to the food system. Excluding food waste reduced protein supply with 3% (to 30 g/(cap*d) – Figure 4.5; No waste). This low effect, while food waste was expected a potent LCF (Röös et al., 2017a, b; Van Zanten et al., 2016; Zu Ermgassen et al., 2016) is due to the high assumed moisture content of food waste. Intake of such waste by pigs, therefore, required considerable supplementation of high quality by-products, which in the absence of food waste were reallocated to dairy cattle with a higher conversion efficiency. To grasp the true potential of relegalizing feeding food waste, drying of food waste should also be assessed.

Besides the inclusion of food waste, also the inclusion of grazing resources from arable land is controversial as it competes with direct plant-based food production. Van Hal et al., 2019 included all grass sources because conversion of such grassland into cropland comes with a release of stored carbon and loss of biodiversity (Foley et al., 2011; Gerber et al., 2013). Excluding grass from arable land (23% of grass resources) reduces animal protein supply from default livestock to 20 g/cap/day (-36%, Figure 4.5; No Managed grassland).

Optimally converting available leftovers into animal protein requires a shift towards a dairy-based consumption pattern (i.e. milk and associated meat). Using default livestock to produce a wider range of ASF, reduces protein availability due to the use of relatively inefficient livestock systems that are unable to value grass. When maintaining the current ratio of protein originating from each type of ASF (current ratio), for example, optimal use of leftover streams results a protein supply of 27 g/cap/day (-13%) (Figure 4.5). Beef and pigs were selected for the required meat production where beef is able to value grazing resources and pigs are best able to consume a wide range of (low quality) co-products (Preston, 1986).

Conclusions

By optimally converting low-opportunity-cost feedstuff (LCF) available in the EU, livestock can supply 31 g animal protein per capita per day (i.e. 40% less than today), covering about half of our daily protein requirements. van Hal et al. (2019) modelling results show that this optimal conversion requires a variation of livestock systems, mostly of lower productivity than conventional systems, confirming our hypothesis. The model selected those livestock systems that have a high conversion efficiency (laying hens, dairy cattle), or are best able to valorise specific LCF (dairy cattle for grass; pigs for food waste). Their reduced productivity enables them to use low quality LCF to meet their nutrient requirements, within their feed intake capacity. If we continue to use mainly high productive livestock, animal protein supply from LCF reduces with 16%. The estimated supply of animal protein (31 g) is sensitive to uncertainties regarding the availability of LCF especially grass.

Fisheries

In Chapter 4.1 (livestock) we found that the optimal use of the available plant based LCF in the EU (i.e. food by-products, food waste and grass resources) through livestock supplies 31 g animal protein per capita per day (Van Hal et al., 2019). While that study considers only terrestrial livestock species, also aquatic animals could contribute to improved global food security and nutrition (Béné et al., 2015), without competing for resources with food crop production. Currently, aquatic animals contribute to food supply through both capture fisheries (this chapter) and aquaculture (Chapter 4.3).

Capture fisheries – harvesting of wild fish – is the only large-scale food production based on a natural resource, globally producing 91 million tonnes in 2016 (FAO, 2018c). As capture fisheries, depend on natural resources, they generally have no feed input, except for the use of bait in some fisheries (long-line and trap fisheries). Animal source food (ASF) resulting from fisheries, thus, in principle do not compete with food production, but is limited in production capacity. Production volume has, therefore, not increased since late 1980s, where earlier growth was achieved by targeting fish further off-shore, deeper and including more species (Morato et al., 2006; Swartz et al., 2010; Zeller and Pauly, 2005).

The fact that capture fisheries do not depend on feed, however, does not automatically imply that ASF provision through fisheries is sustainable. Widespread overexploitation has occurred in the EU (COM, 2009) particularly for specific species such as Atlantic cod (e.g. Jonzén et al. (2002)). Fishing over limits that the ecosystem can sustain compromise current production capacity compared to historical levels (Froese et al., 2018; Rosenberg, 2003; Worm et al., 2006). The status of many European stocks in the northern part of the European Union, however, has improved in recent years, even if major progress is still needed to fulfil the ambitions of the Common Fisheries Policy (EC, 2013) in the European Union (Froese et al., 2018). Globally, 67% of fish stocks assessed (many are not assessed) are today fished within biologically sustainable levels (FAO, 2018c). How much fish that may be produced for human consumption after improving biological levels of stocks remains uncertain as some species have been dramatically reduced (in abundance, distribution and size structure), which may impair future production capacity (e.g. Svedäng and Hornborg (2014)). Even so, improving the state of fish stocks may offer, limited, further growth in production volume (Costello et al., 2016) but requires effective management (Zimmermann and Werner, 2019).

Such management to recover fish stocks do not only consider yield level restrictions but also the adequate choice of fishing gear (Ziegler et al., 2016a). Different fishing practices vary in their habitat impact and bycatch level, also dependent on the areas they are applied in and the species they target (Jennings and Kaiser, 1998). These ecosystem considerations may be included in management objectives, such as fishing gear restrictions or enforcement of protected areas.

To manage sustainable exploitation of shared seas, such shared fisheries are managed through international agreements (ICES, 2018). These agreements include a characterisation of a sustainable exploitation of targeted stocks (Marchal et al., 2016), where fisheries shared in the EU should following the Maximum Sustainable Yield (MSY) framework (EC, 2013). This framework aims to yield the highest achievable catch without long-term negative impacts on a population, and considers both harvested biomass and fish mortality. Each member state may, however, allocate their share of the MSY over their available fishing gear, and set their own objectives for nationally managed stocks (coastal, inland fisheries).

While being in a way an improvement to historical overfishing, MSY as a concept has been subjected to critique for being too theoretical in a complex ecosystem and not e.g. acknowledging species interactions (Larkin, 1977). Overexploitation can easily occur if fishing effort is not sufficiently regulated when e.g. recruitment is lower. The MSY-level should therefore be seen more as a limit that should not be passed, rather than a target. Today, there is also an abundance on scientific literature on alternative approaches, such as 'Maximum Economic Yield' (MEY,Grafton et al. (2007)) or 'pretty good yield'(Froese et al., 2018; Rindorf et al., 2017). Leaving more fish in the ecosystem by e.g. aiming for MEY instead of MSY allows for more efficient fishing, with less impacts per fishing output in terms of e.g. greenhouse gas emissions (e.g. (Farmery et al., 2014; Svedäng and Hornborg, 2015)). There are thus trade-offs between absolute production volume (aiming for MSY) and more sustainable production methods (aiming for MEY) – production loss is however likely small relative to potential energy efficiency gained (Hornborg and Smith manuscript).

Capture fish contribute to food supply directly only through their edible fraction which varies considerably between species and sizes (Table 4.1). Looking at production volumes of fisheries to estimate their contribution to food supply may be misleading. Often, volumes are double-counted as they are reported both by capture fisheries production and aquaculture production (Tacon, 1997). Additionally, some fisheries require bait, e.g. 3 kg herring may be used to harvest 1 kg of lobster (Driscoll et al., 2015). This latter issue, and the fact that some ranging system where wild fish are caught and kept for fattening through input of fish resources, has led to the suggestion of a hybrid category of seafood produced with a combination of fisheries and aquaculture methods (Klinger et al., 2013).In the current study, we estimate potential food supply based on landings data, and consider multiple food-feed uses of the landed fish.

Besides the use of fisheries by-products (e.g. guts, heads, racks, trimmings), the whole fish volume caught may be used as feed ingredients for some species, often small pelagics (Bellido et al., 2011). While sometimes the whole fish is frozen and used as feed without processing, they are generally first reduced to fish meal and oils to use as an ingredient in pelleted feeds for fish, shrimp, chicken or pigs. Globally, 13% of the catches are used for non-food purposes, mainly for feed (FAO, 2018c). The current use of capture fisheries in the EU (Table 4.1) show that some species (Atlantic herring, Atlantic mackerel, European sprat, Atlantic horse mackerel and European pilchard) are used partly as food and partly as feed. This means that for some species consumed, part of the landing as well as part of the whole fish are used as feed. From a feed-food competition perspective, this practice could be improved to optimize use towards direct human consumption since this is more efficient use of nutrients. The same holds for some food-grade species captured in the EU and fully used as feed currently (Cashion et al., 2017).

The nutritional content of seafood differs considerably from that of other food. Seafood is a valuable source of several vitamins, minerals and fatty acids, including vitamins B12, D and A, selenium, iodine and polyunsaturated fatty acids (PUFAs or omega-3 fatty acids), many of which are hard to consume in sufficient amounts from other foods. EU fisheries in 2016 landed over 600 different species only in the Northeast Atlantic (although of 500 of these comprise of small volumes, i.e. less than 1000 tonnes landed per year). This is also an important difference e.g. to the livestock sector which is much less diverse. Taxonomically, the numerous species landed in fisheries cover many different branches (genera, families and orders) resulting in highly different nutritional composition. Interestingly, it has been found that the by-products processed to feed can be more nutritious than the fillets oriented for human consumption (FAO, 2018c).

In this chapter, we assess the amount of human digestible protein (HDP) that can be supplied by sustainable fisheries in the EU. To this aim, we first illustrate current and future sustainable yield for EU fisheries in terms of landings, food and nutrition. Regarding sustainable yields for the short-term future, we follow the MSY framework as currently applied in the EU. For the long-term future, we consider MSY assuming adapted fishing methods to reduce fishing mortality with 80% as proposed by (Froese et al., 2018). Like all ASF, fish products are not only valued for their provision of protein, but also for a wide range of micronutrients (predominantly omega-3 fatty acids, fat-soluble vitamins D and A and vitamin B12). We, therefore, also estimate the provision of these nutrients by non-food-competing fish production as well as other micronutrients considered in the livestock chapter (i.e. zinc, selenium, iron and calcium).

Material and methods

Current and future fisheries yields

To estimate current fisheries yields, data was extracted for 2016 landings from the Northeast Atlantic from the official catch statistics of the International Council for the Exploration of the Seas (www.ices.dk). These landings contain approximately 75% of total EU landings, with the balance e.g. fished in the Mediterranean and Black Seas under third-country agreements. The reason for not including the latter parts is that 1) they constitute numerous stocks for which comparatively sparse information is available in terms of reference points and target yields and 2) they comprise a low proportion of EU fisheries landings.

To be able to relate current landings to potential future landings under more sustainable exploitation levels, we extracted landing data from the ICES advice (ICES, 2016) and later also from the official ICES catch database (ICES, 2018) (as these two sources for the same data did not always harmonize) and target yields for 122 stocks belonging to 20 species from the advice, with the approach to focus effort on the most important species and a manageable amount of stocks. The data official statistics had a higher resolution in terms of countries and was therefore used in the end instead of landings in advice. For the same stocks, fishing quotas and their distribution between EU member states (based on the so called Relative Stability[2]) as well as between the EU and other countries were extracted from EU Council Regulations in order to be able to distribute the future catches between member states based on the same distribution key, which surprisingly was not publicly available. During the process of matching quotas to stocks (in order to be able to aggregate current and future sustainable yields per species, per country and for EU and non-EU countries), 22 stocks could not be matched (for example because the quota was not set for the same geographic area of the stock) or lacked quotas entirely and were therefore excluded.

This data collection process resulted in a final selection of 100 stocks belonging to 16 species, which together constitute 72% of total EU landings in the Northeast Atlantic. The future, sustainable exploitation was defined as following the MSY framework (i.e. the biomass and fishing mortality of all stocks are found within the reference points defined by MSY). For this analysis, the following approaches were taken:

- The “short-term sustainable yield” is defined as current target yield under MSY (in ICES advice(ICES, 2016)).
- The “long-term sustainable yield” was defined as the yield resulting from the scenario employing 0.8 of the target fishing mortality F_{MSY} in a recent publication by Froese et al. (2018). It is the scenario giving the largest sustainable yield, the

[2] The Relative Stability is a fixed distribution between EU member states of the Total Allowable Catch for each fish stock (i.e the annual quota). See Table Appendix B for distribution of species.

highest profitability and resulting in a high degree of rebuilding of stock biomass until 2030.

To quantify the contribution to food security, we translated current and future landings to potential food volume by applying factors for edible yield from the European Market Observatory for Fisheries and Aquaculture (http://eumofa.eu/), complemented with data from the Swedish and Danish Food Agencies (FRIDA, 2018; Sweden, 2018). It is important to recognize that this potential edible yield represents a theoretical maximum, as no losses along the supply chain from fishery to consumption are taken into account. For species that are used both for feed and food, the current post-landing utilization (proportion used industrially) was extracted from EUROSTAT (https://ec.europa.eu/eurostat). It was assumed that everything else was used for food (no definitions are available on what industrial use represents and what other types of use exist). We defined blue whiting, Norway pout and sandeel as species that are currently not used for food at all. Based on the definition of "food grade" in Cashion et al. (2017), blue whiting was considered being food grade and in the long-term scenario, only Norway pout and sandeel were still used for feed (as well as processing by-products from other species). Table 4.1 shows the species included and some characteristics of their current production and use.

Table 4.1. Species included in the study of the current and potential future contribution of EU fisheries to sustainable food and nutrition security.

Species	Landings 2016 (tonnes, ICES)	Food use % Exlc. by-product (EUROSTAT[2])	Edible yield live weight % (EUMOFA)	Nutrient density score (NDS)
Atlantic cod *(Gadus morhua)*	130089	100	35	4.79
Atlantic herring *(Clupea harengus)*	839837	74	52	9.62[3]
Atlantic horse mackerel *(Trachurus trachurus)*	75103	86	54	9.21
Atlantic mackerel *(Scomber scombrus)*	456879	63	61	8.50[3]
Blue whiting *(Micromesistius poutassou)*	222434	0	46	6.07[4]
European hake *(Merluccius merluccius)*	108175	100	42	2.61[3,5]
European plaice *(Pleuronectes platessa)*	98349	100	33	3.45[5]
European pilchard *(Sardina pilchardus)*	73062	98	62	8.6
European sprat *(Sprattus sprattus)*	444022	35	52	10.3
Haddock *(Melanogrammus aeglefinus)*	85325	100	33	2.91[3]
Ling *(Molva molva)*	10740	100	46	3.03[3]
Norway pout[1] *(Trisopterus esmarkii)*	23573	0	0	?
Norway lobster *(Nephrops norvegicus)*	49583	100	42	3.73
Northern prawn *(Pandalus borealis)*	13556	100	36	3.79
Saithe *(Pollachius virens)*	34379	100	39	4.34[3]
Sandeels[1] *(Ammodytes sp.)*	32463	0	0	?

