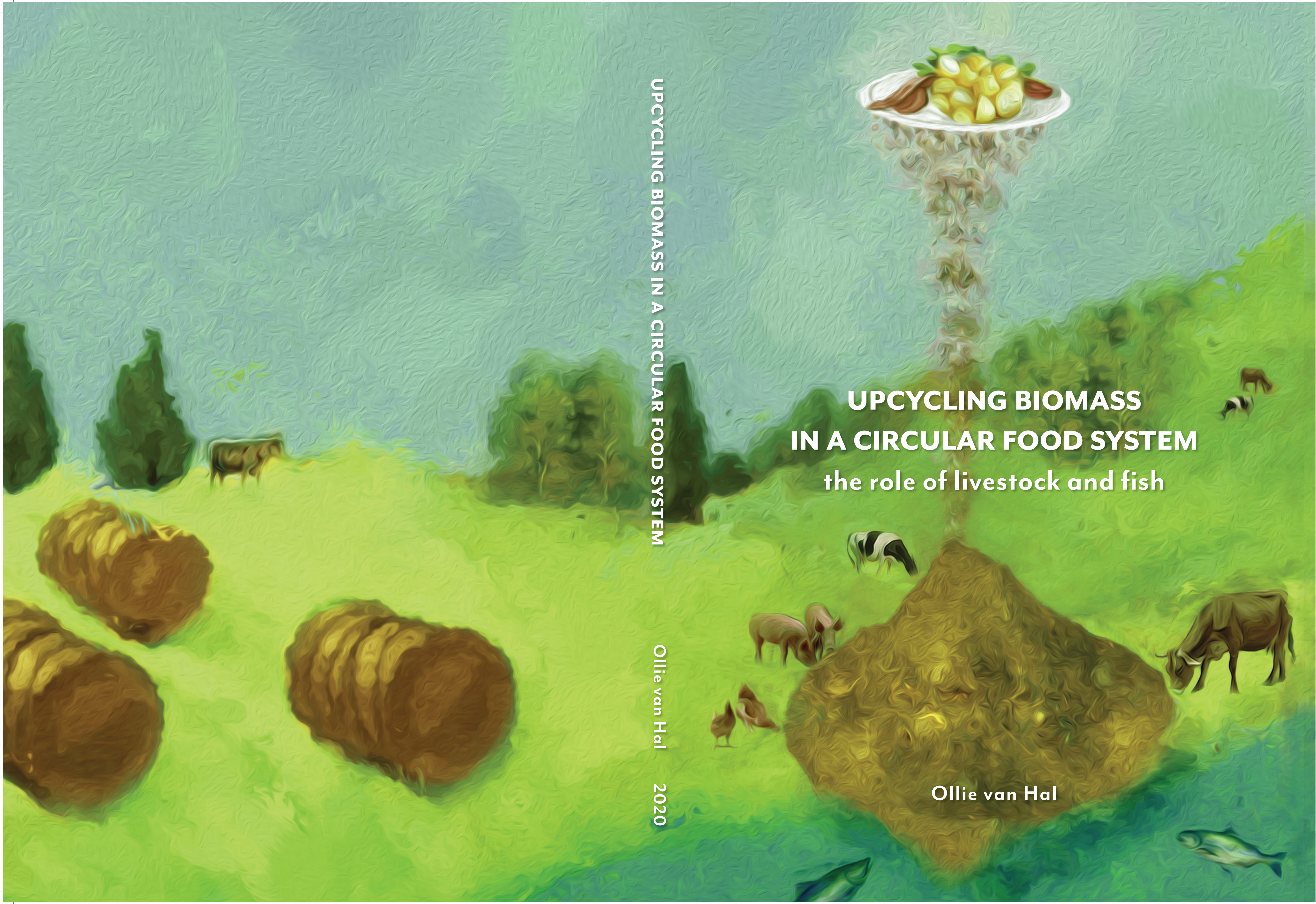

UPCYCLING BIOMASS IN A CIRCULAR FOOD SYSTEM

the role of livestock and fish

Ollie van Hal

UPCYCLING BIOMASS IN A CIRCULAR FOOD SYSTEM
Ollie van Hal

2020

Propositions

1. Each farm animal has a unique role in a healthy and resource-efficient food system.
(this thesis)

2. Metrics used in practice to reduce environmental impacts of animal-source food counteract resource use efficiency of the food system.
(this thesis)

3. Our current economic systems exploit our planet.

4. Solutions proposed by research for development are often ineffective as they are based on limited understanding of those affected.

5. We should not hold on to traditions that harm others.

6. There is no such thing as positive discrimination.

Propositions belonging to the thesis, entitled

‘Upcycling biomass in a circular food system – the role of livestock and fish’

Ollie van Hal

Wageningen, 30 October 2020

Upcycling biomass in a circular food system

– the role of livestock and fish –

Ollie van Hal

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Upcycling biomass in a circular food system
– the role of livestock and fish –

Ollie van Hal

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Abstract

A more circular food system is increasingly proposed to address the challenge of feeding a growing world population while limiting environmental impacts and resource use. A circular food system prioritises resources for direct food supply to avoid feed-food competition. The role of animals is to upcycle resources unsuitable or undesired for human consumption, so called low-opportunity-cost feeds (LCF) into animal-source food. This thesis evaluates the potential of various animals in upcycling LCF in a circular food system by applying an optimisation model that allocates available LCF to that combination of animals that maximise the supply of human digestible protein (HDP) to a EU-28 case study. We first explored the potential of common livestock species in the EU (e.g. pigs, laying hens, broilers, dairy cattle and beef cattle) under various productivity levels. Optimal use of LCF required livestock systems that had a high conversion efficiency (laying hens, dairy cattle), were best able to valorise specific LCF (dairy cattle for grass; pigs for food waste) and could valorise low quality LCF due to their low productivity. When, in addition, considering fish – currently the only natural source of the essential eicosapentaenoic (EPA) and docosahexaenoic (DHA) ω-3 fatty acids – while demanding EPA/DHA requirements are met, fish provide nutritious food via both capture fisheries and fish farming. Even if capture fisheries rebuilds stocks and prioritises edible fish for human consumption, it can only fulfil 40% of EPA/DHA requirements. The farmed fatty fish needed to meet these requirements depend on fisheries by-products to meet their EPA/DHA requirements and livestock slaughter by-products to meet their high fat and protein requirements. A circular food system thus requires a combination of co-dependent animal production systems, tailored to the available LCF and the desired nutrient output. As the availability of food leftovers as LCF is currently restricted by legislation and other barriers, we explored the potential of food leftovers currently not used as LCF. Potential to increase animal protein intake was highest for, currently banned, household waste (+12%) and livestock by-products (+18%) that are allowed in fish feed but currently not used and appear essential to meet human requirements of EPA/DHA ω-3 fatty acids in a circular food system. Improved use and legalisation of inevitable food leftovers can improve the resource use efficiency of both current and future circular food systems. When allowing all LCF in a circular food system, livestock and fish provide an HDP intake up to 39 g per capita per day, less than current animal protein supply but meeting 65% of total protein requirements. A circular food system, thus, requires a reduction in ASF consumption, and a change in the type of ASF we consume, where fish and milk become more prominent. While the used food systems approach illustrates the potential of animal production in a circular food system, it provides little direction to farmers in achieving sustainability objectives.

Currently, they base their sustainability strategies on supply chain life cycle assessments (LCA) that does not account for feed-food competition. In a case study of a novel egg production system, such LCA underestimated the environmental benefit of feeding only LCF with 57% for global warming potential and 96% for land use. The proposed food-based allocation, better captures the complexity of the food system, a first step towards metrics that stimulate circularity. Besides improved understanding of our food system, such novel metrics and changed consumption patterns, the paradigm shift needed to move towards a circular food system requires that policy makers value social and economic aspects within the ecological boundaries of our planet. This way, farm animals can contribute to the resource use efficiency of the entire food system.

Contents

Chapter 1

General introduction

1. Background

The food system faces the continuous challenge of feeding the ever growing world population that is expected to reach 9.7 billion people in 2050 (United Nations, 2015). Since the industrial revolution, and more so, after the second world war, we addressed this challenge in Europe by intensifying agricultural production, through increased use of farm inputs such as mineral fertilizers, pesticides, imported feed, improved plant and animal genetics, advanced machinery and new technology. (Giampietro, 2019; Warde, 2009). Where pre-industrial agriculture was dictated by nature and characterised by scarcities, intensification helped overcome natures limitations and increased yields exponentially (Crone, 2015; Giampietro, 2019). Grain yields, for example, increased from 1 tonne per hectare in pre-industrial agriculture to 1000 tonne per hectare in industrial agriculture (Giampietro, 2019). Mechanisation and specialisation, furthermore, reduced the labour required to produce these yields. Above described developments also disconnected crop and animal production and thereby, reduced the extent to which resources such as manure are shared (de Boer & van Ittersum, 2018). Our agricultural system, therefore, currently operates on a linear system.

While these advances enabled Europe, and many other regions, to feed our growing population with more luxurious diets, we are currently faced with the environmental consequences of this system (Jurgilevich et al., 2016). As agriculture currently globally extracts, uses and disposes resources at a high pace, it is no longer aligned with the rate at which nature generates resources and neutralises wastes (Giampietro, 2019; Haberl et al., 2011; Korhonen et al., 2018). After years of picking the fruits of this system, we run into the limits of available resources and the hazards of undesired emissions and accumulated waste (Jurgilevich et al., 2016; O'Neill et al., 2018). Scarcity of agricultural land, for example, drives destruction of our most valuable forests in terms of biodiversity and carbon storage (Foley et al., 2011). Agriculture, furthermore, has depleted phosphate mines to such extent that their continued availability for agriculture is under threat (Cordell & White, 2015). Imports that feed the European livestock sector, mine soils of nutrients in areas where food security is already threatened (Patnaik, 1996; Smil, 2014). These nutrients accumulate in the European Union (EU) and, combined with mineral fertiliser application, result in eutrophication and acidification of local ecosystems (Oenema et al., 2005; Sims et al., 2005). Finally, our food system contributes 25% to human induced global warming (Bajželj et al., 2014; Tilman et al., 2011).

Together these impacts have reduced earths potential to provide life-sustaining functions, such as food, fibre and fuel (Korhonen et al., 2018). This problem will become worse if we maintain current production and consumption standards to feed the growing population, as we will exceed the ecological boundaries of our planet (Haberl et al., 2011; Steffen et al., 2015; Tilman et al., 2011). To preserve life-sustaining functions for future generations we must, therefore, reconsider our food production and consumption practices (Giampietro, 2019; Springmann et al., 2018; Willett et al., 2019). Our food system is, thus, not only faced with the challenge of feeding a growing population, but must simultaneously increase its resource use efficiency and mitigate environmental impacts. In this light, consumption of animal-source food (ASF) is criticised due to its relatively inefficient use of resources and high environmental impact (Aleksandrowicz et al., 2016; Hallström et al., 2015). In the following sections we discuss the controversy regarding the production and consumption of ASF (1.1), and the role of animals in a circular food system (1.2).

1.1 The animal controversy

Scientifically, production and consumption of ASF is controversial in many ways, but its high environmental impact is a prominent concern. While studies agree that the high environmental impact of ASF should be addressed, controversy is found in the proposed mitigation strategies. Recent reviews illustrate that these studies can be classified based on the core assumptions that shape the mitigation strategies they propose (Frehner et al., 2020; van Zanten et al., 2018). Three distinct paradigms result from this classification; the production paradigm, the consumption paradigm, and the circularity or consistency paradigm. The circularity paradigm is relatively young, as it was introduced in response to limitations of the production and consumption paradigm which will be described in detail first.

The production and consumption paradigms both rely on data and methods of the life cycle assessment (LCA), a standardised method to evaluate the environmental impact of a product or production system (ISO14044, 2016). The production paradigm assumes that the increasing human demand for ASF must be met and, therefore, aims to reduce the impact per kg ASF through changes in the production system (van Zanten et al., 2018). They typically propose to increase the efficiency with which animals convert their feed into ASF, through breeding, feeding and housing strategies (de Vries & de Boer, 2010; Herrero et al., 2016). The consumption paradigm, in contrast, assumes consumption of ASF should be reduced to mitigate the environmental impacts of human diets (Frehner et al., 2020). They typically recommend a vegan or vegetarian diet, or a shift from high impact ASF, such as beef, to low impact ASF, such as milk or chicken (Aleksandrowicz et al., 2016; Hallström et al., 2015). These studies often highlight the health benefits of such dietary change as high consumption of ASF in high-income countries increases the risk of non-communicable diseases (Aleksandrowicz et al., 2016; Willett et al., 2019).

While both production and consumption paradigms provide valuable insights, the LCA methodology used undermines the complexity of our food system (Gamboa et al., 2016; van Kernebeek et al., 2016; van Zanten et al., 2018). While considered a holistic method, LCA takes a supply chain approach, including only those processes that contribute directly to the final product, in this case food (de Vries & de Boer, 2010). LCA, thereby, does not consider that the numerous supply chains that form our food system are interconnected, and that changes in one chain likely triggers changes in others. Due to their supply chain approach, studies under both the production and consumption paradigm, often promote mitigation strategies that counteract the resource use efficiency of the food system as a whole, as will be demonstrated in Section 2.2 (Frehner et al., 2020; van Zanten et al., 2016b). In response, researchers increasingly proposed a shift to the circularity paradigm that uses a food systems approach to account for the consequences of changes in our food system (Garnett, 2011; Schader et al., 2015; van Zanten et al., 2018). Studies under this paradigm indicate that efficient use of resources requires changes in both production and consumption, and highlight that animals have a valuable role in upcycling biomass unsuitable for human consumption into food and other ecosystem services (Frehner et al., 2020; van Zanten et al., 2018). Typically, such studies encourage a more circular food system – as aspired by the EU (EuropeanCommission, 2015) – where the resource use efficiency of the food system as a whole is central (Ghisellini et al., 2016; Jurgilevich et al., 2016).

1.2 A circular food system

A circular food system aims to minimise resource use and environmental impacts by closing the loop of materials and substances (Ghisellini et al., 2016; Jurgilevich et al., 2016). To this aim, the use of finite resources (e.g. phosphate rock and land) should be minimised, while use of regenerative resources (e.g. wind and solar energy) is stimulated (de Boer & van Ittersum, 2018; van Zanten et al., 2019). A system based on renewable resources, however, has to adhere to natures pace and requires moderated consumption (Haberl et al., 2011; O'Neill et al., 2018; Vivien et al., 2019). A circular food system, therefore, requires that we adapt both production and consumption practices (de Boer & van Ittersum, 2018; van Zanten et al., 2019). It, furthermore, requires that resource losses are reduced, while inevitable losses are reused or recycled in a way that adds the highest value to the food system (Ghisellini et al., 2016; Jurgilevich et al., 2016). To move to a (more) circular food system, we must thus focus on the resource use efficiency of the entire food system, rather than of individual subsystems as currently applied in research that advices policy makers (Korhonen et al., 2018). Assuming the food system aims to provide adequate nutrition to all humans, we should value resources based on their potential to provide humans with the nutrients they require. This can be achieved by exploring the opportunity costs of various applications of biomass in the food system, for example as feed or food (Palmer & Raftery, 1999).

Opportunity costs and feed-food competition

Opportunity costs refer to the benefits missed out on when choosing one alternative over another (Palmer & Raftery, 1999). Garnett (2009) illustrated the relevance of opportunity costs in the food system, where they refer to the nutritional costs of choosing to use resources in a specific food production system. She proposed that, given the global constraint on agricultural land, we should consider the opportunity costs of using such land to feed animals rather than produce food for direct consumption. When feeding grains to animals, for example, we lose the nutritional benefits of eating these grains ourselves. This specific application of opportunity cost in the food system, that implies that products consumed by animals may compete for resources with human food supply, is referred to as feed-food competition (van Zanten, 2016). Direct feed-food competition refers to the opportunity costs of feeding animals with products suitable for human consumption. Indirect feed-food competition refers to the opportunity costs of producing feed on arable land suitable for food crop production (van Zanten, 2016).

Feed-food competition counteracts efficient use of resources due to the nutrients lost via emissions and heat when animals convert feed into ASF (Goodland, 1997). Nutrients that do end up in ASF, however, often have a high bioavailability compared to plant based alternatives, such as protein and iron, or are currently only obtained from ASF such as vitamin B12 and EPA/DHA fatty acids (Godfray et al., 2018; Smith et al., 2013; West et al., 2014). Regardless of these nutritional benefits, the environmental and resource costs of the food system are lowest if arable land is used to grow crops for human consumption (Bowles et al., 2019; Foley et al., 2011; Godfray et al., 2010). For land use, this was illustrated with the land use ratio (LUR), which reflects the human digestible protein (HDP) cost of using land to feed animals rather than to produce the most suitable food crop (van Zanten et al., 2016b). Of the livestock systems evaluated by van Zanten et al. (2016b) only dairy cattle grazing on land unsuitable for food crop production provided more HDP than food crops could provide using the same land.

As in high income countries diets contain relatively large amounts of ASF, their environmental impact and resource use is much higher than needed to meet nutrient requirements (Bowles et al., 2019). The opportunity cost of this high ASF consumption even exceeds that of all food waste

(Shepon et al., 2018). High income countries should, thus, reconsider their excessive consumption of ASF, as this results in feed-food competition and inefficient use of resources (Springmann et al., 2018).

Circularity framework

To avoid feed-food competition, a circular food system prioritises the use of resources, especially spatial ones like land and waterbodies, for direct food supply (de Boer & van Ittersum, 2018). This implies arable land should be used for food crop cultivation and waterbodies for sustainable fisheries of which edible fish is used as food (Figure 1). Processing and consumption of this food, however, result in by-products and wastes, unsuitable or undesirable for human consumption. Feeding animals with such food leftovers, and grass resources, especially from land unsuitable for food crop cultivation, has a low opportunity cost as they otherwise find no use in the food system (Bowles et al., 2019; Garnett, 2009). By upcycling these low-opportunity-cost feeds (LCF), animals may contribute to the resource use efficiency of the food system van Zanten et al. (2018). The role of animals in a circular food system is, thus, to upcycle LCF into ASF, to provide protein and other valuable nutrients (van Zanten et al., 2019).

2. Knowledge gaps

2.1 Animals in a circular food system

A recent review of van Zanten et al. (2018) illustrates that the land use of a diet containing a small amount of ASF, produced by feeding only LCF, is lower than that of a vegan diet. They, thereby, show that animals fed solely on LCF indeed increase the resource use efficiency of the food system. The reviewed studies, furthermore, show that farm animals fed only with LCF can provide 7-30 g HDP per capita per day. Variation between studies was largely due to differences in the assumed availability of LCF, and the animal species assumed to upcycle them. While these initial studies are a valuable prove of concept, their case-study approach provides limited insights in how different animals may contribute to a circular food system. To better understand the role of different animals, we must explore the conditions in which these animals should function. These conditions relate to the properties of the LCF they are expected to upcycle and what nutrients the should provide the human population in doing so. Based on these conditions, we can explore which animals are most suitable to a circular food system.

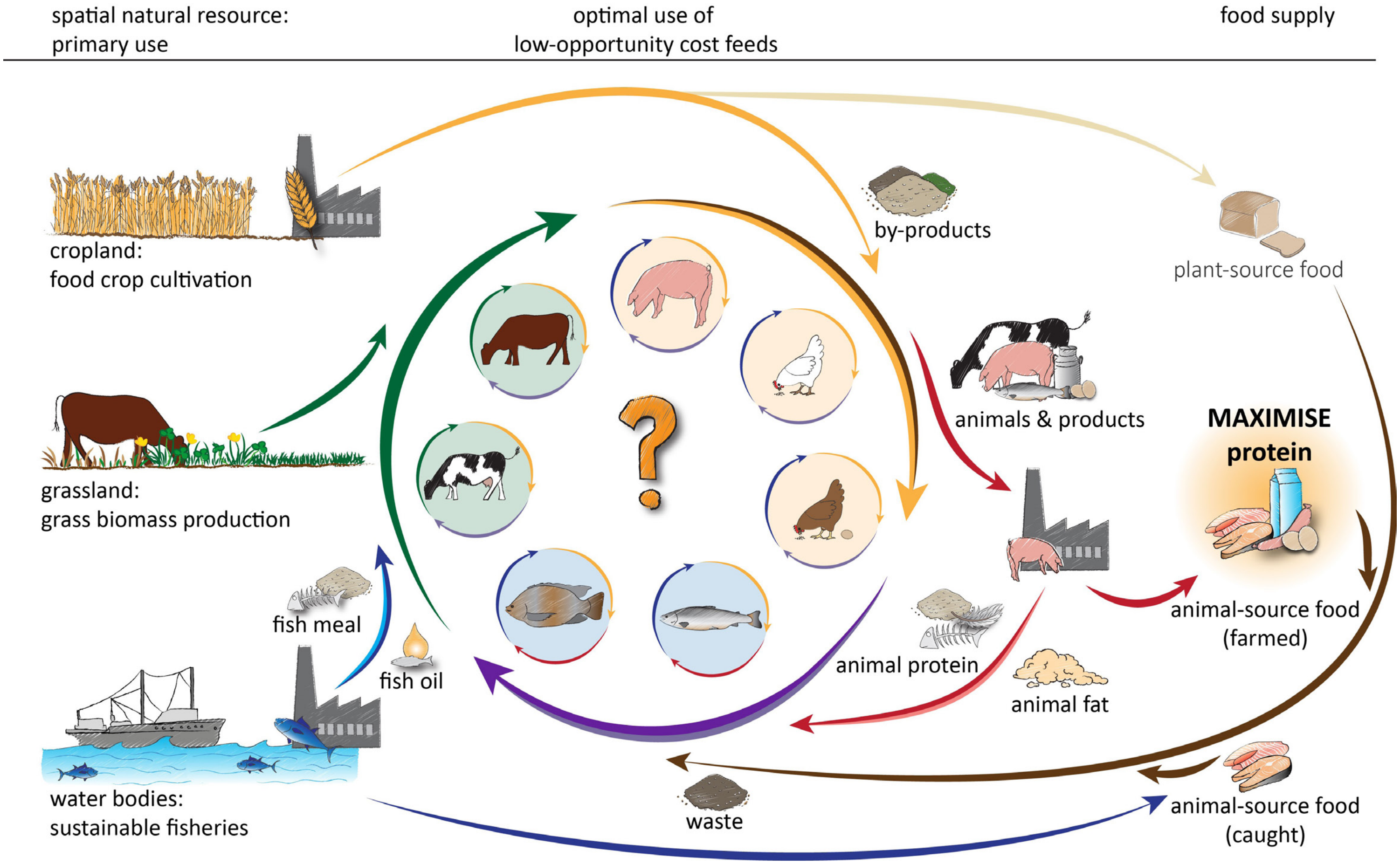

Figure 1 Framework to assess the potential of animals to upcycle available low-opportunity-cost feed into human food; Adapted from van Zanten et al. (2019).

Regarding LCF, it is debated which agricultural products unsuitable or undesirable for human consumption should be used as feed (van Zanten et al., 2018). While most grass resources and food leftovers (losses and wastes from the food system) qualify, it remains uncertain to what extent they should be used. For grass resources there is an ongoing debate about the inclusion of grass produced on land suitable for food crop cultivation, as conversion of such grassland results in release of stored carbon and loss of biodiversity (Foley et al., 2005, 2011; Garnett, 2011; Gerber et al., 2013). Same holds for the inclusion of crop residues, as leaving (some of) these on the field is essential to ensure soil health, the fundament of a circular food system (de Boer & van Ittersum, 2018). Some other food leftovers (e.g. crop by-products) are already fully used as feed, while the use of others (e.g. animal by-products and food waste) is limited by legislation and other barriers (Vernier et al., 2016). Exploring the potential of currently unused food leftovers can increase the potential of animals in a circular food system and the resource use efficiency in our current food system.

Regarding supply of animal-based nutrients, most studies that assessed the potential of animals fed only with LCF focused on the supply of human-edible protein (HDP). ASFs are, however, also known to contain a range of valuable micronutrients (Mertens et al., 2017), such as iron, zinc, vitamin D and selenium. Like protein – iron, zinc, vitamin D and selenium in ASF have a higher bioavailability than their plant-based equivalents (Smith et al., 2013). Moreover, vitamin B12 and eicosapentaenoic (EPA) and docosahexaenoic (DHA) ω-3 fatty acids are currently only obtained from ASF (de Smet, 2012; Duru, 2019). As these nutrients are currently under consumed by much of the EU population, their supply is the most valuable property of animals, especially as proteins are currently over-consumed (de Smet, 2012; Givens & Gibbs, 2008; Oh & Brown, 2003). While vitamin B12 occurs in virtually all ASF, EPA/DHA are mainly found in fatty fish, which are, therefore, essential to derive balanced diets. Due to this variation in nutrient content, a circular food system requires a variation of animal production systems to provide balanced diets.

Regarding animal production systems, previous studies considered only few species, and assumed a high productivity common in industrial agriculture (van Zanten et al., 2018). They, furthermore, manually assigned which animal would value which LCF (van Zanten et al., 2016a). While this served well to prove that animals contribute to a resource efficient food system, to make the most of available LCF their use should be optimised (van Kernebeek et al., 2016). As LCF vary in their nutritional properties, we hypothesise that the optimal use of LCF requires a combination of animal production systems, as animals vary in their ability to value specific LCF. Ruminants, for example, are well adapted to value grass, while the high feed intake capacity of pigs enables them to value bulky LCF such as pulp. Optimal use of LCF may, furthermore, require animals with a lower productivity than common in animal farming in developed countries. The lower nutrient requirement related to such reduced productivity is likely easier to achieve within the feed intake capacity with LCF that often have a relatively low nutritional value.

The few regional studies that optimised the use of LCF by animals aimed to illustrate the potential of a resource efficient food system as a whole (Karlsson & Röös, 2019; van Kernebeek et al., 2016). They, therefore, included only few animal production systems, or provided limited insights into their functioning. To our knowledge, no study has applied such optimisation to explore which animals can value available LCF best. Answering this question requires an optimisation model with a variety of detailed animal production systems (Figure 1) and improved understanding on the availability and nutritional properties of LCF. This model, furthermore, should account for the nutritional value of different types of ASF have for humans.

2.2Feed-food competition in supply chain environmental impact assessment

The above described food systems approach provides valuable insights into the role of different animals in a circular food system, but it provides little direction to farmers in achieving sustainability and circularity objectives. At present governments, farmers, and consumers base their sustainability strategies on farm or product-level LCAs. As explained in Section 1.1, an LCA typically takes a supply chain approach which does not account for interlinkages between the numerous supply chains the food system entails, and thereby overlooks consequences of their applied mitigation strategies on the food system as a whole.

Food system interlinkages relate to processes with multiple outputs for which environmental impacts have to be divided over the resulting products. Producing oil from sunflower seed, for example, also yields meal and hulls. While guidelines propose to consider interlinkages by using labour intensive system expansion methods, LCAs of ASF typically use economic allocation (de Vries et al., 2015; ISO14044, 2016; Zehetmeier et al., 2014). Under economic allocation, the impact of a multifunctional process is allocated to its multiple outputs based on their relative economic value (Guinée, 2002). The economic value of a product, however, does not reflect their (un)suitability for direct human consumption, while feeding humans is the assumed aim of a circular food system (van Zanten et al., 2016b). This results in mitigation strategies that counteract the resource use efficiency of the food system (Frehner et al., 2020; van Zanten et al., 2018; van Zanten et al., 2016b).

This paradox is well illustrated by the contradiction between the principles of a circular food system and mitigation strategies proposed by studies under the production and consumption paradigm (van Zanten et al., 2018). Increased animal productivity, as proposed by the production paradigm, for example, requires additional high quality feed that is produced on arable land suitable for food crop production. Similarly, a shift from beef to chicken, as proposed by the consumption paradigm, increases the demand for high quality chicken feed, while leaving grassland, unsuitable to produce such feeds, unused. Both of these mitigation strategies thus enhance feed-food competition and reduce the efficiency with which arable land is used, effectively moving us away from a resource efficient food system. The proposed transition towards vegetarianism, furthermore, overlooks that meat associated to egg and diary production no longer finds a use in the food system. Under the consumption paradigm, the environmental impact of vegetarian diet is underestimated as part of the environmental impact of milk and egg production is allocated to the inevitable meat production that no longer finds a use in the food system. With a broad application of a vegan diet, environmental impacts could even increase because LCF no longer find a use in our food system. In the absence of nutrients provided by animals upcycling these LCF, the nutrient demand from food crops increases. To promote environmental mitigation strategies that improve the resource use efficiency of the food system, environmental impact assessment requires novel allocation methods that account for feed-food competition and, thus, suit the circular paradigm.

3. Aim

This thesis aims to evaluate the potential of various farmed animals in upcycling LCF in a circular food system, using the EU-28 as a case study, and addresses two main objectives.
The first objective is to explore what combination of animals is needed to optimally use available LCF, considering a variety of production animals and productivity levels. This requires understanding of the conditions under which these animals should function that relate to:

a. the availability and nutritional properties of LCF including food leftovers and grass resources
b. the nutritional purposes ASF should contribute to, and the value of different animals production systems in doing so.

The second objective is to explore how to account for feed-food competition in chain level environmental impact assessment in practice.

Objective one was evaluated for the case study of EU-28, while objective two uses a novel egg production system as a case study.

Outline of this thesis

The structure of the research included in this thesis is illustrated in Figure 1. Chapter 2, 3 and 4 each address objective 1, using the optimisation model illustrated in Figure 2 that allocates available LCF to that combination of animals that best fulfils relevant nutritional purposes. The model is extended in each chapter to consider more LCF, animal production systems and nutritional purposes as illustrated in Figure 1. In chapter 5 I develop and implement a novel allocation method to a case study LCA to addresses objective 2.

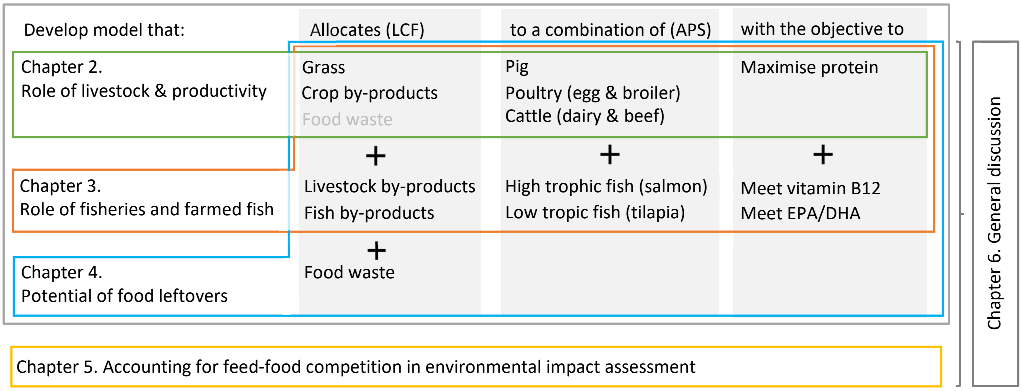

Figure 2 structure and outline of the chapters in this thesis

Chapter 2 identifies the combination of livestock systems, differing in productivity level that optimally converts the LCF available in the EU into HDP. To this aim, we developed a model that allocates available plant based LCF to that combination of animals that maximises HDP supply.

Chapter 3 explores the contribution of capture fisheries and farmed fish to a circular food system. To assess the contribution of farmed fish we extend the model of Chapter 2 with two fish species. This model was used to allocate available animal and plant based LCF to that combination of animals which maximises HDP supply while meeting population requirements for nutrients currently only obtained from ASF.

Chapter 4 explores the ASF and nutrient supply potential of improved collection and legalisation of food leftovers as LCF. To this aim we extend the model of Chapter 3 to include wastage along the food supply chain. We then apply this model to the currently used LCF, which we compare to scenarios of cumulative inclusion of additional LCF moving along the supply chain.

Chapter 5 evaluates the impact of explicitly accounting for feed-food competition on LCA results. A conventional LCA with economic allocation was compared with an alternative LCA with "food-based" allocation that explicitly accounts for feed-food competition. The limitations of economic allocation, illustrated by the impact of accounting for feed-food competition in LCA, were assessed in a case study of an innovative egg production system that avoids feed-food competition.

Chapter 6 brings the findings of all previous chapters together, places them in a wider perspective and gives a final conclusion.

Chapter 2

Upcycling food leftovers and grass resources through livestock: impact of livestock system and productivity

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Abstract

Consumption of animal-source food is criticised, among other reasons, for its relatively high environmental impact. It is, however, increasingly acknowledged that livestock can contribute to nutrition security if they upcycle low-opportunity-cost feed (LCF) – food waste, food processing by-products and grass resources – into nutritious animal-source food. So far, however, no study explored the allocation question "to which livestock should we feed what LCF to maximise livestock's contribution to human nutrition". Here we optimise the use of the LCF available in the EU, using a model that assigns LCF to those livestock systems that maximise animal protein production. We included the five most common livestock systems in the EU – pigs, laying hens, broilers, dairy cattle and beef cattle – considering their nutrient requirements under three productivity levels (low, mid and high). LCF availability is based on current food supply combined with food wastage and food processing data, and current grassland productivity. Our results showed that optimal conversion of LCF available in the EU, could supply 31 g animal protein per EU capita per day. We confirmed that this optimal conversion requires a variety of both livestock systems and productivity levels. Dominant livestock systems were those that have a high conversion efficiency (laying hens, dairy cattle), were best able to valorise specific LCF (dairy cattle for grass; pigs for food waste), and could valorise low quality LCF because of their low productivity. Limiting the model to use only conventional, high productive, livestock reduced animal protein supply by 16% to 26 g/(cap*d). Besides the efficiency with which livestock used the available LCF, the estimated protein supply from livestock fed solely on LCF, was sensitive to assumptions regarding the availability and quality of LCF, especially grass resources. Our model provides valuable insights into how livestock can efficiently use LCF, which is essential for a transition towards a circular food system.

1. Introduction

The food system faces the challenge of feeding a population growing in size and prosperity, while simultaneously reducing its environmental impact (FAO, 2009; Foley et al., 2011; Tilman et al., 2011). The production of animal-source food (ASF) has a high environmental impact relative to other food items, as much energy and protein is lost when converting plant biomass into ASF. No matter how efficiently e.g. cereals are produced, direct consumption of these cereals by humans is ecologically more efficient than consumption of ASF produced by animals fed with these cereals (Garnett, 2009; Goodland, 1997). Many studies, therefore, conclude that reducing or even avoiding the consumption of ASF reduces the environmental impact of the food system most (Aleksandrowicz et al., 2016; Hallström et al., 2015). Moderating the consumption of ASF is especially relevant in regions with an affluent diet and a high ASF consumption (Fairlie, 2010), such as the European Union (EU), the focus area of the current study.

Completely avoiding consumption of ASF, however, has a major drawback; feed resources unsuitable or undesired for human consumption can no longer be converted by livestock into nutritious food (Garnett, 2011). Such low-opportunity-cost feedstuff (LCF), for example food leftovers (i.e. processing by-products and waste) and grass resources (van Zanten et al., 2018), do typically not compete for land with food production. Consuming a limited amount of ASF, from animals fed solely with LCF, appears most land efficient, as such animals provide nutrient-dense food to humans without requiring additional cropland (van Zanten et al., 2018). With land availability being a major limitation to sustainably feeding the future population (Lambin & Meyfroidt, 2011), livestock's role in valuing this LCF is of utmost importance.

Previous studies estimate that feeding livestock solely on LCF provides 7 to 30 g animal protein per capita per day (Appendix A1, Table A1; van Zanten et al. (2018)). The variation between studies in available animal protein per capita per day has two main causes. First, the types of LCF included and their assumed availability as feed differed largely across studies (Table A1). Per capita availability of food leftovers related to current European (Röös et al., 2016, 2017b) or Dutch consumption (Elferink et al., 2008) is, for example, much higher than those related to average global consumption (Schader et al., 2015; Smil, 2014). Inclusion of food waste (Röös et al., 2017a, 2017b; van Zanten et al., 2016a) and assuming soybean oil for all human food oil consumption (Elferink et al., 2008; van Zanten et al., 2016a), furthermore, result in higher animal protein supply estimates. Second, the considered livestock systems and productivity levels differed largely between studies. van Kernebeek et al. (2016), for example, included only high productive pigs and dairy cattle, while van Zanten et al. (2016a) considered low productive, tropical dairy cattle, and estimated pig productivity based on the provided diet.

Although the above mentioned studies underpin that livestock can contribute to global food security, no study so far explored the allocation question "to which livestock should we feed what LCF to maximise livestock's contribution to human nutrition". Such optimal use of available LCF may require various livestock systems, as animals differ in their ability to digest available feeds (Preston, 1986). Ruminants, for example, are better adapted to feed on grass. Additionally, optimal use of available LCF may require reduced livestock productivity (i.e. growth or yield/day) compared to conventional farming systems (i.e. common farming practice). While conventional livestock are generally provided a nutrient dense diet to maximise their productivity, LCF often have a low nutrient density. When using only LFC, the lower nutrient requirement related to reduced animal productivity may be easier to satisfy within the feed intake capacity (FIC) (Zijlstra & Beltranena, 2013). Finally, the contribution of such livestock to food supply was, so far, only measured by their protein provision, undermining their supply of valuable micronutrients valuable such as vitamin-D, vitamin B12, calcium, iron, zinc, and selenium (Macdiarmid et al., 2012; Mertens et al., 2017)

We here aim to identify which combination of livestock systems, differing in productivity level, can optimally convert LCF into animal protein, and how much the resulting ASF contributes to the required intake of nutrients for which ASF is specifically valued. Our approach estimates the potential contribution of livestock fed on currently available LCF to food security and, more importantly, provides insight into how animals can efficiently use such LCF. Adapting current practice considering these insights may improve the efficiency of the entire food system. We use the EU-28 food system as a case study; LCF include by-products and waste related to current EU food supply and grass resources from current grassland in the EU.

2. Methods

To assess the optimal use of LCF, an optimisation model was developed in General Algebraic Modelling System (GAMS) version 24.2., based on the system illustrated in Figure 1. This model maximises the output of animal protein by converting available LCF in Europe (input to the model) into valuable ASF (output of the model) using (a combination of) livestock systems with different productivity levels. We first describe the general structure of the model and subsequently present the model components displayed in Figure 1 in more detail. This description starts with three types of LCF included (model inputs): food by-products, food waste, and grass resources. Subsequently, we describe the five livestock systems included: pigs, laying hens, broilers, dairy cattle, and beef cattle, and their three productivity levels: high, mid, and low. Finally, we describe the computation of the model output, in terms of human digestible animal protein, vitamin D, vitamin B12, calcium, iron, zinc, and selenium.