[1]Classified as non-food grade by Cashion et al. (2017)
[2]Species that are not 0 or 100% food use
[3]Iodine content not available
[4]Niacin and copper content not available
[5]Panthotenic acid content not available

The scenarios modelled (Table 4.2) were hence:

- **Current:** Fisheries landings and utilization as reported by ICES (ICES, 2018) and EUROSTAT
- **Short-term sustainable:** Fisheries landings according to MSY catch levels defined in ICES advice (ICES, 2016) and all species currently consumed, i.e. also those used partly for feed today are 100% directed to food and
- **Long-term sustainable:** Fisheries landings according to catch levels defined by the 0.8 F_{MSY} scenario in Froese et al. (2018) and full direction of all species considered being “food grade” by Cashion et al. (2017) to food.

Table 4.2. Landings (tonnes) food supply (tonnes) and nutrient supply (nutrient density score) of current and future sustainable fisheries.

	Current (2016)			Short-term sustainable (2020)			Long-term sustainable (2030)		
	Landings	Food	Nutrients	Landings	Food	Nutrients	Landings	Food	Nutrients
Herring	839837	324257	3119597	487715	254018	2443843	870792	453538	4363372
Cod	130089	45645	218635	119517	41936	200867	213083	74766	358120
Blue whiting	222434	-	-	131935	-	-	236988	109014	661782
Mackerel	456879	110048	935867	356308	137042	1165425	323380	124377	1057722
Sprat	444022	77829	801644	320817	167091	1721061	567749	295701	3045758
Haddock	85325	27884	81208	56115	18338	53408	110590	36140	105254
Saithe	34379	13482	58465	43513	17064	73999	72732	28522	123690
Plaice	98349	32783	113185	215121	71707	247571	201089	67030	231423
Hake	108175	45837	119737	111181	47110	123064	95482	40458	105687
Horse mackerel	75103	35123	323791	187150	101061	931666	299184	161559	1489392
Sandeel	32463	0	0	106038	0	0	284911	0	0
Norway pout	23573	0	0	191812	0	0	96245	0	0
Norway lobster	49583	20660	77116	35642	14851	55433	66528	27720	103469
Northern prawn	13356	4770	15698	18163	6487	24585	13625	4866	18443
Ling	10740	4940	14976	11261	5180	15702	15589	7171	21736
Sardines	73062	44512	382504	45065	27940	240098	155891	96652	830558

Quantifying the aggregate nutritional value of seafood

To go further in the estimation of contribution of fisheries to food security, each species was associated with an index of nutrient density, which has been developed for seafood specifically (Hallström et al., in press). This score is constructed as a *sum of the ratios between the content of a nutrient in 100 g of edible, raw meat of a species divided by the daily recommended intake (DRI) of that nutrient*. The ratios of all nutrients considered to be beneficial are summed and from this sum the *ratios of the content of undesirable nutrients to the maximum upper level (UL) are subtracted*. Nutrients are all given equal weight and no adjustments are made if the nutrient content in 100g exceeds the DRI. All in all, 21 desirable nutrients important for seafood products and two undesirable nutrients (sodium and saturated fat) were included in the nutrient density score which is a dimensionless indicator (Table Appendix B). The nutritional composition of the analysed seafood was derived from different food composition databases available on-line: the FAO uFishJ (FAO, 2016), the Canadian Nutrient File (HealthCanada, 2015),the Swedish database (Sweden, 2018) the Norwegian database, and the Danish Database (FRIDA, 2018).DRI values for the nutrients included in this study were based on the "nutrient reference values-requirements" (NRVs-R) and the "nutrient reference values–non-communicable disease" (NRVs-NCD, for sodium and saturated fatty acids) developed by Codex Alimentarius for the purpose of nutrition labelling in food products (FAO/WHO, 2017). The RDI for the omega-3 fatty acids is not available from the same source and was therefore derived from the FAO expert consultation on fatty acids in human consumption (FAO, 2010).

The species-specific nutrient density scores were then multiplied with the volumes landed of each species under the three scenarios (current, short-term and long-term) and summed across species to provide a picture of the potential of EU fisheries to contribute to human nutrition (Table 4.2).

Human digestible protein supply

We estimate HDP supply by sustainable fisheries in the EU based on the short-term MSY. To avoid feed-food competition, we assume that for those species that are consumed in the EU (all but Blue Whiting, Sandeels and Norway Pout), the edible fraction of these full yields were used as food. Protein and other nutrient supply by these landings were calculated based on the edible yield (Table 4.1) and the nutrient content of each species collected from (USDA, 2017).

Results

From current to future sustainable yields in EU fisheries

Current EU landings of the stocks included were 2.7 million tonnes (in 2016), or 72% of EU landings in the northeast Atlantic. The short-term sustainable level of harvest is lower, 2.4 million tonnes, i.e. a 10% reduction, indicating the on the short-term, there is a trade-off between production and sustainability. If fishing pressure were better aligned with limits in production capacity, however, an increase of total landings to 3.6 million tonnes would be possible in the long-term scenario, i.e. a 34% increase from the current level (Figure 4.6). The long-term increase would be largest for many pelagic species that are currently mostly used as feed (sandeel, Norway pout, horse mackerel, but also plaice, saithe and sardine landings would more than double compared to today (Table 4.2). The species dominating current landing volumes would still dominate under this scenario, but the contribution of each species to total landings would shift slightly (Figure 4.7).

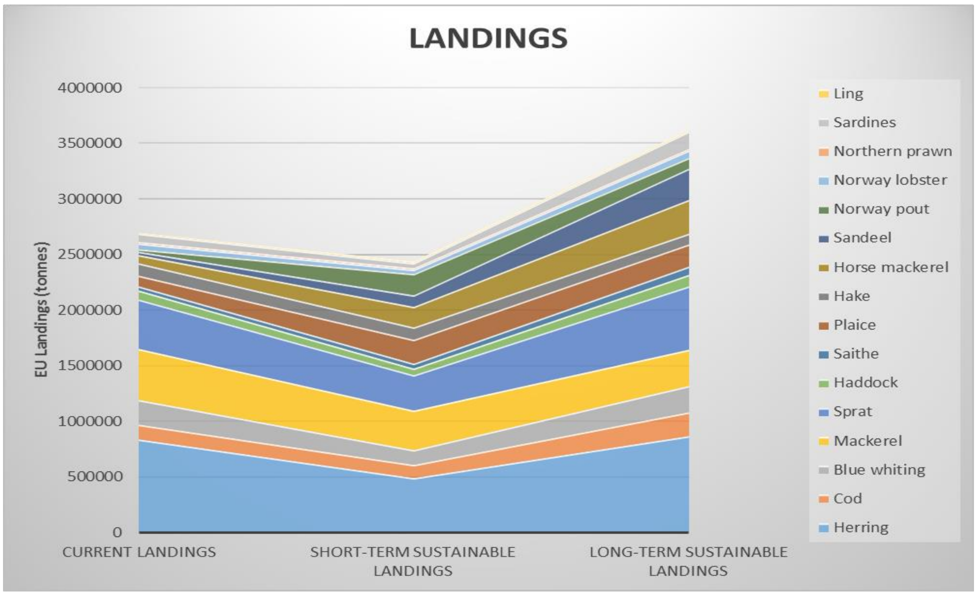


Figure 4.6. Development of EU landing volumes following MSY on the short- and long-term.

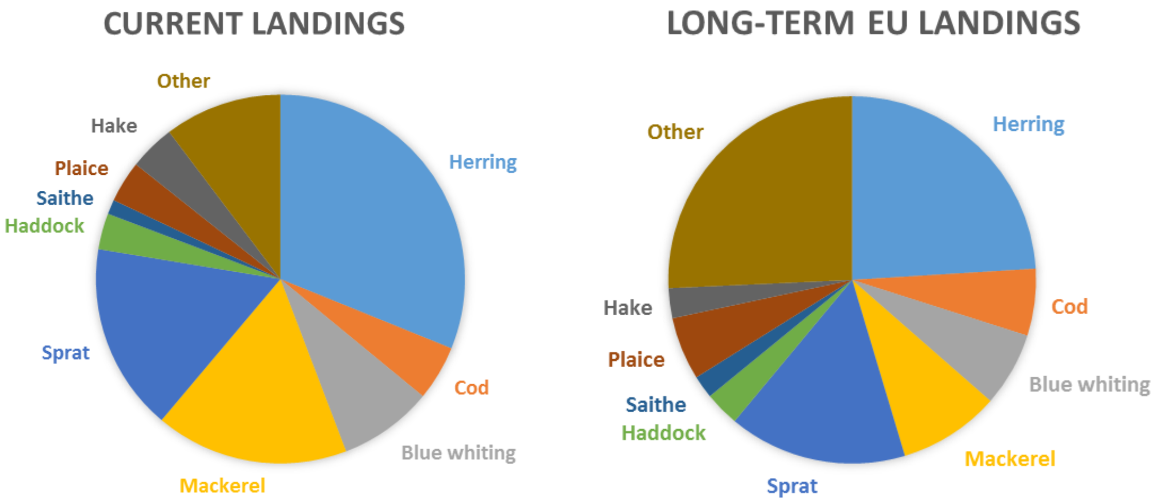


Figure 4.7. Species composition of current and future EU landings.

While landings would decrease on the short-term from fishing at MSY, this could be compensated for by a full redirection of species today used for both purposes entirely to food. This change in practice could result in a short-term increase of food yield – from 7.9 million tonnes to 9.1 million tonnes, a net increase by 15% (Figure 4.8). On the long-term, assuming all food-grade species are used for food, the edible yield from EU fisheries could be almost double from today's level (94% increase).

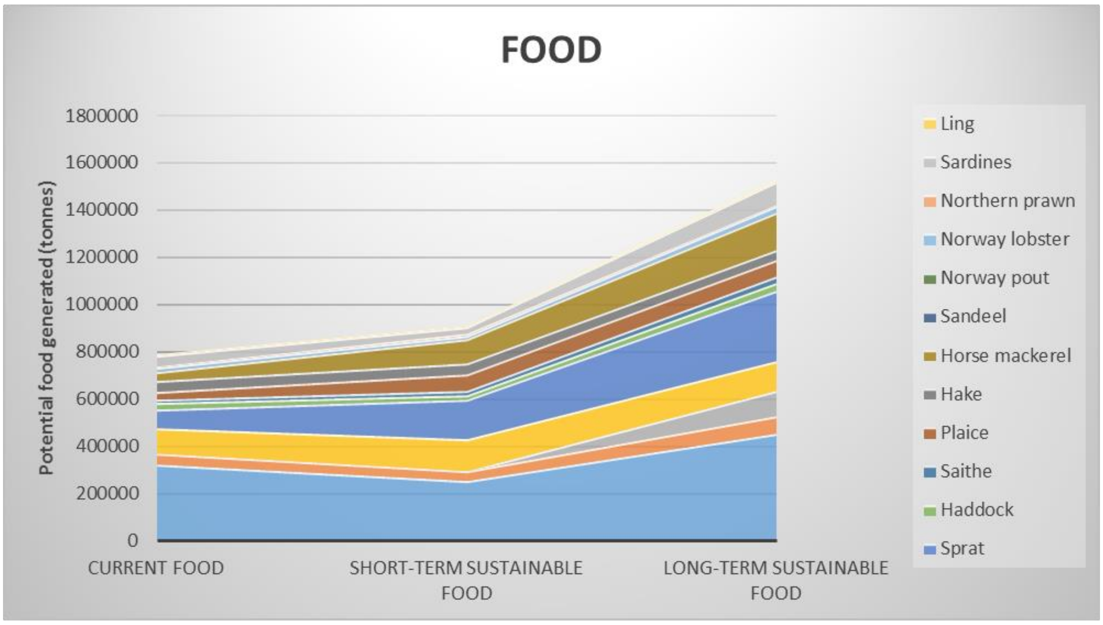
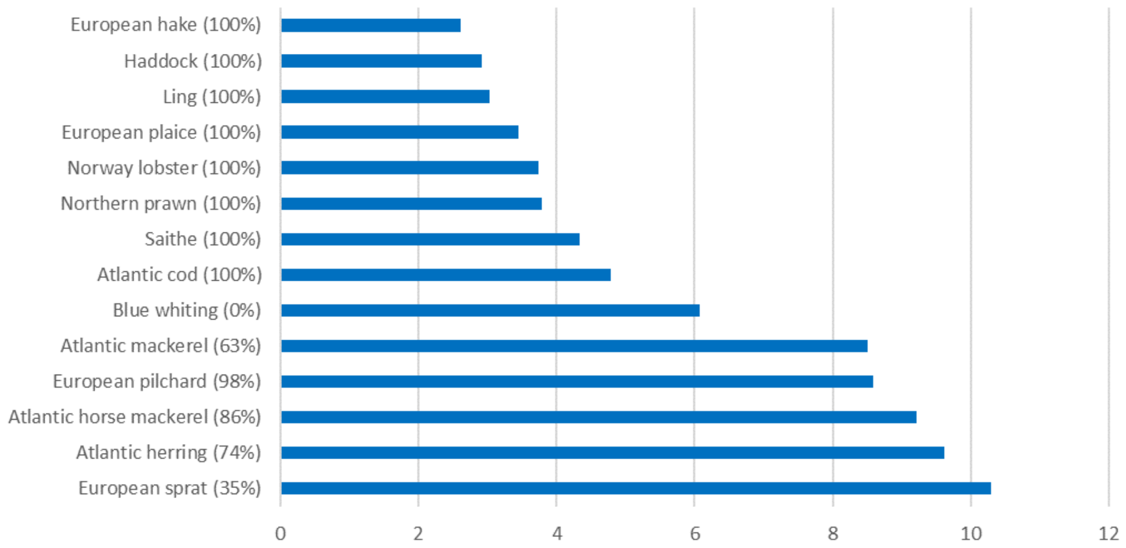


Figure 4.8. The current and potential future food yield from EU fisheries for the 16 species, taking into account both sustainable fishing pressure and supply chains optimized towards prioritizing direct human consumption.