2.1 Model structure

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

$$\begin{array}{ll} \textit{Maximise} & Z=\mathbf{c}'\mathbf{x} \\ \textit{Subject to} & \mathbf{A}\mathbf{x}\geq\mathbf{b} \\ \textit{and} & \mathbf{x}\geq 0 \end{array}$$

where $\mathbf{x}$ is a vector of animal production activities; $\mathbf{c}$ is a vector of human-digestible protein produced per unit of activity; $\mathbf{A}$ is a matrix of technical coefficients; and $\mathbf{b}$ is a vector of quantitative constraints. The objective function of the model is to maximise human-digestible animal protein (HDP) output (Z). Animal protein production is restricted by: the amount of each LCF available, the nutritional value of each LCF for each livestock system, and the nutritional requirements and limitations of the animals in each livestock system. Livestock nutritional requirements are met using only LCF, without use of additives such as synthetic amino acids. The nutritional value of each LCF and the nutrient requirements of various animals were based on the nutritional system of the Dutch animal feed board; referred to as the CVB system (CVB, 2012; van Vliet et al., 1994). This nutritional system provides animal specific net nutrient contents for a wide range of feed products (CVB, 2016) and methods to calculate productivity dependent nutrient requirements for a wide range of livestock systems.

2.2 Computation of available LCF in Europe

We included three types of LCF: by-products and food waste related to current plant-source food supply in the EU-28, and currently available grass resources in the EU-28. While food waste and grazing resources were assumed local resources to be consumed in the country of origin, by-products resulting from food processing (e.g. wheat bran from wheat milling) could be traded between EU countries. Feeding losses (Vermeij, 2017) and grazing losses (van den Pol- van Dasselaar et al., 2002) were assumed unavailable for livestock production. Crop residues, such as straw, were assumed to be left on the field to maintain soil fertility or used for non-feed/food purposes and are thus not considered as an LCF available for livestock production (Reicosky & Wilts, 2005). Also processing losses and food waste related to the ASF production and consumption proposed by the model were assumed unavailable for livestock production as most of them are considered a food safety hazard (Salemdeeb et al., 2017).

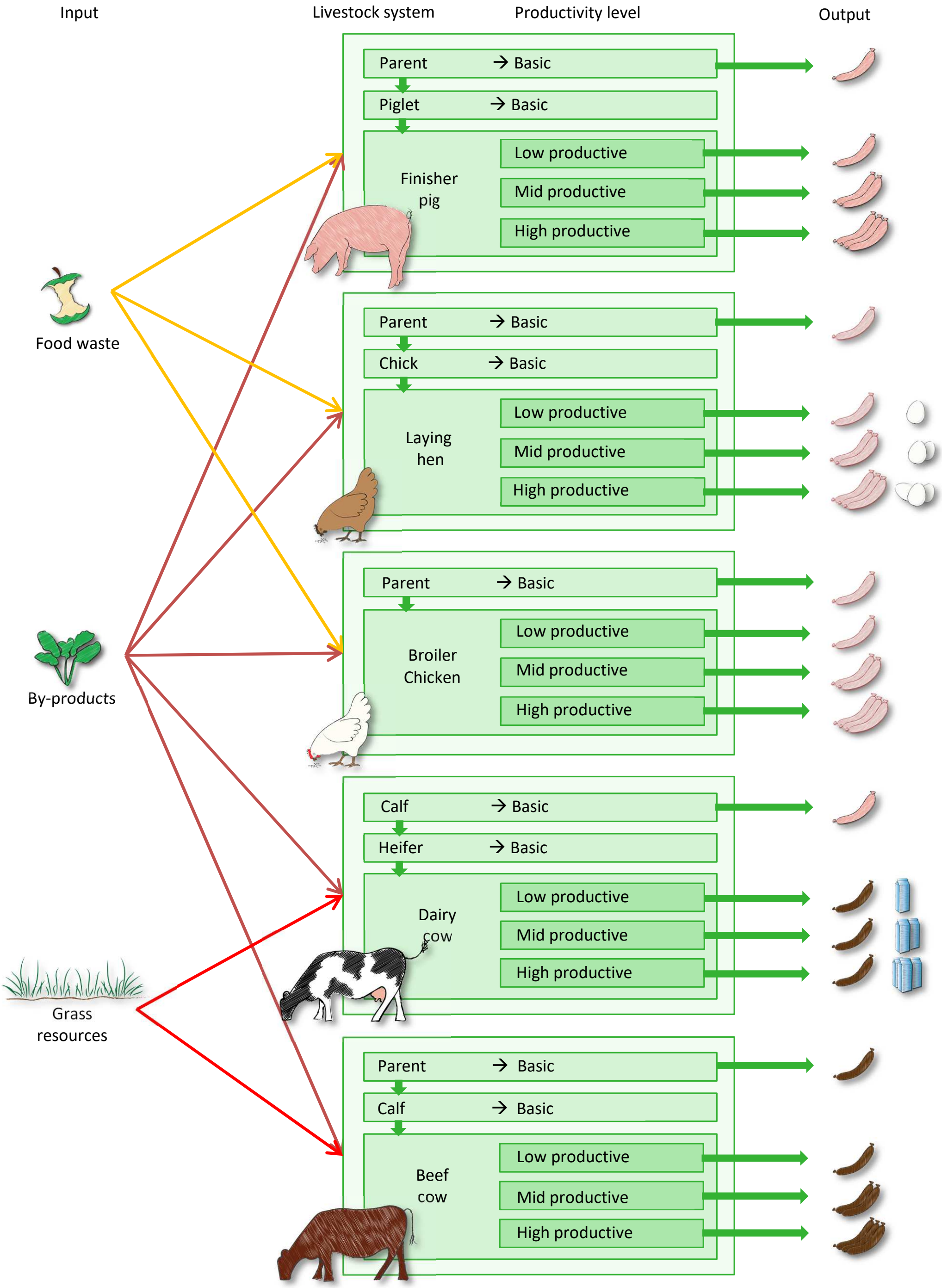

Figure 1. Definition of the livestock systems (pig, laying hen, broiler, dairy cattle & beef cattle) varying in productivity (low, mid, and high), including their inputs (low-opportunity-cost feeds; food waste, food by-products & grass resources) and outputs (animal products; milk, meat & eggs).

between EU countries. Feeding losses (Vermeij, 2017) and grazing losses (van den Pol- van Dasselaar et al., 2002) were assumed unavailable for livestock production. Crop residues, such as straw, were assumed to be left on the field to maintain soil fertility or used for non-feed/food purposes and are thus not considered as an LCF available for livestock production (Reicosky & Wilts, 2005). Also processing losses and food waste related to the ASF production and consumption proposed by the model were assumed unavailable for livestock production as most of them are considered a food safety hazard (Salemdeeb et al., 2017).

The amount of food leftovers related to plant-source food consumed in each EU country was calculated using data on the primary products (e.g. wheat grain) annually used as food according to FAO's food balance sheets FAO (2017c) of 2009 to 2013 (Appendix A2). Available by-products were calculated using so-called technical conversion factors (FAO, 1996; Vellinga et al., 2013), which represent the fraction of main product (e.g. wheat flour) and by-product (e.g. wheat bran) resulting from each process (e.g. wheat milling). For presentation purposes the resulting by-products are classified based on their nutritional properties into cereal by-products, oil seed by-products, roughage like products (i.e. products with a high fibre content), tuber peels, molasses and pulps (Table A2). Each of the considered by-products can be fed to each of the included livestock systems.

Food waste considers products intended for human consumption, wasted in the retailing or consumption phase. Available food waste was calculated by applying waste fractions of Gustavsson et al. (2011), specific to Europe, to the available main products after processing. All food waste was combined into one waste stream, of which the dry matter and nutrient content equals the weighted average of the included products. Thirty five percent of this produced food waste was assumed available as animal feed (in undried form), which is achievable when legalising and stimulating the use of food waste as animal feed (zu Ermgassen et al., 2016). As legalisation of feeding food waste to ruminants is unlikely due to associated health risks (Salemdeeb et al., 2017), only pigs and poultry were allowed to consume food waste, which was provided in undried form.

The amount of grass resources available in the EU was derived from (Plutzar et al., 2016) and classified into three vegetation types – managed grassland, natural grassland and rangeland – based on Haberl et al. (2007) and Plutzar et al. (2016) (Appendix A2). Considering grass from managed grassland as LCF is arguable, as such land could provide food more efficiently under food crop production (Garnett, 2011). We included this grass, however, to avoid negative environmental consequences of converting grassland to cropland, such as the release of soil carbon stocks or the loss of biodiversity (Foley et al., 2005; Foley et al., 2011; Gerber et al., 2013). A range of nutritional values for each vegetation type, collected from field study literature, was converted into three grazing quality classes, over which the available biomass of each vegetation type was assumed to be normally distributed (16% low, 68% mid & 16% high quality; Appendix A2).

2.3 Description of livestock systems

We included the five most prevailing livestock systems in Europe: pig, laying hen, broiler, dairy, and beef production (FAO, 2017d), considering the entire life cycle including food-producing animals (e.g. fattening pig) and non-food-producing animals (e.g. sow, gilt, boar and piglet see Figure 1). The number of non-producing animals relative to a producing animal (Appendix A3) was calculated from the European herd composition (FAO, 2016a, 2016c), supplemented with Dutch averages for pig litter size (AgroVision, 2016) and dairy calving interval (CRV, 2017). As feed requirements of livestock systems are largely determined by the requirements of producing animals (Reckmann et al., 2012), productivity and nutrient requirements of non-producing animals (Appendix A4) were fixed and based on Dutch production averages (CVB, 2012). Such Dutch production averages served as a proxy for conventional livestock production in the EU throughout this study as this sector is highly industrialised and focussed on production efficiency resulting in little variation between countries (Bos et al., 2013).

Regarding the productivity of producing animals, we distinguished three productivity levels: low, mid, and high (Figure 1). For each productivity level, we computed specific nutrient requirements using the CVB system (CVB, 2012; van Vliet et al., 1994). Productivity was expressed in annual-fat-and-protein corrected milk (FPCM) production for dairy cattle, annual egg production for laying hens and average daily gain (ADG) – determining the growing period required to achieve a target slaughter weight – for pigs, broilers, and beef cattle. For each livestock system, performance of the Dutch livestock sector served as a proxy for high-productive animals (Bos et al., 2013). Low productivity of dairy cattle was approximated by the performance of Irish extensive dairy farming (Läpple et al., 2012), while mid productivity was the average of high and low. The same method was used for broilers and beef, for which low productivity was based on Dutch slow growing broilers (Vermeij, 2017), and extensive beef farming in the French Charolaise region (IDELE, 2014). Pig performance under reduced feed quality was simulated using the growth model underlying the CVB system (CVB, 2012), for both low and mid productivity. For laying hens, the CVB system provided nutrient requirements for the average Dutch laying percentage (85% of days an egg is laid), assumed for high productivity, as well as for the lower laying percentages, assumed for mid (75%) and low (65%) productivity. Protein requirements for the considered monogastrics (i.e. pigs and poultry) considered the most limiting essential amino acids lysine and methionine, assuming these requirements will also ensure sufficient intake of other amino acids if the diet contains a variety of products. While maximum feed intake capacity (FIC) of pigs and poultry is expressed in kg fresh matter, for cattle the satiety effect of different feed components was considered in saturation units (SU) (CVB, 2012). The assumed performance and related nutrient requirements for each livestock system under each productivity level are displayed in Table 1; underlying data and calculations are provided in Appendix A4.

2.4 Computation of nutrient output of livestock systems

As the produced ASF is assumed tradable between countries, the output of human digestible nutrients is expressed as an average per EU capita. To compute this output of human digestible nutrients, we converted the ASF output (kg product) of each livestock system and productivity level into nutrient output (Appendix A5), using product-specific human digestible nutrient content data of USDA (2018a). For milk and eggs these nutrient contents were directly available, whereas for meat products, average nutrient contents per kg carcass weight (Figure A7) were calculated, based on relative cut weights and cut specific human digestible nutrient contents including cutting (CBB & NCBA, 2014) and cooking losses (USDA, 2012). The growth development (high versus low productivity) could however effect the nutrient content of each cut. The growth models for pig (van Milgen et al., 2008) and beef (van Vliet et al., 1994) and, for example, predicted an increase in meat protein content under reduced growth. We, therefore, adjusted the weighted HDP content per kg meat accordingly. Due to a lack of data, other nutrients could not be corrected.

2.5 Sensitivity analysis

A sensitivity analysis was conducted to evaluate model responses to changes in key model parameters. We compared results of our baseline optimisation with alternative optimisations, including additional restrictions or alternative data for those parameters we expect most influential and/or uncertain, namely: animal productivity, the inclusion of food waste used as animal feed, the quantity and quality of grazing resources available, and the diversity of produced ASF.

Animal productivity

Besides assessing whether low-productive animals are needed to optimally convert LCF into animal protein, we wanted to quantify the impact of allowing for such reduced productivity on protein supply. This impact was calculated as the difference in animal protein supply from livestock optimally using LCF when allowing for a range of productivity levels, and when only using high-productive animals.

Table 1. Performance and related nutrient requirements (CVB, 2012) for each livestock system (pig, laying hen, broiler, dairy cattle, and beef cattle) under different productivity levels (low, mid, and high)[1]

Livestock system				**Productivity level**		
			Units	High	Mid	Low
Pig	Performance	Growth	ADG[2] (kg/d)	0.80	0.76	0.71
			Period[3a](d)	112	119	128
	Daily nutrient requirements	Energy[4]	NE (MJ)	20	18	17
		Protein[5]	Dlys (g)	15	14	13
			Dmeth (g)	9	9	8
		FIC[6]	DM (kg)	3	3	3
Laying hen	Performance	Yield	Laying %[7]	85	75	60
			Period (d)	392	392	392
	Daily nutrient requirements	Energy[3]	ME (MJ)	1.36	1.29	1.19
		Protein[5]	Dlys (g)	0.74	0.70	0.65
			Dmeth (g)	0.36	0.34	0.32
		FIC[6]	DM (g)	151	151	151
Broiler	Performance	Growth	ADG[2] (g/d)	56	49	42
			Period[3b] (d)	40	48	56
	Daily nutrient requirements	Energy[4]	ME (MJ)	1.18	1.15	1.12
		Protein[5]	Dlys (g)	0.92	0.89	0.87
			Dmeth (g)	0.36	0.35	0.34
		FIC[6]	DM (g)	111	133	148
Dairy cattle	Performance	Milk	FPCM (kg/y)	8862	6807	4751
	Daily nutrient requirements	Energy[4]	FUM	17617	14963	12355
		Protein[5]	IDP (g)	1536	1198	876
			RDPB (g)	>0	>0	>0
		Structure[8]	SV	0.99	0.95	0.90
		FIC[6]	SU	14.5	14.5	14.5
Beef	Performance	Growth	ADG[2] (kg/d)	1.22	1.07	0.93
			Period[3c] (d)	329	374	432
	Daily nutrient requirements	Energy[4]	FUB	7143	6848	6496
		Protein[5]	IDP (g)	484	450	400
			RDPB (g)	>0	>0	>0
		Structure[8]	SV	0.75	0.75	0.75
		FIC[6]	SU	9.6	9.6	9.6

[1] Underlying data and calculations are presented in Appendix A4

[2] ADG = average daily gain, growth per day averaged over the growth period

[3] Period required to grow from:
- [a] weaning (25 kg) to slaughter (115 kg live weight)
- [b] hatch to slaughter (+/-2.3 kg live weight)
- [c] weaning (350 kg) to slaughter (650 kg live weight)

[4] Daily energy requirements expressed in:
- NE = net energy (pigs)
- ME = apparent metabolisable energy (poultry)
- FUM = feed units milk (dairy cattle)
- FUB = feed units beef (beef cattle)

[4] Daily protein requirements expressed in:
- Dlys & Dmeth = intestinal/faecal (pig/poultry) digestible lysine & methionine
- IDB = intestinal digestible protein & RDPB = rumen degraded protein balance (ruminants)

[5] Maximum daily FIC = feed intake capacity averaged over days of production period in:
- DM (monogastrics); due to maturation near slaughter age, broiler FIC varied between productivity levels.
- SU = satiety units (ruminants)

[6] Laying %: number of days in laying period on which an egg is laid

[7] Structure requirement of ruminants expressed in the average SV = structure value of the feed

Inclusion of food waste used as animal feed

The amount of protein that can be produced from LCF is highly dependent on the quantity of LCF available. Regarding the inclusion of food waste, we assumed 35% of the food wasted after the processing stage can be used as feed. In the EU, however, the use of such consumer, catering, and retailing food waste as animal feed is not allowed due to presumed food safety hazards. While our assumption suits the hypothetical future food system, the future availability of food waste as livestock feed remains uncertain as it requires legislative changes (Salemdeeb et al., 2017). Running the model while excluding all food waste does not only indicate the sensitivity of the model to this assumption, but also quantifies the benefits of allowing the use food waste (partly, i.e. 35%) as animal feed.

Quantity and quality of grazing resources

Inclusion of grass biomass from managed grassland as an LCF is debatable as this arable land can be used more efficiently, in terms of food production, under food crop production. We, therefore, explored the consequences of excluding grass resources from managed grassland on our results. While uncertainty regarding the quantity of grazing resources available in Europe is already considerable (Fetzel et al., 2017), uncertainty regarding their nutrient contents is even higher. We addressed this uncertainty in the baseline model by converting the whole range of vegetation specific nutritional values obtained from field study literature into three grass quality classes, over which the available biomass of the corresponding vegetation type was assumed normally distributed (16% low, 68% mid, and 16% high quality). To explore the sensitivity to this assumption, we also tested a uniform distribution of biomass over each quality class (33% for each low, mid, and high quality) (Appendix A2**;** Figure A5).

Diversity in animal-source foods

Optimal conversion of LCF into ASF, likely favours certain production systems that are most efficient in protein production. Such optimal conversion, then requires an extreme change in the types and amounts of ASF consumed, which is likely difficult to achieve (de Bakker & Dagevos, 2012). To assess sensitivity regarding the assumption that conversion efficiency should drive the selection of ASF in the human diet, we ran the model while requiring that the animal protein in the human originates from a diversity of ASF. To reflect consumer preference, this required ASF diversity reflected the origin (milk, meat, and eggs) of HDP the average European diet; a milk:meat:egg (M:M:E) ratio of 28:65:7 (FAO, 2017a).

3. Results

The proposed 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, across all EU countries (Appendix A6; Figure A8). Compared to current EU livestock numbers, an optimal LCF conversion would, therefore, require 78% less pigs and 98% less laying hens, but 9% more dairy cattle besides a complete abolishment of beef cattle and broilers. Almost all food waste was fed to pigs as well as the majority of oil-seed by-products (Figure 2). Laying hen diets also consisted mainly of these products (Figure 3b) – but were produced only in countries where food waste quality was highest (Bulgaria and Czech Republic, Appendix A2; Table A3). Although the majority of by-products was fed to dairy cows (Figure 2), their diet mainly consisted of grass resources (Figure 3c). Grazing resources of the highest quality were fed to dairy cows, while lower quality grass resources were fed to the associated non-producing animals, such as heifers, with lower nutritional requirements (results not shown). Although diet composition varied somewhat between countries (Appendix A6; Figures A9 & A10), especially for dairy, only the EU average feed composition used per producing animal is discussed and displayed in Figure 3.

This optimal use of LCF resulted in an ASF supply of 27 g pork, 610 g dairy (fresh milk equivalents), 33 g beef related to dairy production and one g egg/(cap*d). Relative to current ASF supply in the EU (FAO, 2017a) this is a reduction of 40 g dairy, 160 g meat and 31 g eggs. Collectively this ASF provides 31 g animal HDP/(cap*d), (5 g from pork, 20 g from dairy, 6 g from dairy cattle meat), 19 g less than current average protein consumption in the EU (Figure 4). Besides protein, this ASF also provides a range of valuable micro-nutrients (Figure 5). This ASF consumption also provides 93% of our daily calcium requirements, because of the large role of dairy, and 80% of our vitamin B12 requirements, which we currently mainly obtain via animal-source food. Compared with the current ASF consumption, however, the intake of all nutrients is reduced.

3.1 Animal productivity

When considering only high-productive animals, pigs could no longer use food waste to meet their (high) nutrient requirements within their feed intake capacity, mainly due to the low dry matter content of food waste (Appendix A2; Table A3). The majority of available food waste, therefore, remained unused (Figure 2) and pig numbers reduced with 98% compared to the baseline optimisation to 0.9 million. To achieve their higher nutrient requirements the few remaining pigs were fed only high quality food waste and an increased share of cereal by-products (Figure 3a). The oil seed by-products no longer used by pigs, became available for dairy production (Figure 2). Dairy cattle were fed these oil seed co-products to meet increased nutrient requirements, which also required an increase in grass resource quality and feed intake (Figure 3c). As availability of high quality resources is limited, dairy cattle numbers – the main protein providers in the baseline optimisation – reduced with 49 % to 15 million. Additionally, 6.3 million beef cattle were kept, who valued the lower quality grass resources unsuitable for high-productive dairy cattle (Figure 3d). Despite the large reduction in animal numbers, animal protein supply reduced only by 16% to 26 g/(cap*d) (Figure 4) due to the higher animal protein output per animal.

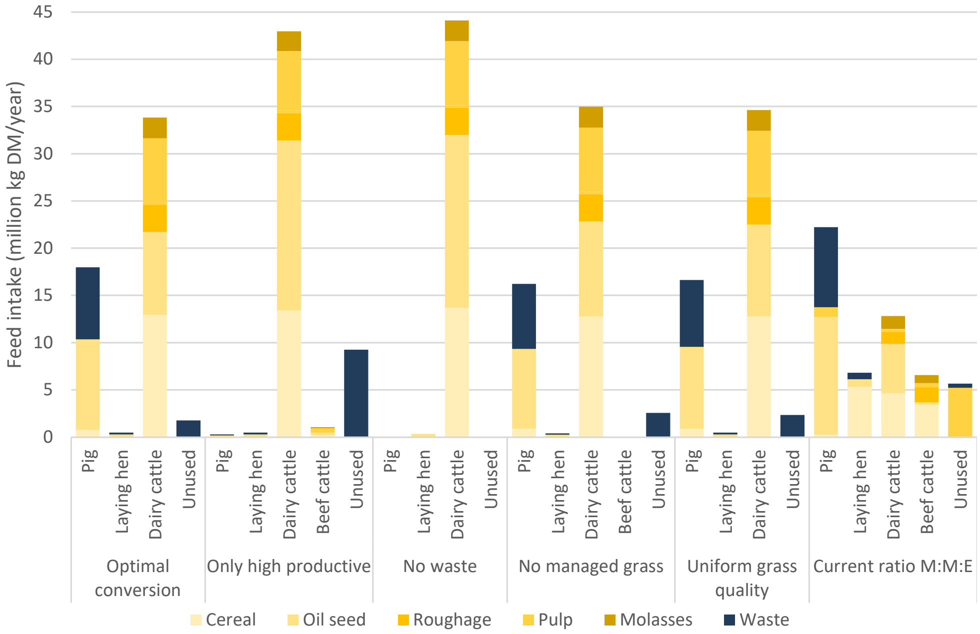

Figure 2 Proposed allocation of available food leftovers (by-products and waste; classification Appendix A2; Table A3) in the EU over the selected livestock systems (pig, laying hen, broiler, dairy, beef) under optimal use of available non-food-competing feed (LCF) and alternative optimisations of the sensitivity analysis (M:M:E is Milk:Meat:Eggs)

3.2 Quantity of food waste used as feed

When excluding all food waste, optimal conversion of LCF no longer requires pigs, which were the main consumers of food waste in the baseline optimisation, whereas the number of laying hens decreased with 55% to 5.3 million. Waste in the laying hen diet was replaced by both cereal and oil-seed by-products (Figure 3a). By-products that in the baseline optimisation were fed to pigs (mainly oil-seed), were now allocated to dairy cattle (Figure 2), sustaining the larger cattle population (+13% to 34 million). With the inclusion of the nutritious oilseed by-products in the cattle diet, a larger share of the grazing resources in the dairy cattle diet was of lower quality (Figure 3c). Supply of animal HDP was reduced by 3% to 30 g/(cap*d) (Figure 4).

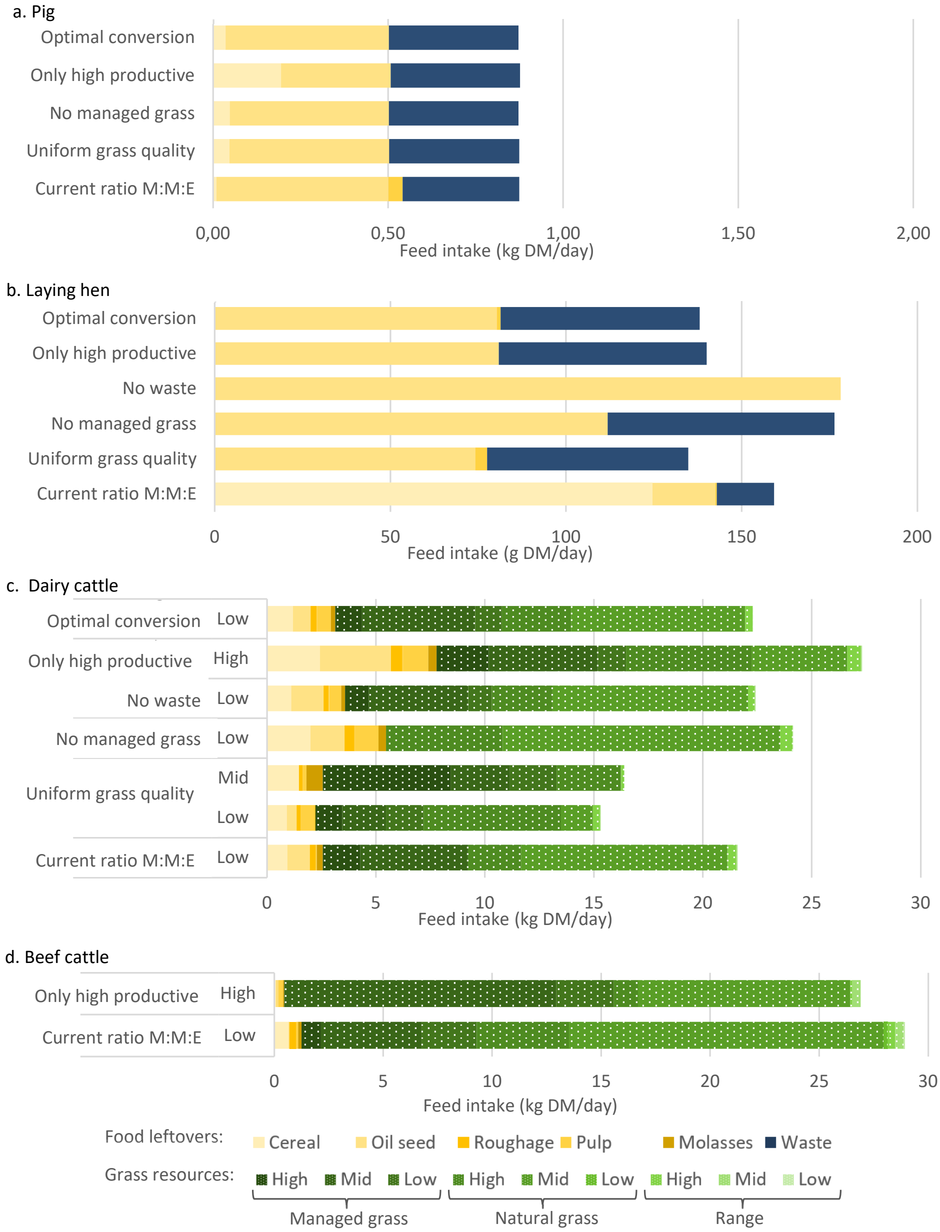

Figure 3 Proposed averaged (EU) diet for each livestock system (a. pig, b. laying hen, c. dairy cattle, d. beef cattle) under the optimal use of food leftovers (classification Appendix A2; Table A2) and grass resources; and alternative optimisation scenarios of the sensitivity analysis. Expressed per production animal per day including related requirement of non-producing animals.

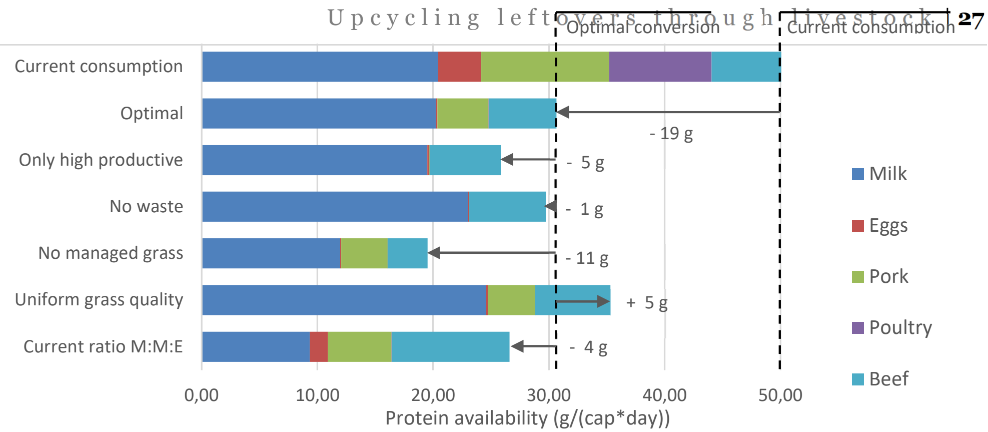

Figure 4. Animal human digestible protein (HDP) supply, per EU capita per day, under optimal conversion of LCF compared with current animal HDP consumption, and alternative optimisation scenarios of the sensitivity analysis

3.3 Quantity and quality of grazing resources

Excluding managed grasslands, the most nutritious grass resource, reduced the number of dairy cows with 40% to 18 million. The dairy cattle compensated the lower availability of grass resources and its lower nutritional value by consuming relatively more by-products (Figure 3c). These by-products were, therefore, to a lesser extend available for pigs and laying hens (Figure 2) resulting in reduced animal numbers (pigs -10% to 50 million; laying hens -35% to 6 million) but similar diets compared to the baseline optimisation (Figure 3a&b). Per capita supply of animal HDP decreased by 36% to 20 g/d (Figure 4).

Assuming the available grass biomass of each vegetation type was uniformly distributed over the grass quality classes, increased the dairy cow numbers with 11% to 33 million compared with the baseline optimisation. Of these dairy cows, 20% (7 million) was mid-productive. Under a uniform distribution more of the available grass biomass is of high quality, with which mid-productive cows met their higher nutritional requirement. Both mid and low-productive dairy cattle reduce feed intake compared to the baseline optimisation by consuming grass of a higher quality (Figure 3c). Pig numbers reduced with 8% to 52 million, while laying hen numbers remained the same. Due to the higher dairy cow productivity, an increased (11%) animal HDP supply of 34 g/(cap*d) was achieved with less animals (Figure 4).

3.4 Diversity of animal-source foods

When demanding a diverse output of ASF, the optimal conversion of LCF logically requires a wider range of animal production systems. With 70 million low-productive pigs, 117 million high-productive laying hens, 14 million low-productive dairy cows, and 14 million low-productive beef cows, various livestock systems and productivity levels were needed. Beef production was mainly grass based (98%), using grass of a lower quality and less food by-products than dairy production

(80% grazing) (Figure 3c&d). In total, however, beef cattle consumed a considerable amount of food by-products, mainly cereal by-products and roughage like products (Figure 2). The remaining food leftovers available from the reduced dairy cattle production (-54%) were fed to monogastrics (Figure 2), where poultry were fed mainly cereal by-products and pigs consumed most of the oil by-products and waste (Figure 3a&b). Collectively these livestock systems provide 280 g milk, 13 g egg, and 90 g meat / (cap*d) (33 g pork, 1 g poultry, 56 g beef). Compared with the baseline optimisation, this reduces protein availability by 13% to 27 g/(cap*d) (Figure 4), due to the use of relatively inefficient livestock systems that are unable to valorise grass. This lower but more diverse supply of animal products does, however, provide more zinc and iron (Figure 5).

4. Discussion

When feeding livestock only with LCF, they provide some nutritious ASF without competing for land with food-crop production. Here we estimate that if we would use LCF available in the EU optimally, we can produce 31 g of animal protein/(cap*d) (Figure 4); just above the range of 9-30 g/(cap*d) (Supplement 1, Table A1) found in previous studies. As previously described, availability of ASF from LCF is mainly influenced by the quantity and quality of LCF available, and the efficiency with which animals utilise these feeds. The following paragraphs present the influence of these factors on our estimate.

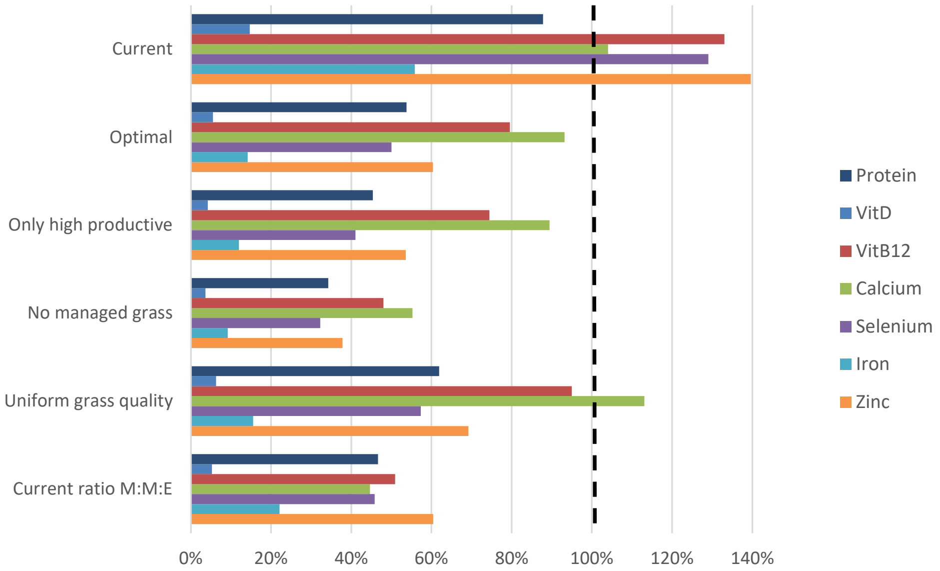

Figure 5 Nutrient supply by ASF, per EU capita per day, relative to daily intake requirements (USDA) under optimal conversion of LCF compared with the current average European diet and alternative optimisation scenarios of the sensitivity analysis

The availability of food leftovers depends on the amount and type of plant-source foods in the human diet. We based this plant-source food consumption on food supply statistics that reflect our current, superfluous, diet likely resulting in a higher leftover availability than, for example, van Zanten et al. (2016a), who based this consumption on a 'healthy vegan diet'. Food leftover availability based on our current diet, served fine to illustrate the need for diverse livestock systems in a circular food system. Striving to use plant resources more efficiently for food production – as a circular food system should – will, however, change the availability of LCF, illustrated by the following three examples. First, numerous food by-products, currently used as feed, could be used as food (e.g. by consuming whole grain instead of plain flour). Second, avoiding overconsumption by restricting our food consumption based on dietary guidelines and consumption of plant based foods that do not provide nutritional benefits (e.g. coffee, sugar) (Alcott, 2008) reduces the availability of related by-products. Third, in terms of food supply, avoiding food waste is more efficient than reusing it as livestock feed (Mourad, 2016). Food waste reductions should therefore be atop of the political agenda, and only unavoidable food waste should be reused as feed, to the second most efficient use in terms of food production (Papargyropoulou et al., 2014).

Besides the availability of food leftovers also their inclusion as an LCF varied among studies. Only few previous studies considered food waste as an LCF (Table A1), as EU law forbids its use as livestock feed (zu Ermgassen et al., 2016). As relegalisation of feeding food waste is currently under debate (EuropeanCommission, 2015), we assumed 35% of the produced food waste can be fed to monogastric livestock, as achieved in Japan where safe feeding of food waste is stimulated (zu Ermgassen et al., 2016). Excluding this food waste reduced the protein supply with 3% (30 g/(cap*d)) compared with the baseline scenario (Figure 4 – No waste). This surprisingly low reduction in protein supply compared to previous studies which nominate food waste as a potent LCF (Röös et al., 2017a, 2017b; van Zanten et al., 2016a; zu Ermgassen et al., 2016) has multiple causes. As our food waste had a relatively low DM content (35-55%), intake thereof by pigs required considerable supplementation of food by-products (Figure 2a). In the absence of food waste, these by-products were reallocated to dairy cattle, which convert them into protein more efficiently. Thus, our reallocation of by-products to dairy cattle limits the impact of excluding food waste, but by providing food waste only in wet form we likely underestimated its potential in the first place. To better understand the potential of relegalising food waste as livestock feed, optimal use of LCF should be assessed under likely future policy scenarios (e.g. feeding retailing waste or slaughter waste to pigs) and provision forms of food waste (e.g. dried vs wet) as well as potential food waste reduction.

Regarding the availability of grass resources, considering grass grown on arable land as an LCF is debatable as it competes with direct plant-based food production (Garnett, 2011). Conversion of such grassland into cropland, however, is associated with a release of stored carbon and often also the loss of biodiversity (Foley et al., 2011; Gerber et al., 2013). We, therefore, included the managed grassland, situated on arable land, as an LCF. Excluding this managed grassland (23% of total grass biomass) reduced the availability of animal protein by 35% to 20 g/(cap*d) (Figure 4 – No managed grass). In contrast to managed grasslands, natural grasslands and rangelands are generally not suitable for crop production and can only contribute to food production through grazing. One could, however, question whether we should use this land for food production at all, rather than spare this land to bind carbon through afforestation, where such is possible (Balmford et al., 2018). Grazed lands, however, contain specific flora and fauna, which may contribute to biodiversity, and hinder the spread of forest fires (Fuhlendorf et al., 2006).

The quality (nutritional value) of grazing resources varies considerably within the EU (Appendix A2), and the distribution of the quality over the available grass biomass of each vegetation type is largely uncertain. Changing the grass quality distribution considerably alters the livestock systems selected and the animal protein supply, as grass resources form the bulk of the available LCF in the EU. Compared to a normal distribution, assuming a uniform distribution, for example, increases the availability of high quality grass (Appendix A2**;** Figure A5), resulting in an increase in dairy cattle numbers and their productivity level, and hence in animal protein supply (34 g/(cap*d); Figure 4 – Uniform grass quality). A more robust assessment of animal protein supply using only available LCF in the EU, requires a concise overview of nutritional value of natural grasslands and rangelands, but was beyond the scope of this study.

The efficiency with which livestock utilise available LCF depends on the considered livestock systems (van Zanten et al., 2018). Where previous studies assumed fixed LCF rations to achieve a fixed (often high) productivity, our model uses LCF more efficiently by formulating nutritionally adequate rations for those animal production systems that maximised protein output. Our results, thus, give insights into what livestock should be used, and which LCF we should feed to what animals to maximise their contribution to nutrition security. The developed model is, furthermore, suitable to explore resource use efficiency of the livestock sector under any given feed availability. Our results confirm that optimal conversion of LCF requires a variety of both livestock systems and productivity levels. Regarding variation in livestock systems, the optimal conversion of LCF into protein required dairy cattle, pigs, and few laying hens. Selection of these livestock systems logically follows from high conversion efficiencies of laying hens and dairy cattle (de Vries & de Boer, 2010), ruminants ability to valorise grass, and pigs ability to consume a wide range of low quality feeds (Preston, 1986), such as food waste. Forcing the model to use less efficient livestock systems by requiring a diverse ASF output, reduced animal protein supply by 13% (to 27 g/(cap*d); Figure 4 – Diverse ASF). Forcing the model to use all considered livestock system including additional requirements on the origin of the produced meat (Pork:Poultry:Beef) will likely reduce this even further.