EU fisheries landings and their nutritional characteristics

The nutrient density score calculated for the different species is shown in Figure 4.9 where it is evident that the most nutritious species, pelagic and semi-pelagic species with a nutrient density over 5, are the ones we use least for food directly. The species that are exclusively used for food today all have a nutrient density between 2.5 and 5. In particular European sprat, rich in vitamin D, B12, A niacin, phosphorous, selenium, iodine, and omega-3 fatty acids is today mainly used for feed (65%). Omega-3 fatty acids is the nutrient most often connected to seafood and in fact sprat has the third highest omega-3 fatty acids content, after Atlantic salmon (farmed) and Atlantic mackerel (wild-caught) (Table Appendix B). Additionally, the top rank of sprat in nutrient density is determined by the significant content of a large number of vitamins and minerals. Similarly, to sprat, mackerel is also high in vitamin B12, niacin, selenium, phosphorous and omega-3 fatty acids, and it additionally contains significant amounts of vitamin B6. Due to the high fat content of pelagic species, they also have among the highest contents of saturated fats (together with Atlantic salmon and Atlantic herring), which are defined as an undesired nutrient and which reduces the score somewhat for these species. At the other end of the scale, we find demersal whitefish species and crustaceans. They have in common that they have low levels of most nutrients and are sometimes high in a few (e.g. shrimp is high in vitamin B12, E, copper; hake in niacin, B12 and selenium; ling in niacin and selenium; Norway lobster in niacin, iodine and selenium). It should be mentioned that iodine values are missing for many of these species, while Atlantic cod has very high iodine values. However, iodine is an important seafood nutrient of which the intake is often too low, so we chose to include it. Calculating the nutrient score without iodine values changes the absolute values, but only causes minor changes in the ranking of species. The largest change is that cod gets the second lowest nutrient score when iodine is excluded, which shows that iodine is an important nutrient in cod.

a)



b)

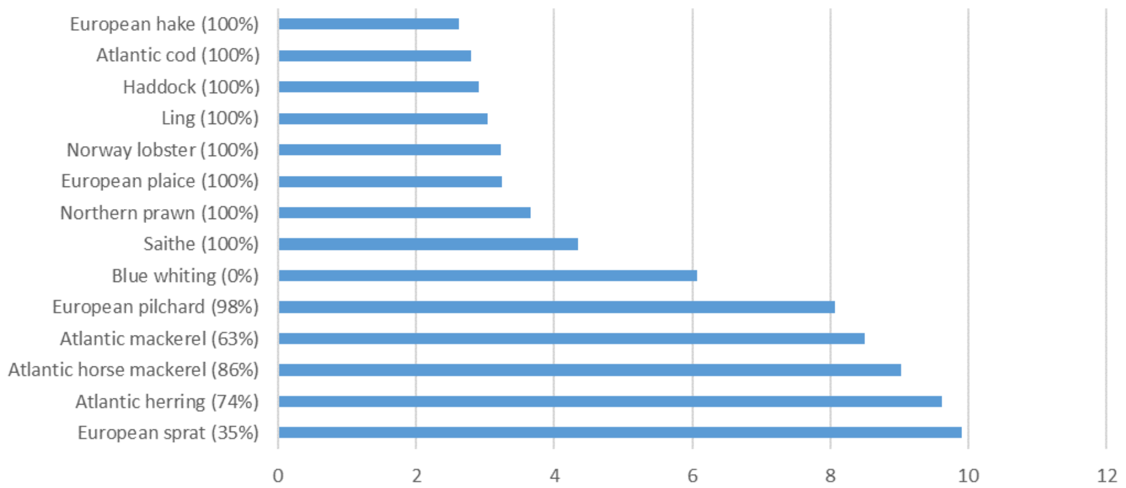


Figure 4.9. Dimensionless nutrient density score calculated based on 21 desired and two undesired nutrients a) with iodine and b) without iodine. Iodine values were missing for herring, mackerel, hake, haddock, ling and saithe) Numbers in brackets are proportion used for food, source for data other than 0 or 100%: EUROSTAT.

The changes in landings and utilization that are modelled in the short- and long-term scenarios change the potential nutritional contribution of EU fisheries (Figure 4.10). The increase in long-term nutritional contribution from fisheries is even steeper than that of pure volume (increased landings and utilization as food), and the relative contribution of different species changes (Figure 4.11) due to the increased utilization of food for the six pelagic top-nutritious species (Figure 4.12). The nutritional contribution of EU fisheries from the species included in this analysis could be 16% higher on the short-term – and 100% higher than today within 11 years (in 2030) if stocks were better managed and landings utilized to prioritize use as food.

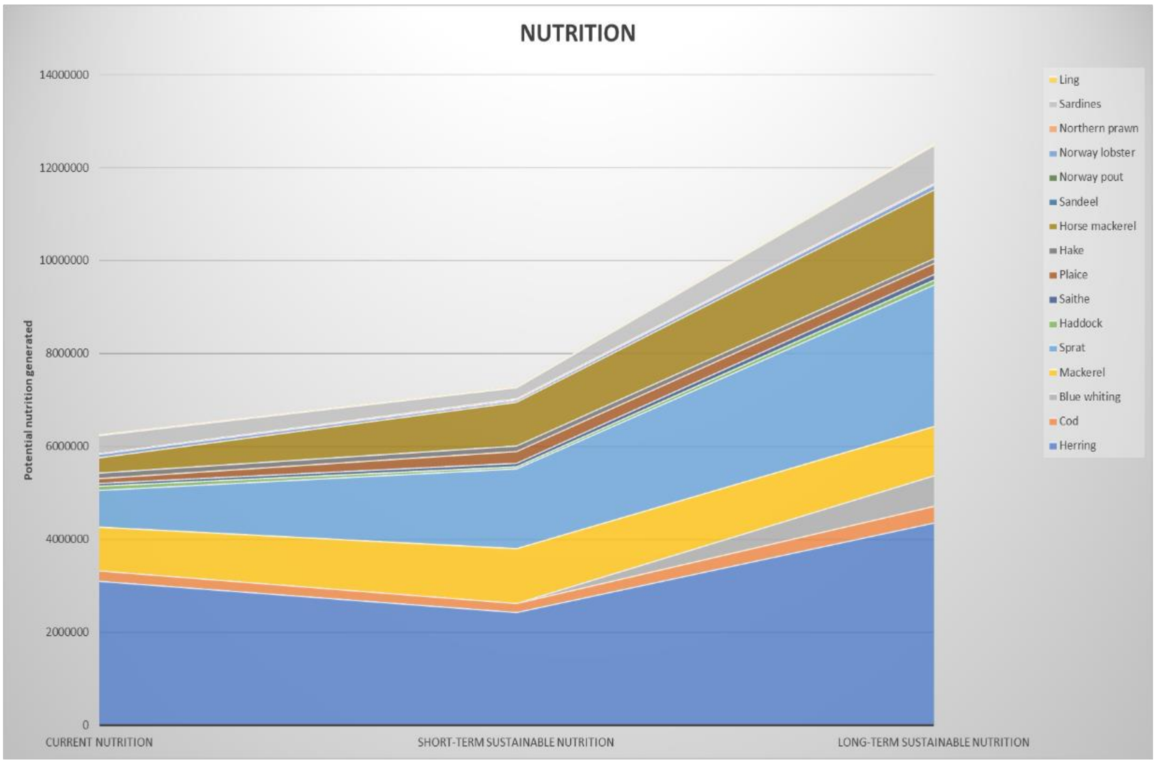


Figure 4.9. The outcome of the (dimensionless) nutrition score for the short- and long-term scenarios involving changes in fishing pressure and in catch utilization.

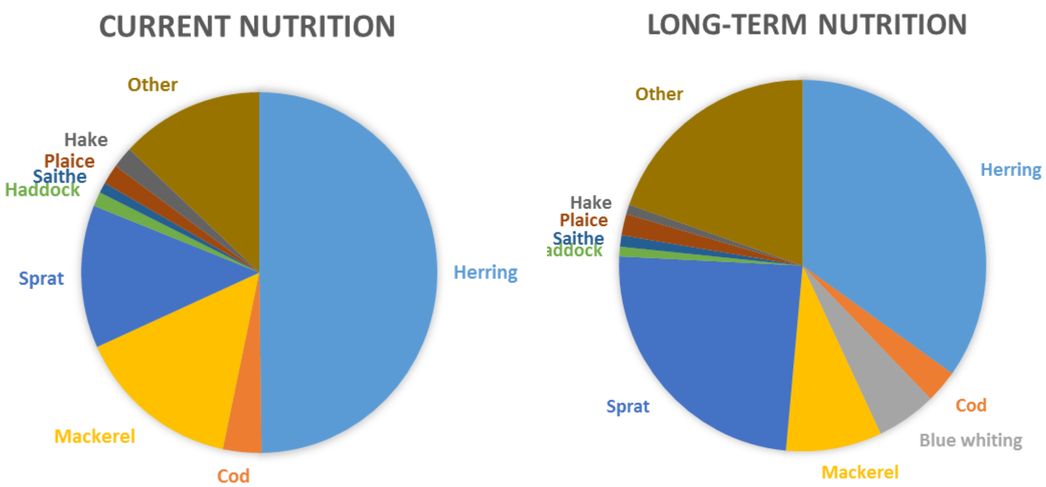


Figure 4.10. The distribution of nutritional value between species in the current and the long-term scenarios.

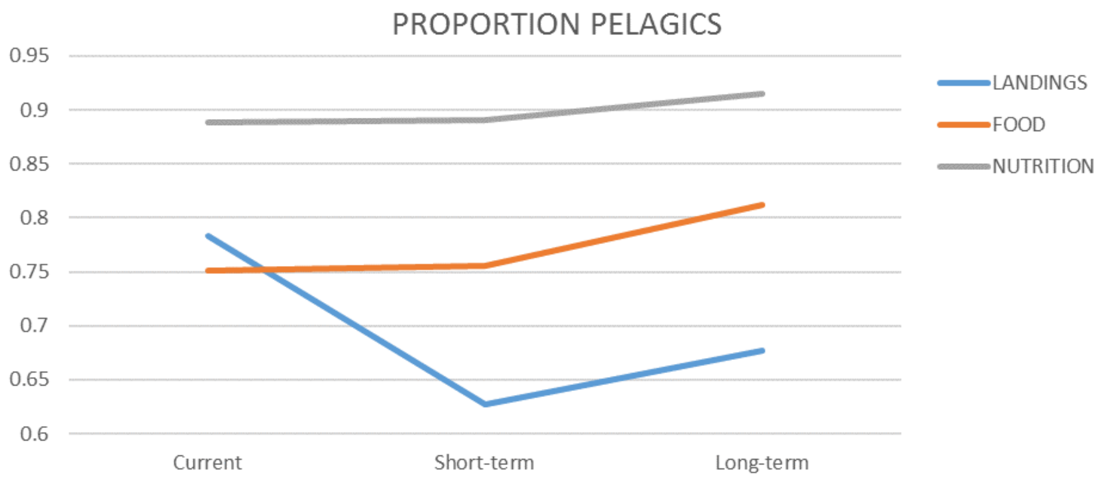


Figure 4.11. Proportion of landings, food yield and nutrition composed by the six top nutritious pelagic species (herring, sprat, mackerel, horse mackerel, sardines and blue whiting).

Human digestible protein supply

The human edible part of the fish landed under short-term MSY, would provide 4.2 g of fish meat. Nutritionally, this fish meat results in a protein daily supply of 1 g/cap and an additional daily provision of 0.4 µg vit B12, 0.1 g omega 3 fatty acids, 1.2 µg vit A, 0.5 µg vit D, 3.7 mg calcium, 1.7 µg selenium and very small amounts of iron and zinc.

Discussion & Conclusion

We have shown that improved management of fisheries and utilization of landings have the potential to considerably increase the contribution of EU fisheries to sustainable food and nutrition security. What are the current obstacles and what is needed to increase the contribution from fisheries to EU food and nutrition security?

Although reaching MSY has been a stated goal for fisheries management in the EU since the 2013 version of the CFP was adopted (EC, 2013) we are still not there. In fact, in the last year before the goal should be reached (2020, originally 2015), quotas are still set above scientific advice given (NEF, 2018). Political action is needed to reduce fishing effort and catches for overfished stocks, which comes with a short-term socio-economic cost. At the same time, subsidies are required to keep some fisheries profitable today (Ziegler and Hornborg, 2014) and stock collapses risk viable fisheries for unforeseen time periods (Pinsky et al., 2011); unsustainable fishing practices also comes at high societal costs and risks – for the stocks fished, the wider marine ecosystem, but also for fishers. Overcapacity in a fishing fleet (excess fishing effort in relation to available resources) is a driver for unsustainable fishing practices and results to low profitability (Ziegler et al., 2016a; Ziegler et al., 2016b). It takes political courage to stick to scientific advice and stand strong against short-term drivers, i.e. groups lobbying for higher quotas and subsidies to fisheries.

On the other hand, the societal benefits in the long-run are obvious.

Pelagic species stand out in this analysis because of their large volumes and their high nutritional values. Many of them are fully or partly used as raw material for feeds today, often because of a lower consumer demand for them as food. Feeding them to species more preferred by consumers, such as salmon or sea bass, can on one hand be seen as transforming something less desired into something more desired. On the other hand, current consumption patterns in the wealthier part of the world such as the EU are rather one-sided; transition towards improved food and nutrition security in the EU need to pay attention to consumer habits. Perhaps there are ways we could challenge ourselves with finding ways into including these highly valuable and sustainable species in our diets directly. This requires innovation in the form of product development and in the creation of consumer trends. Fillets are not the only form to consume seafood, pelagic species could also show up as ingredients in other foods. If industry manages to create convenient, tasty, available and affordable products containing pelagic fish, marketers need to create demand – perhaps the positive health aspects are a more effective message than sustainability. It will be interesting to see if insects or small pelagic fish make it first to European consumers.

Assembling data on EU fisheries was a challenging exercise in many ways. ICES data found in advice is not provided in a standardised format and is therefore difficult to align across stocks and species. We were surprised to find that the distribution of fishing quotas between EU member states is not available, i.e. relative stability, and had to spend considerable effort in extracting it, stock by stock, from ICES advice and EU council regulations to be able to calculate current and future sustainable fisheries production per country (not presented in this report) as well as separating EU- from non-EU catches. The societal interest in this data has been massive (including EU institutions) and we have therefore shared it widely (Table Appendix B shows the proportions aggregated to species). We were also surprised to find that the landings reported in ICES advice do not always and fully correspond to the data found in the ICES catch database. In addition to these inconsistencies, there were many challenges in the geographic resolution of stocks vs. the resolution on which they are managed as well as a general lack of data for many stocks. Of most concern is that many stocks still don't have defined reference points or even quotas.

The analysis of nutrition also suffered from lack of data, making it necessary to combine data from four different databases to be able to calculate the nutrition density score. Nutrient analyses are hence performed in different times, likely using different methodologies. Values for certain nutrients are missing for some species (most importantly iodine, one of the nutrients for which seafood is an important source). The methodology to calculate the nutrition score is still under development. It is possible to in future analysis include more or less nutrients, and aggregate the score in different ways. Here, we did intentionally not weight the nutrients differently to make results general rather than specific for a population. This could have been done, e.g. based on the current intake of each nutrient in relation to the RDI. When nutrient levels are very high, exceeding the capping could be an option (i.e. not counting the content exceeding the RDI). We decided not to apply capping in this study, in line with previous work (Hallström, 2019). Overall, nutrient profiling is useful to illustrate the nutrition characteristics of foods and it has been applied broadly to other types of food (Hallström et al., 2015; Hallström et al., 2018), but without including the nutrients relevant for seafood (i.e. selenium, iodine, omega-3 fatty acids) (Hallström, 2019). Whenever characterising a food with a nutrition score, in particular if comparisons are made, it is important to include the nutrients that are important for all foods to be compared, positive as well as negative nutrients.

It is our hope that this analysis can serve as a basis for a discussion for future priorities in fisheries management and food policies- should e.g. the nutritional value of the catches be an aspect to consider when prioritizing between species in an effort to reach "nutrition-sensitive fisheries management" (Golden et al., 2016). Policies encouraging direct utilization are also needed (Pihlajamäki et al., 2018), as well as strategies to reach out to consumers with a positive message about seafood – which seafood to eat and what benefits it has for the consumer could be emphasized more rather than which should be avoided, which is the current emphasis.

Aquaculture

In contrast to fisheries, many forms of aquaculture (e.g. “the farming of aquatic organisms such as fish, molluscs and aquatic plants” (FAO, 1988)) require an input of feed and may be able to upcycle low-opportunity-cost feed (LFC). Aquaculture species can be classified into two groups, those who are filter-feeders and do not require input of feed (e.g. mussels, seaweeds) and those who do require feed input. Fed species are either omnivorous or carnivorous. Omnivorous species consume a combination of plant and animal based products, and are commercially provided with a nutrient dense feed containing a combination of among others cereals, fish and animal by-products, fish and vegetable oils, and yeast (FAO, 2018b). Omnivorous species are either produced in pond systems or closed tank systems, where it is easier to measure the nutrient flows from feed to fish or crustacean and water. In closed tank systems, feeding non-commercial feed (i.e. leftovers) is complicated as reduced feed use efficiency causes water pollution and might decrease fish health (personal communication Johan Schama). Carnivorous species can also consume a combination of plant and animal-based feed, but the ratio of animal-based protein must be higher than for omnivorous species (Cashion et al., 2017) Atlantic Salmon (*Salmo salar*) is an example of a carnivorous species that through vast amount of investments and research today uses feed relatively efficiently for growth and is in high demand among consumers in the EU (as well as in other parts of the world) (European Commission, 2017).

Aquaculture can make a valuable contribution in upcycling LCF efficiently as they convert feed relatively efficient (Tacon and Metian, 2008) and it is allowed to feed fish on animal- and fisheries by-products, while livestock is not (Jedrejek et al., 2016). Both livestock production and fisheries, typically result in slaughter by-products, as only part of the animal live weight is used for human consumption of which some (e.g. meat and bone meal, animal fat, feather meal, fish meal and fish oil) are suitable as aquaculture feed (Bellido et al., 2011). Furthermore, so called reduction fisheries – fish caught specifically to be processed into feed – provide additional fish-oil and fish-meal (Fry et al., 2018). Some animal by-products and a large share of reduction fisheries yields, however, are suitable for human consumption, and their current use as aquaculture feed is less efficient in terms of food supply (Cashion et al., 2017).

In this chapter we estimate the supply of human digestible protein (HDP) from Salmon aquaculture when feeding only animal based LCF. These animal based LCF include by-products from sustainable fisheries and by-products from livestock production when feeding only crop LCF. Furthermore we illustrate the potential provision of valuable micronutrients (omega-3 fatty acids, vitamins D, A and B12, zinc, selenium, iron and calcium) to human diets.

Methods

We estimated the potential supply of HDP by salmon aquaculture fed only animal based LCF available in the EU-28, using an optimisation model in General Algebraic Modelling System (GAMS) version 24.2. The model maximises HDP output by converting the available animal based LCF in the EU-28 (input to the model) into ASF (output of the model) through farming of Atlantic Salmon. HDP production is restricted by the availability and nutritional content of each feed product for Atlantic Salmon, nutritional requirements of Atlantic Salmon throughout the life cycle and its feed intake capacity (FIC).

Availability of livestock slaughter by-products was calculated by multiplying livestock numbers of Hal et al. (2019) Chapter 4.1 (Livestock) with per animal by-product production (Nour et al., 1983; USDA, 2018a, b) (Table 4.3). The availability of fishery by-products were based on the short-term MSY as quantified in (Chapter 5.2, fisheries). The current use of capture fisheries yields show some species (Atlantic herring, Atlantic mackerel, European sprat, Atlantic horse mackerel and European pilchard) that are used partly as food and partly as feed. This means that for some species consumed in the EU, part of the yielded whole fish are used as feed. From a feed-food competition perspective, this practice is unsustainable as direct human consumption of this fish is more efficient as nutrients are lost in aquaculture production. To avoid feed-food competition we assume that the yielded fish of these species was fully allocated to food. The non-edible fraction (EuropeanCommission, 2017; FRIDA, 2018; Sweden, 2018) of the short term MSY landings were fully processed into oil and meal based on species specific by-product processing according to (Cashion et al., 2016; Cashion et al., 2017). Resulting oil and meal output for missing species were estimated based on species of similar protein and fat content as shown in Table 4.4. The nutritional value of each animal based LCF for Atlantic salmon was obtained from the Ingredient Composition Database (IAFFD, 2018).

Table 4.3. output of slaughter by-products in tonnes per tonne LW and availability of slaughter by-products in the EU.

		Availability (tonnes FM)	
Species	**Product**	**(/tonne LW)**	**Total**
Pig	First Choice Grease	0.010	65225
Pig	Meat/bone meal	0.031	204806
Pig	Blood meal	0.011	75661
Pig	Lard	0.034	224373
Pig	Plasma	0.040	262203
Cow	Tallow	0.112	1171611
Cow	Meat/bone meal	0.073	760520
Cow	Blood meal	0.012	123328
Poultry	Blood meal	0.003	4712
Poultry	By-prod meal	0.115	199459
Poultry	Feather meal	0.065	112848

Table 4.4. Fish oil and meal output per tonne of fisheries by-product for landed species in the EU.

	Yield (kg/tonne)		
Species	Meal	Oil	Reference
Atlantic herring	204	115	Cashion et al., 2016
Atlantic cod	170	17	Cashion et al., 2016
Blue whiting	197	19	Cashion et al., 2016
Atlantic mackerel	194	186	Cashion et al., 2016
European sprat	188	79	Cashion et al., 2016
Haddock	170	17	Cashion et al., 2016
Pollock	170	17	Cashion et al., 2016
European plaice	170	17	Based on Atlantic cod
European hake	170	17	Based on Atlantic cod
Atlantic horsemackerel	194	186	Based on Atlantic mackerel
Sandeels	197	42	Cashion et al., 2017
European pilchard	230	180	Cashion et al., 2017
Norway pout	204	115	Cashion et al., 2016
Norway lobster	160	0	Based on Antarctic krill
Northern prawn	160	0	Based on Antarctic krill
Ling	170	17	Based on Atlantic cod

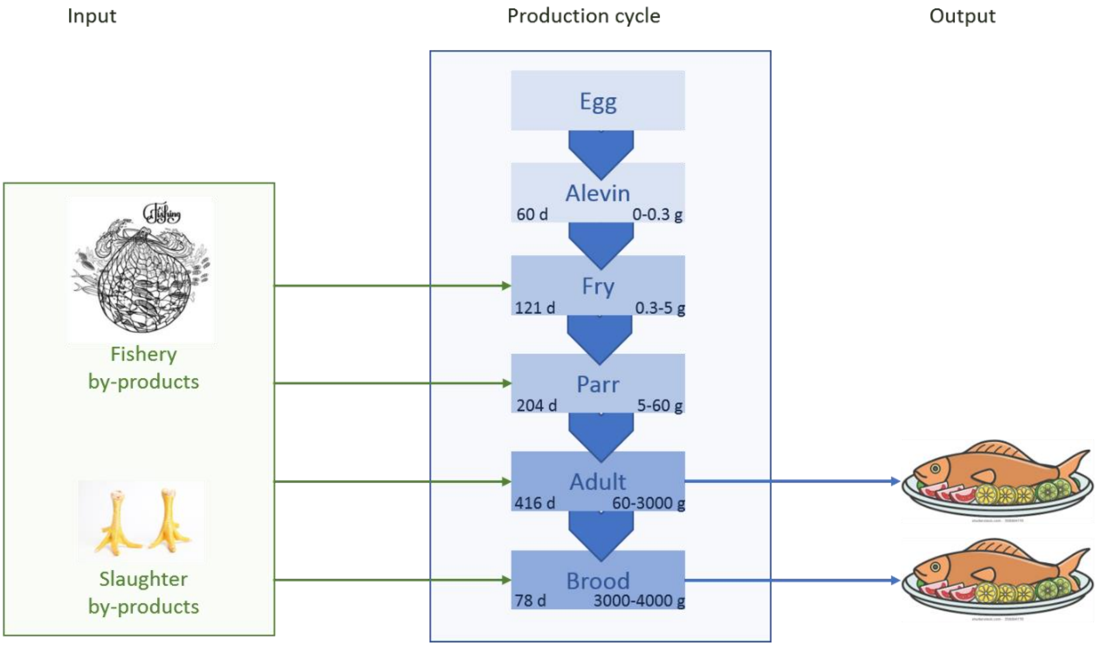


Figure 4.12. Atlantic salmon production system.

The model contained all feed consuming stages of the Atlantic salmon production cycle including fry, parr and adults and breeders. In Figure 4.12 an overview of all life stages including weight development and duration per phase is displayed. The number of each non-producing fish (eggs, alevin, fry, parr and breeders) needed for harvesting one adult was calculated based on (Eskelinen, 1989; EY, 2017; FAO, 2018d; McGeachy et al., 1995) which include the mortalities of each phase. Breeders were assumed to spawn only once to ensure continuous egg production quantities (Sedgwick, 1982), and after egg harvest, breeders were assumed to be harvested providing additional fish meat. Salmon productivity was based on current common practise of feed (FAO, 2018a) and nutrient (FAO, 2018d) intake, growth (FAO, 2018c) and feed conversion ratio of 1.25 (Tacon and Metian, 2008) Nutrient requirement and feed intake in each phase ware based on daily feed intake predictions (FAO, 2018a) assuming a water temperature of 6°C multiplied with nutrient content of the phase specific feed (FAO, 2018d). Nutrient requirements to ensure healthy development were limited to digestible energy (DE), digestible protein (DP), lysine (Lys), methionine (Met), crude lipids (CL) and omega-3 fatty acids (sum n-3) as shown in Table 4.5.

As no data is available on the feed intake capacity (FIC) of salmon, we assumed the current feed intake (FI) recommendations (FAO, 2018) as given in percentage of body weight as such. There are however, indications that when provided with a lower quality feed, salmon tend to increase FI (REF), as is seen in livestock. To assess the effect of the assumed FIC on the utilization of low-cost feeds and on the final output of salmon (meat) per year, additional FIC of 110%, 120% and 130% of the FI recommendation, were tested.

Table 4.5. Daily nutritional requirements of Atlantic salmon (adapted from (IAFFD, 2018) and (FAO, 2018a)

Phase	Time Days	FIC g/d	DE kJ/d	DP g/d	Lys mg/d	Met mg/d	CL mg/d	sum n-3 mg/d
Fry	43.6	0.0	0.3	0.0	0.1	0.1	2.2	0.2
	77.2	0.1	1.2	0.0	0.7	0.4	11.7	0.9
Parr	46.8	0.1	2.6	0.1	1.4	0.8	27.8	1.9
	65.5	0.3	5.8	0.1	3.0	1.6	59.5	4.1
	46.2	0.4	8.2	0.2	3.7	2.0	84.5	5.8
	45.2	0.6	11.5	0.2	4.9	2.7	115.0	7.9
Adult	73.8	2.3	45.5	0.9	18.8	10.5	455.0	31.2
	30.0	4.0	82.0	1.6	32.4	18.0	850.0	50.4
	41.4	5.8	118.9	2.3	47.0	26.1	1305.0	73.1
	43.1	7.7	156.8	2.9	60.6	33.7	1816.9	80.3
	32.0	8.4	172.8	3.2	66.8	37.1	2107.8	88.5
	29.6	10.1	212.6	3.7	76.5	42.5	2657.8	106.3
	28.4	11.0	231.0	4.1	83.2	46.2	3025.0	104.5
	51.0	12.3	257.3	4.5	92.6	51.5	3521.9	116.4
	86.7	15	322.5	5.4	108.0	60.0	4500.0	126.0
Breeder	77.9	19.25	413.9	7.7	155.9	86.6	4620.0	161.7

FIC= feed intake capacity, DE = Digestible energy, DP = Digestible protein, Lys = Lysine, Met = Methionine, CL = Crude lipids, sum n-3 = sum of omega-3 fatty acids

Fisheries input scenarios

We based the availability of fisheries by-products on estimates for short term sustainable landings and, to minimise feed-food competition, assume full human consumption of the edible fraction of species that are currently already consumed in the EU. These assumptions, however, do not reflect our current use of fisheries resources nor do they reflect fisheries practices that are sustainable in the long term or the most efficient use fisheries landings in terms of food provision. For this reason, we explored how our results would change if assume alternative landing quantities and alternative feed-food allocation of these landings. Regarding landing quantities we compare our baseline (short term MSY (ICES, 2016)) with actual 2016 fisheries landings ((ICES, 2018) and long term sustainable yields (Table 4.6). This long term sustainable yield, modelled by (Froese et al., 2018)reflects an MSY for 2030, assuming that fishing mortality is limited to 80% compared to MSY as currently applied by the EU. Regarding the assumed food/feed allocation of fisheries landings, we compared our baseline (full landings of species currently consumed in the EU allocated to food) with the current use in the EU (Eurostat), and with fully allocating all food grade fish fully to food (Table 4.6). Although Blue whiting is a food grade fish (Cashion et al., 2017) it is currently not consumed in the EU. We assess the benefit of directly consuming the edible fraction of the landed Blue whiting as well as the loss of our current consumption where for some species only part of the landings were used to yield the human edible fraction.