Regarding livestock productivity, optimal conversion of LCF required low productive pigs and dairy cattle to valorise LCF with a low nutrient density. The proposed low density LCF diets satisfy the relatively low nutrient requirements within the feed intake capacity. Data on both nutrient contents of LCF and the nutrient requirements of each livestock system contains relatively little uncertainty as they are well validated. This validation, however, holds best under high productivity, and breeding livestock that is suited to feed on LCF may increase efficiency. Data on FIC is less validated, as this knowledge is less valuable for conventional livestock production that strives for high productivity. Results are logically sensitive to assumptions on FIC, as they influence the required nutrient density of the proposed feed. Besides FIC also the applicability of LCF based feed in practice should be tested to consider palatability and voluntary intake. When allowing only for high-productive animals, pigs were no longer able to value food waste within their feed intake capacity, leaving this LCF largely unused while by-products were reallocated to dairy production (Figure 2). This reduced protein supply by 16% (to 26 g/(cap*d); Figure 4 – Only high productivity).

It has to be noted that optimal conversion of LCF under the above described assumptions, resulting in a 31 g/(cap*d) protein supply, would require reformation of the entire food system. This reformation includes fundamental changes related farming practices, food distribution and consumption patterns, resulting in far reaching consequences on, for example, the environmental impact. Regarding farming practices, breeding should focus on livestock well adapted to the available feed quality. Livestock housing should be adapted to lower intensity farming, which provides opportunities to simultaneously address other challenges the sector faces, for example, animal welfare requirements. Regarding consumption patterns, we should consider the impact of the reduced animal product supply (compared to our current consumption) on nutrient intake. While such reduced supply may not be critical regarding protein – protein requirements are still met when halving our animal protein supply to 31 g/(cap*d) – it is relevant for nutrients for which sufficient intake is currently already uncertain. The intake of vitamin B12 and iron by women, for example, is mostly obtained from ASF and does often not meet intake requirements (Biesalski, 2005). As a diverse ASF intake increased supply of iron and zinc at the cost of protein (Figure 5 –

Current ratio M:M:E), combined livestock systems might be most suitable to fulfil our complete nutrient requirement. Furthermore, the reduced ASF consumption could be compensated by artificial supplements or food crops. The cropland area demand for this compensation can be assumed to be much smaller than the set free area on former fodder crop production areas, due to the large conversion losses in livestock systems.

Alternatively, ASF supply from LCF can likely be increased by considering alternative animal production systems with a high conversion efficiency, or the ability to valorise alternative LCF, which should be considered in future research. Small ruminants, for example, are well adapted to graze on low quality grazing an browsing resources, while insects may value manure and aquaculture can legally feed on animal and fish by-products (Parodi et al., 2018), Furthermore, supplementation with a small amount of concentrates (high quality feed), or synthetic amino acids likely increases productivity and ASF supply (van Zanten, 2016), especially when applied in the most critical growth stages (very young animals). In addition to animal protein sourced from LCF, fisheries, if limited to sustainable catch (Froese et al., 2018), can provide animal protein without competing with food crop production.

While this study indicates how livestock fed on LCF can optimally contribute to nutrition security, it does not consider direct environmental impacts of the food system. Indirectly, however, avoiding feed production reduces land use related to food production. Furthermore, previous studies showed that a diet including ASF produced with LCF, reduces land use of the food system by 25% compared to a vegan diet (van Zanten et al., 2018). Compared to current consumption patterns, limiting livestock production to available LCF, reduces greenhouse gas (GHG) emissions by 19-50% (Röös et al., 2017a, 2017b; Schader et al., 2015). Maximising the output of animal protein when limiting livestock production to available LCF, however, likely comes with a trade-off regarding GHG emission, compared to these estimations. Optimal use of leftovers may, for example, require feed and animal protein transport in smaller quantities on a higher frequency and additional processing of food waste, causing additional GHG emission. Furthermore, while reducing productivity enables livestock to consume low quality by-products, it also increases the manure output and methane emissions relative to their production. When considering only high productive livestock, furthermore, a slightly reduced protein supply (- 16%) was achieved with considerably less animals (21 million vs 33 million cattle), which is possibly more desirable from an environmental perspective. Future studies, therefore, should consider both environmental impact and food security.

5. 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. Our 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. To conclude, this paper provides valuable insights into how livestock can efficiently use LCF, using a model that can be applied to any assumed availability of feed resources.

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Chapter 3

The role of fisheries and fish farming in a circular food system

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Submitted

Abstract

Recent studies show that livestock reared under the circular paradigm can contribute significantly to human food supply. By converting biomass unsuitable for human consumption into valuable animal-source food, such livestock upcycle nutrients that would otherwise be lost for food production. These studies, however, focussed solely on livestock, while aquatic animals can also make a valuable contribution to food supply. Fish, for example, is currently our main source of eicosapentaenoic (EPA) and docosahexaenoic (DHA) ω-3 fatty acids. Here we explore the contribution of capture fisheries and fish farming (salmon and tilapia), relative to common farm animals, to a circular food system in an EU-28 case study. We demonstrate that, under the circular paradigm, fish provide nutritious food via both capture fisheries and fish farming. Capture fisheries should increase their food supply by rebuilding fish stocks and prioritising edible fish for human consumption. Such sustainable fisheries, however, can fulfil only about 40% of our daily per capita EPA/DHA requirements. To meet these requirements, we need to additionally farm fatty fish (salmon). These fatty fish, however, depend on by-products from fisheries to meet their own EPA/DHA requirements and on livestock slaughter by-products to meet their high nutrient requirements. Feeding livestock by-products to farmed fish, however, is not common practice due to concerns about consumer acceptance. Fish farming, moreover, competes with livestock production for upcycling of biomass unsuitable for human consumption. We conclude that a circular food system requires a combination of animal production systems, tailored to the available human inedible feed and desired nutrient supply to the human population. Such co-dependent animal production systems are essential to achieve balanced healthy diets with respect for our planet.

1. Introduction

A circular food system is increasingly seen as a promising way to feed our growing population within the carrying capacity of the planet, both by scientists and politicians (European Commission, 2015; Ghisellini et al., 2016; Jurgilevich et al., 2016; Springmann et al., 2018). Central to a circular food system is the efficient use of natural resources, especially spatial resources like arable land, grassland and waterbodies (van Zanten et al., 2019). Efficient use of arable land, for example, prioritises plant biomass for human consumption, as the alternative – using arable land to cultivate animal feed – is less efficient due to metabolic losses when converting feed to food (Foley et al., 2011; Godfray et al., 2010). Animal production should, therefore, focus on upcycling so called low-opportunity-cost feed (LCF) into animal-source food (ASF) and other ecosystem services (Garnett, 2011; van Zanten et al., 2016a). Such LCF, unsuitable or currently undesired for human consumption, include crop residues, by-products from food processing (e.g. beet pulp or rapeseed meal), food waste and grass biomass. Feeding animals solely with LCF is most land use efficient as competition between feed and food production is minimised (van Kernebeek et al., 2016). The availability of LCF is, however, limited and poses a boundary to the production and consumption of ASF in a circular food system (van Zanten et al., 2018).

Recent studies show that livestock fed solely with available LCF can contribute significantly to the supply of nutrients that are highly bio-available, such as protein and iron, or absent in plant-source food, such as vitamin B12 (Godfray et al., 2018; Smith et al., 2013; van Hal et al., 2019; van Zanten et al., 2018). So far, however, studies on the role of animals in a circular food systems focussed solely on livestock, while also aquatic animals can make a valuable contribution to global nutrition security (Béné et al., 2015). Besides providing valuable micro-nutrients, such as vitamin D and selenium, fish are currently our main source of eicosapentaenoic (EPA) and docosahexaenoic (DHA) ω-3 fatty acids, essential e.g. for brain development and functioning, and immune regulation (Kris-Etherton et al., 2009; Racine & Deckelbaum, 2007; Simopoulos, 2009). Humans can desaturate alpha-linolenic acid (ALA) into EPA/DHA, but both ALA intake and desaturation potential are limited (Calder & Yaqoob, 2009). Guidelines for healthy diets (Willett et al., 2019), therefore, include a significant share of fish to fulfil the daily recommended intake of 250 mg EPA+DHA (EFSA, 2017).

Fish are either harvested from the wild (capture fisheries) or farmed (aquaculture) (FAO, 1988). Capture fisheries require no input of feed, and, therefore do not directly compete for resources with food crop cultivation. The current use of human edible parts of captured fish to feed farm animals, however, does cause feed-food competition (Cashion et al., 2017), although at present, there is no food demand for these species. Furthermore, food supply by capture fisheries is ultimately limited by the production capacity of the fish stocks in our water bodies (Hamilton et al., 2020). To avoid overexploitation and to rebuild impaired fish stocks, fish stocks in shared seas are managed through international agreements (ICES, 2016). The impact of these international agreements on rebuilding fish stocks, and the potential of marine ecosystems too supply food, is uncertain, and while progress has been made, it is slower than desired (Froese et al., 2018; Rindorf et al., 2017).

Unlike fisheries, farmed fish generally require a nutrient-dense feed comprised of plant, livestock and/or fish-based ingredients (Tacon, 1997). As part of these feed ingredients are suitable for human consumption (Cashion et al., 2017) or grown on land suitable for food crop production (Fry et al., 2016). Fish farming, therefore, currently results in feed-food competition. For example, only 30% of globally produced fishmeal consists of human inedible fish by-products, while the remainder consists of rendered whole, often food-grade, fish (Cashion et al., 2017; Jackson & Newton, 2016). Nevertheless, farmed fish may play an important role in a circular food system, as they can contribute to the efficient use of LCF for the following reasons. First, fish have relatively high feed efficiencies (Tacon & Metian, 2008). Second, they can feed on animal proteins currently prohibited as livestock feed (EU, 2013a); and third, they can efficiently upcycle EPA/DHA from marine sources into nutritious ASF (Tocher, 2015).

To our knowledge, the contribution of capture fisheries and fish farming to a circular food system is unknown. Understanding the relevance of fish in a circular food system – in terms of nutrient supply and efficient use of resources – can provide direction to strategic development of both capture fisheries and fish farming. This study, therefore, explores the potential role of capture fisheries and fish farming, relative to common farm animals, to a circular food system, using the EU-28 as a case study.

2. Methods

The contribution of capture fisheries and farmed fish to a circular food system was assessed using the methodological framework depicted in Figure 1**.** Efficient use of spatial natural resources implies arable land and waterbodies primarily produce biomass for direct human consumption through food crop cultivation and capture fisheries. LCF associated with this food production (e.g. processing by-products and manufacturing wastes) can be fed to animals, resulting in additional, indirect food supply. While grassland does not supply food directly, ruminants can upcycle grass into an indirect supply of meat and milk. Besides ASF, animals that upcycle LCF provide associated by-products that can be used as feed under strict regulations to avoid transfer of diseases.

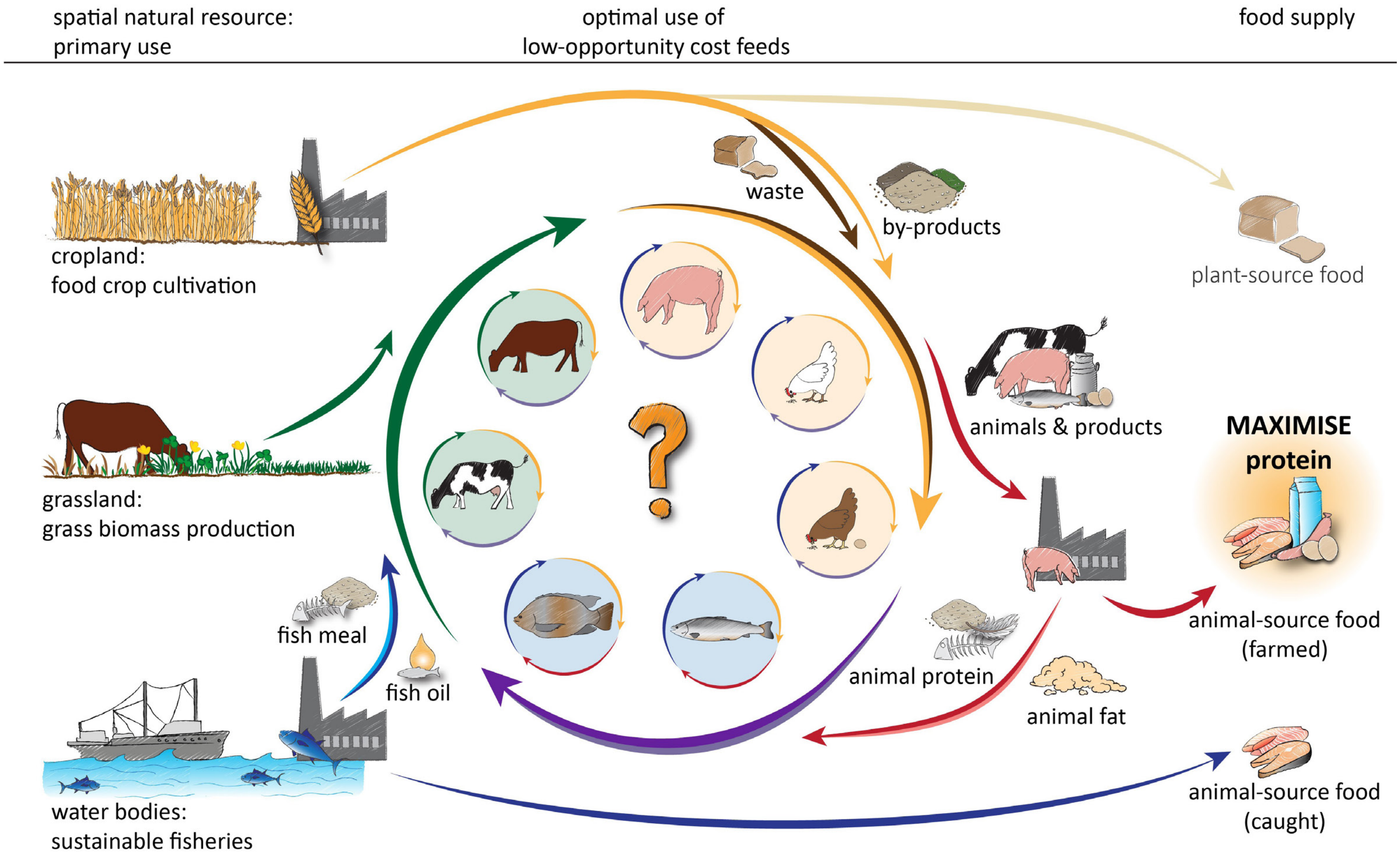

Figure 1 Framework to assess the contribution sustainable fisheries and aquaculture to a circular food system; FFS = former foodstuff; PAP = processed animal protein. Adapted from van Zanten et al. (2019).

To assess the contribution of capture fisheries, we define EU fisheries that align with the principles of a circular food system (Section 2.1). To assess the contribution of farmed fish to the optimal conversion of LCF – where they compete with livestock – we extended the livestock optimisation model of van Hal et al. (2019) with two farmed fish species (Figure 1).This extended model allocates the LCF available in the EU to that combination of fish and livestock that maximises human digestible protein (HDP) supply, while meeting human requirements of vitamin B12 and EPA/DHA. We prioritised meeting the requirements of these nutrients for two reasons. First, they are currently only provided by ASF (Béné et al., 2015; Smith et al., 2013). Second, both vitamin B12 and EPA/DHA are currently under-consumed by a significant part of the EU population while protein is abundantly available (de Smet, 2012; Duru, 2019; Givens & Gibbs, 2008; Oh & Brown, 2003). We, furthermore, illustrate the supply of calcium, selenium, vitamin A, vitamin D, iron and zinc, as their adequate intake might be threatened under changed ASF supply, and ASF vary in contents of these nutrients (Godfray et al., 2018; Mertens et al., 2017).

The model, described in Section 2.2, predicts which animals we should keep and which of the available LCF we should feed them to produce as much HDP as possible, while meeting daily requirements of vitamin B12 and EPA+DHA. In Section 2.3 we quantify available LCF from food crops, grass production and capture fisheries in the EU. Thereafter, we define the included livestock and fish farming systems (i.e. pig, laying hen, broiler, dairy, beef, salmon and tilapia; Section 2.4), and quantify the LCF associated with processing their outputs into food (Section 2.5). In Section 2.6, we explain how we quantified ASF and nutrient supply from fisheries (direct) and animal production systems (indirect) to humans. Finally we performed a sensitivity analysis by comparing our reference scenario (Section 2.1 to 2.5) to scenarios with alternative assumptions (Section 2.7).

2.1 Sustainable fisheries and fish use

Food supply by fisheries is limited by the amount of harvestable fish in waterbodies and how we choose to use these fish. The amount of fish that can be harvested from a waterbody depends on the production capacity of its fish stocks, which in most EUs shared waters is impaired due to overexploitation (Costello et al., 2016; Froese et al., 2018). As the production capacity of a waterbody should be sustained or even restored in a circular food system, we assumed landings (i.e. harvested fish in tonnes of fresh fish) to be limited to the maximum sustainable yield (MSY) implemented in EU legislation (EU, 2013b; ICES, 2016). This MSY represents the highest achievable landings without long-term negative impacts on the population, considering both harvested biomass and fish mortality (EU, 2013b). To avoid feed-food competition we also assumed that the edible yield fraction of all landed food-grade fish is used as food, while only their by-products are rendered into feed.

To estimate EU MSY landings (Appendix B1, Table B1**)**, we first quantified MSY landings of 100 stocks of 16 species in the Northeast Atlantic (ICES, 2016). Subsequently, we quantified the share of these landings available to EU member states based on the current quota distribution (EU council, not publicly available). The selected 16 species were most relevant in terms of biomass landed in 2016, for which coherent data on MSY landings and quota distributions was available (Appendix B1). In 2016, the considered 100 stocks provided 75% of total EU landings (ICES, 2018), the remainder originated mainly from the Mediterranean and Black Seas. Of the 16 species, two were classified as non-food-grade, namely Sandeels *(Ammodytus)* and Norway pout *(Trisopterus esmarki)* (Cashion et al., 2017). For five of the 14 food-grade species, part of the landed whole fish is currently rendered into feed (e.g. European Sprat (*Sprattus sprattus)* (EUROSTAT, 2016)), while landings of one food-grade species (blue whiting (*Micromesistius poutassou*)), was fully rendered into feed (Appendix B1). Here we assumed that all food-graded fish is used as human food instead of as animal feed.

2.2 Optimising low-opportunity-cost feed (LCF) conversion

To assess the optimal conversion of LCF by livestock and fish we extended the optimisation model of van Hal et al. (2019). This extended model has the standard form of a linear programming model:

$$\begin{array}{ll} \textit{Maximise} & Z=\boldsymbol{c}'\boldsymbol{x} \\ \textit{Subject to} & \boldsymbol{Ax}\geq\boldsymbol{b} \\ \textit{and} & \boldsymbol{x}\geq 0 \end{array}$$

Where, $\boldsymbol{x}$ is a vector of animal production activities; $\boldsymbol{c}$ is a vector of HDP produced per unit of activity; $\boldsymbol{A}$ is a matrix of technical coefficients; and $\boldsymbol{b}$ is a vector with quantitative constraints. The objective function to maximise HDP output (Z) is restricted by the availability of each LCF, the nutritional value of each LCF for each animal system, and the nutritional requirements of the animals in each production system. Additional “nutrient constraints” ensure that daily human requirements of vitamin B12 (4 µg) and EPA+DHA (250 mg) are fulfilled (EFSA, 2017). We, furthermore, restrict the allocation of available LCF to animal production systems to follow current EU feed legislation. Current EU feed legislation allows feeding of grass resources, crop residues and processing by-products, and animal fats, such as tallow and fish oil, to all farm animals. To avoid transfer of diseases to animals or humans, feeding of animal proteins is strictly regulated (Table B6) and feeding of food waste from households and catering is prohibited (EU, 2009, 2013a, 2017, 2018).

2.3 Low-opportunity-cost feeds (LCF)

We included the following LCF as model input: crop processing by-products, plant-based former-foodstuffs, grass resources, and by-products of sustainable fisheries. Former-foodstuffs (FFS) are products intended for human consumption but wasted during manufacturing or retailing. Only plant-based FFS are currently allowed as animal feed (EU, 2017, 2018). Crop residues were assumed to be left on the field to maintain soil fertility (van Zanten et al., 2019) and, like feeding losses, were considered unavailable as animal feed (Vermeij, 2017). We assumed that grass resources can be valued only by ruminants in the country of origin, whereas other LCF can be traded freely between EU countries.

The availability of by-products from the processing of EU plant-source food was derived from van Hal et al. (2019) (Appendix A2)**.** The availability of plant-based FFS was based on estimations of their current use in the EU and amounted 5 Mt fresh matter per year (EFFPA, 2019). The composition of these FFS equalled the average composition in the UK (UKFFPA, 2019), the Netherlands (VIDO, 2019) and France (Vernier et al., 2016) (Figures B1 & B2). For reporting purposes, available by-products and FFS were classified based on their nutritional properties (Table A2 & Figure B3)**.** The availability of grass resources derived from van Hal et al. (2019) distinguishes three vegetation types: managed grassland, natural grassland and rangeland (Appendix A2). Managed grassland, while suitable for food crop production, was included to avoid release of carbon and loss of biodiversity and cultural value when converting grassland into cropland (Foley et al., 2011; Gerber et al., 2013). The availability of LCF from fisheries was calculated by applying species specific rendering fractions (output of fish oil and meal) to the inedible part of the landings, which were quantified using the species specific slaughter yield (Table B2)**.** Underlying data, assumptions and calculations are provided in Appendix B2.

2.4 Animal production systems

We included the five most prevailing livestock production systems in Europe (i.e. pig, laying hen, broiler, dairy and beef production (FAO, 2017d)), and two fish farming systems (i.e. salmon and tilapia). We modelled the entire life cycle of these animal systems, including food producing as well as non-food producing animals, such as parent and young stock.

Livestock production systems

The number of non-food producing livestock (e.g. sows, gilts and piglets) relative to a producing animal (e.g. fattening pig) (Appendix A3; Table A6) was based on European herd compositions (FAO, 2016a, 2016c). We distinguished three productivity levels in livestock systems: low, mid and high. Productivity was expressed in annual milk/egg production or average daily gain, where high productivity reflects intensive production using Dutch production averages as a proxy (Bos et al., 2013), and low productivity reflects extensive systems throughout Europe. Production performances, related nutrient requirements (Tables B8 & B9) and net nutrient contents of LCF (CVB, 2016) for each livestock system were adopted from van Hal et al. (2019) as described in Appendix B3.

Fish farming systems

We included two types of farmed fish with contrasting ability to utilise feed. Atlantic salmon (*Salmo salar*), the most prevailing farmed fish species in the EU (EUROSTAT, 2019). Salmon represents a high-trophic carnivore species that requires animal protein in their feed. Nile tilapia (*Oreochromis niloticus*) represents a lower trophic omnivorous species. Tilapia is the most consumed low trophic, farmed fish in EU (FAO, 2018b) and was selected in the absence of commercial farming of such species in the EU due to low profitability (Sprague et al., 2016). As an oily fish, salmon is a rich source of EPA+DHA while these contents are much lower in Tilapia (Sprague et al., 2016).

The number of non-producing animals (e.g. alevin, fry, smolt and brood stock) needed to harvest one producing animal (i.e. salmon or tilapia grower) (Appendix B3; Table B5) was based on species specific mortality (Bhujel, 2014; EY, 2017; McGeachy et al., 1995) and fertility data (Eskelinen, 1989; FAO, 2018a; TIL-AQUA, 2016), assuming mortality occurs evenly over each life phase. We distinguished only one productivity level for fish farming that reflects the high productivity common in the EU, as a lack of data limited us to simulate reduced productivity levels. To define the performance of these high productive fish (Table 1), we first simulated their optimal growth and associated feed and nutrient intake during the entire production cycle using Skretting's AquaSim model. Subsequently, we calibrated simulated growth and feed intake values with values of common practice, using literature. Details on the below described data, assumptions and calculations of fish farming systems are provided in Appendix B3.

Fish growth

As fish are poikilothermic, their growth, metabolism and feed intake depend on water temperatures. For Atlantic salmon, we simulated optimal growth and feed intake assuming the sea water temperature pattern in the Atlantic ocean around Great Britain (SeaTemperatures, 2019), where the majority of EU28 salmon is produced (EUROSTAT, 2019). Simulated growth and feed intake (Figure B3) were calibrated with average feed conversion ratios (FCR: kg feed needed per kg growth) of 1.2 to 1.3 observed in Europe (Tacon & Metian, 2008). The assumed cumulative FCR of 1.22 is attained through a yearlong fresh water phase before transfer to sea cages where fish grow from 77 g to a slaughter weight of 5500 g in 520 days (Table 1).

Table 1 Assumed performance and related nutrient requirements of Atlantic salmon and Nile tilapia

	Performance							Nutrient requirement[3]			
	Period	Growth (g)		Feed intake (g)		FCR[1]		DE (MJ)		DP (g)[4]	
	days	/d	Total	/d	Total	Phase	Cum[2]	/d	Total	/d	Total
Salmon											
Alevin	85	0.00	0.31	0.00	0.19	1.08	1.08	0.000	0.003	0.001	0.093
Fry	25	0.03	0.70	0.02	0.49	0.98	1.01	0.000	0.009	0.009	0.237
Parr	111	0.13	29.01	0.23	25.51	1.14	1.14	0.004	0.48	0.11	11.92
Smolt	143	0.33	47	0.32	45.87	1.20	1.18	0.006	0.84	0.13	18.93
Grower	519	10.47	5433	11.66	6049	1.22	1.22	0.235	122	3.69	1917
Brood stock	32	15.32	490	17.90	573	1.17	**1.22**	0.315	10	7.39	236
Tilapia											
Swim up fry	21	0.02	0.35	0.01	0.30	3.29	3.29	0.000	0.005	0.006	0.134
Fry	21	0.10	2.15	0.06	1.16	0.82	1.16	0.001	0.017	0.022	0.471
Fingerling	18	0.41	7.46	0.40	7.17	1.29	1.18	0.006	0.10	0.15	2.65
Juvenile	29	1.72	50	1.77	51	1.14	1.15	0.022	0.62	0.54	15.76
Grower	107	6.50	695	9.33	999	1.48	1.45	0.109	12	2.62	280
Brood stock	270	1.02	275	7.90	2134	7.76	**1.45**	0.095	26	2.92	788

1: Feed conversion ratio including feed consumed by non-surviving fish, brood stock and their replacement
2: Cumulative FCR summed over all preceding phases; bold value at broodstock represents FCR of entire life cycle
3: Assuming phase specific Skretting feeds nutrient content in Table B6
4: Protein digestibility of conventional feeds assumed:
* Salmon: 87% % (Aas et al., 2015; Dessen et al., 2017; Weihe et al., 2018)
* Tilapia: 92% (Tran-Ngoc et al., 2016)

Nutrient requirement

For Nile tilapia, optimal growth and feed intake (Table 1) were simulated for a tank system with a constant water temperature of 28°C and controlled high oxygen levels. The cumulative FCR of the simulated growth (1.45) falls in the range of values observed in practice (i.e. 1.0-2.6 (Tacon & Metian, 2008)), which include pond systems, in which feed obtained from the pond ecosystem is excluded (Kabir et al., 2019), as well as tank systems with suboptimal oxygen or temperature management (El-Sayed, 2019). This FCR is attained by growing to a slaughter weight of 750 g in 200 days, which is typical for the European market, (Rutten et al., 2004; TIL-AQUA, 2016).

Digestible energy (DE) and protein (DP) requirements to achieve the assumed growth (Table 1) were calculated by multiplying the required feed intake with DE and DP contents in Skrettings' commercial feeds, tailored for each species and life phase. We assumed a protein digestibility of 87% in salmon feed and of 92% in tilapia feed (Aas et al., 2015; Dessen et al., 2017; Tran-Ngoc et al., 2016; Weihe et al., 2018). To ensure fish health as well as appropriate EPA+DHA levels in edible fish tissue (Sprague et al., 2016), we assumed the EPA+DHA content in salmon feed to be larger than 2.5% of DM (Bou et al., 2017). Furthermore, we assumed that the maximum feed intake capacity (FIC) of farmed fish was equal to the simulated feed intake (Table 1). Commercially farmed fish, typically consume feed to their maximum capacity which can be limited by oxygen availability or other physiological constrains (Saravanan et al., 2012, 2013).

DE contents and protein digestibility (PD%) of the considered LCF were obtained from the IAFFD database (IAFFD, 2018). To calculate the DP content of each LCF, its PD% was multiplied with its crude protein content (van Hal et al., 2019). While the IAFFD database gives nutrient content values for a broad range ingredients – including most considered LCF – they do not differentiate between fish species, even though omnivorous fish like tilapia are known to better digest plant-based proteins than carnivorous fish like salmon (Magalhães et al., 2018). To account for this difference, we adjusted PD values of IAFFD based on literature data (Table B7).

2.5 Low-opportunity-cost feed (LCF) from animal production systems

The LCF from ASF production included animal fat, fish oil, meal from blood, plasma, feathers, meat and bones, and fish and bones, which result from slaughtering and meat processing of animals selected for the optimal use of LCF into raw meat or fish. The availability of LCF from livestock production was calculated by multiplying the predicted live weight (LW) output of each livestock system with slaughter and processing yields per kg LW (Appendix B2; Table B3). For pigs and cattle, these fractions were derived from slaughter reports (USDA, 2018b, 2018c), whereas for poultry they were derived from literature (Haslinger et al., 2007; Sams, 2010). The availability of LCF from farmed fish was calculated by multiplying the inedible fraction of the predicted LW with rendering fractions for oil and meal (Table B2). The above described calculations show that the availability of animal-based LCF depends on the animal production systems selected to upcycle available LCF, creating a model loop as shown in Figure 1, that forms no issue in solving optimisation models.

As indicated, we adhere to current legislation regarding use of animal-based LCF as animal feed (Table B4). Amongst others, this EU legislation forbids feeding farmed animals with proteins originating from farmed animals of the same species (EU, 2013a). The farmed fish species in our model, however, are a proxy for a range of species with similar characteristics (e.g. rainbow trout for salmon), that are allowed to feed on each other's by-products. To reflect this we allow for intraspecies recycling of fish farming by-products, meaning farmed fish can consume by-products of farmed fish of the same species.

2.6 Animal source food and nutrient supply

Supply of ASF, expressed per EU capita per day (/cap/d), includes the direct supply from capture fisheries and indirect supply from the farmed livestock and fish selected to upcycle available LCF.

Direct ASF supply from fisheries (kg cooked fish) was calculated by multiplying fisheries landings (Table B1) with species specific slaughter yields (Table B2) and cooking retentions (USDA, 2012). Similarly, supply of edible meat, offal and fish by farmed livestock and fish was calculated by multiplying their predicted LW output with species specific slaughter yields (Tables B2 & B3) and cooking retentions (USDA, 2012). Supply of milk and eggs (kg fresh product), was equal to the predicted output of the production systems. Nutrient supply was calculated by multiplying supply of each ASF with its product specific nutrient content (Appendix B4; Table B8). We consider the nutrients most affected by reducing ASF consumption, namely HDP, vitamins A, D and B12, calcium, iron, zinc, selenium and EPA+DHA (Macdiarmid et al., 2012; Mertens et al., 2017). Nutrient content of cooked meat reflects the weighted average nutrient content of all cuts, and variation in protein content related to productivity (Figure B4) was based on literature (van Hal et al., 2019). Finally, we compare the resulting daily per capita nutrient supply with the nutrient specific daily recommended intake (DRI) (EFSA, 2017).

2.7 Sensitivity analysis

To evaluate model responses to changes in key model parameters, we conducted a sensitivity analysis in which results of the reference scenario (Sections 2.1-2.6) were compared with alternative optimisation scenarios. First, we explored the impact of the "nutrient constraints" implemented in the reference scenario to prioritise meeting the human demand for vitamin B12 and EPA+DHA when optimising the use of LCF. We assess the consequences including these nutrient constraints, by comparing the reference scenario with a scenario in which no nutrients constraints were included (No NC Scenario).

Second, we explored the implications of our assumptions regarding capture fisheries in the reference scenario, where landings were limited to MSY and all edible fish was assumed to be used as food (Section 2.1.). While such fisheries are suited to a circular food system, they do not reflect current practice, where 64% of EU fish stocks are subject to ongoing overexploitation (Froese et al., 2018) and whole food-grade fish are rendered into feed (Cashion et al., 2017). We assessed the impact on ASF supply of shifting from current to sustainable fisheries practices, by comparing the reference scenario with a Current fisheries scenario, that assumed current landings and current fish use (Table B1; Current).

The MSY yields assumed in the reference scenario are, however, only a first step to rebuild overexploited commercially used fish stocks in the EU (EU, 2013b). In the long run, rebuilding stocks to recover their production potential, which may increase food supply, implies a further reduction of fishing pressure that is not yet quantified by legislation (Costello et al., 2016; Froese et al., 2018; Rindorf et al., 2017). Froese et al. (2018) indicated that to effectively rebuild stocks by 2030, fishing pressure should be limited to 80% of levels yielding MSY. We estimated the impact of such stock rebuilding on ASF supply with a Stock rebuilding scenario, where landings reflect predicted MSY landings in 2030 under proposed reduced fishing pressure (Table B1; MSY 0.8) while maintaining the improved fish use of the reference scenario.

3. Results

In our reference scenario that mimics an optimal circular food system, animals supply 620 g fresh milk, 12 g fish, 37 g meat and 4 g offal (edible organ meat) per capita per day (cap/d). Putting this in perspective, this is 28 g more milk, 4 g more fish, 180 less meat and 33 g less egg than currently supplied in the EU (FAO, 2017a). In total, this ASF provides 35 g HDP/cap/d, fulfils the DRI of vitamin B12 (131%) and EPA/DHA (100%), and contributes significantly to the DRI of other essential nutrients (Figure 2). Fish provide 8.3% of total HDP supply (2.9 g/cap/d)), 98% of the DRI of EPA/DHA, and 14% of the DRI of vitamin B12 (0.7 µg/cap/d). Fish, furthermore, contribute significantly to the DRI of fat-soluble vitamin D, but this DRI is uncertain as synthesis of vitamin D from sunlight is highly variable in humans (EFSA, 2017). The contribution of fish to most other considered nutrients is relatively small, while livestock play a more essential role. Milk supply, for example, nearly fulfils the DRI of calcium, while meat significantly contributes to both iron and zinc supply. Due to its high vitamin A and B12 content, offal has a relatively large contribution to the DRI of these nutrients (Figure 2).

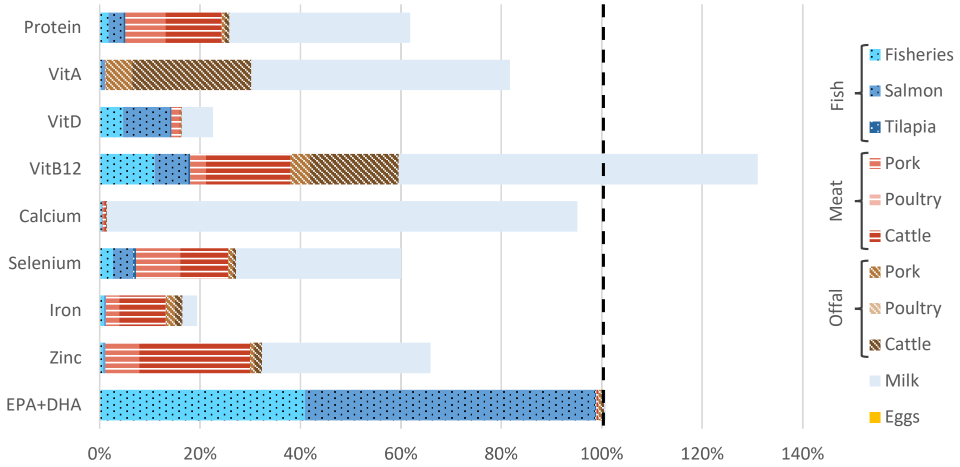

Figure 2 Contribution of animal source food supplied by fisheries and animal production systems to the daily recommended intake (DRI) of protein and relevant nutrients in the reference scenario for a circular food system.

Fisheries

About 38% of the daily supply of edible fish (4.5 out of 12 g/cap/d) originates directly from capture fisheries (Figure 3a; Reference). The various species from capture fisheries fulfil 2% of daily DRI of HDP (1 g/cap/d), 11% for vitamin B12 (0.45 µg/cap/d) and 40% for of EPA+DHA (100 mg/cap/d) (Figure 3). The contribution of each species to HDP supply follows that of their product supply (Figure 3a,b), indicating a similar protein content among fish species. In contrast, herring, mackerel and sprat have a relatively high contribution to the intake of vitamin B12 and EPA+DHA, because their flesh contains relatively high amounts of these nutrients (Figure 3c,d).

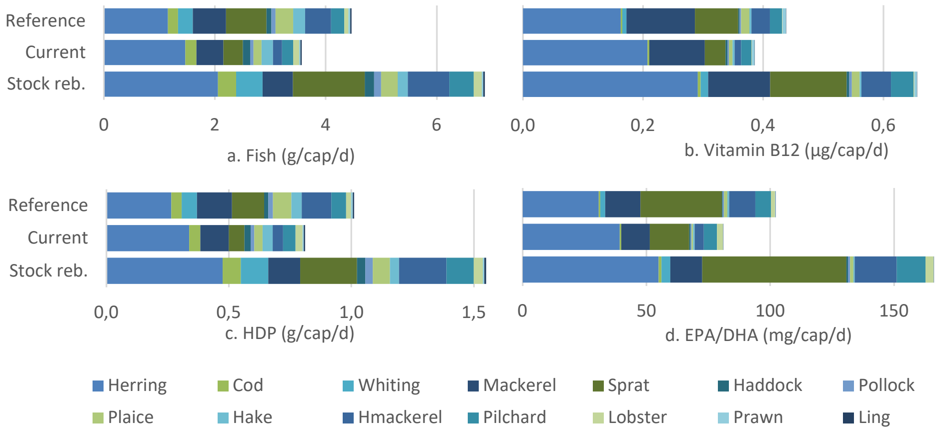

Figure 3 Contribution of food-grade fisheries species to the supply of (a) fish, (b) human digestible protein (HDP), (c) vitamin B12 and (d) EPA+DHA in the reference, current fisheries and stock rebuilding scenarios.

Farmed fish

Salmon farming, the only included production system with a high EPA/DHA output, was selected to fulfil the majority (58%) of the DRI for EPA/DHA. As salmon require a protein dense, EPA/DHA containing feed, they received all available high protein animal by-products (Figure 4) and their diets comprised mainly of fish based ingredients (Appendix B5; Figure B5). Contrastingly, tilapia received all available bone meal, which has a lower protein quality (Figure 4), and their diets consisted mainly of cereal and oilseed products (Figure B5).

a. c.