Table 4.6. Current and future sustainable (short and long term) capture fisheries yields and current and feed-food competition avoiding allocation of captured fish to food as used for the sensitivity analysis.

	Fisheries landings			Allocation to food		
Fish species[1]		Sustainable			Consumed	Food-grade
Name	Current	Short term[2]	Long term[3]	Current[4]	species[5]	species[6]
Atlantic herring	839837	487715	870792	0.74	1	1
Atlantic Cod	130089	119517	213083	1	1	1
Blue whiting	222434	131935	236988	0	0	1
Atlantic mackerel	456879	356308	323380	0.63	1	1
European sprat	444022	320817	567749	0.35	1	1
Haddock	85325	56115	110590	1	1	1
Pollock (=Saithe)	34379	43513	72732	1	1	1
European plaice	98349	215121	201089	1	1	1
European hake	108175	111181	95482	1	1	1
Atlantic horse mackerel	75103	187150	299184	0.86	1	1
Sandeels	32463	106038	284911	0	0	0
European pilchard	73062	83721	155891	0.98	1	1
Norway pout	23573	191812	96245	0	0	0
Norway lobster	49583	35642	66528	1	1	1
Northern prawn	13356	18163	13625	1	1	1
Ling	10740	11261	15589	1	1	1

1 Considering the most exploited species (covering 90%? Of total fisheries landings)
2 Short term sustainable yield is based on MSY scenario of (ICES, 2016)
3 Long term sustainable yield is based on 0.95 target yield according to (Froese et al., 2018)
4 Current consumption based on EUROSTAT for species used for both food and feed
5 Of all species we currently consume 100% of landings is allocated to food
6 Of all species considered prime or food grade by Cashion et al. (2017) 100% is allocated to food

Results and discussion

The optimal conversion of fishery and animal by-products by Atlantic salmon aquaculture requires 553 million harvested salmon adults (and related breeders) per year. To achieve this, salmon aquaculture used only 55% of the available feed products. Unused products consider mostly fats (68% of tallow and 25% of fish oils), and some meals with the lowest protein content (Norway lobster meal and cow meat and bone meal). The feed composition per life phase (Figure 4.13) shifts from predominately fish based in the fresh water phase (fry and parr) to animal based in later life stages. The overall content of protein-rich meal (animal and fish meals) decreases continuously from fry to breeder by 13% to 74%. Requirements of macronutrients as well as omega-3s are met by 100-130% throughout the production cycle, whereas amino acids lysine and methionine are many times over the requirements, with lysine being highest over all phases ranging between 362% and 423% of the daily requirements since animal and fish meals are abundant in these amino acids, as shown in Figure 4.14.

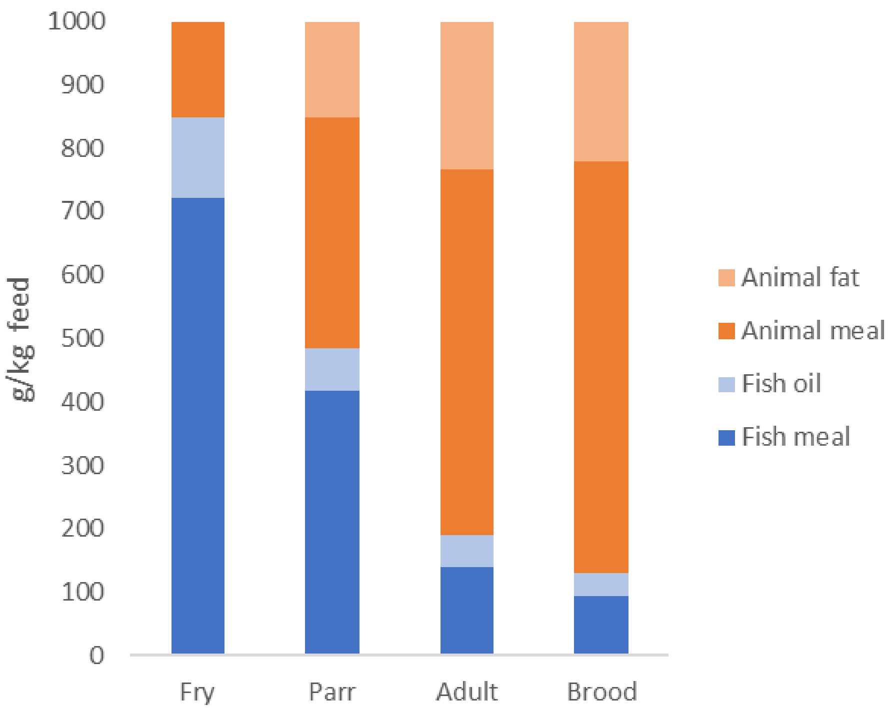


Figure 4.13. Feed composition throughout the life phases of Salmon Aquaculture when optimally feeding only animal based LFC available in the EU.

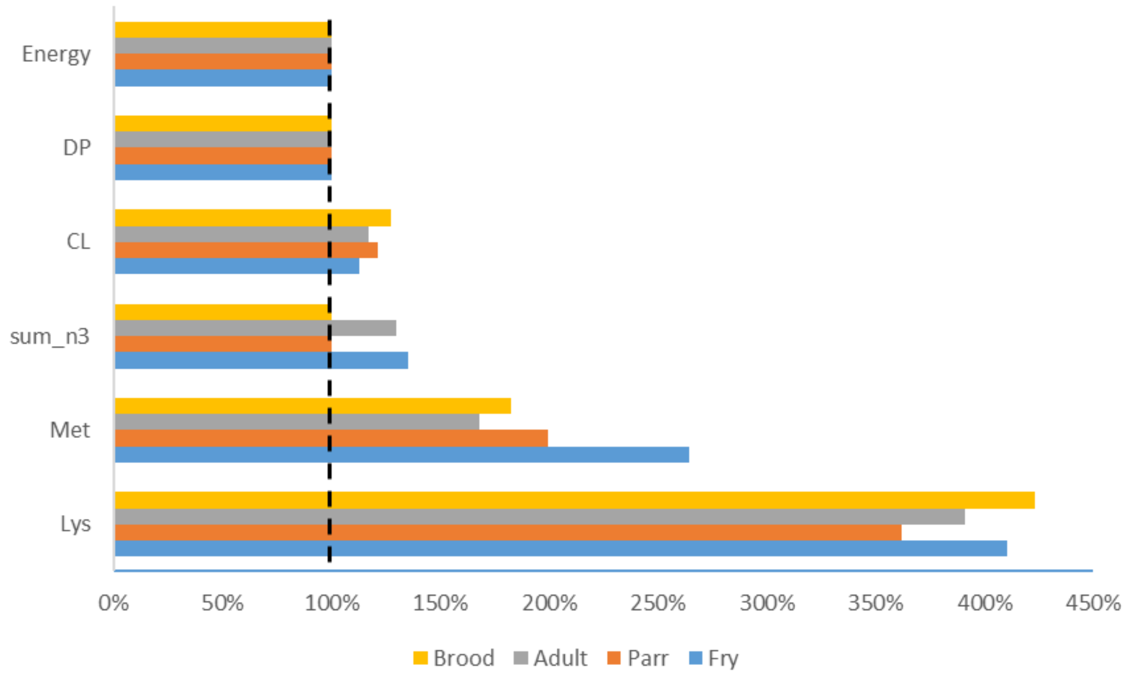


Figure 4.14. Fulfilment of nutrient requirements in the life phases of salmon aquaculture when optimally feeding only animal based LFC available in the EU.

This optimal use of animal based LCF available in the EU results in a daily per capita supply of 4.9 g salmon meat, 18% less than consumed in 2016 (EuropeanCommission, 2017). Nutritionally, this salmon meat results in a protein daily supply of 1 g/cap and an additional daily provision of 0.67 µg vit B12, 0.1 g omega 3 fatty acids, 3 µg vit A, 0.6 µg vit D, 0.7 mg calcium, 1.9 µg selenium and very small amounts of iron and zinc.

Feed intake capacity

Assuming a higher salmon FIC increases the salmon aquaculture production when feeding only animal based LCF available in the EU. Under 110% FIC, fish numbers increase by 29% to 714 harvested adults. This production increased protein supply from 1 to 1.3 g /(cap*d). Increasing FIC further (to 120% or 130%), however, does not increase salmon production as availability of protein containing LCD limits production. Under 100% FIC 75% of available animal based LCF in the EU are used, and unused products consider only fish oils and tallow which doesn't contain protein.

Landing quantities

Using the by-products from current landings rather than short-term sustainable landings for salmon aquaculture increased protein supply with 2% (Figure 4.15). While, capture fisheries land 12% more than the short-term MSY, the yield of species exclusively used for feed (Norway pout, Sand eels and Blue Whiting) are 35% lower. As a result, the feed availability including non-edible parts of species used for food, stays almost the same with 3.65 million tonnes compared to 3.64 million tonnes, with a similar oil to meal ratio.

Using the by-products of the long-term MSY proposed by (Froese et al., 2018), has more impact on salmon protein supply with a 10% increase to 1.1 g/(cap*d).

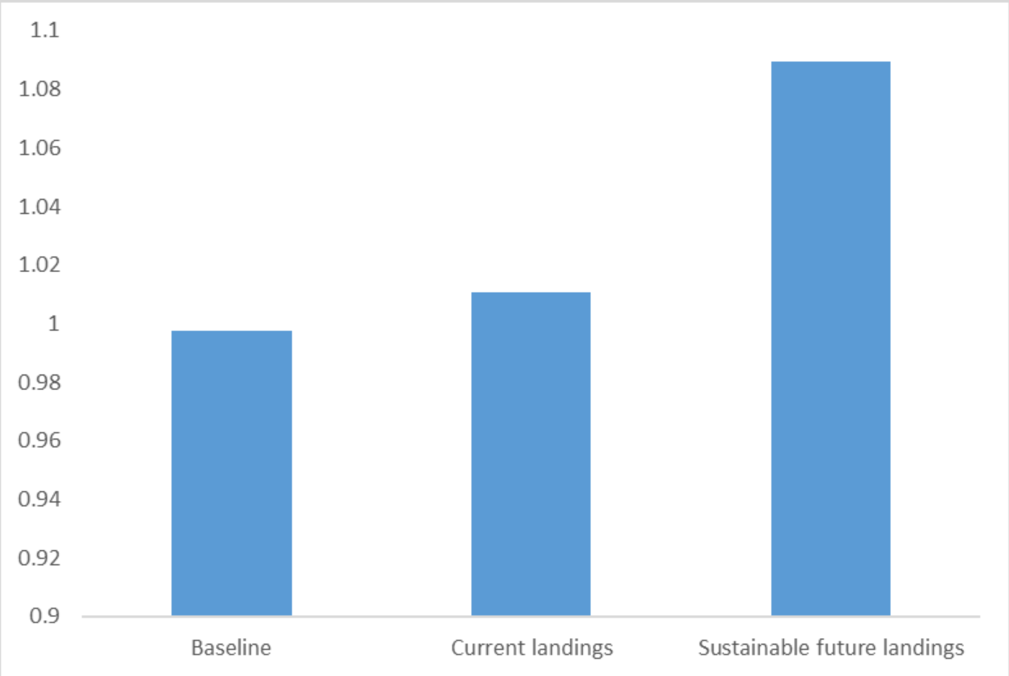


*Figure 4.15. Salmon protein supply (g/(cap*d)) under different fisheries landings*

Feed/food allocation

While we assumed that the full fisheries yield of species currently consumed in the EU is allocated to food, in reality, for some species part of these yielded whole fish are allocated to feed. This, however, considers only few species, of which for most already the majority of the landings is used as food. Compared to our baseline, current practice thus provides more feed, increasing Salmon protein supply slightly (Figure 4.16). Contractively, when extending our human consumption to all food-grade fish, including Blue Whiting, salmon protein supply reduces slightly.

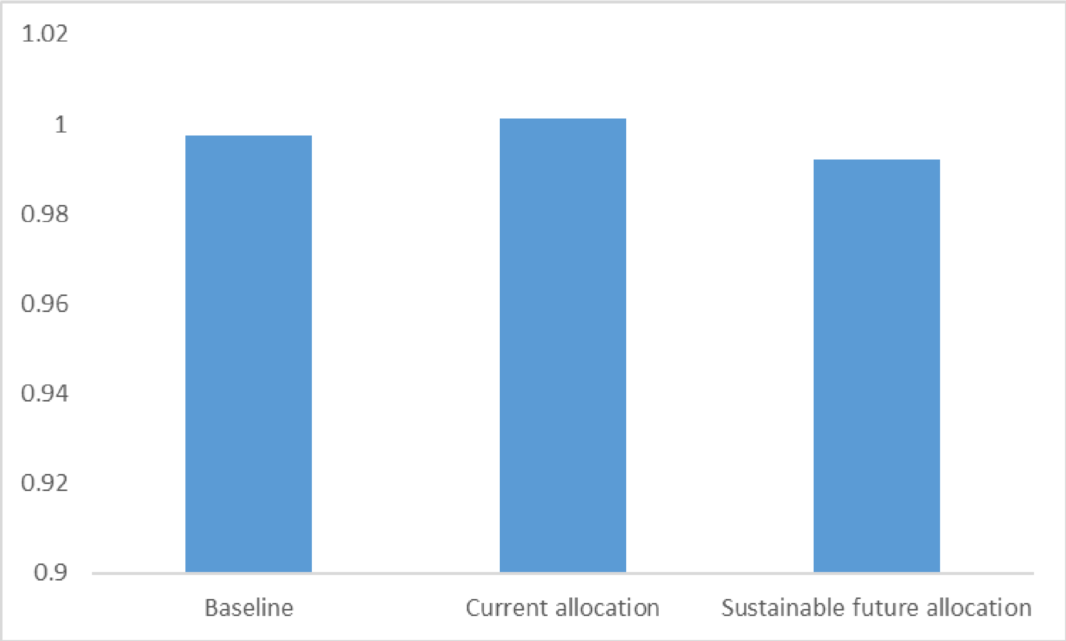


*Figure 4.16. Protein (g/(cap*d)) output per food allocation scenario*

Reducing food waste: a focus on fruit and vegetables

In this report we assessed innovations related to the use of food waste as livestock feed. First priority, however, should remain to prevent food losses and waste. The United Nations, therefore, set the target to globally half per capita food waste at the retail and consumer levels by 2030 (Craig, 2017). After minimising wastage, alternative options handle food waste should be considered in the following order: re-use or redistribute food waste as human food, recycle as livestock feed, fertilizer or compost, recover energy through, for example, anaerobic digestion, and finally, landfill the remainder (Figure 5.1).

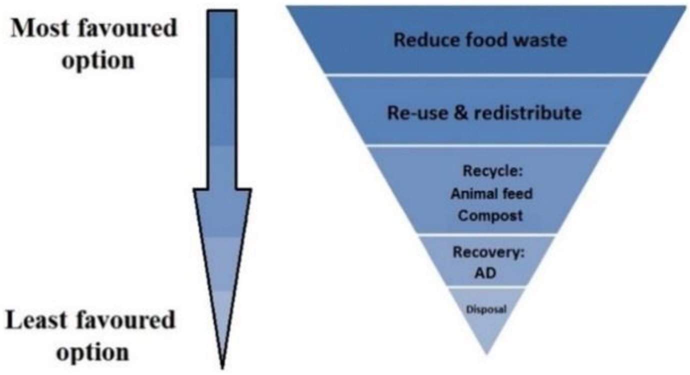


Figure 5.1. The food waste hierarchy of Salemdeeb et al. (2017), AD is anaerobic digestion.

Material and Methods

As prevention is discussed as the most sustainable option in handling food waste (Papargyropoulou et al. 2014), we assessed the potential impact of halving per capita food waste at the retail and consumer level by 2030 making use of the SUSFANS assessment system and parts of the SUSFANS toolbox (SUSFANS D1.4, WP9, WP10). In the course of the SUSFANS project, a comprehensive set of metrics has been developed in order to assess the sustainability of EU food and nutrition security (SUSFANS D1.3, D6.3 (forthcoming)). The SUSFANS toolbox was used to simulate a 50% reduction in consumer food waste by 2030 under two scenarios (a) reduction of food waste in the EU and (b) reduction of food waste globally. Fruits and vegetables are wasted to a higher share than many other products. Thus, avoiding fruit and vegetable waste is regarded as a potential innovation pathway to make food systems more sustainable from a consumer perspective (SUSFANS D5.3). Due to its relevance for the food waste discussion, scenario impacts on the fruit and vegetable chain are separately presented in this chapter. The resulting effects were compared to the business-as-usual reference situation in 2030 (in line with 'REF0' in SUSFANS D10.2, hereafter referred to as '2030 reference'). The scenarios were implemented in the partial equilibrium agri-economic model CAPRI, which has a global coverage with an especially detailed representation of the EU agricultural sector. The reference consumer food waste shares were based on the waste percentages for distribution and consumption by food group and world region published by (FAO, 2011).

Results: all food groups

The enforced halving of food waste at consumer and retail level was implemented as a respective reduction of food purchases. The resulting drop in demand caused an adaptation of agricultural production. Since food group specific waste shares were underlying in the model, the uniformly implemented 50% reduction led to food group specific responses. As for example EU consumer cereal waste shares were assumed to be higher (about a quarter of cereals demanded) than the waste share of meat products (less than a sixth), halving both waste shares implied a stronger reaction in cereal than in livestock demand. Price and trade adjustments alleviated the transmission of the demand reaction to the supply side. For example, in the scenario based on a solely European food waste cut, EU food demand decreased by 9%, while total EU agricultural demand (including food, feed, and biofuel demand) dropped by 4% and EU agricultural production decreased by less than 2% compared to the 2030 reference scenario. These reactions are partly expressed in the competitiveness indicators presented in Figure 5.2. EU and global agricultural production dropped in both food waste reduction scenarios, though considerably less if assuming only a change in food waste for EU consumers. One explanation is the limited drop in producer prices in the 'EU only' scenario. Furthermore, EU agricultural producers can compensate the domestic demand decrease with increasing exports if the change is limited to the European context. As shown in Figure 5.2, imports to the EU decrease relatively stronger than EU production which explains furthermore the differences between EU supply and demand reactions.

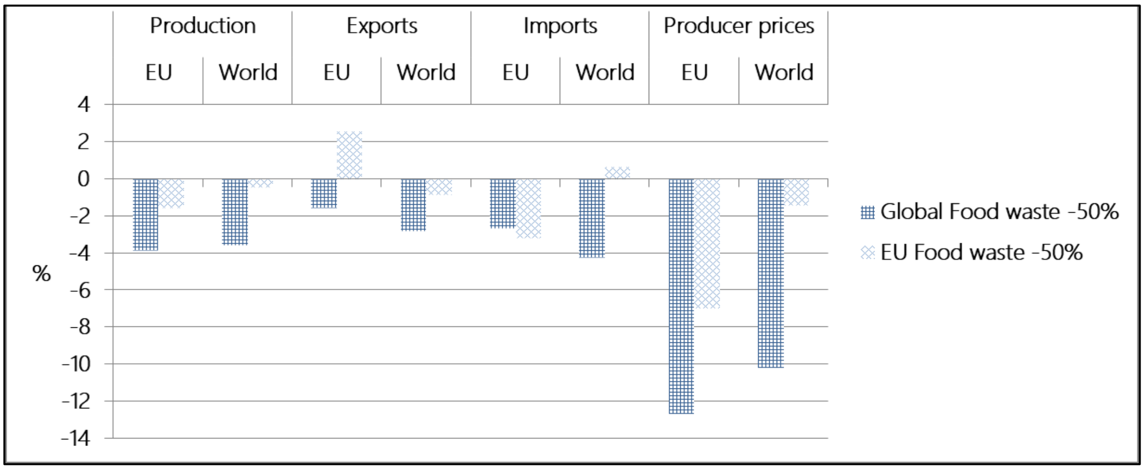


Figure 5.2. Change in the competitiveness of the agri-food business due to halving the food waste at consumer and retail level globally or only in the EU by 2030.

Diet and nutrition indicators were partly affected by food waste reductions. Since the food waste reduction was implemented as a purchase decrease (and not as an intake increase), revealed dietary effects were solely driven by the induced price and food supply changes. Calories increased marginally while the food summary and the nutrient summary scores[3] have improved more strongly due to adjusted food intake compositions as shown in Figure 5.3 For food waste changes restricted to the EU, average global food intake remained nearly unaffected.

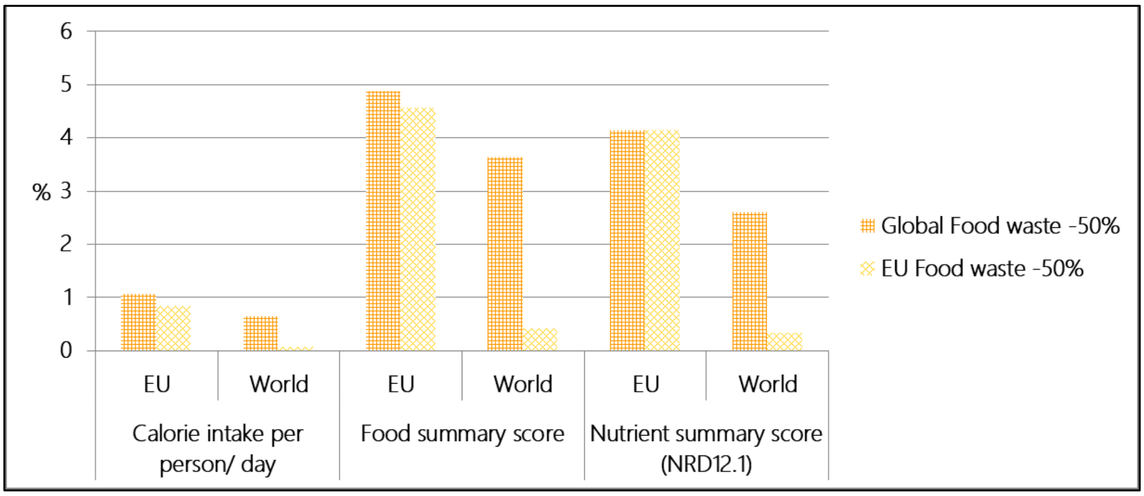


Figure 5.3. Change in diet and nutrition indicators due to halving the food waste at consumer and retail level globally or only in the EU by 2030.

Food waste is first of all considered a waste of resources and responsible for avoidable environmental deterioration. In Figure 5.4 a selection of changes in environmental indicators arising from cutting food waste are presented. Food waste reduction decreased environmental impacts related to agricultural food production in both scenarios. A global food waste cut created greater improvements also at EU level, as restricted trade opportunities limited possible leakage effects. Especially greenhouse gas and nitrogen emissions related to agricultural food production would decrease driven by the drop in production.

[3] See SUSFANS D1.3 for dietary summary score formulas

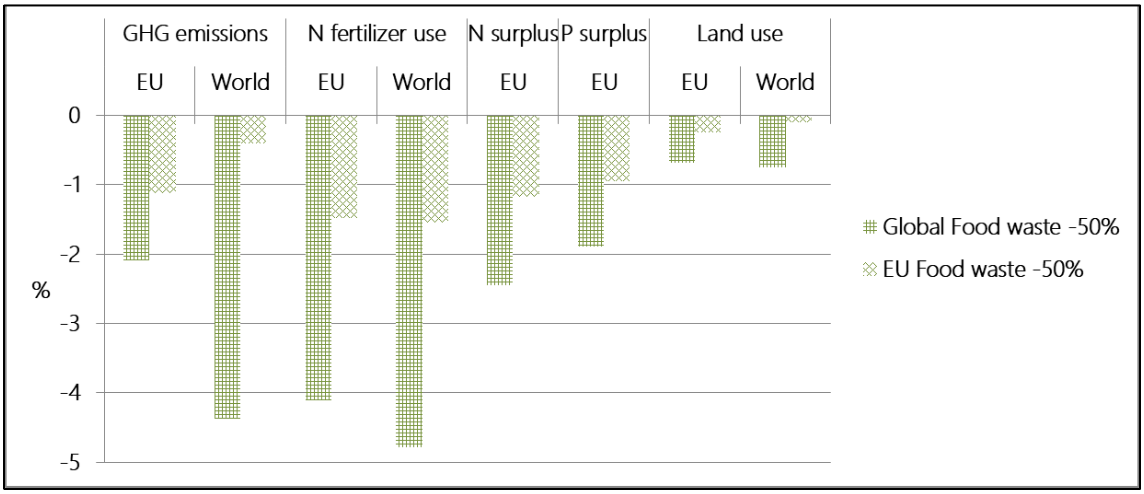


Figure 5.4. Change in environmental impacts from agricultural production due to halving the food waste at consumer and retail level globally or only in the EU by 2030 (N = nitrogen, P = phosphorous).

Results: the fruit and vegetable chain

The fruit and vegetable chain showed similar reactions to the food waste reduction scenarios as the overall agri-food sector. However, impact sizes were a bit stronger compared to the effects in the total agricultural sector shown above (Figure 5.5) likely driven by the larger waste amounts related to the corresponding food group.

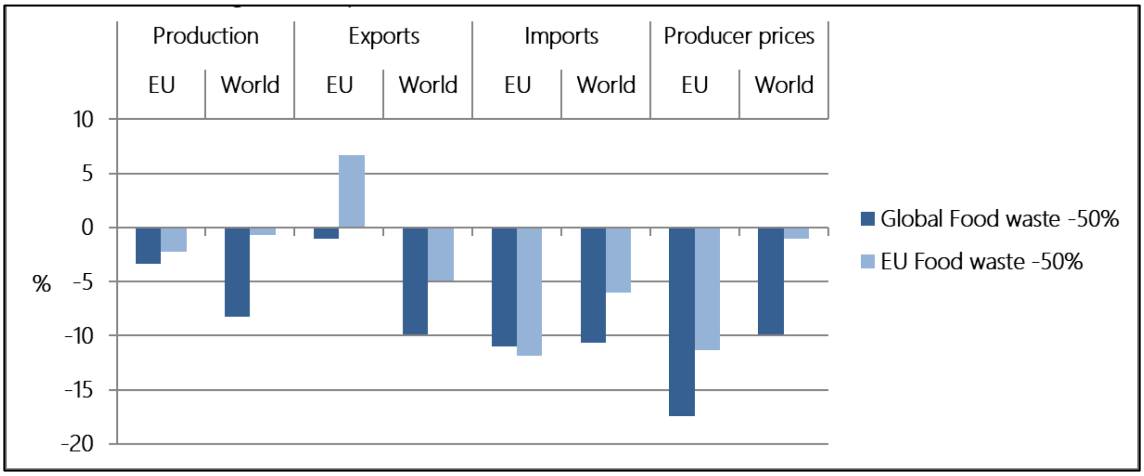


Figure 5.5. Change in the competitiveness of the fruit and vegetable business due to halving the food waste at consumer and retail level globally or only in the EU by 2030.

While the assumed cut in consumer food waste has led to reduced food purchases, the consequential drop in food prices has led to a slight increase in fruit and vegetable calorie intakes and an improvement in the fruit and vegetable food based summary score as shown in Figure 5.6. This demonstrates that despite its direct impacts on food system sustainability, food waste reductions can also have an indirect impact on healthy diets and nutrition.