Optimal use of LCF

Optimal conversion of LCF requires 442 million farmed salmon (2.2 Mt harvested fish), 1 billion tilapia (0.4 Mt harvested fish), 52 million low-productive pigs and 30 million low-productive dairy cows, but no poultry or beef cattle. The selected animal production systems used all available food leftovers (by-products and FFS), while leaving part of the natural grassland (47%) and shrubland (82%) unused (Figure 4). Fish diets contained the majority of the animal-based LCF, whereas

b. d.

livestock diets contained the majority of the plant-based LCF. Pig diets consisted mainly of cereal and oilseed by-products (Figure B5), but their low productivity and intake of some animal fat enabled them to upcycle some bulky LCF, such as pulp and roughage (Figure 4). The diet of dairy cattle included as much grass as possible and was supplemented with plant-based food leftovers (Figure 4). High quality grass resources were fed to dairy cows and young stock, while bulls only grazed natural grass and shrubs, to maximum the intake of this low quality feed (Figure B5). These roles of livestock are in line with findings of van Hal et al. (2019)

3.1 Excluding nutrient constraints

Results were hardly affected when excluding the constraint to meet human vitamin B12 and EPA+DHA requirements. The No NC scenario resulted in a protein supply of 36 g/cap/d (0.5 g higher than in reference), and fulfilled 99% of DRI of EPA+DHA and 136% of DRI of vitamin B12. These results indicate that only EPA/DHA requirements constrained protein supply in the reference scenario, and that this restriction had only limited effect on protein supply. The effect on the number of farm animals selected to produce this protein, however, was larger. Compared to the reference scenario, the number of salmon reduced with 4%, tilapia with 19%, pigs with 21%, whereas cattle numbers increased with 4% (Figure B8 – No NC**)**.

3.2 Alternative fisheries scenarios

On the one hand, current fisheries practice resulted in lower direct protein supply than the reference scenario (-0.2 g/cap/d), as their higher landings (+0.1 g/cap/d) did not compensate for the loss in food supply due to the current use of edible fish as animal feed (-0.3 g/cap/d; Figure 3 **-** current fisheries**).** On the other hand, the use of edible fish as feed under current fisheries practices, enabled higher salmon production(+16% 511 million, 2.6 Mt of harvested live fish) and tilapia production (+48% 0.5 billion, 0.2 Mt harvested live fish) compared to the reference scenario (Figures B7b & B8). Besides the extra fisheries by-products, this farmed fish required high quality protein, which was attained from pig by-products. The increased demand for these pig by-products drove the selection of pigs (+2%) over dairy cattle (-1%) who's by-products are banned as feed for all production animals in the EU (Figure B8). Total animal protein supply was 0.1 g/cap/d lower for current fisheries than in our reference scenario (Figures B7a).

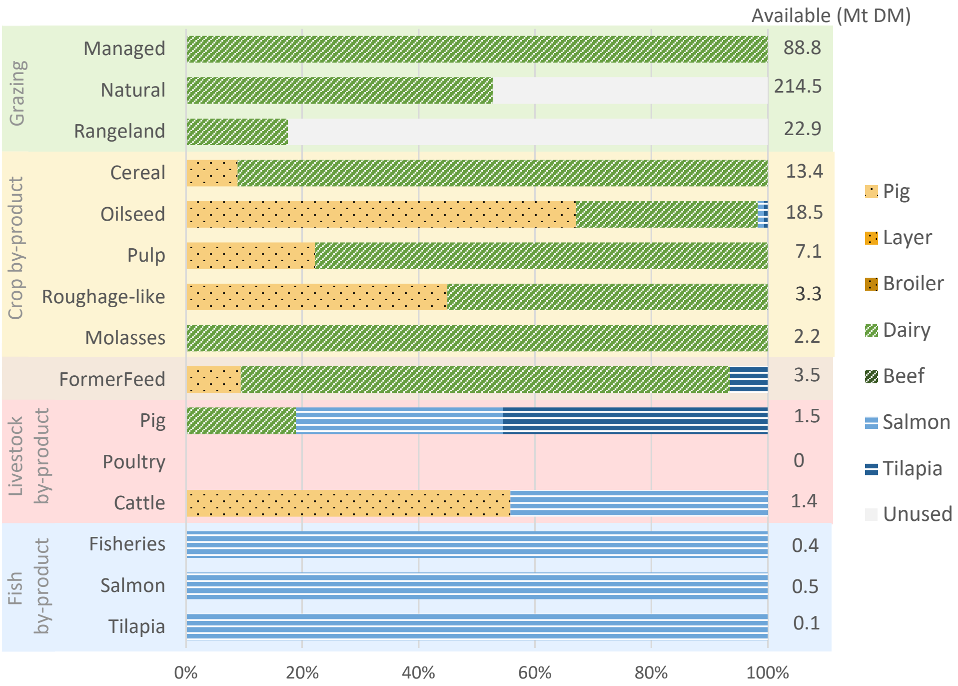

Figure 4 Allocation of available LCF **(**classified based on their origin**)** over the included animal production systems as % of available LCF. Absolute mass allocation is provided in Figure B6 to whom we refer for a thorough discussion of the role of livestock species and productivity.

Stock rebuilding (MSY 0.8; Froese et al. (2018)) increased direct ASF supply with about 50% to 6.9 g/cap/d (Figure 3 – Stock rebuilding**)**. We observed a similar increase in protein and vitamin B12 supply, while the increase in EPA/DHA supply was larger (~65%), because landings of species rich in these fatty acids (i.e. herring and sprat) increased most. Stock rebuilding not only increased the direct supply of EPA/DHA from fisheries, but also increased the availability of EPA/DHA containing fish by-products. These high quality fish by-products were allocated to farmed salmon, enabling them to value more oilseed meal and increase their production with 21% to 536 million animals and 2.7 Mt harvested fish (Figures B8 & B9b). Pig and tilapia production both reduced with 9% (Figure B8) which freed up food leftovers for dairy production, enabling them to value more natural grass biomass (Figure B9b) and increase cattle numbers with 1% (Figure B8)**.** All in all, reducing the fishing pressure increased the total supply of animal protein with 2% to 36 g/cap/d, while the supply of EPA/DHA increased beyond DRI to 350 mg/cap/d (Figure B7). When excluding fisheries, no feasible solutions were found as human EPA/DHA requirement could not be met.

4. Discussion

We demonstrate that under the circular paradigm, fish provide nutritious ASF through sustainable capture fisheries and farmed fish fed with LCF. The assumed sustainable fisheries provide about 25% more HDP than current fisheries do. To achieve this increase in protein supply, we should prioritise using edible fish for human consumption, which also compensates for the temporary reduction in landings needed to adhere to MSY. To prioritise edible fish for human consumption, we should overcome practical limitations that currently cause rendering of whole food-grade fish into feed. We might want to stimulate seasonal consumption and preservation of, for example, sardines and herring, to overcome the seasonality and perishability of their landings (Ganias, 2014). Similarly, we could stimulate the consumption of low value food-grade fish like blue whiting (Cashion et al., 2017).

Besides avoiding feed-food competition, capture fisheries should rebuild impaired fish stocks (Froese et al., 2018). Fisheries landings were therefore reduced to MSY, which reflects the production capacity of the fish stocks in our waterbodies. We however underestimated food supply by EU capture fisheries by only considering MSY landings of the most relevant stocks and species in the Northeast Atlantic, which currently provide 75% of EU fisheries landings. This underestimation, however, is limited as the majority of stocks in the excluded Black and Mediterranean seas are severely impaired and require severe yield reductions to adhere to MSY (Froese et al., 2018). The MSY assumed in EU legislation and our reference scenario, however, are only a first step to rebuilding impaired fish stocks, and fishing pressure should be further reduced (EU, 2013b; Froese et al., 2018; Thorpe et al., 2017). In our Stock rebuilding scenario, we found that, in the long run, such reduced pressure can increase direct fish supply with 53% (Figure 3). Part of this observed increase may, however, be due to methodological differences underlying the MSY estimations in our reference (ICES, 2016) and Stock rebuilding (Froese et al., 2018) scenario. Nevertheless, reducing fisheries pressure appears essential to rebuild impaired fish stocks and, therefore, for feeding our growing population in the future.

To maximise food supply from natural waterbodies, we should also explore consumption of alternative aquatic foods not yet included in our analysis (SAPEA, 2017). Consuming food from lower trophic levels, such as seaweed, filter feeders and herbivorous finfish, is always beneficial as nutrients are lost between trophic levels. Globally, current captured seafood, for example, only contains about 0.04% of the EPA/DHA produced by primary aquatic producers (zooplankton and phytoplankton) (Hamilton et al., 2020). The potential of tapping into low trophic levels in natural aquatic ecosystems by balanced harvesting, however, is uncertain (Duarte et al., 2009; Zhou et al., 2019).

In line with previous indications, we found that sustainable fisheries alone cannot fulfil our human demands for EPA/DHA (Hamilton et al., 2020; Sprague et al., 2016). To meet these requirements, we additionally need to farm fatty fish. In our analysis, for example, about 60% of the daily recommended intake of EPA/DHA was provided by farmed salmon (Figure 2). To produce EPA/DHA rich ASF, however, farmed salmon requires EPA/DHA containing feed commonly achieved by including fish by-products (Hamilton et al., 2020; Sprague et al., 2016). Of the fish by-products allocated to salmon farming, 40% originated from fisheries, 9% from tilapia and 51% from salmon farming (Figure 4). While current legislation bans feeding farmed salmon with meal of other farmed salmon (EU, 2013a), we allowed this in our model as our salmon farming system represents a wide range of fish species with similar properties, such as rainbow trout and seabass. Given the large share of salmon by-products in the salmon diet, we conclude that such a diversity of species, able to recycle each other's by-products, is essential for efficient use of EPA/DHA in a circular food system.

Our results also confirm that fish farming, and thereby the supply of EPA/DHA to humans, depend on capture fisheries (Hamilton et al., 2020; Sprague et al., 2016). This dependency is illustrated by the fact that salmon could not be produced if fisheries were excluded from the model (model infeasible), and their increased production with increasing availability of fisheries by-products (Figures B7b & B8). To fulfil the growing demand for EPA/DHA by our future population, four main solution pathways have been suggested (Hamilton et al., 2020; SAPEA, 2017; Sprague et al., 2016). First, precision feeding, which implies feeding relatively much ALA to young fish that are best adapted to elongate ALA into EPA/DHA (Bell & Koppe, 2010), while keeping EPA/DHA rich ingredients to feed fish at harvesting stages where they are upcycled into the ASF most efficiently (Bell et al., 2003; Codabaccus et al., 2013). Second, farming fish species that are better able to convert ALA into EPA/DHA, such as rainbow trout (*Oncorhynchus mykiss*) (Mente et al., 2019) and other freshwater species (Rodrigues et al., 2017). Third, in-vitro production of EPA/DHA by micro algae for both feed and food, an industry that is still in its infancy (Peltomaa et al., 2018; Vigani et al., 2015). Fourth, reconsidering human consumption of fish oil from industrial grade fish or fish by-products, which is far more efficient than feeding it to salmon, but hampered by food quality issues (Hamilton et al., 2020; Jackson & Newton, 2016).

Besides EPA/DHA rich ingredients, farmed fish, especially salmon, require high quality protein to meet requirement within their feed intake capacity. When limited to LCF, fish feeds can only reach such high protein content by including a large share of processed animal proteins (PAPs, e.g. fish, blood, bone and meat and bone meal; Figure 4). The farmed fish in our model require such high-quality proteins because they are highly productive. Like low-productive livestock (Figure B5; pigs and dairy), fish with a lower productivity might be better able to value lower quality LCF. Unlike livestock, however, fish are generally forced to reduce their feed intake when provided with low quality feeds as their digestion requires additional oxygen, which is often limitedly available in aquatic environments (Saravanan et al., 2013). This reduced feed intake, in combination with lower nutrient contents in LCF reduces growth rate, which increases the relative share of feed required for maintenance. This relative increase is however lower for poikilothermic fish than homothermic livestock (Fry et al., 2018). While such low productive fish can value more LCF, their increased excretion of non-digestible nutrients can cause practical problems. For salmon in sea cages increased excretion of non-digestible nutrients might cause addition eutrophication and environmental degradation of their surroundings (Nordvarg & Johansson, 2002; Qi et al., 2019). For Tilapia housed in tanks an increased excretion of non-digestible nutrients might cause adverse health effects (Austin, 1998), where for tilapia in pond ecosystems such non-digestible nutrients can feed the pond ecosystem thereby increasing the amount of natural food for fish (Kabir et al., 2019). In its current form tilapia pond systems are, however, unsuitable for Europe's temperate climate.

In summary, high-productive fish that require animal-based LCF are likely most suitable to a circular EU food system. These farmed fish have a valuable role in upcycling livestock PAPs, as they are the only farm animals allowed to eat them currently (EU, 2013a). Livestock, however, appears more suitable to upcycle most plant-based LCF, especially those of low nutritional quality, but full understanding of the potential of farmed fish requires that we consider a broader range of fish species. Here we found that livestock provide the majority of all considered essential nutrients, except vitamin D and EPA/DHA, as dairy upcycled grass resources and pigs plant-based food leftovers. Low productivity enabled this livestock to consume low quality LCF, but supplementation with high quality LCF was needed to upcycle as much low quality LCF as possible. Livestock thus competes for such high quality LCF with the farmed fish needed to meet EPA/DHA requirement. Animal-based LCF, however, were consistently allocated to farmed fish, even when relaxing the EPA/DHA requirement constraint (Figure B9; Excl. NRC).

In practice, use of livestock PAPs as aquafeed is limited in the EU due to country level legislation and industry concerns about consumer acceptance (IUCN, 2017). Using livestock PAPS in fish feeds, increases overall resource efficiency, as this frees high quality plant-based LCF for livestock. This strategy is also highly relevant in our current food system where much more animals and thus by-products are produced. The EU relegalised feeding of livestock PAPs as aquaculture feed in 2013, to enable efficient use of these nutritious by-products within the food system (EU, 2013a). Currently, the EU is exploring further amendments to the food safety legislations implemented to avoid future outbreaks of transmittable diseases (EU, 2009, 2018). While these legislations specifically target avoiding transmission of diseases between animals and to humans, they also hinder the efficient use of LCF that are potentially contaminated with such PAPs considering most food waste (EU, 2009, 2018). To stimulate legalisation of PAPs and food waste as animal feed, future research should clearly demonstrate their potential as well as the risks of feeding them to livestock and farmed fish.

Our findings show that a circular food system requires a combination of co-dependent animal production systems (e.g. fish farming requires capture fisheries and livestock by-products) to achieve balanced healthy diets with respect for our planet. Efficient use of available LCF requires a combination of animals that collectively have a high production efficiency, and are best able to upcycle specific feeds and/or supply essential nutrients. Selected animals are, thus, tailored to the available LCF and the desired nutrient supply to the human population, to which we made assumptions in the current study that should be considered when interpreting our findings. Here, we based availability of plant-based LCF on current consumption and focused only on nutrients typically obtained from ASF, while in a circular food system integrated crop and animal production should optimise the use available land to meet all population nutrient requirements within our environmental ceilings. Finally, to explore the full potential of fish in a circular food system, we considered only its biophysical components. Considering also societal and or economic aspects is relevant to design of a realistic future circular food system and stimulate the transition towards it. While predicted nutrient supply and animal numbers are only indicative of their potential, we are convinced that we deduced valuable principles for the use of fish in a circular food system. Given these principles, farmed fish have a large potential to upcycle LCF, as they appear relatively efficient, are essential in utilizing livestock PAPs and have the ability to upcycle EPA+DHA into their food outputs.

5. Conclusion

Our findings clearly show that capture fisheries as well as fish farming play an important role in a circular food system. Capture fisheries should increase their contribution to the food supply by prioritizing edible fish for human consumption and by rebuilding fish stocks. EU fisheries alone, however, are not enough to meet population requirements for the essential ω-3 fatty acids EPA and DHA. To meet these requirements, we need to additionally farm a variety of fatty fish species rich. These fish currently depend on fisheries to fulfil their EPA/DHA demand. Furthermore, when fed only with LCF these fish can only meet their high protein requirements by feeding on livestock by-products, uncommon in EU fish farming, but essential to the efficient use of resources. We conclude that a circular food system requires a combination of animal production systems tailored to the available LCF and desired nutrient supply to the human population and fish is essential in a healthy and environmentally-friendly diet.

Data availability

The authors declare that the data supporting the findings of this study are either provided in within the article and its supplementary material, or come from public databases traceable with the references provided.

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Chapter 4

Feeding food leftovers to farm animals: the potential of improved use and legalisation

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Abstract

Recent studies show that animals can contribute to a circular food system by upcycling low-opportunity-cost feeds (LCF) – products unsuitable for human consumption such as grass and food leftovers – into valuable animal-source food (ASF). Variation in the estimated amount of ASF such animals provide is to a large extent due to differences in the assumed availability and quality of LCF. The availability of food leftovers as LCF is currently restricted by legislation and other barriers. So far, no study has comprehensively analysed the ASF supply potential of enhancing the availability of food leftovers as LCF. Here we use a circular food system approach to model ASF supply potential of improved use and/or legalisation of food leftovers as LCF, when feeding animals only with LCF in an EU-28 case study. Our results showed that, of the considered food leftovers, household waste and livestock by-products have most potential to increase animal protein supply. Optimal use of currently used LCF (given their assumed availability) provides an intake of 27 g animal protein per capita per day. Reintroducing household swill can increase this intake with 12%, while using livestock by-products is fish feeds increases protein intake with 18%, and is essential to meet human requirements of EPA/DHA ω-3 fatty acids. Feeding swill, however, requires legislative change, and feed quality and safety remain difficult to safeguard even with the development of a collection and processing system. In contrast, livestock by-products are allowed in fish feed, but currently not used indicating other barriers to the transition towards a circular food system. We conclude that improved use and legalisation of inevitable food leftover can improve the resource use efficiency of both current and future circular food systems. Efficient use of available LCF requires a combination of animals tailored to the available LCF and the desired nutrients for human consumption.

1. Introduction

To feed our growing world population with limited natural resources, scientists and politicians recommend a transition to a more circular food system (EuropeanCommission, 2015; Jurgilevich et al., 2016; Springmann et al., 2018). A circular food system prioritises efficient use of natural resources to provide nutrition security for all humans (van Zanten et al., 2019). This implies that the limited land and water surfaces available for food production should, where possible, be used to provide food directly through food crop cultivation and sustainable fisheries (van Hal et al., 2020). Currently, however, a large share of these resources is used to produce animal feed which is less efficient due to animal metabolic losses (Foley et al., 2011; Godfray et al., 2010). While current animal production systems are major pollutants to the environment, animals fed only with biomass unsuitable or undesired for human consumption can contribute to food security while lowering the pressure on nature resources use (van Zanten et al., 2019). The role of farm animals in a circular food system, therefore, is to upcycle such biomass, referred to as low-opportunity-cost feeds (LCF), into valuable animal-source food (ASF) (de Boer & van Ittersum, 2018). LCF include grass resources and biomass lost along the food supply chain, so called food leftovers (Foley et al., 2011; Garnett, 2011; van Zanten et al., 2018). Food leftovers include crop residues (unharvested crop biomass), by-products (unintended outputs of crop processing) and food waste (products intended for human consumption but wasted along the supply chain) (FAO, 2011). As a circular food system assumes that the majority of the crop residue is left on the field to maintain soil fertility, "food leftovers" from now on refer to by-products and waste only (de Boer & van Ittersum, 2018).

A recent review of van Zanten et al. (2018) indicated that livestock fed only LCF can provide 7-30 g human digestible protein (HDP) per capita per day. Variation in HDP between these studies mainly results from difference in assumed LCF availability and which animals upcycle them. Most of the reviewed studies used a scenario approach and assigned available LCF to specific animal production systems (APS), while to make most of available LCF their use should be optimised. Using an optimisation model (van Hal et al., 2019, 2020) illustrated that optimal use of LCF requires various livestock and farmed fish species, each especially adapted to upcycle specific LCF (i.e. cattle valuing grass) and/or supply specific nutrients to humans (i.e. EPA/DHA fatty acid supply by fish). This model, that considers nutritional quality of LCF, can also be used to explore the potential of food leftovers that are currently not used as animal feed, to facilitate the debate on what food leftovers should be considered LCF.

While feeding animals is the most efficient use of food leftovers from a food systems perspective, this use is often limited by legal or practical restrictions (Papargyropoulou et al., 2014). Current legislation allows feeding plant-based leftovers such as by-products and industrial waste as well as animal fats, such as tallow and fish oil (EU, 2017). Feeding animal proteins, however, is strictly regulated to avoid spread of transmittable diseases, such as bovine spongiform encephalopathy (BSE), through contaminated feed (EU, 2009, 2013a). While this legislation primarily limits feeding processed animal protein (PAPs) – the main transmitter of these diseases – it also applies to food wastes potentially contaminated with animal protein (EU, 2017, 2018). Due to its rigidity, this legislation is criticised for hindering resource use efficiency (zu Ermgassen et al., 2016). In response, the EU is exploring legislative change to facilitate a safe use of PAPs and food waste as animal feed, starting with the legalisation of livestock PAPs in fish feeds (EU, 2013a). Regardless of this legalisation in 2013, livestock PAPs are still barely used in fish feeds, indicating that not only legal but other barriers related to society, politics, economy and technology, may restrict the use of food leftovers as LCF (BioMar, 2018; IUCN, 2017). This is also the case for retailing waste for which the use as LCF appears limited due to a lack of economic incentive to collect these wastes (Truong et al., 2019).

To stimulate a transition towards a circular food system as aimed by the EU it is essential to assess the potential of feeding unused LCF streams to farm animals in terms of protein supply (Priefer et al., 2016). To our knowledge, no study has coherently assessed the potential of enhancing the availability of food leftovers as LCF. Here we assess the ASF supply potential of improved use and/or relegalisation of food leftovers as LCF in a circular food system (i.e. animals are fed only with LCF) using the EU-28 as a case study. To this aim we compared the optimal use of currently used LCF with various scenarios that add food leftovers currently banned or not fully recovered as feed. Exploring which food leftovers can be used as LCF not only extends potential animal production in circular food system but is also relevant in our current food system to reduce dependency on externally sourced feeds, as is needed to develop appropriate policies.

2. Methods

We assessed how much additional ASF could be supplied by improved use and/or legalisation of food leftovers as LCF in a circular food system, using an optimisation model developed by van Hal et al. (2019, 2020). This model allocates available LCF to that combination of farmed animals that maximise human digestible protein (HDP) supply, while meeting human requirements of nutrients currently only obtained from ASF. The model, thereby, predicts which animals we should keep and which of the available LCF we should feed them to produce as much HDP as possible, while also meeting daily requirements of vitamin B12 and of the essential Ω3 fatty acids EPA and DHA. We prioritised meeting requirements of these nutrients – currently under consumed by much of the EU population – as their supply is the most valuable food function of animals (van Hal et al., 2020) especially under the current abundance of protein (de Smet, 2012; Duru, 2019; FAO, 2017c; Givens & Gibbs, 2008; Oh & Brown, 2003).

We first describe the general structure of the model (Section 2.1) and the included animal production systems (Section 2.2). To assess their ASF supply potential we applied this model to various scenarios of improved use and/or legalisation. Section 2.3 describes these scenarios and their assumed availability of LCF. While this study focusses on the ASF supply potential of increasing the availability of LCF for farmed animals, ASF can also be obtained from nature (hunting/ranging/fisheries). To provide a complete picture on ASF supply in an EU circular food system, we included edible fish obtained though sustainable fisheries (Appendix B1; Table B1), but excluded ASF supply from terrestrial wild animals which is currently negligible in the EU (FAO, 2017a). For sustainable fisheries we assumed landings to be limited to the Maximum Sustainable Yield (MSY) and all edible fish to be used for human consumption (van Hal et al, 2020).

2.1 General model structure

The used optimisation model (van Hal et al., 2019) has the standard form of a linear programming model:

$$\begin{array}{ll} \textit{Maximise} & Z=\boldsymbol{c}'\boldsymbol{x} \\ \textit{Subject to} & \boldsymbol{A}\boldsymbol{x}\geq\boldsymbol{b} \\ \textit{and} & \boldsymbol{x}\geq 0 \end{array}$$

where $\boldsymbol{x}$ is a vector of animal production activities; $\boldsymbol{c}$ is a vector of HDP produced per unit of activity; $\boldsymbol{A}$ is a matrix of technical coefficients; and $\boldsymbol{b}$ is a vector with quantitative constraints. The objective function to maximise HDP output (Z) is restricted by the availability of each LCF, their nutritional value for each animal production system, and the nutritional requirements and limitations of the animals in each production system. Additional "nutrient constraints" ensure that daily human requirement of vitamin B12 (4 μg) and EPA/DHA (250 mg)(EFSA, 2017), currently only obtained from ASF are fulfilled (de Smet, 2012). When unable to meet one of these nutrient constraints (model infeasible), we lower it to the maximum attainable supply of that nutrient, given the available LCF.

2.2 Animal production systems

The model includes the five most prevailing livestock production systems the EU, i.e. pig, laying hen, broiler, dairy and beef production (FAO, 2017d), and two fish farming systems with contrasting feeding habits. Atlantic salmon (*Salmo salar*), the most prevailing farmed fish in the

EU (EUROSTAT, 2019), represents high-trophic carnivorous species that require animal protein in their feed. Nile tilapia (*Oreochromis niloticus*), the most consumed low trophic farmed fish in EU (FAO, 2018b) was selected in the absence of commercial farming of such species in the EU (Sprague et al., 2016). Fatty fish like salmon are rich in EPA/DHA while contents in Tilapia are much lower (Sprague et al., 2016).

The model includes the entire life cycle of these animal systems. For livestock, young and parent stock (e.g. sows, gilts and piglets) needed relative to a producing animal (e.g. fattening pig) (Appendix A3, Table A6) was based on European herd compositions (FAO, 2016a, 2016c). For farmed fish this was based on species specific mortality (Bhujel, 2014; EY, 2017; McGeachy et al., 1995) and fertility data (Eskelinen, 1989; FAO, 2018a; TIL-AQUA, 2016), assuming mortality occurs evenly across life phases (Appendix B3; Table B5). For livestock the model included three productivity levels (low, mid and high), where productivity was expressed in annual milk/egg production or average daily gain. High productivity reflects intensive production using Dutch production averages as a proxy (Bos et al., 2013), low productivity reflects extensive systems throughout Europe, and mid productivity is situated in between. Fish farming included only high productivity which reflects common practice in the EU. Fish performance was defined by first simulating optimal growth and feed intake using Skrettings AquaSim model, which was then calibrated to values commonly found in practice using literature. Production performances and related nutrient requirement for each animal production system were adopted from van Hal et al. (2019) for livestock (Table 1 of Chapter 2) and van Hal et al. (2020) for farmed fish (Table 1 of Chapter 3).

Supply of ASF and nutrients by the animal production systems selected for optimal use of LCF is expressed per EU capita per day (cap/d). Supply of edible meat/fish (kg cooked product) and offal by farmed livestock and fish was calculated by multiplying their predicted live weight (LW) output with species specific slaughter yields (Appendix B2; Tables B2 & B3) and cooking retentions (USDA, 2012). Supply of milk and eggs (kg fresh product) was equal to the predicted output of the production systems. To provide a complete picture on ASF supply in an EU circular food system, we included fish supply from sustainable captured fisheries. This direct fish supply (kg cooked fish) was calculated by multiplying sustainable fisheries landings (Appendix B1; Table B1) with species specific slaughter yields (Appendix B2; Table B2) and cooking retentions (USDA, 2012).

Total ASF supply was translated into ASF intake by multiplying it with product specific waste coefficients for processing, retail and consumption in the EU (Caldeira et al., 2019). Depending on the scenario, the wasted animal product may be provided as LCF as described in Section 2.3. Nutrient intake (HDP, vitamin B12 and EPA/DHA) was calculated by multiplying the intake of each ASF with product specific nutrient contents (Appendix B4; Table B8). Nutrient content of cooked meat reflects the weighted average nutrient content of all cuts, and variation in protein content related to productivity (Figure B4) was based on literature (van Hal et al., 2019). Finally, to compare nutrient intake from ASF (/cap/day) with the nutrient specific daily recommended intake (DRI) (EFSA, 2017).

2.3 Availability of LCF

Here we included grass resources and food leftovers as LCF. Availability of grass resources was derived from van Hal et al. (2019), and included three vegetation types: managed grassland, natural grassland and rangeland (Appendix A2, Figure A2). Managed grassland, while suitable for food crop production, was included to avoid release of carbon and loss of biodiversity and cultural value when converting grassland into cropland (Foley et al., 2011; Gerber et al., 2013). We assumed grass resources can only be valued by ruminants in the country of origin.

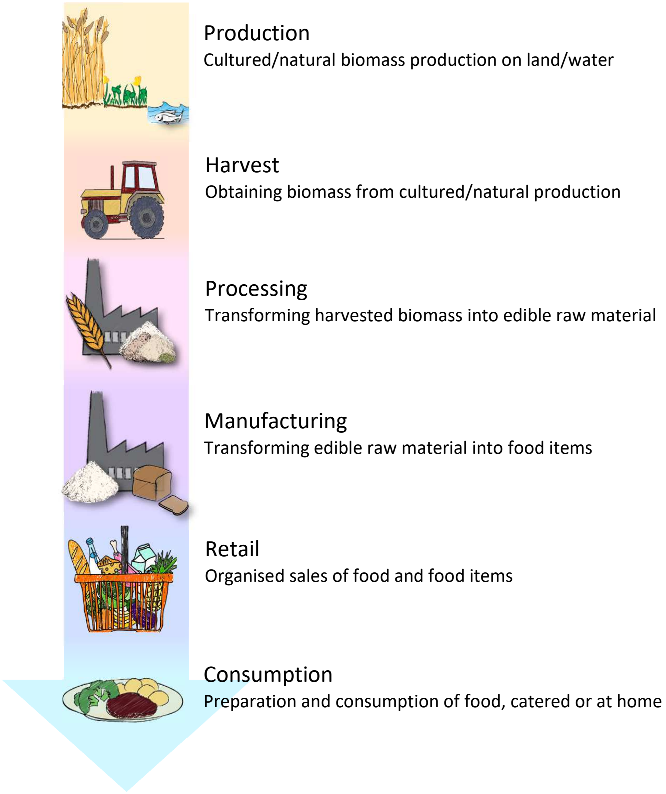


Figure 1 the food supply chain, its stages and their definitions

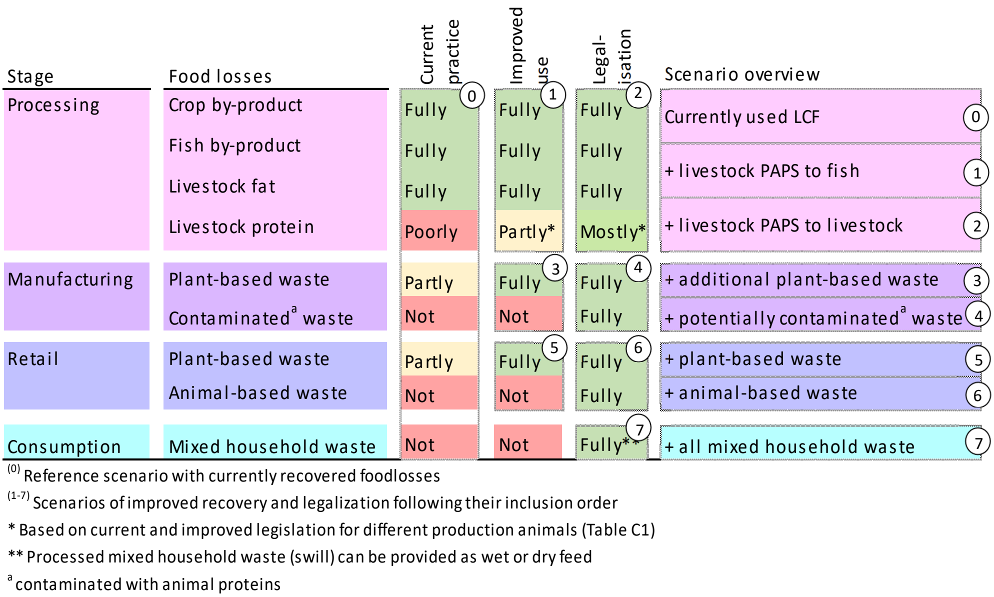
To assess the availability of food leftovers as LCF, we used the food supply chain as illustrated in Figure 1. This chain ranges from the production of biomass in cultured systems (e.g. crop cultivation or animal farming) or natural systems (e.g. fish in nature), to human consumption, via harvesting, processing, manufacturing and retail. In this section we move along the chain to explore where biomass is lost and which of these leftovers are already used as feed, or could be made available as LCF through improved use (biomass allowed as feed but not fed in practice) and legalisation (biomass banned as feed) (Table 1). Based on this exploration we defined our reference scenario (0), which reflects the current use of food leftovers as LCF. Additionally we developed 7 scenarios that, moving along the supply chain, additively include first food leftovers that can be used as LCF under current legislation, followed by those that require legislative change. This implies we add the LCF made available in each scenario, to those available in the reference scenario, and the previous scenarios (Table 2). To assess the ASF supply potential of the LCF added in each scenario, we compared its results to those of the previous scenario. We chose this approach for two reasons. First it enables us to clearly illustrate the potential of using a certain food leftover stream as LCF. Second, the order of inclusion reflects the common view that feed safety is easiest to guarantee in the early industrial stages of the supply chain (Luyckx et al., 2019). Even though losses occur in each stage of the supply chain, we excluded the production and harvesting stages, as much of the biomass lost in these stages should be returned to the soil in circular food system to maintain/improve soil health which is the fundament of our food system (de Boer & van Ittersum, 2018; van Hal et al., 2019). Furthermore, we differentiate between food processing and food manufacturing, as they are separated in practice and result in different leftovers.

Processing leftovers

Food leftovers from processing – transforming harvested crude material (e.g. wheat grain) into edible raw material or food (e.g. wheat flour) – consider by-products (e.g. wheat bran) and waste (e.g. spilled grain or flour). By-products from crop and fish processing are already fully used as animal feed (Vernier et al., 2016) and were, therefore, all assumed available in the reference scenario (0). The availability of crop by-products as LCF (Appendix A2; Figure A2) was derived from van Hal et al. (2019). The availability of fisheries by-products was derived from (van Hal et al., 2020) that applied species specific rendering fractions (output of fish oil and meal) to the inedible part of the landings, quantified using the species specific slaughter yield (Appendix B1; Tables B1 & B2). Similarly, the availability of LCF from farmed fish was calculated by multiplying the inedible fraction of the predicted LW output of each species, with rendering fractions for oil and meal (Table B2). Note that fish meal may not be fed to ruminants due to below described legislation.

Feeding of livestock processing by-products is restricted by EU legislation (Appendix C1) as well as other barriers. The relevant EU legislation restricts the use of PAPs as feed for food producing animals. This legislation (Table C1) focuses on PAPs from bodily tissues that are the main transmitter of diseases like BSE and foot and mouth disease (EU, 2009, 2013a). Animal fats, egg and dairy products are, thereby, excluded from this legislation and can be used as animal feed under feed-safety regulations. PAPs cannot be fed to ruminants as this practice is the suspected origin of BSE. Monogastric livestock, in contrast, are allowed to consume fish meal, hydrolysed feather meal and hydrolysed blood components, as long as they do not originate from ruminants or their own species (EU, 2009). Since a 2013 amendment, farmed fish are allowed to feed on all PAPs of non-ruminant origin (EU, 2013a).

Table 1 Extent to which food leftovers from each stage of the supply chain are used as LCF currently (reference scenario 0), or coould be made available under improved use and/or legalisation (scenario 1-7), and an overview of the added LCF per scenario.



Stage	Food losses	Current practice	Improved use	Legal-isation	Scenario overview
Processing	Crop by-product	Fully ⓪	Fully ①	Fully ②	Currently used LCF ⓪
	Fish by-product	Fully	Fully	Fully	+ livestock PAPS to fish ①
	Livestock fat	Fully	Fully	Fully	
	Livestock protein	Poorly	Partly*	Mostly*	+ livestock PAPS to livestock ②
Manufacturing	Plant-based waste	Partly	Fully ③	Fully ④	+ additional plant-based waste ③
	Contaminated^a waste	Not	Not	Fully	+ potentially contaminated^a waste ④
Retail	Plant-based waste	Partly	Fully ⑤	Fully ⑥	+ plant-based waste ⑤
	Animal-based waste	Not	Not	Fully	+ animal-based waste ⑥
Consumption	Mixed household waste	Not	Not	Fully** ⑦	+ all mixed household waste ⑦

(0) Reference scenario with currently recovered foodlosses

(1-7) Scenarios of improved recovery and legalization following their inclusion order

* Based on current and improved legislation for different production animals (Table C1)

** Processed mixed household waste (swill) can be provided as wet or dry feed

[a] contaminated with animal proteins

Currently, all animal by-products allowed by these legislations are used as feed (FEFAC, 2019), with the exception that the fish farming industry avoids using livestock PAPs (IUCN, 2017), as reflected in the reference scenario (0; Table 1). The use of livestock PAPs in fish farming is avoided due to social and technical barriers, such as concerns regarding consumer acceptance, especially of pescatarians, that might not want their fish to be fed with the livestock they avoid eating. We assess the potential of overcoming these barriers in the improved use of processing LCF scenario (1) that reflects what is achievable within current legislation if all LCF were used in the most efficient way.

With the 2013 amendment, the EU showed a willingness to explore legislative change to aid and stimulate efficient use of resources in the food system (EU, 2013a). In the legalisation of processing LCF scenario (2) we assess the ASF supply potential of possible future legislation amendments (Table C1). We based the assumed amendments on the ongoing debate, where feeding of PAPs to ruminants and feeding organs of the nerve system to any food producing animal are argued to pose too much risk to public health and thus shall remain prohibited (EU, 2009). Feeding PAPs, including those of ruminants, to monogastric livestock and farmed fish, are considered more likely to be legalised and, therefore, assumed available as LCF in this scenario. The availability of livestock by-products in each scenario was calculated by multiplying the predicted LW output of each livestock system, with slaughter and cutting fractions per kg LW (Table C8). For pigs and cattle, these fractions were derived from slaughter reports (USDA, 2018b, 2018c), whereas for poultry they were derived from literature (Haslinger et al., 2007; Sams, 2010).

<u>Manufacturing leftovers</u>

Food leftovers from manufacturing – transforming edible raw material (e.g. wheat flour) into (combined) food items (e.g. bread) – consider wasted ingredients, food items and intermediaries (e.g. dough). Legislation specifies these wastes may be used as feed as long as they fulfil food quality standards and are not contaminated with animal proteins besides dairy or egg (EU, 2018). In Europe, much of the waste produced in industrial manufacturing is collected by specified companies, so called former foodstuff (FFS) processors (EFFPA, 2019). These companies facilitate separated collection by food manufacturers, were safe crop, egg and dairy wastes are processed into feed ingredients and spoiled or contaminated wastes are digested anaerobically to produce energy (VIDO, 2019). Currently, as reflected in the reference scenario (0), about 5 Mt of FFS are recovered as LCF per year. We based the composition of these plant-based FFS on the average of composition in the United Kingdom (UKFFPA, 2019), the Netherlands (VIDO, 2019) and France (Vernier et al., 2016) (Figure C1). Processing of these FFS results in the availability of feed ingredients, as illustrated in Table C2.