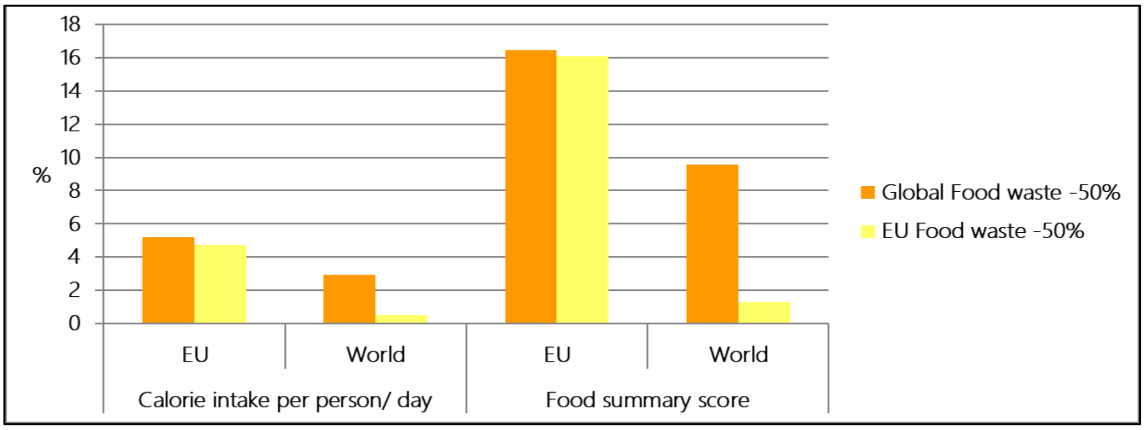


Figure 5.6. Change in fruit and vegetable intakes and in the food summary score for fruit and vegetables due to halving the food waste at consumer and retail level globally or only in the EU by 2030.

Regarding the effects on environmental indicators related to the fruit and vegetable chain, corresponding greenhouse gas emission (GHGE) values were disentangled from those related to the remaining agricultural sector. In Figure 5.7 below, it is shown that fruit and vegetable related greenhouse gas emissions drop more strongly due to the cut in food waste in relative terms than the emissions for the total agricultural sector. However, fruit and vegetable emissions account for only a share of about 1% of total agricultural greenhouse gas emissions.

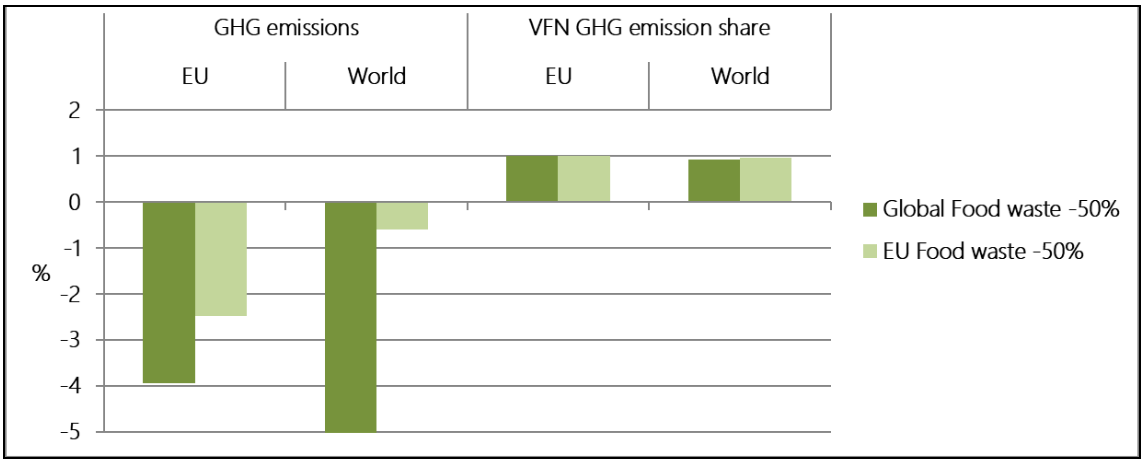


Figure 5.7. Change in fruit and vegetable related GHGE due to halving the food waste at consumer and retail level globally or only in the EU by 2030 and the share of GHGE related to fruit and vegetables in overall agricultural GHGE.

Discussion

Our results are in line with existing literature (Röös et al., 2017b; Usubiaga et al., 2018; Willett et al., 2019) that has addressed a 50% reduction of food waste in the context of sustainability and dietary assessments. We added an extended view on additional sustainability dimensions including economic considerations like trade and leakage effects to the existing body of research. Furthermore, we addressed dietary and nutritional concerns that, despite being affected only to a limited extent by the imposed demand change, are crucial components of any food system analysis.

Halving food waste can push sustainability and nutrition indicators in socially and politically desired directions. However, the presented impacts are limited in extent. The conducted assessment focussed on consumer decisions regarding purchased food quantities. To complement this analysis, questions related to dietary quality and intake were addressed in D10.4 (forthcoming).

The presented indicators did not account for impacts related to current waste treatments (e.g. disposal in landfills, transportation, recycling). This is a clear limitation of our analysis. The true environmental impacts related to food waste are in addition dependent upon its further use and the potential alternatives to this utilization. Future research should address this research gap.

Furthermore, food waste is often also discussed as an ethical question (Gjerris and Gaiani, 2013) considering more than 800 million people being undernourished globally (FAO, 2018e). We did not address any concerns regarding equity, justice and redistribution of food in this context. There is a great difficulty in finding a way of appropriate quantification of these concerns and deficient model coverage in this respect. These aspects should be included in future research on this topic.

The reduction of food waste at consumer level was introduced in the CAPRI modelling system neglecting any costs or necessary interventions related to the implementation of such a change in reality. To stimulate changes in consumers behaviour knowledge is required about the causes related to the high amount of food waste at households in high-income countries. In literature multiple causes are mentioned, such as packaging size, portion size, absence of meal planning, the price of food (e.g. consumers can afford to waste food), too strict not-to-be-used-after dates or lack of knowledge about food and of food preparation skills. Moreover, food waste is affected by, for example, household size (single households waste more per person) and composition (households with children waste more than those without), age (younger people waste more food), education, or the simple fact that some consumers do not perceive (unavoidable) food waste as a waste or feeding food to their pets as a waste. Food waste also occurs because consumers are used to be able to buy the best and newest products, and demand a broad variety of products and full shelves. And, food waste can result from the interaction between the behaviour and attitude of consumers, for whom food is a relatively cheap product that can be bought and discarded, and the retailer, whose interest is to sell as many products as possible.

Although the importance of reducing food waste is clear, it is in the hand of policy makers to choose the pathway how to support consumers to realize this change. In D5.3 different pathways have been proposed including shifts to convenience products, technological solutions and the empowerment of consumers. Setting incentives for consumer food waste reductions should nevertheless be seen as only one element in a set of multiple demand- and supply-side interventions needed in order to reach sustainability goals for the EU food system.

General discussion and conclusion

Many challenges lie ahead for the EU to achieve Sustainable Food and Nutrition Security. One must not forget that the global food system is increasingly connected, between sectors and countries, and is increasingly subjected to shocks (sudden production loss) depending on a range of different factors that may or may not be managed for (Cottrell, 2019). In a world with less stable climate, which has been a key success factor for modern agriculture, improved adaptive capacity for all countries is vital. This report has presented some options for an improved sustainability performance of the EU food system.

The results from Chapter 4 showed that non-competing animal production supplies 33 g of protein /(cap*d) (5 g from pork, 20 g from dairy, 6 g from dairy meat, 1 g from fisheries meat, 1 g from salmon meat). This supply fulfils 60% of our protein requirement. Requirements of omega-3 in the form of DHA and EPA are met by 66% from salmon and captured fish. Collectively livestock and fish fulfil the full vitamin B12, which is only available in animal and fish products. Calcium requirements are met by 94%, iron by 15%, zinc by 61% and selenium by 55% (Figure 6.1).

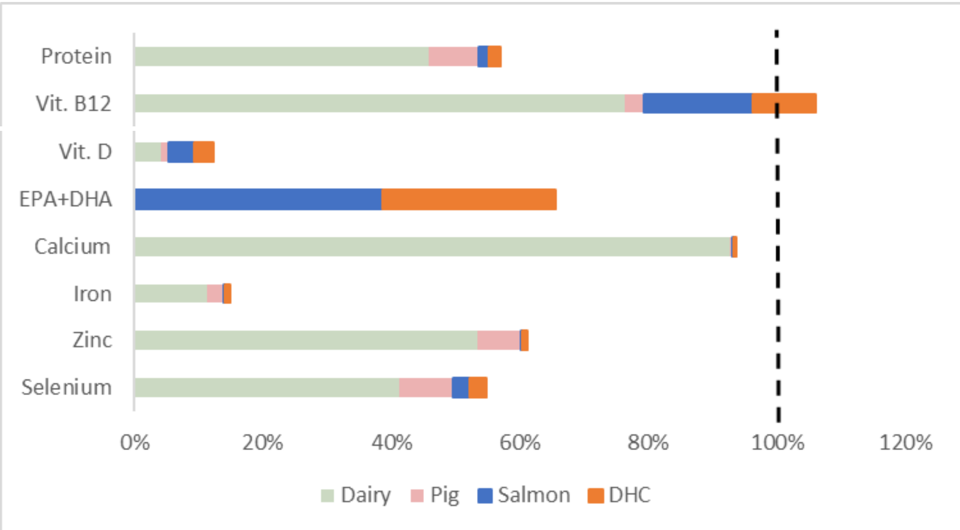


Figure 6.1. Contribution of livestock production, fisheries and Atlantic salmon aquaculture to recommended daily intake of selected nutrients (EFSA, 2017).

Our results therefore show that farmed animals (livestock and fish) reared under the circular paradigm can play a crucial role in feeding humanity. Such farming requires a transition towards circularity in the food system and, therefore, a paradigm shift, as our current food industry is built around the linear extract-produce-consume-discard model (Van Zanten et al., 2019). Furthermore, it requires a reduction in the consumption of ASF as the average protein supply in the EU is 60 g per person per day – with potential negative implications for production although a response in EU trade may prevent much of that impact. Such a transition will require increased collaboration between governmental institutions and private industries for managing key resources, consumer education, and supporting policies and investment to ensure that livestock can contribute to meeting critical SDG in the near future (Van Zanten et al., 2019).

Although our results showed that farm animals reared under the circular paradigm can play a crucial role in feeding humanity, we also showed that we cannot meet our daily nutrient requirement from low-cost animals but need to evaluate other opportunities. To meet our daily recommended nutrient intake – besides adding plant-based foods – non-conventional foods can be used. Chapter 3 showed that non-conventional foods, such as insects, contain the complete array of essential nutrients and in a mixture of non-conventional foods makes them better substitutes for animal-source foods than plant-source foods. Moreover, future foods are efficient use of limited land resources if substituted for animal-source foods, and if produced with renewable energy, they also offer benefits in terms of greenhouse gas emissions. However, to include non-conventional foods in dietary recommendations, more research is needed to elucidate the bioavailability of nutrients and the nutrient losses after processing.

New products and improved utilization of current production will also need to pay attention to consumer acceptance since this will play a main role in the adoption of these foods. As shown in Chapter 4, small pelagic fish are highly nutritious but may have low consumer interest. SUSFANS D2.1 showed that consumers are more willing to replace their meat consumption with other animal-source foods (e.g., eggs, fish, cheese) than to replace it with in-vitro meat or insects. The elaboration of food products made from non-conventional foods should therefore focus on making attractive products for consumers. There is, for example, evidence that negative taste expectations for edible insects can be removed or reduced by serving insects with familiar carrier products (Hartmann and Siegrist, 2017), and presenting them in processed forms (Hartmann and Siegrist, 2016).

Potential trade-offs

To prevent trade-offs in future sustainable food systems we would like to stress three areas of attention for further research:

1. Van Zanten et al. (2018) showed that diets containing animal protein from low-opportunity-cost livestock use less arable land (about one quarter) than a vegan diet and considerably less arable land than the current diets (BAU) (Figure 3.1). Van Zanten et al. (2018) furthermore showed that nitrogen losses and GHG emissions are reduced compared with a business as usual scenario, but not necessarily reduced emission compared with a vegan diet. Thus what might be sustainable from a land-use perspective might not be so in terms of the climate impact and therefore result in trade-offs that are inherent in sustainable food systems (Van Zanten et al., 2018). Future research should, therefore, utilize a systems perspective when further exploring the environmental benefits and draw-backs of avoiding feed-food competition.
2. Another trade-off that might occur is the competition for leftovers between feed and fuel production. In the Netherlands, for example, almost all food waste is used to produce bio-energy. Reducing the availability of food waste might result

in a reduction of the production of bio-energy – and potentially increase use of fossil fuels unless other energy sources are developed (Van Zanten et al., 2015). A transition towards renewable energy sources is, therefore, a requirement.

3. Our calculations indicate a trade-off between the prevention of food waste (Chapter 5) and the use of food waste as animal feed (Chapter 4). Although one could see this as a trade-off we also showed that excluding food waste from our analysis in Chapter 4.1 resulted only in a reduction of 3% in term of protein supply. We might have underestimated the potential of food waste as livestock feed, as we assumed food waste was provided on a wet basis making it less attractive from a feed nutritional point of view. Further research is therefore needed to assess the potential environmental contribution of removing the current regulatory ban on using food waste in the food chain in the EU. The scientific and social support against the ban, which prevents major innovation in this sector in Europe, is growing substantially (Ermgassen et al., 2016; The Pig idea, 2018 and REFRESH, 2018). With an increasing need to address environmental problems, it is important to consider all possible mitigation options within an integrated scientific framework.

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Appendix A

Farmed edible insects are increasingly seen as an important building block of a sustainable food system. Insect-based feed is often suggested as a sustainable feed alternative as insects, for example, can grow on a wide variety of low-value residual organic resources and generally have high protein and lipid contents. The literature review assessed in Chapter 3.2 provide information on the environmental impact of farmed insects. Farmed insects can be used either as food or as feed. Although from an environmental potential it is more beneficial to use insects as food, its use in human diets will be driven by factors such as consumer acceptance, food safety and costs. In Figure A1 and A2 we show the nutrient content and environmental impact of three insect-larvae species compared to feed and food ingredients.

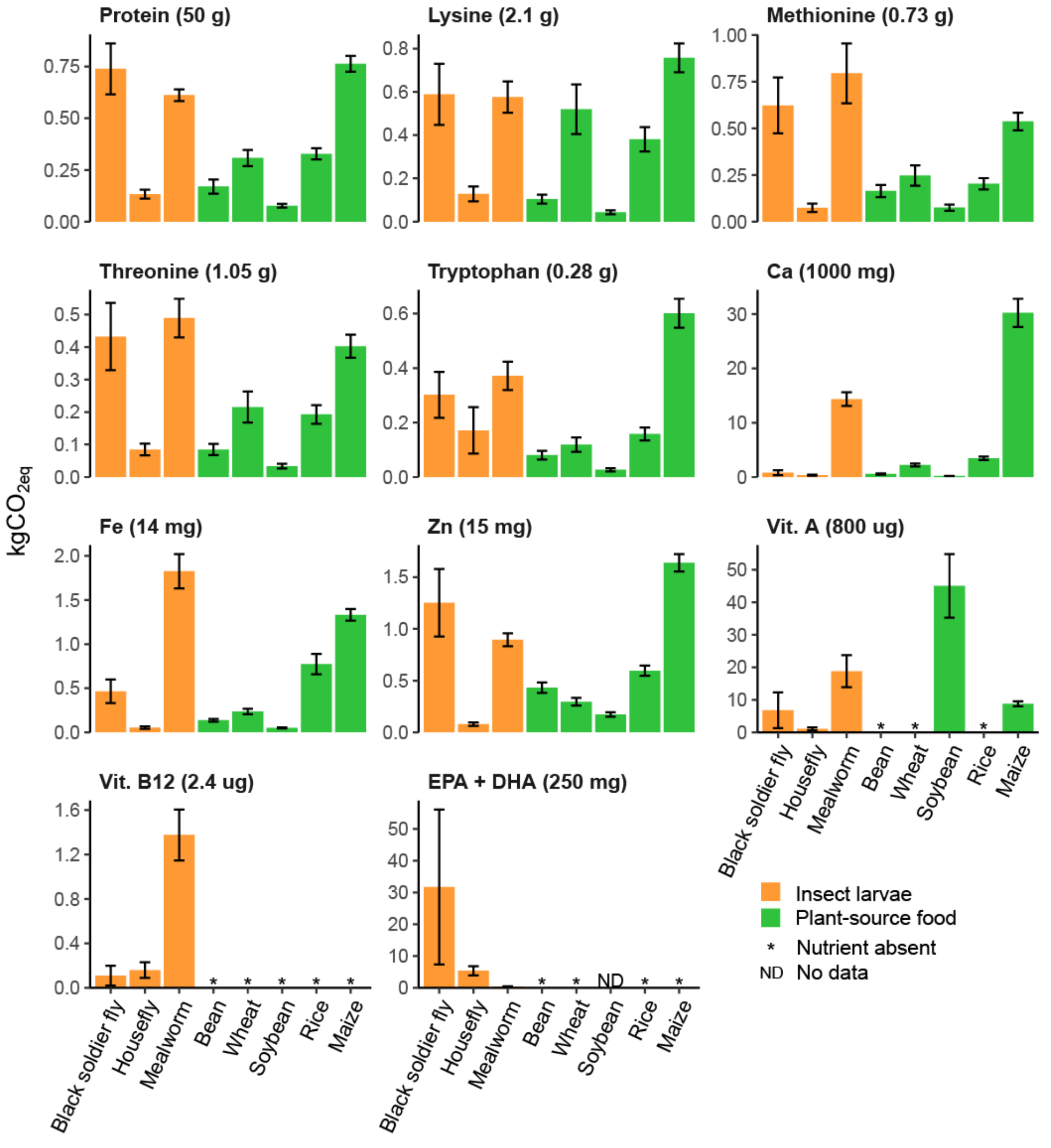

Figure A1 GWP per unit of nutrient of larvae of black soldier fly, housefly and mealworms compared to food/feed ingredients.

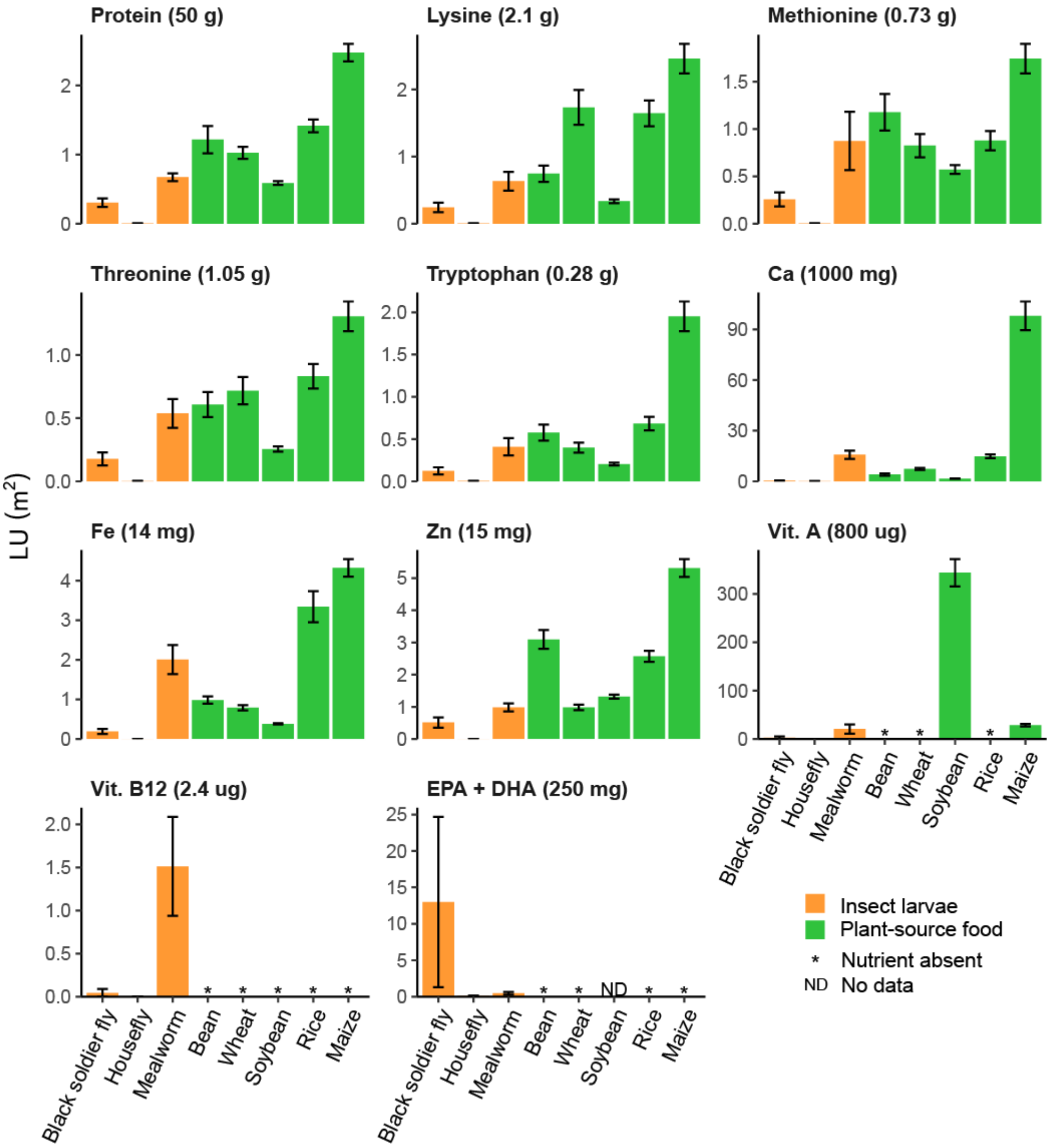

Figure A2 LU per unit of nutrient provided by larvae of black soldier fly, housefly and mealworms compared to food/feed ingredients.

Appendix B

Table B1 Nutrient content per 100 g of raw edible portion of seafood species, desirable nutrients light grey, undesirable nutrients dark grey.

Nutrient	Protein	PUFA	Ca	Cu	Iron	K	Mg	P	Zn	Iodine	Se	SFA	Na
RDI*	50	2.75	1000	0,900	22	3500	310	700	14	150	60	20	2000
Units Species	G	G	mg	mg	Mg	mg	mg	mg	mg	µg	µg	g	mg
Atlantic cod	18.2	0.21	8.70	0.018	0.150	373	24.7	196	0.36	300	30.98	0.090	74
Atlantic herring	18.0	1.71	57.0	0.092	1.10	327	32.0	236	0.99	No data	36.50	2.04	90
Atlantic horse mack	18.6	1.22	39.6	0.100	1.08	379	29.1	220	0.41	29	53.3	1.660	65
Atlantic mackerel	18.6	2.65	12.0	0.073	1.63	314	76.0	217	0.63	No data	44.10	3.257	90
Blue whiting	16.1	0.915	429	No data	1.75	264	63.0	309	1.10	0.023	0.06	0.754	425
European hake	16.5	0.090	41.0	No data	0.50	365	24.0	142	0.30	No data	20.00	0.090	74
European plaice	21.1	0.140	12.2	0.050	0.07	412	24.3	185	0.43	32	29.00	0.090	100
European sprat	17.6	1.53	157	0.080	1.65	246	31.0	381	2.71	59.0	22.60	2.440	68
Haddock	16.3	0.182	11.0	0.021	0.17	286	21.0	227	0.32	No data	25.9	0.091	213
Ling	19.0	0.150	34.0	0.110	0.65	379	63.0	198	0.78	No data	36.5	0.12	135
Norway pout	18.5	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
Norway lobster	24.0	0.290	60.0	No data	0.80	274	25.0	183	1.3	77	50	0.14	53
Northern prawn	17.6	0.150	21.0	0.360	0.22	88.0	37.0	147	1.12	20	23	0.090	630
Saithe	19.4	0.440	60.0	0.050	0.46	356	67.0	221	0.47	No data	36.50	0.135	86
Sandeels	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data

*RDI source: Codex Alimentarius (FAO)

Table B1 (continued) Nutrient content per 100 g of raw edible portion of seafood species, all defined as desirable nutrients.

Nutrient	Vit A	Vit D3	Vit E	Thiamin	Riboflavin	Niacin-eqs	Pantothenic acid	Vit B6	Folate	Vit B12	Source nutrition database
RDI	800	10	9	1,2	1,2	15	5	1.3	400	2.4	
Units Species	µg	µg	mg	mg	mg	mg	mg	mg	µg	µg	
Atlantic cod	2.30	2.11	0.63	0.050	0.045	5.26	0.150	0.145	11.0	1.12	FAO
Atlantic herring	28.0	4.2	1.07	0.092	0.233	6.57	0.645	0.302	10.0	13.7	Canada
Atlantic horse mack.	4.35	27.3	0.63	0.080	0.150	7.84	0.323	0.335	2.00	6.83	FAO
Atlantic mackerel	50.0	2.00	1.52	0.176	0.312	12.5	0.856	0.399	1.00	8.71	FAO
Blue whiting	2.37	4.00	0.35	0.160	0.400	No data	0.330	0.160	15.7	7.73	Norway
European hake	10.0	0.70	0.39	0.100	0.200	6.03	No data	0.180	12.0	1.30	Sweden
European plaice	0	1.97	0.42	0.360	0.080	9.30	No data	0.290	11.9	0.70	Sweden
European sprat	60	20.3	0.76	0	0.150	7.60	0.710	0.270	17.6	10.4	Sweden
Haddock	17.0	0.20	0.45	0.020	0.057	6.90	0.221	0.281	9.00	1.83	Canada
Ling	30	0	No data	0.11	0.190	5.85	0.320	0.304	7.00	0.560	Canada
Norway pout	No data	No data	No data	No data	0.090	0.90	No data	No data	No data	No data	Denmark
Norway lobster	15	0.50	1.5	0.080	0.060	6.90	No data	0.210	17.0	0.500	Sweden
Northern prawn	0	0	3.93	0.040	0	4.20	0.210	0.040	14.0	3.52	Sweden
Saithe	14.0	1.00	0.23	0.047	0.185	6.903	0.358	0.287	3.00	3.19	Canada
Sandeel	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	-

*RDI source: Codex Alimentarius (FAO)

Table B2 Distribution of TACs of stocks of the species included between EU member states, the "Relative Stability" for separate stocks summed up (%)

Species	Belgium	Den-mark	Estonia	Finland	France	Ger-many	Greece	Ireland	Latvia	Lituania	Nether-lands	Poland	Portugal	Spain	Sweden	UK
Atlantic herring	1,1	18,4	4,4	13,4	5,0	8,9	0	1,7	2,4	0,7	11,8	6,7	0	0	14,3	11,2
Atlantic Cod	1,1	16,6	0,5	0,4	7,4	13,4	0,2	1,1	1,9	1,2	3,0	7,6	4,0	11,0	6,4	23,8
Blue whiting	0	13,6	0	0	9,4	5,2	0	10,4	0	0	16,4	0	3,4	20,7	3,3	17,6
Atlantic mackerel	0,1	7,6	0	0	3,9	5,3	0	17,1	0	0	7,9	0,4	1,6	7,6	1,2	47,3
European sprat	0	15,4	10,4	4,7	0,1	5,7	0	0	12,5	4,5	0,1	26,5	0	0	19,6	0,6
Haddock	0,7	6,6	0	0	13,6	2,7	0	7,3	0	0	0,3	0	0	0	0,7	68,0
Pollock	0,1	6,7	0	0	50,8	21,3	0	0,7	0	0	0,3	0	0	0	0,9	19,2
European plaice	5,9	27,7	0	0	5,2	4,7	0	1,1	0	0	30,1	0,7	0	0	0,8	23,6
European hake	0,6	4,3	0	0	51,1	0,2	0	3,0	0	0	0,5	0	2,4	27,4	0,2	10,3
Atlantic horse mackerel	0	8,6	0	0	2,6	4,5	0	14,2	0	0	18,8	0	23,8	21,4	0,4	5,8
Sandeels	0	94,3	0	0	0	0,1	0	0	0	0	0	0	0	0	3,5	2,1
Norway pout	0	99,9	0	0	0	0	0	0	0	0	0,1	0	0	0	0	0
Norway lobster	1,6	13,0	0	0	12,9	0,1	0	13,2	0	0	0,8	0	0,3	2,5	3,8	51,9
Northern prawn	0	67,8	0	0	0	0	0	0	0	0	0,2	0	0	0	25,0	6,9
Ling	0,5	8,2	0	0	26,3	5,2	0	4,7	0	0	0	0	0	17,5	0,2	37,4
European pilchard*	0	3	0	0	34	3	0	0	0	0	6	0	19	22	0	13