Processors of FFS have joined forces in an association to improve the use of FFS as feed, and estimate that they could each year recover an additional 2 Mt (EFFPA, 2019). We assumed these additional FFS had a similar composition as those currently fed in the improved use of manufacturing LCF scenario (3). In the legalisation of manufacturing LCF scenario (4) we added available plant-based FFS that are possibly contaminated with PAPs. We assumed these additional FFS consisted of cereal-based FFS only, of which in total 7.4 Mt fresh matter is wasted per year (Caldeira et al., 2019). The composition of these additional cereal-based FFS was assumed to be similar to those of cereal-based FFS in previous scenarios. Safe use of these possibly contaminated FFS as feed requires standardised treatment even if they are still of food quality (Luyckx et al., 2019).

Retail and consumption leftovers

At retail, food is mainly wasted for economic or commercial reasons. To provide consumers with choice and a high availability of products, both wholesalers and supermarkets overstock, resulting in wastage of mainly fresh cereal, meat, fruit and vegetable products (Cicatiello et al., 2017; Teller et al., 2018). Technically, products wasted at retail are FFS, and can be used as feed under the same regulations as manufacturing waste (EU, 2018). This implies that plant, egg and dairy-based products that are still fit for human consumption can be transformed into feed. Currently, as reflected in the reference scenario (0), virtually no food wasted at retail is used as animal feed, likely due to lack of economic incentive for the retailing industry to develop the infrastructure to safely recover their waste (Truong et al., 2019). The costs of oversupplying and wasting food are covered by high margins on products that do get sold (Teller et al., 2018). Furthermore, the industry is not transparent on how much food is wasted as this may threaten their revenue model in the current climate of reducing food waste (Cicatiello et al., 2017; Teller et al., 2018).

Optimally, retailing waste is collected in separate product streams, and processed into feed ingredients, requiring similar facilities as for manufacturing waste. The already developed FFS processing industry is willing to take up this task, which requires improved collaboration with the retailing industry (EFFPA, 2019). In the improved use of retail LCF scenario (5) we assumed that only plant-based retailing waste, derived through such collection, was available as LCF. In the legalisation of retail LCF scenario (6) we assumed that also animal-based retailing waste, currently banned as feed (EU, 2018), was available as LCF through legislative change. Besides separate collection, these animal-based wastes should be stored cold and treated into PAPs to ensure feed safety.

The availability of retailing and consumption wastes, was based on a recent study of Caldeira et al. (2019), that used a mass balance approach to quantify wastage for various product classes in each stage of the EU food supply chain. For plant-based products, we assumed the absolute amount of waste reported by Caldeira et al. (2019). For product classes that contain nutritionally differing products, we based the composition of the reported waste on underlying data provided by (Caldeira et al., 2019) for cereals and EU consumption for fruits and vegetables (FAO, 2017c). The resulting availability of plant-based feed ingredients from retail and available household waste is provided in Table C3. For animal-based products, we multiplied the waste coefficients for each phase, provided by (Caldeira et al., 2019), to the ASF supplied by sustainable fisheries and the animals selected for the optimal use of LCF.

Unlike retailing wastes, all food wasted at consumption, either at home or in food service facilities is banned as feed for food producing animals (EU, 2009, 2018), which is reflected in the reference scenario (0). This ban) result in high chances of contamination with inedible material, such as plastics (Truong et al., 2019). Furthermore, in most EU member states, food waste is collected mixed with other organic wastes results from the difficulty to guarantee safe collection of this waste, as handling by many actors (consumers every fortnight to be composted in regional facilities (WRAP, 2016). Using consumer food waste, thus requires a combination of improved use and legislative change. Such improved use should be facilitated by governments with a combination of clear instructions and new infrastructures (WRAP, 2016). As household food waste is sensitive to spoiling, it should be collected regularly. To ensure feed safety, the collected waste may not contain any inedible material and biohazardous contaminants should be inactivated with heat treatment and/or fermentation (Luyckx et al., 2019). Such processing, commonly applied in Japan, results in a wet feed called swill that can be fed as it is (with 20-30% DM) or dried to a concentrate feed (with >80% DM). This drying requires a high amount of energy which can be partly obtained from the heat produced in other processes. Here we assess the potential of providing household swill wet (7a) and dried (7b).

Nutrient content of LCF

To clearly illustrate the allocation of LCF in our results, crop by-products were classified based on their nutritional properties (Table C4), while other LCF were classified based on their origin. To assess ration composition, all LCF were classified based on nutritional properties. The nutrient content of each LCF and their availability to livestock (CVB, 2016) were adopted from (van Hal et al., 2019). The availability of nutrients in LCF for farmed fish (IAFFD, 2018) were adopted from (van Hal et al., 2020) that differentiate protein digestibility between farmed fish species based on literature (Appendix B; Table B8). Nutrient content of swill is calculated as the weighted average nutrient content of the included products. For wet swill we assume water is added during processing resulting in a DM content of 25%, while dried swill is afterwards dried to a DM content of 80%.

3. Results

To illustrate the potential of improved use and legalisation of food leftovers as LCF in a circular food system, we first describe the optimal use LCF that currently already used as LCF (reference scenario). Thereafter, we illustrate the cumulative effect of making more LCF available in each step of the supply chain, in terms of nutrient supply and number of farm animals produced. To this end, we compared the nutrient supply from ASF and animal numbers from each scenario to that of the previous scenario. As population requirements for vitamin B12 were met for each scenario and its intake follows the pattern of HDP intake (correlated) we show only HDP and EPA/DHA intake.

3.1 Reference scenario

The optimal use of the currently used LCF provides a daily per capita intake of 470 g milk, 25 g fish (captured and farmed), 16 g meat, 2 g edible organ (offal) and 1 g egg. Putting this in perspective, this is 180 g less milk (-27%), 17g more fish (+200%), 32 g less egg (-96%) and 200 g less fish (-92%) than current daily per capita supply in the EU (FAO, 2017a). In total this ASF supply provides 27 g HDP (cap/d) (Figure 2a), 47% of DRI (Appendix C; Figure C2), fulfils vitamin B12 requirement, but was not able to meet recommended EPA/DHA intake. The maximum achievable EPA/DHA intake of 219 mg/cap/day fulfils 88% of DRI. The optimal use of currently used LCF requires 25 million low productive dairy cows, 12 million low productive laying hens, 368 million salmon and 26 billion tilapia (Figure 3d-h). Together these animals use all available plant and fish-based food leftovers (by-products and FFS), while leaving part of the natural grassland (62%) and rangeland (82%) unused (Figures 3h & C3).

Dairy cattle valued as much grass as possible, supplemented with the majority of plant-based food leftovers (Figure 3g). High quality grass resources were fed to the dairy cows and young stock, while bulls only grazed natural grass and shrubs, resulting in high intake of low quality feed (Figure C3). Although laying hens valued all feather meal, the majority of their diet consisted of cereal and oilseed by-products (Figures C2 & C3). All fish by-products were fed to farmed fish (Figure C3). Salmon diets were, furthermore, supplemented with enriched cereals wasted at processing (biscuit meal), whereas tilapia diets consisted mainly of oilseed meal and cereal by-products and wastes (Figure C4). Despite salmon being the only model animal can effectively upcycle EPA/DHA from marine ingredients into EPA/DHA, a large share (30%) of these ingredients were fed to tilapia with lower EPA/DHA contents, even though population requirement for these fatty acids is not met. This indicated that salmon production was limited by either energy or protein requirements or the ratio between the two.

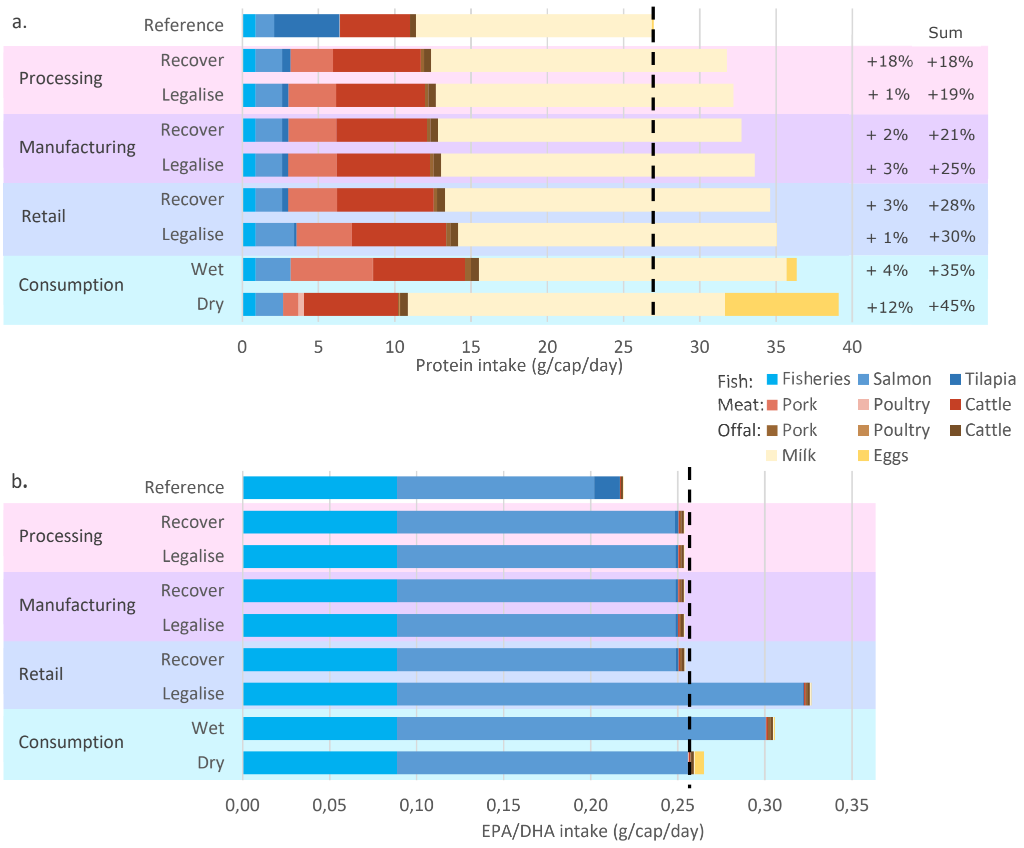


Figure 2 Cumulative impact of improved use and legalisation of food leftovers in each stage of the food supply chain on a. animal protein supply and b. EPA/DHA omega 3 fatty acid supply.

Partially legalising livestock proteins for as feed for livestock (Table C1) further increased HDP intake, but only with 1% (Scenario 2; Figure 2a). This increase was mainly due to the use of processed ruminant protein now available for fish, pigs and poultry (Figure 3b). Using these animal proteins, increased salmon production to 520 million harvested fish while requiring less cereal by-products (Figure 3g). With this increase in salmon production, fewer tilapia were needed (-25%) to meet EPA/DHA, freeing up cereal by-products (Figure 3h). These cereal by-products were reallocated to pig production, whose numbers increased to 43 million (+13%; Figure 3d). In short, the additional LCF obtained from food processing increased HDP intake to 32.2 g HDP, i.e. an increase of 19% compared to the reference scenario (Figure 2a).

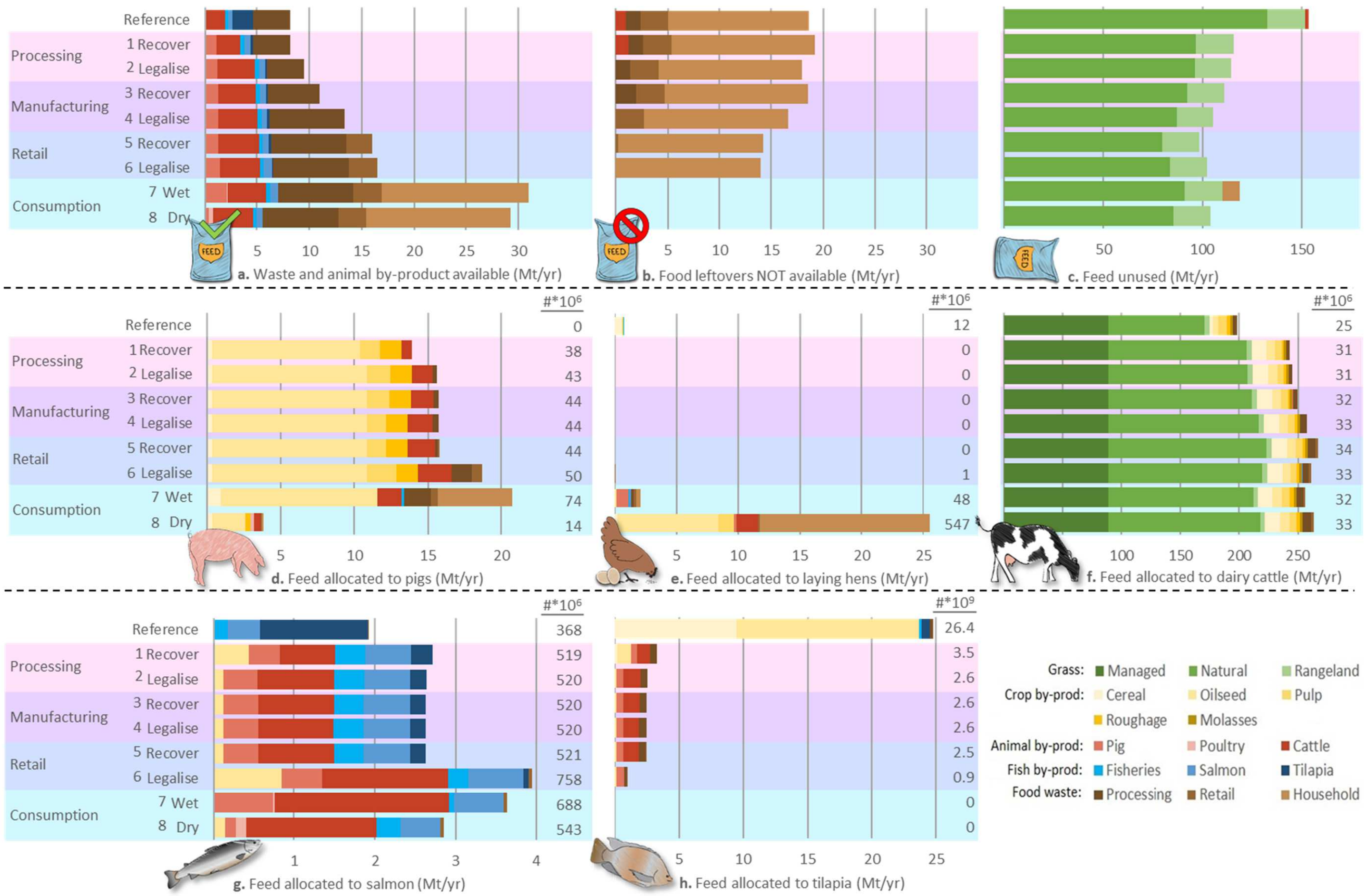


Figure 3 Availability of food leftovers (a-c), their allocation to livestock (d-f) and farmed fish (g-h) and animal numbers (*10⁶) needed for optimal use in the reference scenario and under cumulative improved recovery and legalisation in each stage of the supply chain.

Potential of manufacturing and retail waste

The potential of manufacturing and retail wastes as LCF was limited (Scenario 3-6). Each improved use or legalisation scenario in these stages showed a similar response, except for legalising animal products wasted at retail (Scenario 6; Figure 2a). The common response was a small increase in HDP intake (2-3%; Figure 2a), achieved by a continued increase in dairy production to 34 million (+ 9%; Figure 3f). This dairy cattle were either fed directly with the newly available food waste or with the products displaced from pig diets by this waste, enabling them to value more nature grass (Figure 3d & f).

While legalising animal products wasted at retail (Scenario 6) did not have a big effect on animal protein supply (+1%; Figure 2a), it had a large effect on which animals were selected to produce this protein. All of the animal products made available were allocated to salmon farming, increasing their production to 758 million harvested live fish (3.8 Mt; Figure 3g). Due to this increase in salmon production, human EPA/DHA intake increased to 325 mg/cap/d, far above the recommended intake (Figure 2b). This indicates that high-trophic farmed fish, such as salmon, are most efficient at upcycling animal by-products and wastes, and require such products to meet their high nutrient requirement. Despite no longer needed to meet human EPA/DHA requirement, 954 million tilapia were produced to upcycle pig bone meal, which was of too low protein quality to feed salmon or laying hens (Figure 3h). Adding the additional LCF obtained from manufacturing and retail increased HDP intake to 35 g HDP, an increase of 30% compared to the reference scenario (Figure 2a).

Potential of consumption waste

Legalising household waste as livestock feed had a relatively large impact (Scenario 7). When provided as wet swill, HDP intake increased with 4% (Figure 2a; Scenario 7a). Of this newly available wet swill , 36% was allocated to pigs (Figure 3d), increasing pig production to 74 million pigs (+49%), as pigs are well adapted to value waste and wet feeds due to their relatively high feed intake capacity (Zijlstra & Beltranena, 2013; zu Ermgassen et al., 2016). When upcycling 5 Mt of wet swill, however, pigs were no longer able to value the 2 Mt of pulp and 1.5 Mt of roughage-like by-products they previously consumed (Figure 3d). Instead, these bulky crop leftovers were fed to dairy cattle, displacing 7.6 Mt of natural grass from their diets to be left unused (Figure 3c,f). Furthermore, 3% of wet swill with the highest quality was allocated to laying hens and 61% (8.6 Mt) was left unused (Figure 3c,e). For laying hens to be able to value swill, they were supplemented with highly nutritious fisheries and pig by-products, and cereal manufacturing waste (Figure 3e), making these less available for tilapia, salmon and dairy production. As a result salmon production reduced to 688 million harvested fish (-10%), dairy to 32 million cows (-3%), and no tilapia was farmed (Figure 3d,g,h). In short, adding wet swill from household waste increased HDP intake to 36.3 g/cap/d, i.e. an increase of 35% compared to the reference scenario (Figure 2a).

Providing swill as a dry feed instead increased HDP intake with 10% (Figure 2a; Scenario 7b), by feeding 99% of this dried swill to 547 million laying hens and leaving only 1% for pig production (Figure 3b, d and e). To value dried swill, the laying hens required much of the available animal by-products and high quality oil seed meal previously fed to salmon, reducing their numbers to 543 million harvested fish (-22%)(Figure 3e,g) still enough to meet EPA/DHA requirement (Figure 2b). Pigs went back to valuing some pulp and roughage-like by-products, but their numbers reduced to 14 million (-88%). Most crop by-products, retailing and manufacturing waste, and some fish oil was, therefore, left available for cattle to increase their numbers to 33 mln (+3%) and value more natural grass (Figure 3d, f). In short, adding dried swill from household waste increased HDP intake to 39.1 g/cap/d, i.e. an increase of 45% compared to the reference scenario (Figure 2a).

4. Discussion

We found that, in the proposed circular food system ASF intake can fulfil between 50 and 69% of HDP requirement. We, thereby, demonstrated that improved use and legalisation of food leftovers as LCF can increase HDP intake up to 45% (Figure 2). While human vitamin B12 requirements were met in each scenario, the intake of EPA/DHA appeared critical, as these requirements could not be met in the reference scenario. We first discuss the optimal use of currently used LCF (reference scenario), and then discuss the potential of currently unused food leftovers as LCF (Scenario 1-7).

Optimal use of LCF currently used in the EU, requires a smart combination of dairy cows, laying hens, farmed salmon and tilapia (Figure 3d-h), which all have a relatively high production efficiency. Dairy cattle and laying hens achieve this high efficiency by providing a daily product, while fish, being poikilothermic and unaffected by gravity, have low maintenance requirements (de Vries & de Boer, 2010; Fry et al., 2018). In line with previous studies, dairy cattle were fed a large share of the available crop by-products to enable them to value as much of the low quality grass as possible (Figure 3f; (van Hal et al., 2019). Laying hens were selected to value feather meal as they are the most efficient species allowed to value these PAPs (Figure 3e). They were kept at low productivity to limit their use of high quality LCF that were needed for dairy and fish farming. Farmed fish were, namely, needed to provide humans with EPA/DHA. As the population requirements for EPA/DHA could not be met, their supply was maximised and highly influential in the selection of animals. Surprisingly, much of the EPA/DHA containing fish by-products were fed to tilapia that are inefficient at upcycling EPA/DHA, indicating salmon production was limited by other nutrient requirements (Figure 3g,h).

Our results show that, of the considered currently unused food leftover streams, livestock PAPs and dried household swill have the highest ASF supply potential. Livestock PAPs, when fed to farmed fish (Scenario 1) increased HDP supply with 18% (Figure 2a), whereas using dried household waste as feed (Scenario 7b) increased HDP supply with 12% (Figure 2a). To make more food leftovers available as LCF we must overcome legal and other barriers, which interestingly appear easiest for PAP s than for livestock by-products and hardest for household wastes as discussed below.

Livestock PAPs have a high potential as LCF due to their high quality. We found that if livestock PAPs are available as LCF, high-trophic fish are most efficient in upcycling them (Figures 2b & 3g). The inclusion of high quality livestock protein and fats enabled farmed salmon to upcycle more EPA/DHA containing feed ingredients and meet human EPA/DHA requirement (Figure 2b, 3g). Allowing livestock PAPs as fish feed increased the upcycling efficiency of EPA/DHA and was needed to meet human EPA/DHA requirement in circular food system (Figure 2b; shift from tilapia to salmon), which is in line with EFPRA (2016) and van Hal et al. (2020). Salmon production was selected to value livestock PAPs also when they were allowed as livestock feed (Scenario 3) and when human EPA/DHA requirements were already met (Scenario 6) (Figure 2b, 3g).

Livestock PAPs are currently allowed to be used to feed fish farmed for human consumption (EU, 2013a). Their safe collection and processing is, furthermore, relatively easy to organise as they are produced in slaughter facilities that operate under HACCP standards (EFPRA, 2016). While use of livestock PAPs in fish feed appears easy to achieve, their application has remained limited since their legalisation in 2013 (BioMar, 2018; IUCN, 2017). To stimulate the efficient use of such food leftovers, research into the technical or social barriers that limit their application is needed. Such research is especially relevant for livestock PAPs, due to their ASF supply potential, and their role in upcycling EPA/DHA as discussed above. Preliminary research shows that constraints partly relate to concerns about consumer acceptance (Krogdahl, 2016). Pescatarians, for example, may not want their fish to be fed with the livestock they avoid eating (IUCN, 2017). Pescatarians, however, are a minority of fish eaters, and consumption of imported seafood that was fed with livestock PAPs is plentiful (Tacon, 2012). To our knowledge, potential technical (feed formulation, farming) and environmental (local ecosystem) barriers to using PAPs as fish feed have not been studied. The benefit of feeding farmed fish with livestock PAPs is likely even higher in our current food system, due to higher availability of PAPS than in the circular food system illustrated here.

Also for the fish farming industry the use of livestock PAPs is of interest as limits to the availability of fisheries by-products – historically their main feed ingredient – has driven them to explore and use alternative high quality feed ingredients (Tacon & Metian, 2015). So far they explored mainly plant-based ingredients, where soy is preferred due to its high protein quality, but unlike PAPS additional soy production causes environmental impacts (EFPRA, 2016).

Household swill has high potential as LCF due to both its abundance and high feed quality when dried. Potential is highest when household swill is dried, as almost all can be fed to highly efficient laying hens (Figure 3e). While feeding food waste to laying hens is uncommon, a Japanese study has illustrated its feasibility, and a Dutch company proclaimed its interest in doing so (Kipster, 2017; Ruttanavut et al., 2011). Drying of feed ingredients, however, requires large amount of energy, which increases its environmental impact (Vellinga et al., 2013). This impact can be limited by the use of renewable energy or heat generated, as is often used when drying manure and compost fertiliser (Kipster, 2017; Loizia et al., 2019; van Zanten et al., 2015b). When provided wet, only pigs were able to value this bulky swill (Figure 3d), in line with previous study that single pigs out as best up-cycler of swill due to their relatively high feed intake capacity (van Hal et al., 2019; zu Ermgassen et al., 2016). Compared to dried swill, wet swill has less potential in terms of ASF supply (Figure 2a). Pigs have lower production efficiency and were not able to value all swill (Figure 3c).

Despite the high ASF supply potential dried household swill, (Figure 2a, Scenario 7), legalising household waste as LCF is hard to realise. EU guidelines indicate that safe feeding of household swill requires legislative changes and development of collection and treatment infrastructures (Luyckx et al., 2019). While we can inactive pathogens by heat and fermentation treatments, we depend on numerous households to ensure that food waste is not contaminated with inedible material (Luyckx et al., 2019). The collection potential of household food waste and the amount that can be used as feed is, therefore, limited (Levis et al., 2010). In Japan, where feeding of swill is legal and centrally organised, about 40% of all food wasted at the household is fed to livestock after 15 years of effort (zu Ermgassen et al., 2016). While the full potential of feeding household waste (+ 4 g HDP/cap/d; Figure 2a) is, therefore hard to achieve, we likely underestimates generation of food waste in the consumption stage. For simplicity reasons we assumed all consumption takes place in the household, while in reality, consumption partly takes place in food service facilities where wastage is higher (Caldeira et al., 2019). Furthermore, there are recent indications that food wastage in households is underestimated systematically (van den Bos Verma et al., 2020).

Using food wasted during manufacturing and retail (Scenario 3-6) as LCF also has potential to increase HDP intake, albeit lower for than at processing or consumption (+2-3%; Figure 2a). This potential is limited by the low availability of these wastes, though their high quality enables the use of more low quality grass (Figure 3c). The FFS industry strives to make more manufacturing and retailing waste available as feed, which requires improved collection from manufacturers in eastern Europe, and improved collaboration with wholesalers and supermarkets (Priefer et al., 2016; Truong et al., 2019). Proposed obligatory waste reporting may motivate retailers to reduce or recycle them to maintain their image (Priefer et al., 2016). This may stimulate initiatives currently limited to pioneers such as Lidl Nederland (van Woensel Kooy, 2020), who use empty delivery trucks to return expired bread back to the manufacturer that already collaborates with FFS processers. With packaging being a major constraint to the use of retailing waste (Levis et al., 2010), highly sophisticated unpacking methods used already by FFS processors makes them a valuable partner for retailers.

While using food leftovers as LCF increases the resource use efficiency of the food system, we acknowledge that prevention of leftovers is even more efficient and that leftovers may have other valuable uses in the food system. While prevention of food waste is prioritised in EU policy, not all waste and by-products can be avoided (EU, 2008). Unavoidable leftovers, are most efficiently used as feed, but must refrain from using recycling as justification to continue wasting (Caldeira et al., 2019). Prominent other uses of LCF are as organic fertiliser or to produce bio-energy (Muscat et al., 2019). While there are many alternatives for renewable energy production, organic fertilizers are essential for soil health and crop production (Hijbeek et al., 2017; Sharma et al., 2019). As a healthy soil is the fundament of a circular food system (de Boer & van Ittersum, 2018), future research should explore which leftovers have most value for feeding the soil or the animal. Such research requires an integrated soil-crop-animal model that optimises the use of natural resources to feed humans efficiently while minimising environmental impacts.

We simulated animal production in a circular food system, given a predefined availability of LCF. We, however, acknowledge that in a circular food system crop production should be optimised which affects the availability of plant-based LCF. While this affects the predicted ASF supply, we are confident that the illustrated principles for improved use of food leftovers as LCF hold regardless. We summarised these principles into the following three recommendations. First, when feeding only LCF, human EPA/DHA requirements can only be met when farmed fish are fed livestock by-products, which would also improve the resource use efficiency of our current food system. We, therefore, recommend research into the technical, social and/or economic restrictions that currently limit the use of livestock by-products in fish feeds in the EU. Second, we find that for efficient use of LCF, high quality LCF should be combined with low quality LCF to achieve an average nutrient content that enables animals to meet their nutrient requirement while upcycling low quality LCF. We, therefore, recommend to use highly nutritious manufacturing and retailing waste to enable the use of more low quality LCF. Third, low quality LCF are must most efficiently if they are fed to those animals that are best adapted to upcycle them. As pigs are best adapted to eat wet feeds, they were fed most pulp, and when available, wet household swill, which required supplementation with high quality LCF. When dried, however, household swill has a relatively high nutritional quality, and is most efficiently upcycled by laying hens without demanding a lot of other high-quality LCF. As other high quality LCF could then be used to value grass, we recommend that, if taking the effort to develop an infrastructure to collect and processing household waste, generated heat should be reused produce a dried swill.

5. Conclusions

Our findings show that improved use and legalising food leftovers as LCF improves the resource use efficiency of the food system and can increase HDP from ASF up to 45%. Use of livestock PAPs in fish feed has most potential in terms of HDP supply (+18%) and is essential to meet human EPA/DHA requirements in a circular food system. While seemingly easy to achieve, better understanding of why livestock by-products are currently not used in fish feed is needed, also to enhance resource use efficiency in our current food system. Besides PAPs, feeding dried household swill also has a high ASF supply potential (+12%), but safe feeding of this waste is reported to require considerable effort. Due to low quantities, food leftovers from manufacturing and retail have limited potential in terms of protein supply (each +5%), but their use enables especially ruminants to value more low quality grazing resources. We conclude that improved use and legalisation of inevitable food leftover can improve the resource use efficiency of both current and future circular food systems. Efficient use of available LCF requires a combination of animals tailored to the available LCF and the desired nutrients for human consumption.

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Chapter 5

Accounting for feed-food competition in environmental impact assessment: towards a resource efficient food-system

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Abstract

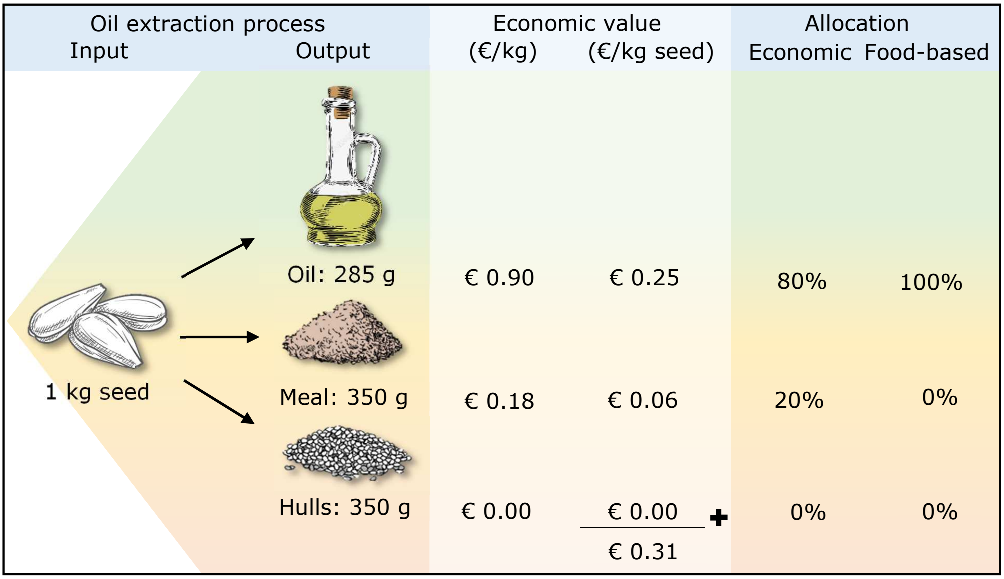
This study demonstrates the effect of better accounting for feed-food competition in life cycle assessment (LCA) to derive mitigation strategies that contribute to efficiently feeding the growing world population. Economic allocation, commonly used in LCA, falls short in accounting for feed-food competition as it does not consider interlinkages in the food system. The authors hypothesise that an alternative "food-based" allocation better accounts for food-feed competition by assigning no environmental impact to feed products unfit for human consumption. To evaluate the impact of accounting for feed-food competition on LCA results, economic and food-based allocation were compared in an LCA of a novel egg production system that feeds only products unsuitable or undesired for human consumption. Using economic allocation, the global warming potential (GWP) of 1.13 kg CO_2-eq, energy use (EU) of 11.86 MJ, land use (LU) of 2.99 m^2, and land use ratio (LUR) of 1.70 per kg egg of the case study farm were all lower than that of free range or organic eggs. Avoiding feed-food competition on this farm reduced the environmental impact per kg egg by 48-58% for GWP, 21-37% for EU, 34-47% for LU and 32% for LUR, compared to free-range laying hens fed a conventional diet. Accounting for feed-food competition with food-based allocation further reduced impacts per kg egg by 57% for GWP to 0.49 kg CO_2-eq, 40% for EU to 7.19 MJ, 96% for LU to 0.11 m^2, and 88% for LUR to 0.30. This improved LCA better captures the complexity of the food system.

1. Introduction

Animal-source food (ASF) supplies humans with high quality protein and essential micro-nutrients (Craig & Mangels, 2009), but it's production has significant negative environmental impacts (Steinfeld et al., 2006). These impacts include climate change (Vermeulen et al., 2012), ecosystem pollution (Gerber et al., 2013), biodiversity loss (Newbold et al., 2016) and use of scarce resources such as land, water, and fossil-energy (Steinfeld et al., 2006). Globally, the livestock sector is responsible for ~15% of anthropogenic greenhouse gas (GHG) emissions (Gerber et al., 2013), and uses ~80% of farmed land (Poore & Nemecek, 2018).

Feed cultivation is responsible for the majority of greenhouse gas (GHG) emissions and almost all land use (LU) of livestock production (de Vries & de Boer, 2010). Globally, it occupies ~40% of all arable land (Mottet et al., 2017) on which food crop cultivation is more efficient (Garnett, 2011) as nutrients are lost when converting plant into animal biomass (Godfray et al., 2010). To address arable land availability, a major limitation to sustainably feeding the world's future population (Lambin and Meyfroidt, 2011), recent studies propose to avoid this inefficiency by feeding livestock only with products that humans cannot or do not want to eat (van Zanten et al., 2018). These 'low-opportunity-cost feedstuffs' (LCF) include crop residues, e.g. wheat straw or beet tails, and by-products, e.g. wheat middlings or sugar beet pulp, of food crops grown on arable land, food waste, and grazing resources from non-arable land (Schader et al., 2015). Livestock fed with only LCF upcycle nutrients that would otherwise be lost to the food system into ASF (Bowles et al., 2019), without using additional arable land (Garnett et al., 2015). By avoiding competition between feed and food crop production (Röös et al., 2017a), they contribute to a more efficient food supply (van Kernebeek et al., 2016).

Despite this scientific acknowledgement of the relevance of avoiding feed-food competition, the state of the art life cycle assessment (LCA) used to assess environmental impacts of ASF production falls short in addressing this issue as it is not designed to include interlinkages in the food system (van Zanten et al., 2018). Producing oil from sunflower seed, for example, also yields meal and hulls (see Figure 1). In an LCA of ASF, the environmental impact of this multifunctional process is allocated to its multiple outputs (e.g. oil, meal and hulls) based on their relative economic value (De Vries and de Boer, 2010), a method defined as economic allocation (Guinée, 2002). Of the impact of cultivating and processing one kg of sunflower seed, 80% is allocated to the resulting 285 g sunflower oil as this oil represents 80% (€0.25/€0.32) of the economic value of the process outputs (Figure 1). The economic value of a product, however, does not reflect their (un)suitability for direct human consumption (van Zanten et al., 2016b).



Oil extraction process Input	 Output	Economic value (€/kg)	 (€/kg seed)	Allocation Economic	 Food-based
1 kg seed	Oil: 285 g	€ 0.90	€ 0.25	80%	100%
	Meal: 350 g	€ 0.18	€ 0.06	20%	0%
	Hulls: 350 g	€ 0.00	€ 0.00 +	0%	0%
			€ 0.31		

Figure 1 Environmental impact allocation over the co-products resulting from the multifunctional process sunflower seed crushing under traditional economic and food-based allocation as introduced in this paper (mass distribution of outputs & price of outputs (Vellinga et al., 2013).

By not considering whether used feeds are fit for human consumption or compete for land with food crop production, mitigation strategies proposed by LCA studies may increase the resource use of the entire food system (van Zanten et al., 2018). LCA studies by Herrero et al. (2016), for example, propose to reduce the environmental impact per kg ASF by increasing animal productivity, defined as animal output over feed input (Balmford et al., 2018). This productivity increase requires high quality feeds (de Vries et al., 2015), typically including food crops or feed crops grown on arable land, thereby increasing competition with food production (Wilkinson & Lee, 2018). Negative implications of such strategies, i.e. increased pressure on arable land, are overlooked as the state of the art LCA ignores their consequences on interlinked production systems (van Zanten et al., 2018).

To move towards a resource efficient food system, LCA's shortcoming in considering food system interactions such as feed-food competition should be addressed. This study presents a first step towards achieving this by introducing a novel allocation method that reflects the (un)suitability of feed products for human consumption. This food-based allocation assigns zero environmental impact to by-products unsuitable or undesired for human consumption whereas the determining (food) product is given full allocation. Of the environmental impact of cultivating and processing one kg of sunflower seed, 100% is now allocated to the resulting 285 g sunflower oil as this is the only edible end-product which drives sunflower seeds production (Figure 1).

This study evaluates the impact of explicitly accounting for feed-food competition on LCA results. A conventional LCA with economic allocation was compared with an alternative LCA with "food-based" allocation that explicitly accounts for feed-food competition (Figure 1). Both LCAs were extended with the land-use ratio (LUR) indicator which provides insights into the land use efficiency of the entire food system (van Zanten et al., 2016b). The limitations of economic allocation, illustrated by the impact of accounting for feed-food competition in LCA, were assessed in a case study of an innovative egg production system that avoids feed-food competition.

2. Material and Methods

The impact of explicitly accounting for feed-food competition in LCA was explored. LCA is a holistic approach to evaluate the environmental impact throughout a product's entire life cycle (Baumann & Tillman, 2004). Following the LCA protocol (Guinée, 2002), the goal and scope definition and inventory analysis are described in the material and methods, the impact assessment in the results and interpretation of the results in the discussion.

2.1 Goal and scope definition

LCA was applied to a case study of 'Kipster', an innovative egg production system designed to produce eggs with respect for animals, farmer, and planet. The system avoids feed-food competition, produces and uses solar energy, and rears the male chicks associated with egg production for meat (Kipster, 2017). First, the environmental impacts of this system were benchmarked against free range and organic egg production, using traditional LCA with economic allocation. Subsequently, the impact of accounting for feed-food competition in LCA was illustrated by comparing economic with food-based allocation (Figure 1). How each allocation method applies to the feed used by Kipster is described in section 2.2.4, i.e. the inventory assessment of feed production.

The indicators LU (m^2) and GWP (CO_2-eq) were selected as livestock production contributes significantly to land use and climate change (Steinfeld et al., 2006), and EU (MJ) for its inherent relation with GWP. To calculate GWP, the three main GHGs related to agriculture, CO_2, CH_4 and N_2O, were summed using their CO_2-eq weighting factors for 100-year time horizon: 1 for CO_2, 28 for biogenic CH_4, 30 for fossil CH_4 and 265 for N_2O (Myhre, 2013). Where LU quantifies the amount of land needed to produce one kg egg, the land use ratio (LUR) was included to indicate whether this land could have been used more efficiently to produce plant-source food (van Zanten et al., 2016b), for more detail see section 2.3.

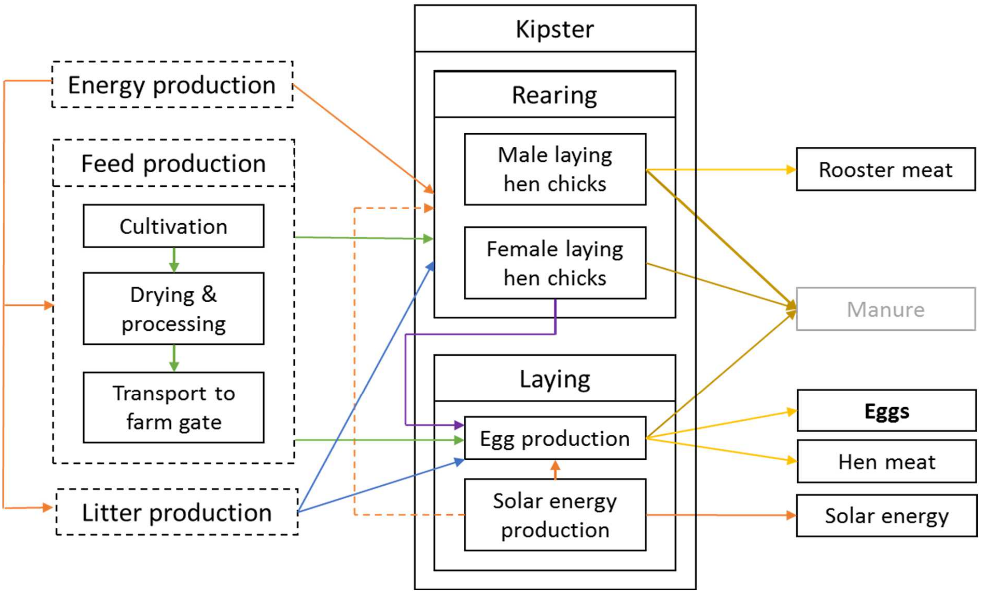


Figure 2. Production chain of the Kipster egg production system.

The LCA, performed from cradle-to-farm-gate, included the following processes: rearing female and male chicks, egg production, solar energy production, manure management, feed production, and other off farm processes such as bedding material and energy production (Figure 2). The hatching phase and parent stock were excluded.

2.2 Inventory analysis.

The following section quantifies the inputs and outputs related to each farm process (Table 1): chick rearing (2.2.1), egg production (2.2.2), and solar energy production (2.2.3). The environmental impacts per unit of these inputs and outputs are then quantified for the off-farm processes: feed production (2.2.4), bedding material and energy production (2.2.5), and manure management (2.2.6).

Rearing female and male chicks

Female chicks were reared from hatch to the egg productive stage, whereas male chicks were reared as slow-growing broilers. Kipster rears male chicks in response to societal concerns about the conventional culling of day-old male chicks. In the European union only 16% of these chicks is used as feed for zoo animals or reptiles while the rest is wasted (Bokma & Leenstra, 2010). Production data and inputs and outputs related to female chicks reared for Kipster (Table 1) are in line with the Dutch average production (Vermeij, 2017). Male chicks are reared under similar circumstances (Table 1) and reach a slaughter weight of 1.5 kg in 119 days (Zanders & Claessens, 2018), resulting in a meat yield of 580 g per chick (Loetscher et al., 2015; USDA, 2018a). Based on the principles of system expansion, this valuable meat output, is expected to replace free range broiler meat with an average GWP of 7.01 kg CO_2-eq, EU of 41.2 MJ and LU of 9.96 m^2 per kg (Appendix D1).

Egg production

Inputs and outputs related to the egg production phase (Table 1) were based on technical results of Kipster. The DeKalb white laying hens produce eggs for 64 weeks after a 3 week adaptation period, and are kept at a density of 6.7 animals per m^2 (Zanders & Claessens, 2018). At the end of the egg production phase, hens of 1.5 kg are slaughtered. The resulting 580 g meat per hen (Loetscher et al., 2015) was accounted for using similar system expansion assumptions as reported for rooster meat.

Table 1 Production data, inputs and outputs of rearing male and female laying hen chicks and the laying phase

		Female chicks	Male chicks	Laying hens
Production data				
Round size	# animals	24,840	24,930	24,000
Round duration	days	119	119	470
Mortality	%	3.5	4.75	7.81
Housing density	animals/m^2	10.50	10.50	6.70
Farm input	*(/animal/round)*			
Feed	kg	5.6	7.3	55.33
Bedding material	kg	0.015	0.015	0.088
Diesel	l	30	-	-
Gas	m^3	0.15	0.15	-
Electricity	kWh	2.35	2.35	8.36
Farm output	*(/animal/round)*			
Eggs	kg	-	-	23.17
Meat	kg	-	0.58	0.58
Manure	kg	2.48	3.14	13.12
Solar energy	kWh	-	-	16.71

Solar energy production

The Kipster laying hen barn is covered with 1,097 solar panels, producing ~385,479 kWh solar energy per laying round, covering the energy requirement of both the rearing and the laying phases (Appendix D5; Table D10). The surplus solar energy sold to the grid is assumed to replace average Dutch grid electricity which has a higher environmental impact (Table 3).

Feed production

In the rearing phase, both female and male chicks were fed a conventional diet (Appendix D2). Laying hens were fed a diet consisting of LCF specifically designed for Kipster to avoid feed-food competition. Energy providing LCF included bakery rest streams (e.g. bread crumbs, biscuit sand, crispbread, dough melange, rice waffle, rusk) and candy rest streams (e.g. candy syrup, waffle syrup), while European sunflower and rapeseed meal provided protein (Appendix D2; S1). The environmental benefits of two potential future protein-rich LCF were explored in two diet scenarios (Appendix D2; S2-S3) with the same nutritional value of 11.8 MJ metabolisable energy, 6 g digestible lysine and 3 g digestible methionine per kg. The alternative protein source in the oilseed scenario (S2) was soybean meal. As the demand for soybean meal drives soybean production, it's considered a feed crop that competes for arable land with food crop production (van der Werf et al., 2005). In a future circular food system where soybean cultivation is limited to the demand for soybean oil, soybean meal is a by-product unsuitable for human consumption. In the insect scenario (S3), the alternative protein source was meal from larvae fed on food waste and manure, both being unsuitable as livestock feed (van Zanten et al., 2015b). Feeding insects to livestock is not permitted in the EU (Veldkamp et al., 2012), but has the potential to reduce the environmental impact of livestock production (Sánchez-Muros et al., 2014).

The impact of each feed ingredient (Appendix D2) was derived from Feedprint (Vellinga et al., 2013), supplemented for larvae meal (van Zanten et al., 2015b), additives (Garcia-Launay et al., 2014), soybean oil and lecithin (Ecoinvent, 2013), and fish oil (AgriBalyse, 2017). Feed production impacts include those related to feed cultivation, drying/processing and transport to the farm but exclude those related to land use change. The environmental impact per kg feed, for each allocation method (Table 2), was calculated by multiplying the impact per kg feed ingredient with its relative use in the diet.

Table 2 Global warming potential (GWP), energy use (EU) and land use (LU) per kg feed for each phase/scenario, under economic and food-based allocation.

	Economic allocation			Food-based allocation		
Feed	GWP (kg CO_2-eq)	EU (MJ)	LU (m^2)	GWP (kg CO_2-eq)	EU (MJ)	LU (m^2)
Rearing female	0.65	5.84	1.96	0.54	6.16	1.34
Rearing male	0.65	6.53	1.65	0.46	4.95	0.91
Laying hen S1	0.37	3.44	1.02	0.13	1.75	0.01
Laying hen S2	0.30	3.75	0.85	0.20	2.79	0.27
Laying hen S3	0.40	4.39	0.09	0.30	3.66	0.02

Using economic allocation, impacts related to cultivation and processing were allocated to the resulting co-products based on their relative economic value (Figure 1). This implies that of the impact of cultivating and processing 1 kg sunflower seed, 80% was allocated to the resulting sunflower oil, and 20% to sunflower meal (Vellinga et al., 2013). Food industry wastes such as dough melange were assumed to have no economic value according to LCA regulations (FEFAC, 2018). Using food-based allocation, all cultivation and processing impacts were allocated to the determining (food) product (Figure 1). This implies that the impact of cultivating and processing 1 kg sunflower seed was fully allocated to the sunflower oil driving these processes, and none to the associated sunflower meal, as it is unfit for human consumption. Environmental impacts related to the processing of a by-product, for example, drying sunflower meal, were allocated to this by-product. Although soybean meal drives soybean production, under food-based allocation no impact related to cultivation or processing of soybeans was allocated to it, assuming that in a future circular food system soybean production will be limited to oil demand.

Bedding material and energy production

Other off-farm processes include the production of animal bedding material and energy sources used on the farm and for transport. The environmental impact of each of these inputs (Table 3) was derived from Ecoinvent (2013).

Manure management

CH_4 and N_2O emissions from manure handling and storage were computed using a tier 2 approach (IPCC, 2006), country specific data from van Bruggen et al. (2014), and IPCC default values (IPCC, 2006), (Appendix D3). Laying hen manure was dried before storage and no leaching or volatilisation was assumed to occur (Oenema et al., 2000).

Table 3 Global warming potential (GWP), energy use (EU) and land use (LU) related to the production of farm inputs (Ecoinvent, 2013)

Farm input	GWP [1] (kg CO_2-eq)	EU (MJ)	LU (m^2)
Diesel (l)	0.22	3.39	0.004
Gas (m^3)	2.10	38.95	0.002
Electricity[2] (kWh)	0.74	2.98	0.014
Solar power (kWh)	0.11	1.31	0.010
Bedding material[3] (kg)	0.07	0.76	0.005

[1]: GWP includes production and combustion of energy sources
[2]: Dutch average grid electricity
[3]: Wood chips

2.3. Land use ratio

The LUR, an indicator of land use efficiency, is defined as the maximum amount of plant-based human digestible protein (HDP) that can be derived from the land used to cultivate the feed to produce one kilogram HDP from ASF (van Zanten et al., 2016b). A LUR below one implies that livestock produce more HDP per m^2 than food crops could on the same land. As described in detail in Appendix D4, the

$$LUR = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} (LO_{ij} \times HDP_j)}{HDP\ of\ one\ kg\ ASF}$$

where LO_{ij} is the land area (m^2) occupied for a year to cultivate the amount of feed ingredient i (i=1,n) in country j (j=1,m) needed to produce 1 kg ASF, in this case eggs and chicken meat, including rearing young stock. HDP_j is the maximum amount of *HDP* that can be produced per m^2/year by direct cultivation of food-crops in country j. The denominator contains the amount of *HDP of one kg ASF* (van Zanten et al., 2016b).

3. Results

Using economic allocation, the GWP per kg Kipster egg was 1.13 kg CO_2-eq, the EU was 11.86 MJ, and the LU was 2.99 m^2 of which 61-73% resulted from the laying phase (Figure 3). These results consider the impacts avoided by replacing grid energy with surplus solar energy, and replacing broiler meat with rooster and laying hen meat (Appendix D5; Table D6). The solar energy surplus of 80,476 kWh reduced egg production phase GWP by 0.095 kg CO_2-eq, EU by 1.42 MJ, and LU by 0.002 m^2 per kg eggs (Appendix D5, Table D10). The 12,900 kg meat produced from culled laying hens further reduced GWP by 0.17 kg CO_2-eq, EU by 0.99 MJ and LU by 0.24 m^2 per kg egg. The 13,750 kg meat produced from male chicks reduced GWP of rearing male chicks by 0.18 kg CO_2-eq, EU by 1.06 MJ, and LU by 0.26 m^2 per kg egg.

3.1 Food-based versus economic allocation

Food-based allocation reduced the GWP per kg Kipster egg to 0.49 kg CO2-eq, EU to 7.19 MJ, and LU to 0.11 m2 (Figure 3). The majority of this reduction occurred in the laying phase, as only laying hens were fed an LCF-based diet. The contribution of the laying phase to the total impact per kg egg was reduced to 55% for GWP, 44% for EU, and -206% for LU. The negative LU of the laying phase, the hatched area in Figure 3, resulted from the LU avoided by replacing broiler meat with laying hen meat (0.24 m2/kg egg), being higher than the LU in the laying hen phase (0.02 m2/kg egg). The reduction in GWP (26%) and EU (13%) in the rearing phase was relatively small, while the reduction of LU was 59%.

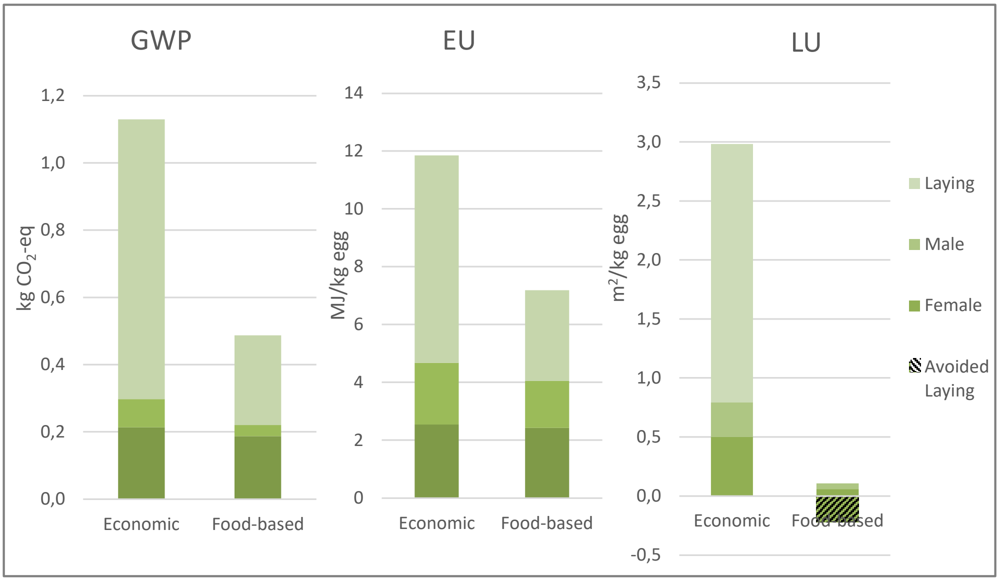


Figure 3. Global warming potential (GWP), energy use (EU), and land use (LU)/kg egg of Kipster as a whole using economic and food-based allocation, and the contribution of rearing of female and male chicks and egg production.

Using economic allocation, the majority of the GWP, EU, and LU per kg Kipster egg was related to feed production (Table 4). For GWP, a relatively large share (14.5%) of the impact originated from manure management. For EU, the use and production of farm energy sources accounted for 22.5%. While feed production remained the dominant impact source, food-based allocation reduced its contribution to all indicators (Table 4).

Table 4 Percentage of Kipster's global warming potential (GWP), energy use (EU) and land use (LU) resulting from energy use/production, feed production, bedding production, and manure management under economic and food-based allocation.

	Economic			Food-based		
Input	GWP	EU	LU	GWP	EU	LU
Energy	5.8	22.5	0.0	9.9	32.4	0.0
Feed	79.7	77.5	99.9	65.3	67.6	99.8
Bedding material	0.0	0.0	0.0	0.0	0.0	0.0
Manure	14.5	0.0	0.0	24.8	0.0	0.0

3.2 Diet scenarios

With economic allocation, neither of the alternative diets (S2-S3) reduced the impact per kg egg for all indicators simultaneously, compared to the baseline diet (S1) (red dashed line, Figure 4). The insect meal diet (S3) greatly reduces LU while slightly increasing EU and GWP. Food-based allocation results in a lower environmental impact on all indicators for all diets, most pronouncedly for LU. The difference between allocation methods is less pronounced for the insect meal diet (S3) due to the high EU of insect rearing and the low economic value of the insect feed. With food-based allocation, the lowest impact on all indicators is achieved using the baseline diet (S1) (black dashed line, Figure 4).

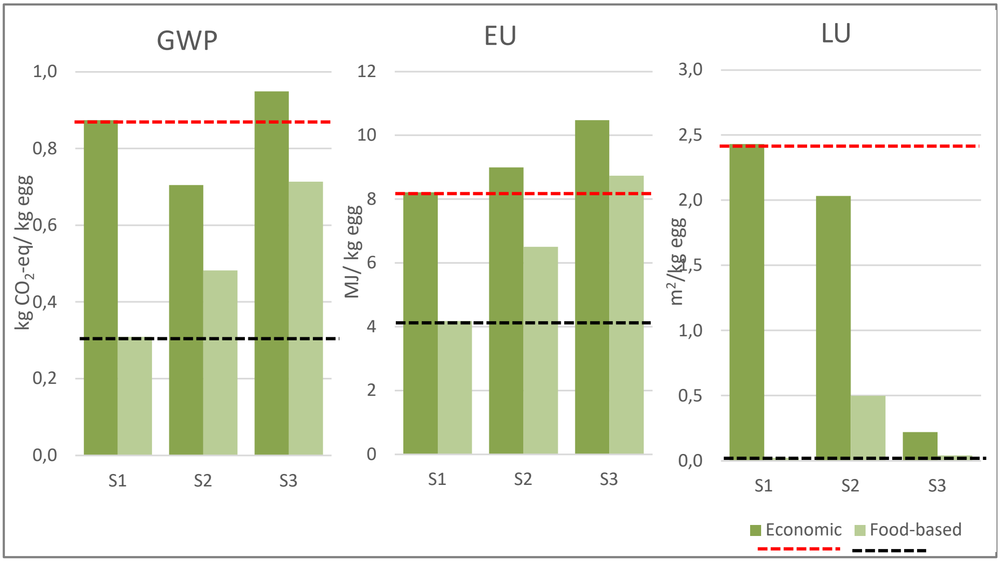


Figure 4 the environmental impact (GWP, EU, LU)/ kg egg from the Kipster system using alternative diets (S2 soy bean meal, S3 insect meal), compared to the current diet (S1) using economic and food-based allocation.

3.4 Land use ratio

Using economic allocation, the LUR of the laying phase alone is ≥1 for both S1 (1.14) and S2 (1.06). This implies that the land used to produce laying hen feed could yield more HDP if used to produce human food crops (Figure 5a). The LUR of S3 was 0, implying an absence of competition for land between feed and food production. Adding the 0.57 LUR of the rearing phase to consider the entire Kipster system resulted in an LUR of 1.70 for S1, 1.63 for S2, and 0.57 for S3 (Figure 5b). Using food-based allocation, the LUR of the laying phase is 0 for S1 and S3. The LUR of 0.36 for S2 implies that some feed-food competition occurs. Adding the 0.30 LUR of the rearing phase results in an LUR of 0.66 for S2 and 0.30 for S1 and S3 (Figure 5b). These <1 LUR's imply that Kipster produces protein more efficiently than achievable with food crops grown on the same land, thereby contributing to food system efficiency.

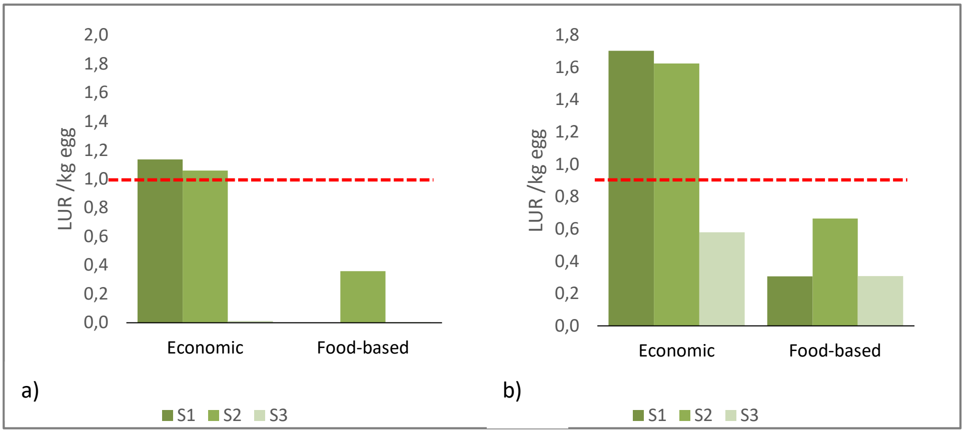


Figure 5 Land use ratio (LUR) of a) Kipster laying phase and b) Kipster as a whole under the current (S1) and alternative (S2-3) diets, using economic and food-based allocation.

4. Discussion

Before discussing the impact of allocation methods on LCA results, LCA results based on economic allocation are benchmarked against those found in literature. For this comparison, GWP results were recalculated using previously assumed equivalence weighing factors: 1 for CO2, 25 for CH4 and 298 for N_2O (Forster P., 2007). The environmental impact per kg Kipster egg was lower than that of commercial free range or organic eggs (Table 4) due to avoided feed-food competition, on-farm solar energy use, supply of surplus solar energy to the grid, and rearing male chicks. While use and supply of solar energy reduced Kipster's environmental impacts, rearing male chicks resulted in a net impact increase; the impacts of growing male chicks were higher than impacts avoided by their meat output (Appendix D5; Table D6). This is a clear example of a sustainability trade-off, where addressing a social sustainability issue, namely culling of day-old chicks (Kipster, 2017), results in an environmental cost. Excluding the benefits of solar energy use and supply and the costs of rearing male chicks (Appendix D5, Tables D6 & D11), resulted in a GWP of 1.43 kg CO_2-eq, EU of 14.77 MJ, and LU of 2.70 m^2 per kg egg, and an LUR of 1.42. Compared to free range laying hens fed a conventional diet (Table 5), feeding only LCF to laying hens reduced GWP by 48-58%, EU by 21-37%, LU by 34-47%, and LUR by 32%. This was due to the small environmental impact allocated to LCF due to their relatively low economic value, and is in line with findings from studies assessing the impact of feeding specific LCF such as rape seed meal(van Zanten et al., 2015a), waste fed insects (van Zanten et al., 2015b), and food waste (zu Ermgassen et al., 2016).

Table 5 Global warming potential (GWP), energy use (EU), and land use (LU) per kg egg from free range and organic systems found in literature and of Kipster found in this study.

	GWP		EU		LU		LUR
Study	Free range	Organic	Free range	Organic	Free range	Organic	Free range
Dekker et al. (2011)	2.75	2.54	23.45	20.55	4.08	6.76	-
Leinonen et al. (2012)	3.38	3.42	18.78	26.41	5.10	-	-
Van Zanten et al. (2016)	-	-	-	-	-	-	2.08
Kipster (current study)	**1.14**	-	**11.86**	-	**2.98**	-	**1.70**

Accounting for feed-food competition with *food-based allocation* further reduced the environmental impact per kg egg by 57% for GWP, 40% for EU, 96% for LU (Figure 3), and 88% for LUR (Figure 4). As to date, Kipster only avoids feed-food competition in the laying phase, the main impact reductions are achieved there. The reduction is most pronounced for LU, while the limited reduction in EU and GWP is due to the smaller contribution of feed production on these impacts (Table 4) and the energy needed to process LCF into compound feed, such as animal fat refinery, drying and additive production. GWP and EU can be further reduced by avoiding heavily-processed co-products, improving production processes, or using renewable energy sources. The second law of thermodynamics determines that recycling materials in a circular food system always requires energy which, by definition should be obtained from renewable sources (Korhonen et al., 2018).

A conventional LCA with economic allocation not only underestimates the mitigation potential of strategies directed at avoiding feed-food competition, it even promotes the use of food crops as livestock feed (van Zanten et al., 2018). This has been demonstrated in studies aiming to reduce the environmental impact of livestock production, as well as in studies aiming to reduce the impact of human diet. The latter typically recommend replacing grass-based beef with meat from fast-growing livestock such as broilers (Hallström et al., 2015) which are fed high quality feed-like cereals.

Accounting for feed-food competition in LCA is essential to promoting the circular food system and economy strived for by the Dutch government (Rijksoverheid, 2016) and the European Union (European Commission, 2015). This study illustrates the potential of food-based allocation to account for feed-food competition. Food-based allocation is simplified and binary; a product is allocated all the impact of cultivation and processing when suitable for human consumption, and none when unsuitable. This simplistic allocation – assuming products are either food or not – is applicable in the case study, where only products unfit for human consumption are fed to livestock. When assessing conventional systems with a high-quality feed diet, the impact allocated to each product should reflect its value for human nutrition. Developing this type of allocation method is complex, as it requires implementing a measure expressing nutritional value including multiple nutritional aspects such as the nutrient density score (van Kernebeek et al., 2014). This score considers the nutrient content per 100 g of a product relative to the daily recommended nutrient intake, and averages the score per nutrient into one final score (Drewnowski & Fulgoni III, 2014). Besides the complexity of implementing this score in an allocation method, it does not fully account for the nutritional benefits of ASF, for example, essential vitamin B12 is only available in animal products, and the amino acid composition matches daily requirements better than plant-source foods (Ertl et al., 2016).

Food system modelling (van Kernebeek et al., 2016) or scenario studies (Schader et al., 2015) are the most promising methods for capturing the complexity of the food system. Although these methods are unsuited to assessing or monitoring the impact of an individual product or production system, they provide valuable insights into how much ASF can be consumed when feeding only LCF. van Zanten et al. (2018) reviewed these food system studies and showed that feeding livestock LCF only, globally provides about 9-23 grams of animal protein per capita per day. Per capita availability of ASF when feeding only LCF can be further increased by optimally using LCF (van Hal et al., 2019) and exploring alternative LCF ingredients such as insect meal, as in S3 in this study. The insect meal diet (S3) showed reductions of LU at the cost of an increase in EU and GWP. The high EU and GWP relate to the assumed high EU from larvae rearing and processing, based on an experimental trial of rearing larvae on food waste and manure conducted by a Dutch waste processor (van Zanten et al., 2015b). Both can be reduced by using renewable energy and developing industry-scale larvae rearing systems (van Zanten et al., 2015b), which can only occur when European legislation no longer prohibits the use of waste-fed insects in animal feed (van Zanten et al., 2015b).

Avoiding feed-food competition assumes that the ultimate goal of the food system is to feed humans efficiently, thereby neglecting other purposes served by agricultural production. In reality, the debate around competition for agricultural resources should not only consider the production of food and feed, but also the production of fibre (e.g. cotton), fuel (e.g. wood, biofuels), and the provision of other ecosystem services. This competition framework is complex and has not been comprehensively studied (Muscat et al., 2019). In the larger perspective of the battle for biomass, leftovers from the agricultural sector should be considered for other purposes than feeding livestock, keeping in mind that livestock feeding is seen as the most valuable use of food waste and by-products (Papargyropoulou et al., 2014). Including feed-food competition in the environmental impact assessment of food is an important first step towards a more efficient agricultural system.

5. Conclusion

Compared to free range laying hens fed a conventional diet, feeding only low-opportunity-cost feeds (LCF) reduced GWP by 48-58%, EU by 21-37%, LU by 34-47% and LUR by 32% in case of economic allocation. This was caused by the small environmental impact allocated to LCF due to their relatively low economic value. Using food-based allocation, the impact per kg egg was further reduced by 54% for GWP, 38% for EU, 94% for LU, and 88% for LUR. An LCA with economic allocation underestimates the environmental benefits of avoiding feed-food competition. Although food-based allocation illustrates the inadequacy of LCA in accounting for the complexity of the food system, it is as yet simplistic, and should be further developed to reflect the nutritional value of co-products for human nutrition. To promote mitigation measures that improve the resource use efficiency of the entire food system, improved LCAs that capture the complexity of the food system are needed.

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Chapter 6

General discussion

1. Introduction

The food system is faced with the challenge to feed a growing world population while limiting environmental impacts and resource use (Giampietro, 2019; Springmann et al., 2018; Willett et al., 2019). The EU aims to address this challenge by shifting to a more circular food system, as increasingly proposed by scientists (European Commission, 2015; Giampietro, 2019; Jurgilevich et al., 2016). A central principle of a circular food system is to prioritise the use of resources for direct food supply to avoid feed-food competition. This implies arable land should be used to cultivate food crops, and the edible yield of sustainably caught fish should be used for direct human consumption (de Boer & van Ittersum, 2018; van Zanten et al., 2019). This food production and consumption, however, results in leftovers that are unsuitable or undesired for human consumption, such as food processing by-products and food waste (Caldeira et al., 2019). Farm animals can contribute to a circular food system by upcycling these food leftovers and grass resources, into valuable animal-source food (ASF) that contains essential nutrients (Garnett, 2009, 2011; van Zanten et al., 2018). As such low-opportunity-cost feeds (LCF) otherwise have a less valuable role in the food system, a diet containing a small amount of ASF from animals fed only LCF appears most resource efficient (van Zanten et al., 2018).

A review that explored the role of animals in a circular food system shows that animals, fed only LCF, can provide 7-30 g human digestible protein (HDP) per capita per day (cap/d) (van Zanten et al., 2018). While the reviewed studies illustrated that farm animals have a role in a circular food system, they gave limited insight into how different animals can contribute to the efficient use of LCF. This thesis, therefore, aims to evaluate the potential of various farmed animals in upcycling LCF in a circular food system, using the EU-28 as a case study, and addresses two main objectives. The first objective is to explore what combination of animals is needed to optimally use available LCF, considering a variety of production animals and productivity levels. The second objective is to explore how to account for feed-food competition in chain level environmental impact assessment in practice. In Section 2, I will address the first objective by describing the unique role of different animal production systems (APS) to the optimal use of LCF. In Section 3, I will address the second objective by illustrating the relevance of accounting for feed-food competition in life cycle assessment (LCA) in order to derive mitigation strategies that stimulate a resource efficient food system (Section 3). Finally, I discuss how these findings contribute to the transition towards a circular food system, describe what further research and societal change is needed (Section 4), and provide the conclusions of this thesis (Section 5).

2. Animals in a circular food system

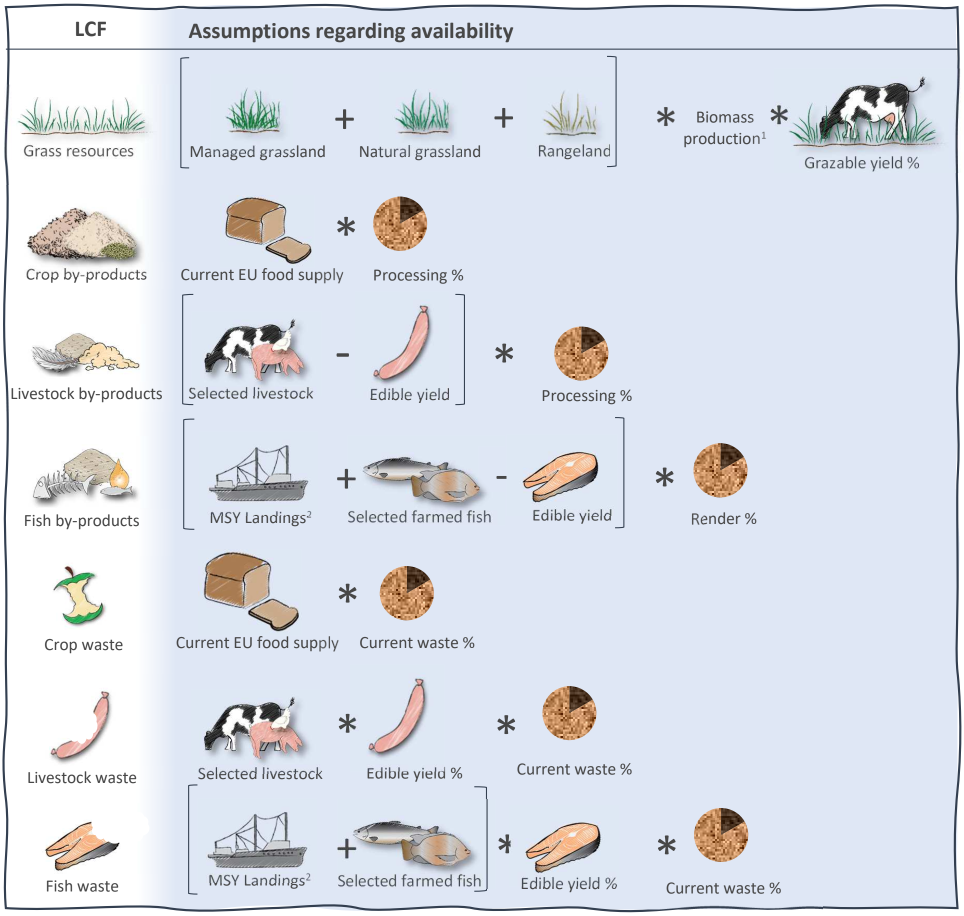
To evaluate the value of different animals to a circular food system, I first explored under which two conditions these animals should function. The first condition relates to the availability and nutritional properties of the biomass expected to be available as LCF in a circular food system (Section 2.1), whereas the second condition relates to the nutrients humans want to derive from ASF (Section 2.2). To assess the potential of different animals given these conditions (Section 2.3), I developed an optimisation model that allocates available LCF to that combination of animals that contributes most to required nutrient supply (Chapter 2, 3 and 4). Finally, the answer to objective one is presented in section 2.4.

2.1 Low-opportunity-cost feeds (LCF)

There is much debate on what products should be considered LCF and differences in their assumed availability causes high variation between studies that predicted ASF supply when feeding only LCF (van Zanten et al., 2018). So far, most studies manually formulated LCF based rations and did not explore the potential applications of each LCF. van Zanten et al. (2016a) and Elferink et al. (2008), for example, assigned all food leftovers to pigs, while Röös et al. (2017b) assigned most of them to dairy cattle. The optimal allocation of LCF to different animals, so far was unknown. Below I explore the nutritional properties of the products expected to be available as LCF in a circular food system, and the potential role of different farm animals in upcycling them based on these properties. I considered both grass and a wide range of food leftovers (assumptions are illustrated in Figure 1).

Grass

Grass resources consist of a variety of fibrous biomass obtained from managed grassland, natural grassland, or rangeland. Managed grassland is used to produce grass with use of management like fertiliser application, irrigation and/or harvesting, while natural grassland and rangeland are typically grazed extensively (Bruinenberg et al., 2002). Rangelands typically contain woody vegetation (Plutzar et al., 2016). My exploration of the nutritional quality of grass resources potentially available as LCF in an EU circular food system, illustrated that grass makes a major contribution to ASF supply due to its high availability throughout the EU and its provision of a balanced ration to ruminants. Below I discuss the value of grass and grazing to a circular food system and how limitations in data availability, and my assumptions, influenced my results.



[1] Grass biomass production was based on net primary productivity (Chapter 2)
[2] MSY Maximum Sustainable Yields as defined in EU fisheries policy (EU, 2013b)

Figure 1 Included low-opportunity-cost feeds (LCF) and their assumed availability.

In my assessment I assumed all produced grass resources were available as LCF, and as long as it was used in the country of origin, grass could be combined with other LCF. Predicted dairy cattle rations typically combined low quality grass with high quality grass, and food leftovers (Chapter 2, 3 and 4). This ration reflects traditional European farming systems where, especially in mountainous areas, dairy livestock graze extensively in summer and are fed cultivated grass and cereals at the homestead in winter (Dodgshon & Olsson, 2007). Prevalence of such transhumanist farming systems that use natural grassland and rangelands is, however, threatened for two reasons. First, they conflict with modern lifestyle standards as mountain pastures are often remote (from roads and farmstead), low productive and can only be used seasonally (Dodgshon & Olsson, 2007; Fetzel et al., 2017a; Hinojosa et al., 2016). Second, the farmland at the homestead is increasingly intensified to produce crops with a higher value (Kristensen et al., 2004; Vicente-Serrano et al., 2004). When left unused, natural grasslands and rangelands are generally encroached by forest, which likely increases their carbon storage and is beneficial to mitigate climate change (Arora & Montenegro, 2011). Proponents of preserving the use of natural grassland and rangeland, however, stress that they not only contribute to food supply, but also provide specific biodiversity, cultural values and a buffer against forest fires (Bengtsson et al., 2019; Caballero, 2007; Fetzel et al., 2017a; Krahulec et al., 2001).

For grass produced on managed grassland its availability as LCF is also under debate. To some extent this managed grassland is suitable for food crop cultivation, which would result in more efficient use of resources (Garnett, 2011; van Kernebeek et al., 2016). Conversion of grassland into cropland, however, is controversial as it results in release of stored carbon, loss of biodiversity and cultural value (Foley et al., 2005; Foley et al., 2011; Gerber et al., 2013). In Chapter 2, I illustrated that managed grassland is responsible for about 36% of animal protein supply in the simulated circular food system (van Hal et al., 2019a). The extent to which this land is used to cultivate grass, thus, has major impact on the extent of animal production in a circular food system. Achieving a consensus on the use of managed grassland requires better understanding of the above described controversy (Section 4.1). In conclusion, my approach illustrated the role of grass resources of different qualities in a circular food system. Future research that takes in account additional constraints to the use of this grass is, however, needed to better understand the role of ruminants in a circular food system.

Food leftovers

Food leftovers consist of biomass that enter the food supply chain but are not be consumed by humans, and include a variety of crop-residues, food processing by-products and food wastes. Crop residues are unharvested crop biomass, while by-products are unintended outputs of food processing, and food waste are products intended for human consumption but wasted along the supply chain (FAO, 2011). While, to some extent, crop residues are currently used as feed, a circular food system assumes most crop residues are left on the field to maintain soil fertility (de Boer & van Ittersum, 2018). While there is debate on how much crop-residues a healthy soil requires, I excluded crop residues as feed since they are of limited feed value, and are more likely used as bedding material for animals (de Boer & van Ittersum, 2018; Hijbeek et al., 2017). For all other food leftovers, I explored their availability and nutritional properties as LCF in chapters 2, 3 and 4.

Crop processing by-products

In Chapter 2 I explored the nutritional properties of crop processing by-products available as LCF. Processing of harvested crop products (e.g. wheat grain or sunflower seeds) into food items (e.g. sunflower oil) or ingredients (e.g. wheat flour), results in by-products (e.g. wheat bran and sunflower meal) that humans cannot or do not want to eat. Currently, most of these crop processing by-products are collected separately and used as animal feed (Vernier et al., 2016). The different crop by-products available vary in their nutrient content and can be classified based on their nutritional properties (Chapter 2). Cereal by-products, such as wheat bran, contain both energy and protein but can be quite fibrous. Oilseed by-products, such as sunflower meal, are protein rich and are commonly used as protein source. Molasses, a by-product of sugar production, contains a high amount of glycogenic energy. By-products from vegetables and tubers, pulps from sugar and juice production and hulls of various crops are generally bulky, implying they have a low nutrient content as they contain much fibre or water.

Animal processing by-products

While I only considered plant-based food leftovers in Chapter 2, the animals selected to upcycle LCF also produce animal-based food leftovers that could also be used as LCF. I was the first to explore their role in a circular food system (see Chapter 3 and 4). Like crop processing, slaughter and processing of live animals into food items (meat) results in various by-products that, although humans cannot or do not want to eat them, are highly nutritious (USDA, 2018b, 2018c). Animal by-products are already collected and can be processed into meals that contain processed animal proteins (PAPs) and rendered animal fat. For livestock, residual meat, bones, feathers, blood and organs are collected separately resulting in meals that differ in quality, that of bone and feather meal being lowest. For fish, all slaughter by-products are collected together, and rendered into fish oil and a protein rich fish meal (Cashion et al., 2016). Livestock fat is generally highly saturated, while fish oil is not and contains valuable fatty acids.

Food waste

In what form food wastes can be collected and recycled depends on the stage of the supply chain they are generated in. At the manufacturing stage – where food ingredients are combined into food items – wasted ingredients and finished products are collected separately by the former foodstuffs (FFS) industry, which processes them into feed ingredients (EFFPA, 2019). The majority of FFS consist of cereal-based products, either enriched with fat (bread) or with sugar (pastry). As FFS were intended for human consumption they are generally highly nutritious. Retailing waste, if collected in separate streams, could produce similar feed ingredients, but provides relatively more wasted fresh foods, such as meat and vegetables (Cicatiello et al., 2017; Teller et al., 2018). Meat and vegetables could be processed into meat meal and a bulky wet feed, respectively. At home, households collect all inedible parts and food scraps together resulting in mixed food waste (Truong et al., 2019; zu Ermgassen et al., 2016). To ensure the safety of mixed household food waste as feed, biohazardous contaminants should be inactivated with heat treatment and/or fermentation resulting a wet feed (swill) that can be fed as is (with 20-30% DM) or dried to a concentrate feed (with >80% DM) (Luyckx et al., 2019).

Consumption patterns and LCF generation

van Zanten et al. (2018) indicated that most variation between studies in the assumed generation food leftovers related to differences in assumed human consumption patterns. The healthy vegan diet assumed by van Zanten et al. (2016a) generated less LCF than currently available as used as a starting point by Elferink et al. (2008). To secure healthy diets in a circular food system, we must not only reduce ASF consumption, but also adapt our plant-based food consumption to compensate for this reduction and to avoid overconsumption (Jurgilevich et al., 2016). To use resources efficiently we should, furthermore, avoid generation of waste and by-products where possible (EU, 2008). As we must refrain from recycling as a justification to continue wasting, food wasted for commercial reasons should be avoided (Caldeira et al., 2019). Similarly, generation of some by-products can be avoided and may even result in healthier diets when, for example, whole grains are consumed instead of white flour (Borneo & León, 2012). These changes in consumption patterns affect the generation of food leftovers and, thus, how much ASF can be produced in a circular food system. In this thesis, I approximated the availability of plant-based LCF in a circular food system based on current plant-based food consumption in the EU, marked by overconsumption (FAO, 2017c) (Figure 1). While this slightly overestimated the availability of LCF, it suits my aim to evaluate the role of different animals in a circular food system. Availability of animal-based LCF was based on our model explorations and thus reflected ASF consumption tailored to a circular food system (Figure 1).

Legislation and other barriers to the use of LCF

The use of food leftovers as LCF is currently limited by legislation and other barriers. In Chapter 4 I explored what biomass lost along the food supply chain is currently used as LCF and which could potentially be used in the future. While plant and fish by-products are already fully used as feed (Vernier et al., 2016), use of livestock by-products is restricted by legislation implemented to avoid the spread of diseases like bovine spongiform encephalopathy BSE and foot and mouth disease (EU, 2009, 2013a). The legislation bans PAPs from bodily tissues, the main disease transmitter, but allows feeding animal fats, egg and dairy products under feed-safety regulations. While directed at animal by-products, feed legislation also applies to food wastes potentially contaminated with animal protein (EU, 2017, 2018). Thereby, it bans feeding of any household waste to food producing animals, which we found to have a high ASF supply potential, especially when provided in dried form. Safe feeding of such household swill, however, requires considerable effort, both in terms of legalisation and development of collection and treatment infrastructures (Luyckx et al., 2019). In contrast, most manufacturing and retail waste is allowed to be used as feed, but remains unused due to a lack of economic incentive (Truong et al., 2019). The animal protein supply potential of these wastes is limited due to their low quantities, but their high quality enables upcycling of low quality LCF.

Since a 2013 amendment to stimulate efficient resource use, farmed fish are allowed to feed on PAPs of non-ruminant origin (EU, 2013a). As this did not increase use of livestock by-products in fish feeds, also barriers other than legislation limit the use of food leftovers as LCF (BioMar, 2018; IUCN, 2017). Understanding and potentially overcoming these limitations is of high relevance, as we found livestock by-products are highly nutritious, and using them in fish feed has a high ASF supply potential (Chapter 4). Future research is, however, needed to consider the consequences of using currently unused food leftovers as LCF, as they are currently often used as compost, and may play a crucial role in maintaining soil health, the fundament of a circular food system (de Boer & van Ittersum, 2018; Hijbeek et al., 2017).

2.2 Desired outcomes of animal production

While humans value ASF for various reasons, I focussed on their role in nutrient supply. Regarding macronutrients, ASF mainly provides proteins and fats that, historically, were highly relevant for nutrition security, but are currently overconsumed in the EU (FAO, 2017c). Animal proteins have a high bioavailability and their amino acid composition matches well with human requirements. While livestock fats are considered unhealthy, as they are saturated and rich in cholesterol, fish oil is generally unsaturated and considered essential to a healthy diet (Grundy, 1997; Willett et al., 2019). Fish are currently our main source of eicosapentaenoic (EPA) and docosahexaenoic (DHA) ω-3 fatty acids, essential for brain development and functioning, and immune regulation (Kris-Etherton et al., 2009; Racine & Deckelbaum, 2007; Simopoulos, 2009). While humans can desaturate alpha-linolenic acid (ALA) into EPA/DHA, both ALA intake and desaturation potential are limited (Calder & Yaqoob, 2009). It is therefore recommended that diets contain a significant share of fish to fulfil the daily recommended intake of 250 mg EPA/DHA (EFSA, 2017).

Regarding micronutrients, ASF is valued for its high bio-availability of iron and zinc, and supply of nutrients mainly obtained from ASF, such as selenium, or even only obtained from ASF such as vitamin B12 (Godfray et al., 2018; Smith et al., 2013; van Hal et al., 2019a; van Zanten et al., 2018). While the optimisations in chapter 2, 3 and 4 maximise HDP supply, I also illustrate the supply of all nutrients of which sufficient intake may be at risk when reducing ASF food supply: vitamins A, D and B12, calcium, iron, zinc, selenium and EPA+DHA (Macdiarmid et al., 2012; Mertens et al., 2017). As the ASF provided by livestock and fish vary in their content of these nutrients (Table 1), a combination of animal production systems is needed to derive balanced diets. In chapter 3 and 4 meeting human requirements of vitamin B12 and EPA/DHA was prioritised as they are currently only provided by ASF and under-consumed by a significant part of the EU-28 population (de Smet, 2012; Duru, 2019; Givens & Gibbs, 2008; Oh & Brown, 2003).

Table 1 Nutrient content per kg fresh matter of the included animal source food (USDA, 2019), for each nutrient the foods with the highest contents are marked dark green and with a high content light green.

			PUFA		Vitamins			Minerals			
	DM*	Protein	EPA	DHA	A	D	B12	Calcium	Iron	Zinc	Selenium
Product	kg	g	g	g	µg	Mg	µg	mg	mg	mg	µg
Pig meat	0.51	291	0.0	0.0	38	10	8	173	11	30	396
Pig offal	0.33	198	0.6	0.2	163	8	91	155	68	34	367
Cattle meat	0.41	293	0.0	0.0	20	1	31	129	28	69	307
Cattle offal	0.34	231	0.5	0.1	584	5	313	383	45	46	191
Milk	0.12	33	0.0	0.0	460	1	5	1130	0	4	37
Poultry meat	0.38	260	0.1	0.4	46	0	3	140	12	19	210
Poultry offal	0.32	272	0.1	0.3	18	0	94	140	70	42	596
Eggs	0.26	123	0.0	0.1	175	20	15	540	16	12	301
Salmon	0.35	254	6.9	14.6	690	140	40	150	3	4	414
Tilapia	0.28	262	0.1	0.8	0	37	19	140	7	4	544

*Dry matter content (DM): note that low dry matter content of milk and eggs causes relatively low protein contents

2.3 Potential of various animals

In circular food system, ASF can be obtained from harvested wild animals or from farm animals fed LCF, considering both terrestrial animals (livestock when farmed) and aquatic animals (fisheries and aquaculture). Sustainable harvest of wild animals should not exceed the restorative capacity of ecosystems (Froese et al., 2018). For fisheries – the harvest of wild fish that is a common source of food in the EU – historic over-exploitation has compromised the production potential of fish stocks in the EU (Hamilton et al., 2020). In Chapter 3, I proposed that fisheries tailored to a circular food system requires that harvest is limited to the maximum sustainable yield (MSY) implemented in EU legislation (EU, 2013b) and that all edible fish should be used for human consumption. I found that such fisheries provide 2 g HDP (cap/d) and fulfil 40% of EPA/DHA requirements. As terrestrial wild animals make a limited contribution to EU food supply, I did not explore their potential (FAO, 2017a). In chapter 2, 3 and 4 I assessed what characteristics of different livestock and farmed fish are of value in a circular food system and if reduced livestock productivity enables better use of available LCF. Below I discuss the value of the considered farm animals to the optimal use of LCF.

Ruminant livestock

Ruminants are terrestrial animals with a complex digestive system adapted to degrade fibrous feed through anaerobic digestion. While in the EU food producing ruminants include various types of cattle, sheep and goats, I used the most common species (dairy and beef cattle) as a representative (Chapter 2). During rumination, rumen microbiota digest mechanically degraded fibre into volatile fatty acids (energy) and microbial biomass (protein) used for animal metabolism and production (Baldwin, 1995). Research showed rumination is essential both for ruminant health (Webb et al., 2013) and welfare (Kok et al., 2017). Historically, humans used ruminants to graze fibrous vegetation and valued both the food and manure they provided (Dodgshon & Olsson, 2007). Since the onset of the industrial revolution ruminant production has intensified and specialised, which increased productivity and replaced roughage with concentrate feeds (Hinojosa et al., 2016; Kristensen et al., 2004; Vicente-Serrano et al., 2004). Recent efforts to mitigate GHG emission enhance this trend, as the potent GHG methane is produced from volatile fatty acids produced specifically when degrading fibre (Baldwin, 1995; Garnett et al., 2017). With this transition, ruminant production became less directed at upcycling grass, which has reduced the resource use efficiency of our food system (Dumont et al., 2018; Wilkinson & Lee, 2018).

My results show that in a circular food system, ruminants revert to their traditional role of valuing grass. As dairy cattle provide a daily product, they upcycle grass more efficiently than beef cattle (de Vries & de Boer, 2010). Throughout this study the model selected dairy cattle to upcycle as much grass resources as possible. Regardless of the low productivity of the selected dairy cattle, their nutrient requirements could only be met by supplementing their diets with high quality LCF, such as oil seed meals and enriched cereals (bread meal). Furthermore, these cattle were unable to upcycle all grazing resources and left up to 62% of nature grass and 82% of rangeland unused. Increased availability of high quality LCF, however, enabled them to value more of the low quality grass (Chapter 4). Although the nutrient content of milk was relatively low due to its low DM content, its daily supply provided much HDP and vitamin B12, and is an excellent source of calcium. The meat and offal that accompany this milk production are rich in iron, zinc and especially vitamin B12.

Dairy cattle were likely unable to value low quality grass due to their assumed nutrient requirements. The equations of the Dutch feed system underlying these requirements have been validated for Holstein Frisians, specifically bred for a high milk production and inefficient under low production (CVB, 2012). Future research should indicate how well marginal grass can be valued by traditional breeds, developed over centuries to thrive in these circumstances (Caballero, 2007). Considering the use of marginal grassland is often limited by remoteness as discussed in Section 2.1. Beef farming that requires less management, therefore, may be more realistic on these lands. We furthermore found beef cattle were better adapted to value low quality grass (Chapter 2). To stimulate use of marginal grasslands, small ruminants (i.e sheep and goats) may be of value as their small size and agility enables them to travel further and through rougher areas. As small ruminants browse rather than graze, they are well adapted to value rangeland biomass and grass left unharvested by cattle (Gordon et al., 1996). As the use of fibrous low quality grass may result in high methane emissions, GHG emissions should be considered when exploring the value of extending grazing of natural grassland and rangeland in a circular food system.

Monogastric livestock

Monogastric livestock are food producing, terrestrial animals with one stomach that in the EU include pigs and poultry (FAO, 2017d). Monogastric livestock convert feed into ASF more efficiently than ruminants, but their feeds typically contain more human edible products and high quality feed crops (de Vries & de Boer, 2010; van Zanten et al., 2016b). Historically, humans kept pigs to convert food waste, often of the farm household, into ASF and manure (White, 2011). Pigs were especially suitable for this role due to their high feed intake capacity (FIC), as they eat almost everything (zu Ermgassen et al., 2016). Poultry, historically, were mainly farmed for egg production and kept in backyard systems, where they scavenged on insects, plants and harvest spills, but were also fed some cereals (Dixon, 1850). Both pigs and poultry thus helped get rid of a hazardous wastes, while providing food and manure. As no artificial fertiliser was available, manure was valuable for food crop cultivation (Woods, 2012). Currently, these animals are kept in highly specialised and intensified systems (Woods, 2012), where breeding and technological improvements increased productivity, but also require more and better quality feed (White, 2011).

My results show that in a circular food system, pigs revert to their role as “waste bin” while laying hens were mainly appreciated for the high efficiency at which they convert LCF into eggs. Throughout this study the model selected pigs to upcycle wet and fibrous food processing by-products, and (when provided) treated wet household swill. When such household swill was dried, however, it became a high quality feed ingredient, which was more efficiently converted by laying hens (Chapter 4). While our model included broilers (chickens kept for meat production), these were never selected, indicating other animals provided the demanded nutrients more efficiently. Similarly, laying hens of low productivity were never selected, emphasising they were valued for the efficiency at which they convert high quality LCF. While both meat and eggs provided by monogastrics contributed to HDP and vitamin B12 supply, eggs may also contribute to the supply of vitamin A.

Farmed fish

Farmed fish consider finfish farmed in aquaculture systems, which are highly industrialised in Europe (European Commission, 2017). While the EU currently farms a variety of carnivorous and omnivorous fish species of different trophic levels, I used the high trophic, carnivorous and fatty Atlantic salmon and low trophic, omnivorous Nile tilapia as a representative species. Historically, fish farming traditions started in early Egyptian and Chinese civilisations (Malindine, 2019). In Europe they were introduced in their modern form– where eggs are fertilised and the hatched fish are fed and harvested – in the 18th century (European Commission, 2019). Gradually, this system intensified from feeding fish to keeping fish in fully controlled environments (European Commission, 2019). Fish farming is increasingly implemented to meet the demand for fish as supply from fisheries is limited by nature's production potentials (Froehlich et al., 2018; HLPE, 2014).

My results show that in a circular food system, farmed fish have an important role in upcycling animal-based LCF. Under current legislation, only fish are allowed to feed on most livestock PAPs, and are, therefore, the only means to upcycle these valuable feeds (EU, 2013a). Also when this legislative restriction was released most livestock PAPS were fed to farmed fish, indicating these production systems are most efficient at upcycling animal by-products (Chapter 4). Farming of fatty fish like salmon that are rich in EPA/DHA is, furthermore, essential to meet human EPA/DHA requirements as, even under fish stock recovery as fisheries alone cannot meet this demand. In my optimisation, salmon production was, thus, driven by the demand for EPA/DHA, and supply of these nutrients is their main role in the proposed circular food system.

To supply EPA/DHA, and for their own health, these fatty fish require feed with a high EPA/DHA content, commonly achieved by including fish by-products (Hamilton et al., 2020; Sprague et al., 2016). As supply of EPA/DHA containing fish by-products from fisheries is limited, and current legislation bans feeding farmed fish with by-products of farmed fish of the same species (EU, 2013a), a circular food system requires a variety of fatty fish that can efficiently upcycle each other's by-products. Besides EPA/DHA rich ingredients, farmed fatty fish require high quality proteins to meet their protein requirement within their feed intake capacity. When limited to LCF, fish feeds can only reach such high protein content by including a large share of livestock by-products, which are currently avoided in aquafeeds as discussed in Section 2.1. I found the use of livestock by-products enables salmon to value EPA/DHA containing LCF more efficiently, which is essential to meet EPA/DHA requirements. Like laying hens, farmed tilapia was mainly valued for its efficiency in upcycling high quality LCF. Whether laying hens or tilapia were selected depended on the types of available high quality LCF to feed them.

The farmed fish in our model required high quality feed because they were highly productive. Fish with lower productivity might be better able to value lower quality LCF, as illustrated for dairy cattle and pigs (van Hal et al., 2019a). Reduced productivity in fish, however, likely has limited potential as it increases excretion of non-digestible nutrients causing eutrophication and environmental degradation for cage farmed salmon (Nordvarg & Johansson, 2002; Qi et al., 2019) and adverse health effects for tilapia farmed in tanks (Austin, 1998). Lower trophic fish, and species well adapted to synthesise EPA/DHA out of shorter chained fatty acids, such as rainbow trout (Mente et al., 2019) and various fresh water species (Rodrigues et al., 2017), are likely of more value and should be explored in future studies.

2.4 Conclusions on the optimal use of LCF

Results showed that optimal use of LCF can provide an HDP intake up to 39 g (cap/d), and fulfil the full requirements of EPA/DHA and vitamin B12. While this intake is significantly lower than current supply of animal protein (61 g/cap/d), it fulfils up to 65% of total protein requirements (FAO, 2017c). Compared to current consumption, this protein is, furthermore, to a larger extent obtained from fish and dairy, and less from meat. A circular food system, thus, not only requires a reduction in ASF consumption, but also a change in the type of ASF we consume. As fish is the only source of EPA/DHA, increased fish consumption is needed to meet EPA/DHA requirements, while protein and vitamin B12 were mainly provided by milk and meat. While protein supply from animals fed only LCF is higher than in previous studies (7-30 g/cap/d; (van Zanten et al., 2018)), this increase is only partly due to the optimised use of LCF, as differences in study region and assumed availability of LCF confounds the comparison.

Optimal use of LCF requires a combination of animals tailored to the available LCF and the desired nutrient supply to the human population (van Hal et al., 2019a; van Hal et al., 2020). Human demand for EPA/DHA drives farming of fatty fish that require a feed comprised of fish and livestock by-products. To maximise the use of low quality LCF, they are fed to species that are best adapted to upcycle them and are typically combined with high quality LCF. While all ruminants are adapted to value low quality grass, dairy appears most efficient but may be unsuitable for valuing remote grasslands. In these areas low productive beef or sheep may be more realistic. The high feed intake capacity of pigs enables them to value wet by-products, such as pulp and (when available) wet household swill. Remaining high quality LCF, not needed to meet EPA/DHA requirement or facilitate upcycling of low quality LCF, were fed to animals with a high feed conversion efficiency. High quality animal-based LCF were typically fed to salmon, while those of plant origin were fed to laying hens or tilapia. If remaining plant-based LCF could not formulate a complete ration for hens or fish, they were used to increase dairy productivity (Chapter 2). Note that these principles are based solely on resource use efficiency and do not consider environmental impacts. When considering, for example, GHG emissions, the focus on dairy production and feeding more fibre may be less desirable. Future research is needed to illustrate synergies and trade-offs between environmental and circularity objectives and provide balanced solutions.

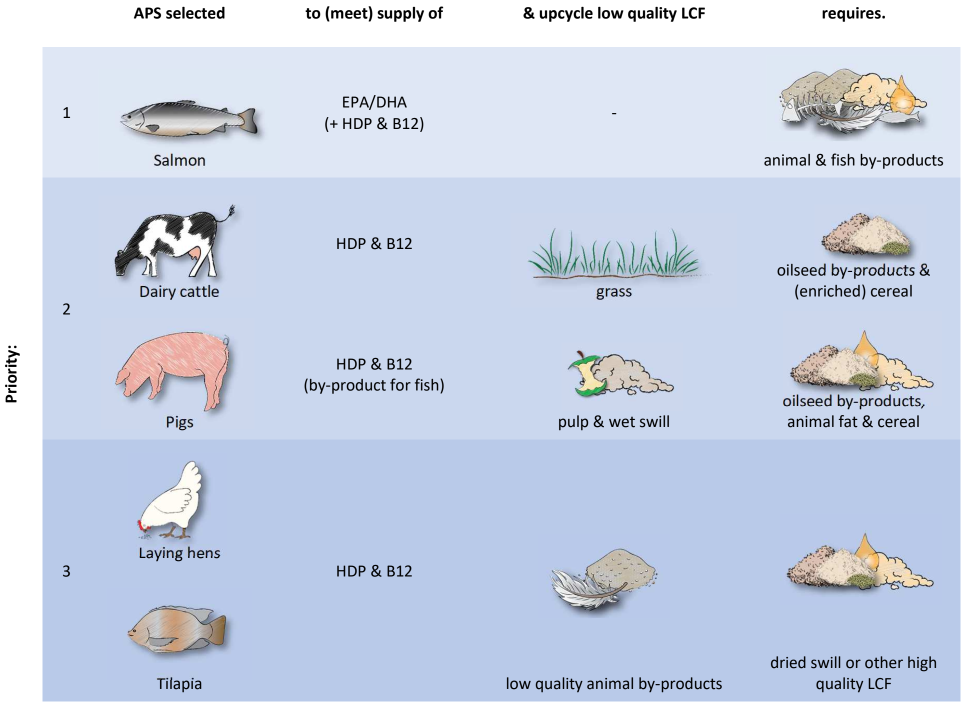


Figure 2 Principles to the selection of animal production systems (APS) for the optimal use of available low-opportunity-cost feeds to maximise human digestible protein (HDP) intake while meeting intake requirements of EPA/DHA fatty acids and vitamin B12

3. Supply chain environmental impact assessment for circularity

Currently governments, farmers, and consumers base their sustainability strategies on LCAs which typically take a supply chain approach. This approach does not account for interlinkages between the numerous supply chains the food system entails, and thereby overlooks consequences of their recommended mitigation strategies on the food system as a whole. LCA studies directed at reducing the environmental impact of ASF or human diets, therefore, often propose mitigation strategies that counteract the resource use efficiency of the food system as a whole, effectively moving us away from circularity (Frehner et al., 2020; van Zanten et al., 2018). A prominent example of such mitigation strategies is reducing impacts per kg ASF by lowering the feed conversion ratio (FCR: kg feed needed per kg ASF) through, for example, breeding strategies (Herrero et al., 2016). A consumption oriented example is to replace products produced by animals with a high FCR (e.g. grass-fed beef) with those of animals with a low FCR (e.g. concentrate fed chicken) (Aleksandrowicz et al., 2016; Hallström et al., 2015). Generally, lowering the FCR increases the use of high quality ingredients, inherently moving the food system away from resource use efficiency.

The interlinkages overlooked in LCA studies relate to multifunctional processes for which environmental impacts must be divided over the resulting products. LCA on ASF typically allocate environmental impacts to multiple outputs (e.g. sunflower oil and meal) based on their relative economic value, which does not reflect their suitability for human consumption (de Vries & de Boer, 2010). While the findings of LCA studies with such economic allocation remain valuable, as they illustrate the current impact of value chains, they will lead towards a circular food system (Frehner et al., 2020). In Chapter 5, I illustrate this controversy and initiate the development of a new supply chain environmental impact assessment that is suited to the circularity paradigm (van Hal et al., 2019b). To this end I compared a conventional LCA with economic allocation to an alternative LCA with so called feed-food allocation. This feed-food allocation relates the full impact of a multifunctional production process to the resulting human edible products, while products unsuitable for human consumption receive no impact. In case of soybean meal – accountable for most of the revenues of soybean cultivation – economic allocation allocates the majority of impact to soybean meal, while with feed-food allocation soybean oil carries the full burden under the assumption soybean cultivation is limited to the human demand for oil.

I applied both allocation methods to a novel egg production system that aims for circularity and feeds only LCF. Results show that, when using economic allocation, feeding only LCF reduces the impact per kg egg with 48-58% for global warming potential (GWP) and 34-47% for (land use) LU, due to the low economic value of LCF. When using feed-food allocation, the environmental impact was reduced with 57% for global warming potential and 96% for land use, showing the larger mitigation potential of feeding LCF. While this case study illustrates the relevance and potential of accounting for feed-food competition in LCA, the used feed-food allocation has two main limitations. First, feed-food allocation is binary, implying that products are either suitable or unsuitable for human consumption and does, therefore, not yet consider the variation in nutritional value. Accounting for the nutritional value for human consumption is, however, complex due to the large variety of nutrients foods provide (van Kernebeek et al., 2014). Second, LCA, being a supply chain approach, is unable to account for the availability of LCF. While feed-food allocation accounts for the environmental benefits of feeding LCF, it gives no insights into the allocation question 'which animals should we fed what LCF' or about the total number animals we can keep, which requires a food systems approach applied in Chapter 2, 3 and 4.

4. Towards a resource efficient food system

My thesis illustrated that animals play a valuable role in a circular food system and provided insights into what this role entails for various animals. In this section we address the advances in use of LCF (4.1) food systems modelling (4.2), societal change (4.1) needed to move towards a food system that can feed our growing population with respect for our planet.

4.1 Improving the use of LCF

My findings illustrate that feeding farm animals with LCF improves to the resource use efficiency of the food system and can reduce the environmental of ASF. In Chapter 4, I illustrated that food leftovers, that are currently not used as LCF due to legislation and other barriers, have a high ASF supply potential. To increase the resource use efficiency of animal production the barriers to feeding food leftovers should better understood and, where possible, overcome. Of the considered food leftover streams, livestock PAPs appeared most potent; they increased HDP supply by 18% and are essential to meet human EPA/DHA requirements. As legislation allows feeding of these PAPs to farmed fish (EU, 2013a), their limited use fish feed in the EU is caused by other barriers, of which improved understanding is needed. In contrast, the considerable effort required to safely feed household waste, the second most potent leftover stream, is well reported (Luyckx et al., 2019). While, when provided dry, this waste can increase HDP supply by 12%, it requires legislative change and feed safety is difficult to guarantee. In contrast, most food wasted in manufacturing and retail are allowed to be used as feed, but remain unused due to a lack of economic incentive (Truong et al., 2019). The animal protein supply potential of these wastes (+5%) is limited due to their low quantities, but their high quality they enables upcycling of low quality LCF. Improving the use of these food leftovers as LCF and understanding the barriers that limits such practice should be a priority of the industry to increase their resource use efficiency. This development may be stimulated by improving the transparency of resource use along the food supply chain(Jackson et al., 2020).

4.2 Food systems modelling

To evaluate the role of animals in a circular food system, I optimised the use of LCF by different farm animals given a predefined availability of plant-based LCF and focused on nutrients specifically provided by ASF (Section 2.4). While this approach served well to the aim of the study, in a circular food system not only animal production but also crop production should be optimised, which would affect the availability of plant-based LCF. We, therefore, need a full food systems modelling approach to further refine our understanding on the role of animals in a circular food system.

An integrated model

Modelling the entire food system requires integration of soil, crop and animal components, to optimise use of available resources to meet all human nutritional requirements while minimising emissions to stay within our planetary boundaries. Besides various animal production systems, such a model should include various plant production systems, and their associated use of land, fertilisers and other inputs (van Kernebeek et al., 2018). To explore the full potential animals, a wide range of animal production systems should be included, such as traditional cattle breeds, goats and sheep, other fish species and insects (Section 2.3). Optimally, the model should use improved data on grass availability and quality, and account for restrictions to its use such as remoteness and seasonality (Section 2.1).

A full food systems model would provide valuable insights to or solve remaining dilemma’s posed in this thesis. By minimising GHG emissions, for example, it could address land use change related issues, such as the conversion of arable grassland into cropland or marginal grasslands into forest. While in my thesis dairy cattle is prominent, minimising GHG may affect this conclusion as enteric methane emission and land use change emission are major contributors. Optimising the whole food system, furthermore, indicates the best use of resources in terms of food supply and gives valuable insights in which food leftovers should be used as fertiliser and which as feed. It effectively moves us from increasing yields per resource towards people fed per resource accounting both for direct (crop) and indirect (animal) food supply (Cassidy et al., 2013; van Zanten, 2016). Finally, this model can provide improved understanding of the value of animals in a circular food system based on all the nutrients they supply (van Zanten et al., 2019).

While in essence the described model would predict how to meet human dietary requirements with the lowest environmental burden, it could also estimate the environmental and resource costs of more extravagant diets to help policy makers and consumers make informed choices. If society wishes to consume more ASF than can be produced using only LCF, animal diets should be supplemented with high quality feeds that may increase their productivity or enable the production of more animals. To minimise the environmental costs of animal source food, the supplementation of high quality feed should be directed at increasing the efficiency with which LCF could be upcycled. Finally, to move towards circularity of agriculture at large, other agricultural functions such as energy and material production should be included as well (Muscat et al., 2019).

4.3 Societal change

A transition towards a circular food system, that stays within ecological boundaries, requires a paradigm shift in which all food system actors need to reconsider basic assumptions, norms and values nested deep within our societies (Clough, 2005; Jackson et al., 2020; van Zanten, 2016). Historically, humans have farmed animals and consumed their products since the onset of settlement, but production methods and consumption have changed drastically over time (Tauger, 2013). In the last century, ASF consumption increased with prosperity (Kearney, 2010; Speedy, 2003) and, in many high income countries, reached a level where it is no longer nutritionally beneficial and possibly even harmful (Willett et al., 2019). ASF are, however, not only consumed to provide nutrients, but for a variety of reasons including taste and habit (Clough, 2005; Dowsett et al., 2018). Negative impacts of ASF consumption that besides environmental impacts consider inequality issues and animal ethics, are increasingly acknowledged (Cassidy et al., 2013; Dowsett et al., 2018; Smil, 2014). While each person copes differently with the moral conflict between harming our planet and/or animals and the pleasure of consuming ASF (Piazza et al., 2015), small reductions in ASF consumptions have been observed in the EU (Vranken et al., 2014). While awareness increases due to political (LNV, 2019) and industry (Kipster, 2017) development, well guided collaboration across the food system is needed to take collective responsibility (Jackson et al., 2020)

A circular food system requires that society can make informed decisions regarding food consumption, based on not only economic but also social and environmental benefits and costs (de Boer & van Ittersum, 2018). Such decisions require insights in the environmental cost of ASF production and what is possible within ecological boundaries which can be illustrated through integrated food system modelling (Section 4.1). Additionally, such research on the biophysical components of the food system, should be combined with social research to propose and stimulate a realistic food future.

While researchers gain knowledge on the principles of a circular food system, policy agendas are set, industries are developing and consumers become more aware, the state of the earth requires immediate action (Herrero et al., 2020). I, therefore, end my discussion with no regret solutions that can be implemented directly or with small adjustments to foster the transition towards a circular food system. Previous research indicates, we should target management (fertiliser/irrigation) at closing yield gaps; second, we should eat less, specifically ASF; and third, we should reduce food losses (de Boer & van Ittersum, 2018; van Zanten et al., 2019). Based on this thesis I add we should consume all human edible fish obtained through fisheries, and animal production systems should efficient use available LCF in their rations.

5. Conclusion

This thesis illustrates that animals can contribute to the resource use efficiency of a circular food system by upcycling LCF: biomass unsuitable for human consumption. To make most of available LCF, their use should be optimised. I illustrated that by optimising the use of LCF, animals can provide up to 39 g HDP /cap/d, considerably more than previously illustrated in research (7-30 g/cap/d). While this comparison is confounded by differences in the assumptions regarding the availability of LCF, this thesis illustrated that animals are crucial in a circular food systems and provided valuable principles about the role of animals in a circular food system.

Optimal use of LCF requires a combination of livestock and farmed fish. Animals in a circular food system should, thus, be tailored to available LCF and the nutrients we wish them to supply, where the role of each animal depends on their feeding characteristics and the nutrients in the ASF they provide. While some animals are well adapted to value specific low quality LCF, they must be combined with high quality LCF to formulate rations to derive an average nutrient content that can meet the nutritional need of each animal. Grass resources, for example, are used most efficiently by dairy cattle as ruminants are well adapted to value this feed and dairy cattle is especially efficient as it provides a daily product. Wet or fibrous food leftovers are used most efficiently by pigs that are known to have a high feed intake capacity.

While ASF contain a variety of valuable nutrients, vitamin B12 and EPA/DHA are currently only obtained from ASF and should, therefore, be prioritised, next to our basal requirement of protein. While vitamin B12 is found in most ASF, fish is currently the only natural source of EPA/DHA in human diets. Fisheries (wild caught fish) supply is limited by production potentials in nature and cannot fully fulfil EPA/DHA requirements. A circular food system, therefore, also includes farmed fatty fish, that when feeding only LCF, can only be fed by using fish and livestock by-products.

A transition towards a circular food system requires a paradigm shift; consumers should change consumption pattern, industries should redesign production systems and policy makers should value social and economic aspects within the ecological boundaries of our planet. As environmental impact assessments that currently advise policymakers often counteract resource use efficiency, I made a first step to adapt these supply chain assessments to the circular paradigm. Understanding how many animals we can produce and which LCF we should feed them, however, requires food system modelling that can incorporate the partial food system model developed in thesis. Development of these scientific tools and the societal change needed to foster the transition towards a circular food system both take considerable time to realise, while we need to act know to preserve our planet for future generations. While conducting the needed bio-physical and social research we should, therefore, implement the no-regret solutions previously proposed for a circular food system, to which I add that animal production should efficiently use available LCF in their rations. Upcycling of animal-based LCF – that could be used in fish feeds tomorrow – has high potential to increase the resource use efficiency of our food system.

Appendix A

A1 - Animal protein supply estimates on low-opportunity-cost feeds

Table A1 Estimates of per animal protein supply when limiting livestock production to low-opportunity-cost feed (LCF) availability, adapted from (van Zanten et al., 2018).

	Input (LCF)				Output	
Article	Food waste	By-product	Grass-resources	Crop-residues	Products	Protein g/(cap*d)
Elferink et al. (2008)[A]		x			meat	27
Smil (2014)[C]		x	x	x	meat	10
Schader et al. (2015)[C]		x	x		meat, milk, eggs	9
van Kernebeek et al. (2016)[1A]	X	x	x		meat, milk	7
van Zanten et al. (2016a))[C]	X	x	x		meat, milk	21
Röös et al. (2016)[2A]		x	x		meat, milk	22
Röös et al. (2017a)[2B]	X	x	x		meat, milk	23
Röös et al. (2017b)[2C]	X	x	x		meat, milk	30

[1] included only 10% of produced waste, use of grass resources is very limited as land use is minimised

[2] additional concentrates were fed to maintain high productivity

Scale: [A] National, [B] Europe, [C] Global

A2- Availability of low-opportunity-cost feeds

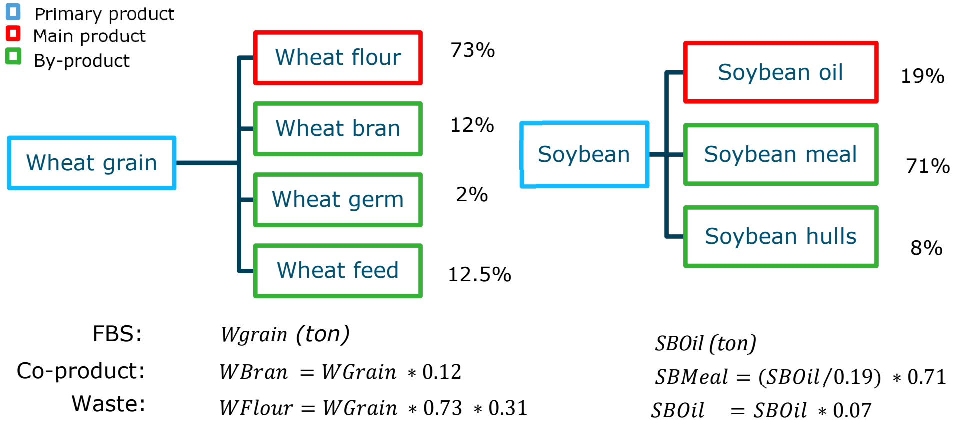
Plant based food leftovers

We related the annual availability of food leftovers (processing by-products and waste) to plant-source food supply in each EU country, between 2009-2013, according to FAO's food balance sheets (FBS) (FAO, 2017c). These FBS provide data on the amount of crop product available per country per year, and to what uses each product was allocated. Here, we consider only the amount of product allocated to food supply, generally expressed in primary product equivalents. The annual food supply of wheat, for example, was expressed in tonne of the primary product wheat grain (Figure A1) that are needed for the actual supply of processed products such as wheat flour (Becker et al., 2001). For some products (e.g. oil crops and beer), however, the FBS expressed supply in tonne of processed products (e.g. soybean oil (Figure A1) and beer) (Becker et al., 2001).

Crop processing by-products

The amount of by-products related to food supply in each EU country were calculated using technical conversion factors provided by FAO (1996), or Vellinga et al. (2013) for oilseeds and wheat. These factors represent the fraction of main product (e.g. wheat flour) and by-products (e.g. wheat bran, germ and feed [middling]) resulting from each process (e.g. wheat milling) relative to the input of one unit of primary product (e.g. wheat grain). The amount of wheat bran available in each country, for example, was calculated by multiplying the annual food supply of wheat grain equivalents, with the wheat bran fraction resulting from the wheat milling process, under the assumption that all wheat is consumed in the form of wheat flour (Figure A1). The annual supply in primary product equivalents of products that the FBS expresses in tonne of processed products (e.g. soybeans), were calculated by dividing the annual consumption in tonne of processed product by the main product fractions from the process that they already went through (e.g. soybean oil extraction) (Figure A1). The nutrient content of each by-product was based on the CVB system (CVB, 2016a). As the by-products were assumed to be tradable, the available by-products in all countries in the EU-28 were summed together. Their total supply is displayed in Figure A2 using a classification based on nutritional properties (Table A2).

Figure A1 Example calculation of waste (wasted wheat flour/soybean oil) and by-product (produced wheat bran, germ and feed/ soybean meal and hulls) available based on food supply (tonnes wheat grain or soybean oil) according to food balance sheets (FBS) using wastage fractions (0.31 for cereals, 0.07 for oils; Gustavsson et al. (2011)) and technical conversion factors of (Vellinga et al., 2013)



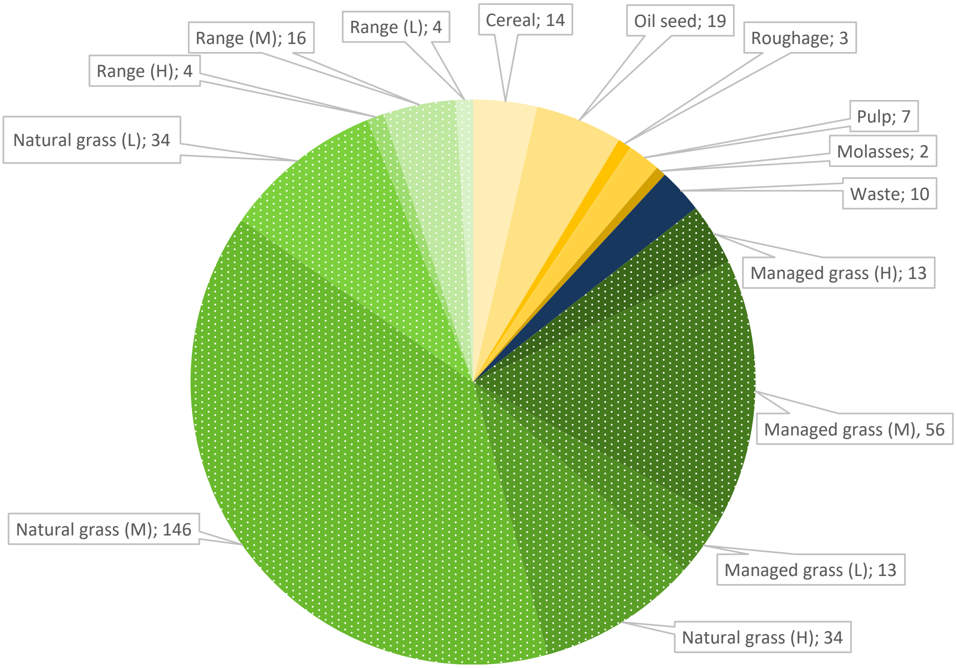


Figure A2 Total EU availability of low-opportunity-cost feeds (LCF), excluding feeding losses, in million tonne DM. LCF include food processing by-products (classified: cereals, oilseeds, roughages, pulps, molasses), food waste (waste) and grass resources of managed grassland, natural grassland and rangeland of high (H), mid (M), or low (L) quality.

Table A2 Classification of food co-products based on their nutritional properties

By-product	Type	Classification
Wheat_bran	Cereal by-product	Cereal
Wheat_germ	Cereal by-product	Cereal
Wheat_feedmeal	Cereal by-product	Cereal
Barley_byprod	Cereal by-product	Cereal
Barley_rootlet	Cereal by-product	Cereal
Brewers_grain_spend	Cereal by-product	Cereal
Maize_bran	Cereal by-product	Cereal
Maize_germ_meal	Oil by-product	Oilseed
Rye_bran	Cereal by-product	Cereal
Oat_offals	Cereal by-product	Cereal
Oat_hulls	Shell, hull or straw	Roughage like by-products
Rice_hulls	Shell, hull or straw	Roughage like by-products
Potato_peel	Tuber by-product	Pulp
Sweetpotato_peel	Tuber by-product	Pulp
Sugarbeet_toptails	Shell, hull or straw	Roughage like by-products
Sugarbeet_molasses	Molasses	Molasses
Sugarbeet_pulp	Pulp	Pulp
Soyabean_hulls	Shell, hull or straw	Roughage like by-products
Soyabean_meal	Oil by-product	Oilseed
Groundnut_shells	Shell, hull or straw	Roughage like by-products
Groundnut_meal	Oil by-product	Oilseed
Sunflowerseed_meal	Oil by-product	Oilseed
Rapeseed_meal	Oil by-product	Oilseed
Cottonseed_meal	Oil by-product	Oilseed
Copra_meal	Oil by-product	Oilseed
Sesameseed_meal	Oil by-product	Oilseed
Palm_fiber	Shell, hull or straw	Roughage like by-products
Palm_effluent	Oil by-product	Oilseed
Palm_kernel_meal	Oil by-product	Oilseed
Olive_residue	Oil by-product	Oilseed
Citrus_pulp	Pulp	Pulp
Grape_pomace	Pulp	Pulp
Coffee_husk	Shell, hull or straw	Roughage like by-products
Cocoa_husk	Shell, hull or straw	Roughage like by-products

Waste

Available waste products were calculated applying Europe specific consumption waste fractions of Gustavsson et al. (2011) to the available main products after processing, i.e. multiplying the tonnes of main product available for consumption with the product type specific consumption waste fraction (Figure A1). All waste products within each country were combined into one waste stream in this country, as waste was assumed not to be traded, of which the nutrient content equals the weighted average of the included products based on the CVB system (CVB, 2016a). The availability of food waste as feed (35% of the produced food waste (zu Ermgassen et al., 2016)) and its nutritional value for pigs, laying hens, and broilers (to which the food waste can be fed) in each country is displayed in Table A3, total availability of food waste in the EU is displayed in Figure A2.

Table A3 Per country availability (tonne DM and FM) of the food waste stream as animal feed and the country specific nutrient content of this waste stream for pigs, laying hens, and broilers per kg DM.

	Available waste		Nutrients/ kg DM								
	DM	DM	Pig			Laying hen			Broiler		
Country	Tonne	fract.	NE	Dlys	Dmeth	ME	Dlys	Dmeth	ME	Dlys	Dmeth
Austria	164176	0.41	10.9	2.39	0.68	12.6	2.08	0.60	12.2	2.08	0.60
Belgium	232175	0.45	11.3	2.02	0.72	13.2	1.55	0.57	12.6	1.55	0.57
Bulgaria	145770	0.55	12.1	3.15	1.06	14.2	2.68	0.90	13.5	2.68	0.90
Croatia	78733	0.45	11.4	2.66	0.80	13.3	2.24	0.68	12.7	2.24	0.68
Cyprus	14844	0.38	9.8	2.56	0.71	11.4	2.25	0.62	10.9	2.25	0.62
Czech R.	190349	0.47	11.7	2.72	0.85	13.7	2.26	0.71	13.1	2.26	0.71
Denmark	114791	0.44	10.6	2.49	0.77	12.4	2.10	0.66	11.9	2.10	0.66
Estonia	26380	0.41	10.8	2.47	0.75	12.6	2.04	0.65	12.2	2.04	0.65
Finland	88430	0.42	10.9	2.56	0.78	12.6	2.16	0.67	12.1	2.16	0.67
France	1177293	0.43	10.7	2.50	0.78	12.5	2.11	0.66	11.9	2.11	0.66
Germany	1487008	0.44	11.2	2.51	0.77	13.0	2.11	0.66	12.5	2.11	0.66
Greece	229272	0.33	9.9	3.30	0.77	11.4	2.99	0.70	10.9	2.99	0.70
Hungary	155231	0.42	11.1	2.82	0.84	12.9	2.38	0.71	12.2	2.38	0.71
Ireland	86360	0.41	10.8	2.50	0.77	12.6	2.04	0.64	12.0	2.04	0.64
Italy	1305040	0.41	10.3	2.93	0.83	12.0	2.59	0.71	11.3	2.59	0.71
Latvia	36708	0.39	10.3	2.38	0.71	11.9	1.96	0.63	11.6	1.96	0.63
Lithuania	68075	0.45	11.2	2.70	0.85	13.0	2.23	0.72	12.5	2.23	0.72
Luxembourg	8111	0.36	9.9	2.40	0.74	11.5	2.05	0.63	10.9	2.05	0.63
Malta	9820	0.40	9.7	2.65	0.75	11.3	2.30	0.64	10.8	2.30	0.64
Netherlands	285071	0.38	10.6	2.12	0.61	12.4	1.73	0.52	12.0	1.73	0.52
Poland	869757	0.43	11.2	2.72	0.81	13.0	2.27	0.70	12.5	2.27	0.70
Portugal	204983	0.36	10.0	2.80	0.75	11.6	2.46	0.66	11.1	2.46	0.66
Romania	515570	0.41	11.0	2.97	0.87	12.8	2.54	0.75	12.2	2.54	0.75
Slovakia	101246	0.47	11.2	2.63	0.84	13.1	2.19	0.70	12.5	2.19	0.70
Slovenia	37224	0.45	11.3	2.59	0.86	13.2	2.18	0.74	12.5	2.18	0.74
Spain	733866	0.36	10.5	3.29	0.78	12.2	2.95	0.70	11.7	2.95	0.70
Sweden	158035	0.41	10.5	2.46	0.71	12.2	2.10	0.62	11.7	2.10	0.62
UK	1359989	0.43	12.4	2.44	0.70	14.3	2.01	0.59	13.7	2.01	0.59

Grass resources

The amount of grass resources available in each EU country and their nutritional value, were based on spatially explicit data on the distribution and productivity of grazing land of several vegetation types, linked to a vegetation specific nutrient content. Grassland in each EU country was quantified from the land use maps of Plutzar et al. (2016). These spatially explicit (1 km scale) maps combine remote sensing land cover data (CORINE) and tier 2 census data on land use (CAPRI) to divide the available land in the EU over land use classes, one of them being grassland. Besides the land used for grass production according to the combined census and remote sensing data, this class includes all land not allocated a land used and deemed suitable for grazing.

The grassland class covers multiple of vegetation types (i.e. managed grassland, natural grassland, moors & heathland, sclerophyllous and transitional, shrub and woodland) that vary in grazing suitability, due to differences in grazable fraction, nutrient content, and digestibility of the produced biomass. Plutzar et al. (2016) aggregated these vegetation types into managed grassland (meadows & pastures) and other grassland. The natural grassland included in the "other grassland" is, however, more suitable for grazing than the included rangeland types (Astigarraga et al., 2009). We, therefore, reclassified the "other grassland" into natural grassland and rangeland using the country specific distribution of grassland over grazing suitability classes of Haberl et al. (2007). This earlier global study used methods similar to Plutzar et al. (2016) with a lower resolution yielding slightly less accurate results. They distributed grassland over four grazing classes based on vegetation type and productivity, where class 4 included all shrub land and woody vegetation we classified as rangeland (Figure A3). Our natural grassland, therefore, included grazing class 2 and 3 and the remainder of grazing class 1, after subtracting managed grassland quantified by Plutzar et al. (2016).

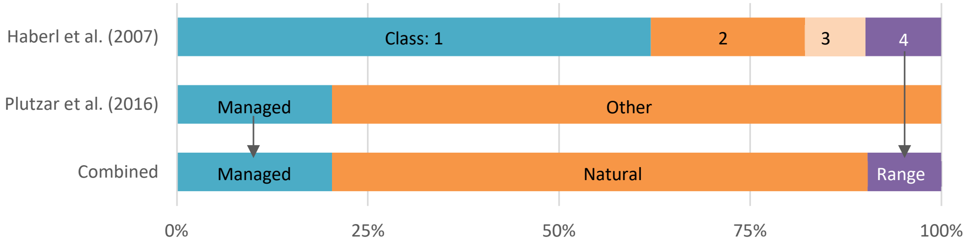


Figure A3 Distribution of available grass biomass over grazing classes (managed grassland, natural grassland, and rangeland) based on the classifications of Haberl et al. (2007) (quality class 1 to 4) and Plutzar et al. (2016) (managed grassland and other grassland)

The amount of biomass available of each vegetation type (managed grassland, natural grassland, rangeland) in each EU country, was calculated using an additional layer of the Plutzar et al. (2016) maps considering the spatially explicit actual above ground net primary production (aNPPact). This aNPPact is an indicator of the actual annual amount of carbon (kg) produced per hectare in above ground biomass. The amount of grazable aNPPact of each vegetation type (i) in each country (j) was calculated with the following equation:

$$aNPPact_{ij} = \sum^{k} grassland_{ijk} \times aNPPact_{jk} \times grazable\ fraction_{i}$$

Where *grassland* is the amount of grassland (ha) of each vegetation type (*i*) in each pixel (*k*) of each country (*j*) and $aNPP_{jk}$ was the above ground net primary production of carbon in each pixel (*k*) of each country (*j*). The *grazable fraction* of the *aNPPact* in each vegetation type (*i*) – the proportion of the annually produced above ground carbon available for grazing – was adapted from (Haberl et al., 2007) (Table A3) This grazable fraction was estimated based on the herbaceous fraction of the produced biomass (woody vegetation was assumed ungrazable), vegetation height, (biomass more than 1.2 m above the ground was assumed inaccessible) and seasonality. To convert the resulting grazable *aNPPact* (kg carbon/grazing class/country) into grazable biomass (kg DM/vegetation type/country) – displayed in Figure A4 – a factor 2 was used (IPPC). This availability of grazing resources was summed for the EU in Figure A2.

While the nutrient content and digestibility of grass resources of intensively managed grasslands is well studied, estimating the nutritional value of grass resources of natural grassland and rangeland is more difficult. Natural grasslands, for example, contain multiple species, that differ morphologically and in maturity stage at any given point (Bruinenberg et al., 2002). Generally, resources form natural grassland have a lower nutrient content than resources from intensively managed grasslands (Bruinenberg et al., 2003). Not only do many species in natural grassland, chemically have a lower protein and energy content also their digestibility is lower (Tallowin & Jefferson, 1999), due to the different genetic make-up, and higher maturity which increases their content in lignified cell wall material (Bruinenberg et al., 2002). Higher maturity is caused by variation in maturity between species and a late harvest to maintain the nature value of the grassland (Korevaar, 1986).

Table A4 The range nutritional value of the different vegetation types

	Grazable	Nutrient content /kg DM[2]					
Grazing class	%aNPP[1]	VEM	VEVI	DVE (g)	OEB	SV	SU
Managed grassland	75%	830-1006	880-1062	60-95	60-90	1.5-2.2	0.89-0.9
Natural grassland	60%	550-750	450-730	30-40	20-45	2.3-3.5	1.25-1.45
Shrub land	40%	490-735	400-720	15-30	4-34	3-3.4	1.4-1.6

[1] based on Haberl et al. (2007).

[2] based on literature (Astigarraga et al., 2009; Bruinenberg et al., 2002; Bruinenberg et al., 2003; Bruinenberg et al., 2004; Daccord et al., 2007; Deprez et al., 2007; Hayes et al., 2016; Korevaar, 1986; Mancilla-Leytón et al., 2012; Paton et al., 1999; Rogosic et al., 2006; Schippers, 2012; Schneider et al., 2009; Tallowin & Jefferson, 1999).

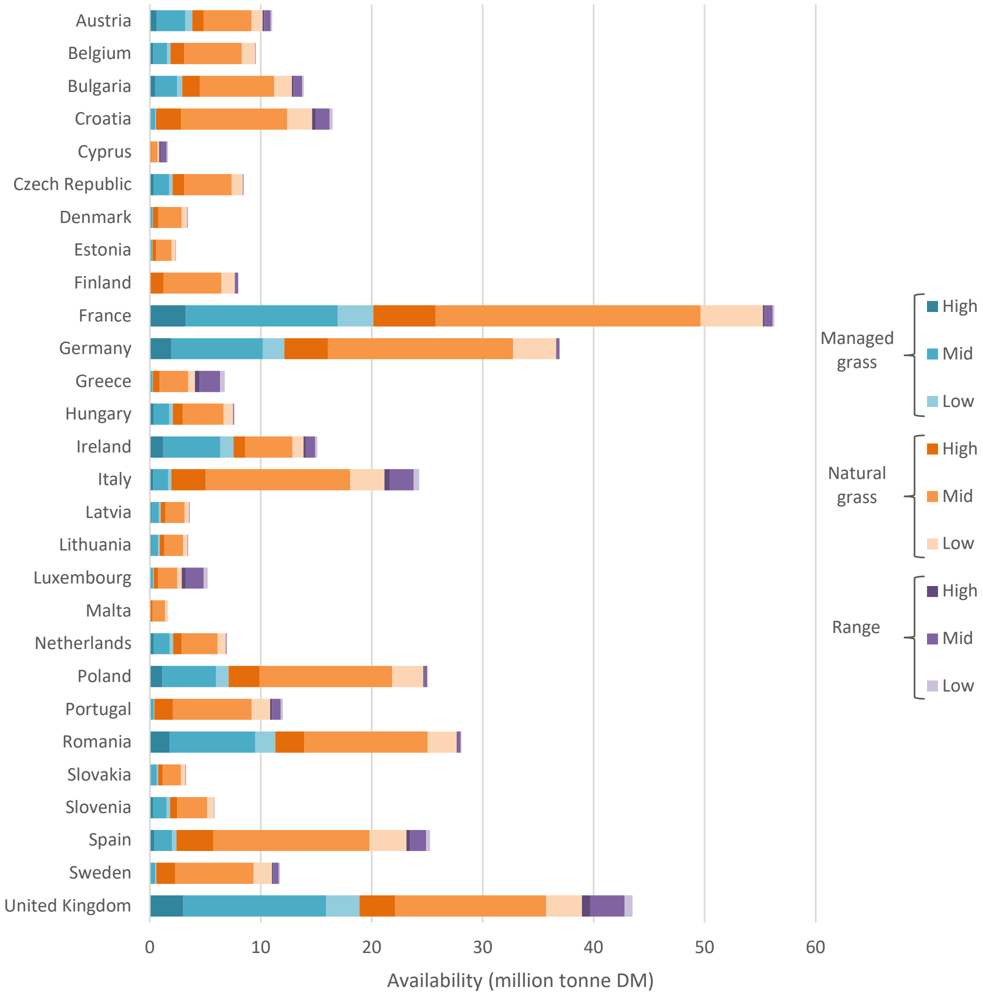


Figure A4 Available biomass (million tonne DM) in each grazing class (managed grassland, natural grassland, and rangeland) under each grazing quality (high, mid, low) in each EU 28 country, including feeding losses.

Data on the nutrient content and digestibility of each vegetation type (managed grassland, natural grassland and rangeland) were collected from literature and converted to the units of the CVB system using the following formulas:

- Energy content in kJ metabolisable energy (ME) was converted into feed units milk (FUM) assuming: FUM = (0.0003392 x q + 0.0654656) x ME. Where q, the percentage of ME that is utilised as net energy (NE) ranging from 60 to 40 depending on the quality of the feed, 40 being poor rangelands (CVB, 2016a).
- Energy content in kJ ME was converted into feed units beef (FUB) assuming: FUB=ME * 0.08054 for low quality, and ME * 0.09728 for high quality grazing (CVB, 2016a).
- Crude protein (CP) was first converted into digestible protein (DP) using the protein digestibility percentages provided in each study. This DP was, thereafter, converted into intestinal digestible protein (IDP), based on the IDP:DP ration (73:130) grass provided by (Tamminga, 2007).
- The rumen degraded protein balance (RDPB), structure value (SV) and satiety units (SU) were estimated from comparable products in CVB 2016. For managed grasslands this were various types of grass, for natural grassland this was late harvested grass, and fresh lucerne of various qualities, and for shrub land this was pea green, fresh lucerne, and pea straw (CVB, 2012).

Table A5 Nutritional values of each grass quality class (low, mid and high) for each vegetation type

	Grass	Nutrient content /kg DM					
Vegetation type	Quality	FUM	FUB	IDP (g)	RDPB	SV	SU
Managed grassland	Low	830	880	60	60	2.2	0.9
	Mid	918	971	77.5	75	1.85	0.895
	High	1006	1062	95	90	1.5	0.89
Natural grassland	Low	550	450	30	20	3.5	1.45
	Mid	650	590	35	32.5	2.9	1.325
	High	750	730	40	45	2.3	1.2
Rangeland	Low	490	400	15	0	4.3	1.66
	Mid	612.5	560	22.5	17	3.65	1.53
	High	735	720	30	34	3	1.4

For each vegetation type, these data resulted in a range nutrient content (Table A4), where a high nutritional value (high energy and protein content) was correlated to low structure value and saturation value. Based on this correlation, the range of nutritional values was converted into three grass quality classes for each vegetation type (high, mid, and low; Table A5). The biomass of each vegetation type was assumed the be normally distributed over the three grazing quality classes (16% low, 36% mid, and 16% high quality; Figures A5 & A2). For the sensitivity analysis, the biomass available of each vegetation type was alternatively assumed to be uniformly distributed over the grazing quality classes in each grazing class (33% of each high, mid, and low grass quality, Figure A5).

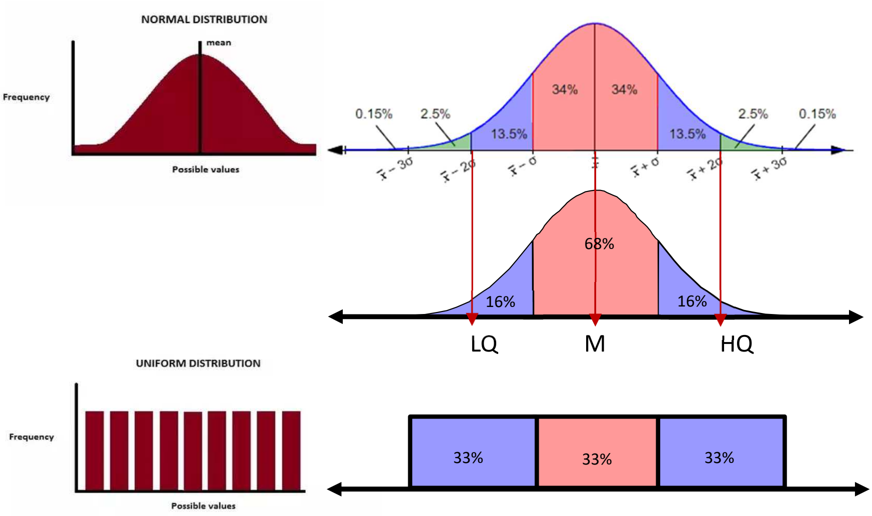


Figure A5 Normal distribution vs uniform distribution of nutrient content over the available biomass

A3 – Livestock herd composition

The herd composition (i.e. the number of non-producing animals relative to a producing animal; Table A6) was calculated from the European herd composition (FAO, 2016a, 2016c); missing data on pig litter size and dairy calving interval were based on Dutch averages (AgroVision, 2016; CRV, 2017), serving as a proxy for conventional high productive livestock (Bos et al., 2013). Note that, due to death and selection, additional producing animals are needed to achieve the production of one producing animal.

Table A6 The number of non-producing animals relative to producer animals in each livestock system.

Animal type	Herd component	Occurence
Pig	Fattening pig	1.04
	Sows	0.04
	Boars	0.00
	Piglets	1.20
	Gilts	0.02
Laying hen	Laying hen	1.08
	Laying cock	0.10
	Breeder hen	0.01
	Breeder cock	0.00
	Layer replacement chick	1.03
	Breeder repl. chick	0.01
Broiler	Broiler	1.04
	Breeder hen	0.03
	Breeder cock	0.00
	Repl.chicks	0.01
Dairy	Dairy cow	1.45
	Dairy bull	0.01
	Repl.calf	0.51
	Repl. heifer	0.47
	Veal calf	0.57
Beef	Beef cow	1.03
	Breeder cow	1.28
	Breeder bull	0.05
	Breeder repl. calf	0.27
	Breeder repl. heifer	0.25

A4 – Livestock nutrient requirements and product output

Nutrient requirements for each livestock system were derived from the CVB system of the Dutch animal feed board (CVB, 2012; van Vliet et al., 1994). Below we describe in detail the product output and nutrient requirements of both non-producing animals (e.g. young stock and/or parent stock) and producing animals of the five considered livestock systems; pig, laying hen, broiler, dairy cattle, beef cattle. Energy requirements are expressed in MJ net energy (NE) for pigs, MJ apparent metabolisable energy (AME) for poultry, feed unit milk (FUM) for dairy cattle, and feed unit beef (FUB) for beef cattle. For monogastric, protein requirements were expressed in g digestible lysine (DLys) and methionine (DMet) for pigs based on ileal digestibility and for poultry based on faecal digestibility. For ruminants protein requirements were expressed in intestinal digestible protein (IDP) and rumen degraded protein balance (RDPB) for cattle. The RDPB is a measure of digestible protein available in the intestine by estimating microbial protein production in the rumen, based on the energy to protein ratio of the ingredient. Additionally, rations of ruminants should meet a minimum structure value (SV), to ensure rumen functioning. Maximum feed intake capacity (FIC) was expressed in kg fresh matter for monogastrics and in satiety units (SU), which considers saturation effects of each ingredient, for ruminants (CVB, 2012).

Non-producing animals

For non-producing animals, both nutrient requirements and product output were based on conventional production systems (Dutch average used as proxy). Besides the CVB system, additional data was used for the nutritional requirements and feed intake capacity of all beef herd components (Hubrecht et al., 2013), veal calves (Vermeij, 2012), and young laying and breeder hens (NRC, 1984). Resulting nutrient requirements are displayed in Table A7. Animal source food output was estimated using meat fractions of sows and gilts (AgroVision, 2016), dairy cows and beef breeding cows (Nour et al., 1983a, 1983b), and breeding hens for broilers and laying hens (Loetscher et al., 2015; M. Haslinger, 2007).

Producing animals

For producing animals of each livestock system we included the productivity levels (high, mid, low). Below we describe, in detail, the assumed performance for each livestock system under each productivity level and the methods and assumptions used to determine their nutrient requirement. As proposed methods by the CVB system differ among livestock systems, each livestock system required a tailored approach. The nutrient requirement are expressed in the units of the CVB system, of which an overview is provided in Table 1 of the main article.

Pig

Variation in pig productivity was achieved by assuming different growth curves for a growth from 25 to 115 kg live weight (LW) resulting in variation in average daily gain (ADG) and duration of the growth period. The input-output relation of the high productive pigs was based on the performance and related nutrient requirement of high performance fattening pigs in the Netherlands (CVB, 2012). A high-productive pig grows from 25 to 115 kg LW in 118 days, resulting in 3.02 rounds of pigs per year and an ADG of 759 g/day (Table 1, main article). Achieving this growth required an average daily intake of 2.11 kg of a standard feed, containing 9.5 MJ NE and 6.7 g Dlys and 4.1 g Dmeth per kg (CVB, 2012), resulting in the daily nutrient intake displayed in Table 1 of the main article. Over the entire growth period, a pig then consumes 2240 MJ NE, 1705 g DLys and 1045 g DMeth.

Table A7 Period length, daily feed intake capacity (FIC), daily nutrient requirements, and required structure value of the diet of non-production animals of different animal types (a.-d.), expressed in the nutritional values of the CVB system

		Average daily requirement/capacity					
	Period	FIC	Energy	Protein		Milk	Structure
a. Pig	(d)	(kg)	NE (MJ)	Dlys (g)	Dmet (g)		
Sow	365	7.70	28.17	16.68	9.60		
Boar	365	8.00	28.16	14.72	9.27		
Piglet	70	0.57	4.08	4.22	2.53		
Gilt	133	3.52	14.87	13.35	6.67		
b. Poultry	(d)	(kg)	AME (MJ)	DLys (g)	DMet (g)		
Breeder	365	0.15	1.37	0.70	0.35		
Cock	365	0.15	0.83	0.42	0.21		
Juvenile	119	0.06	0.53	0.34	0.17		
c. Dairy cattle	(d)	(SU)	FUM	GDP (g)	UPB	(g FM)	(SV/kg DM)
Bull	365	21.8	6300	225	-65.00		1.00
Veal calf	178	4.1	3493	290	-3.46	2.25	1.48
Repl. calf	365	7.0	4094	244	-3.37	0.56	1.48
Repl. heifer	365	13.0	7094	380	-47.51		1.30
d. Beef cattle	(d)	(SU)	FUM	GDP (g)	UPB	(g FM)	(SV/kg DM)
Breeder cow	365	13.4	8666	483	-23		0.65
Bull	365	21.8	5850	150	-100		0.60
Repl. calf	365	1.4	1235	94	-6	x[a]	1.48
Repl. heifer	365	7.6	7395	506	-55		1.30

[a] Beef calf suckles for 9 months, nutrient requirements in this period are included with the dam.

Growth curves of mid and low productive pigs were simulated using InraPorc (van Milgen et al., 2008), a pig growth simulation model representing the methods used by CVB (CVB, 2012). Reduced growth was simulated by maintaining (high productive) pig characteristics while reducing the feed energy content, assuming a maximum average feed intake of 3 kg Under this maximum feed intake, the nutrient requirements of the high productive pigs could be met when feeding a ration with an energy content down to 6.7 MJ NE/kg. Mid productive pigs were simulated providing a diet containing 6.16 MJ NE/kg, which resulted in an ADG of 710 grams (6% lower than the high productive pigs). This extended the growth period to 126 days resulting in 2.83 rounds of pigs grown per year. The low productive pigs were simulated providing a diet containing 5.72 MJ NE/kg, had an ADG of 690 g (12% reduction), resulting in a 134 day growth period and 2.65 rounds of pigs per year. Performance as well as average daily nutrient requirements of all productivity levels are provided in Table 1 of the main article.

The average daily FIC of 3 kg (Lee et al., 2002; Quiniou & Noblet, 2012) was assumed to remain equal for each productivity level as was the death rate of 3.9 % (FAO, 2016c) during the entire growth period. This death rate implies a loss of 0.04 producing pig per slaughtered producing pig, assumed to occur evenly throughout the growth period. Carcass yield was based on InraPorc and varied between productivity levels (high: 77%, mid: 76%, low, 74%).

Laying hens

Variation in laying hen productivity was achieved by assuming different laying percentages (% of days eggs are laid) during the 56 week laying period. The egg weight was kept constant at 60 g per egg, being the average commercial egg weight over the laying period (Bozkurt et al., 2012). The laying percentage of the high-productive hen was set at 85%, closest to the Dutch average laying percentage of 85.7% (LEI, 2017). Hens with this laying percentage require a total input of 541 MJ NE, 294 g DLys and 143 g DMeth over the entire laying period (CVB, 2012). The laying percentage was reduced to 75% for mid-productive hens and 60% for low-productive hens as these were the levels provided by (CVB, 2012). Average daily nutrient requirements of all productivity levels are provided in Table 1 of the main article. The average daily FIC of 150 g (Forbes, 2007; Morris, 1968) was assumed to remain equal for each productivity level as was the death rate of 7 % (FAO, 2016c), during the entire laying period. This death rate implies a loss of 0.08 laying hen per producing laying hen, assumed to occur evenly throughout the laying period. Considering this death rate and the 56 week laying period, implying 0.93 production rounds per year.

Broilers

Variation in broiler productivity was based on the average performance of fast and slow growing broilers in the Netherlands, provided by (CVB, 2016b). The input-output relation of the high productive broilers was based on the performance and related nutrient requirement of fast growing broilers in the Netherlands. They grow to 2.26 kg LW in 40 days, resulting in 9.1 rounds of broilers per year and an ADG of 56 g. To achieve this growth, a broiler needs 47.4 MJ NE, 36.7 g DLys and 14.3 g DMeth over the entire growth period. The low-productive broilers were based on slow growing broilers, which grow to 2.50 kg LW in 56 days, resulting in 6.5 rounds per year and a ADG of 42 g. They require an intake of 62.8 MJ NE, 48.7 g DLys and 19.0 g DMeth over the entire growth period. The mid-productive broiler was the average of these two, growing to 23.3 kg LW in 49 days, resulting in 7.6 rounds per year and an ADG of 49 g. They require an intake of 55.1 MJ CE, 42.7 g DLys and 16.6 g DMeth over the entire growth period. Average daily nutrient requirements of all productivity levels are provided in Table 1 of the main article. The average daily FIC of 114 g (Leeson et al., 1996) was assumed to remain equal for each productivity level as was the death rate of 4.3 % (FAO, 2016c), during the entire growth period. This death rate implies a loss of 0.05 broilers per slaughtered broiler, assumed to occur evenly throughout the growth period.

Dairy

Variation in productivity of dairy cows was achieved by assuming different annual milk yields. For high productive cattle, the average Dutch milk production, between 2012 and 2016, amounting 8860 kg fat and protein corrected milk (FPCM) per cow per year (CRV, 2017) served as a proxy. For low productive dairy cattle the average milk yield of extensively farmed Irish dairy cattle of 4750 kg FPCM was assumed. Productivity of mid productive dairy cattle was assumed 6800 kg, exactly between high and low productivity. Productivity related nutrient requirement were calculated using the following formulas (CVB, 2012):

$$FUM = (42.4\ \times BW^{0.75} + 442 \times FPCM) \times (1 + (FPCM - 15) \times 0.00165)$$

and

$$IDP(g/day) = ((2.75 * BW^{0.5} + 0.2\ \times BW^{0.6})/0.67) + (1.396 \times P + 0.000195 \times P^{2})$$

where FUM = energy requirement in feed unit milk, BW = body weight (593 kg), FPCM = fat and protein corrected milk, IDP = intestinal digestible protein requirement (g/day) and P = milk protein production (g/day). Resulting average daily nutrient requirements of all productivity levels are provided in Table 1 of the main article.

For the milk output, the milk needed to feed the replacement and veal calves, 320 kg, was subtracted from the average annual production resulting in an annual output of 8644 kg FPCM for high productive cows, 6589 kg FPCM for mid productive cows and 4534 kg FPCM for low productive cows. A SV of at least 0.99 should be achieved for high productive, 0.95 for mid productive, and 0.90 for low productive dairy cows (CVB, 2012). This required SV is calculated by deviating from 1 by subtracting 0.01 for every kg that the daily produced FPCM is below 25 kg and subtracting 0.05 for every percentage that the milk fat percentage is below 4.4% (CVB, 2012). The daily FIC of 14.5 saturation units (SU) (CVB, 2012) was assumed to remain equal for each productivity level as was the annual death rate of 4 % and selection rate 31 % (FAO, 2016c). This selection and death rate combined imply a loss of 0.45 dairy cows per milked dairy cow, assumed to occur evenly throughout the year.

Beef

Variation in productivity of beef cattle was achieved by assuming different growth curves for a growth from 250 to 650 kg LW. The first 9 months the calf remains, suckling, with the dam to which the nutrient requirement during this period is assigned. Productivity of productive beef cattle was based on the optimal growth curve of late ripe beef cattle growing from 250 to 650 kg live weight in a period of 328 days resulting in 1.11 rounds of beef per year and an ADG of 1217 g (CVB, 2012; van Vliet et al., 1994). For low productive beef cattle the ADG of grass fed beef in the Charolaise region in France of 930 g was assumed, requiring a 431 day growth period resulting in 0.85 rounds per year. Productivity of the mid productive beef cattle was the average of high and low productivity (ADG 1070 g; 375 day growth period; 0.97 rounds per year). Productivity related nutrient requirement were calculated using the following formulas (CVB, 2012):

$$FUB = (368.4 \times BW^{0.75}) + (22.94 \times \mathrm{PD} + 39.31 \times \mathrm{FD})$$

and

$$IDP(g/day) = ((2.75 * BW^{0.5} + 0.2 \times BW^{0.6})/0.67) + (\mathrm{PD}/\mathrm{Ke})$$

where FUB = energy requirement in feed unit beef, BW = body weight (varying through growth), PD and DF represent growth dependant protein/fat deposition, provided by (van Vliet et al., 1994), IDP = intestinal digestible protein requirement (g/day) and Ke = growth dependant protein efficiency provided by (van Vliet et al., 1994). As nutrient requirements vary throughout the growth period, they are calculated for each 50 kg growth stage. Resulting average daily nutrient requirements of all productivity levels are provided in Table 1 of the main article. The daily FIC of 10.7 SU (van Vliet et al., 1994), the minimum SV of the diet of 0.75 and the death rate during the growing period of 3% (FAO, 2016c) were assumed to remain equal for each productivity. This death rate implies a loss of 0.03 beef cows per slaughtered beef cow, assumed to occur evenly throughout the growth period.

A5 - Nutrient content of livestock products

The output of ASF available for human consumption, for each livestock system and productivity, is expressed in human digestible protein (HDP) and essential micronutrients (vitamin -D, -B12, calcium, iron, zinc, and selenium) per kg product (milk, meat, and eggs). Calculating the nutrient output requires data on the nutrient content per kg of the different animal products, which were collected the USDA database (USDA, 2018a). While for milk and eggs the available data could be used directly, for meat these nutrient contents are generally specified for the different cuts while we require an average of all cuts in the animal. Although previous studies have used estimations on the average protein content of the edible meat of various animal types, for other nutrients no data was available. Weighted average nutrient contents per kg of carcass weight, taking in account cutting (CBB & NCBA, 2014) and cooking losses (USDA, 2012) (see Figure A7), were, therefore, calculated from the USDA database (USDA, 2018a). The weighted average protein content per kg of broiler carcass calculated from the USDA database as described above was adjusted to account for the different meat protein content found under the different productivity levels in (Fanatico et al., 2005). For the pig (van Milgen et al., 2008) and beef (van Vliet et al., 1994) carcass a similar correction was made, based on protein deposition related to the growth curve. The protein content of each animal product after corrections, as used in the model is displayed in Figure A6.

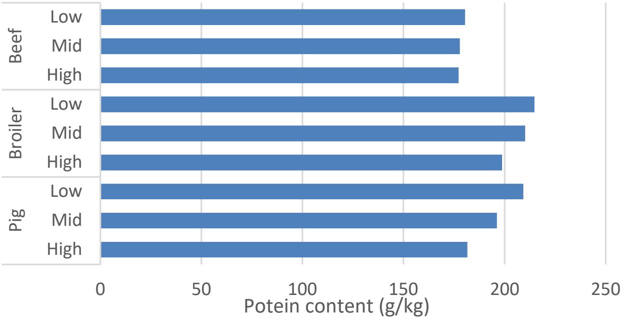


Figure A6 Human digestible protein content per kg of carcass weight for pigs, broilers, and beef cattle adjusted for predicted variation in protein deposition under varying productivity

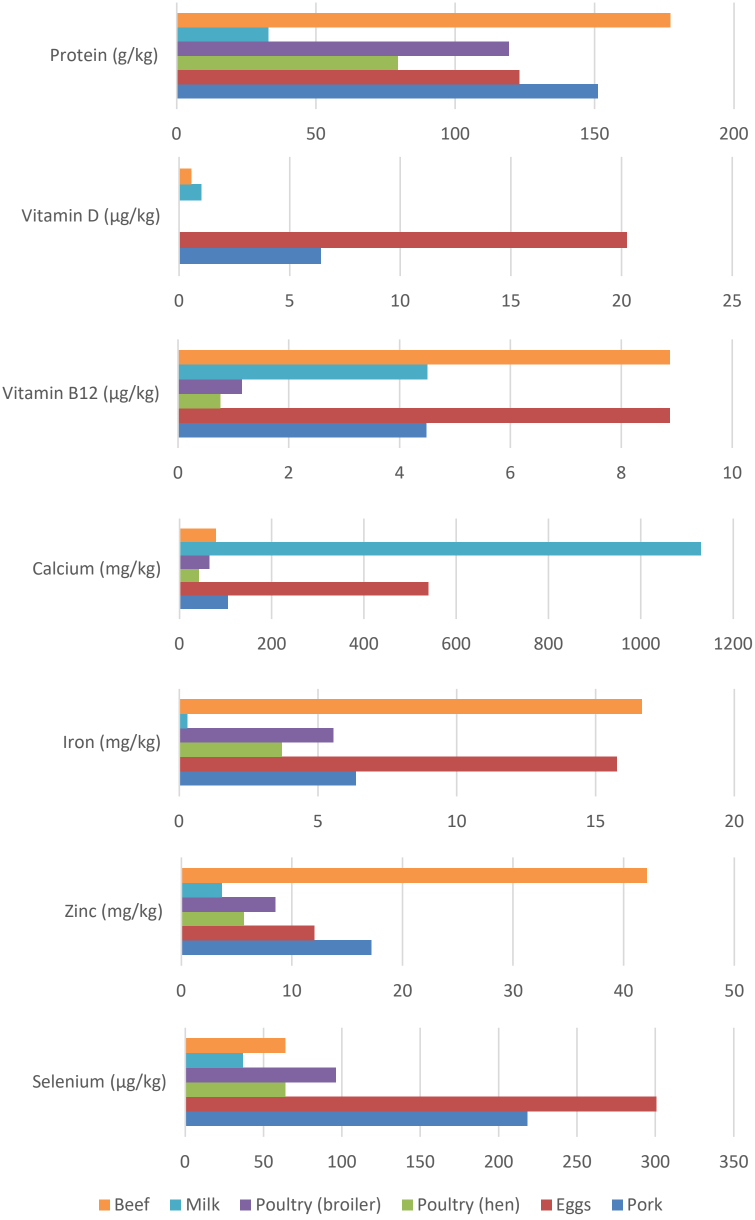


Figure A7 Human digestible nutrient content per kg of each animal product, for meat expressed per kg carcass weight accounting for cutting and cooking losses adapted from (USDA, 2012, 2018a).

Appendix A6 - Additional results chapter 2

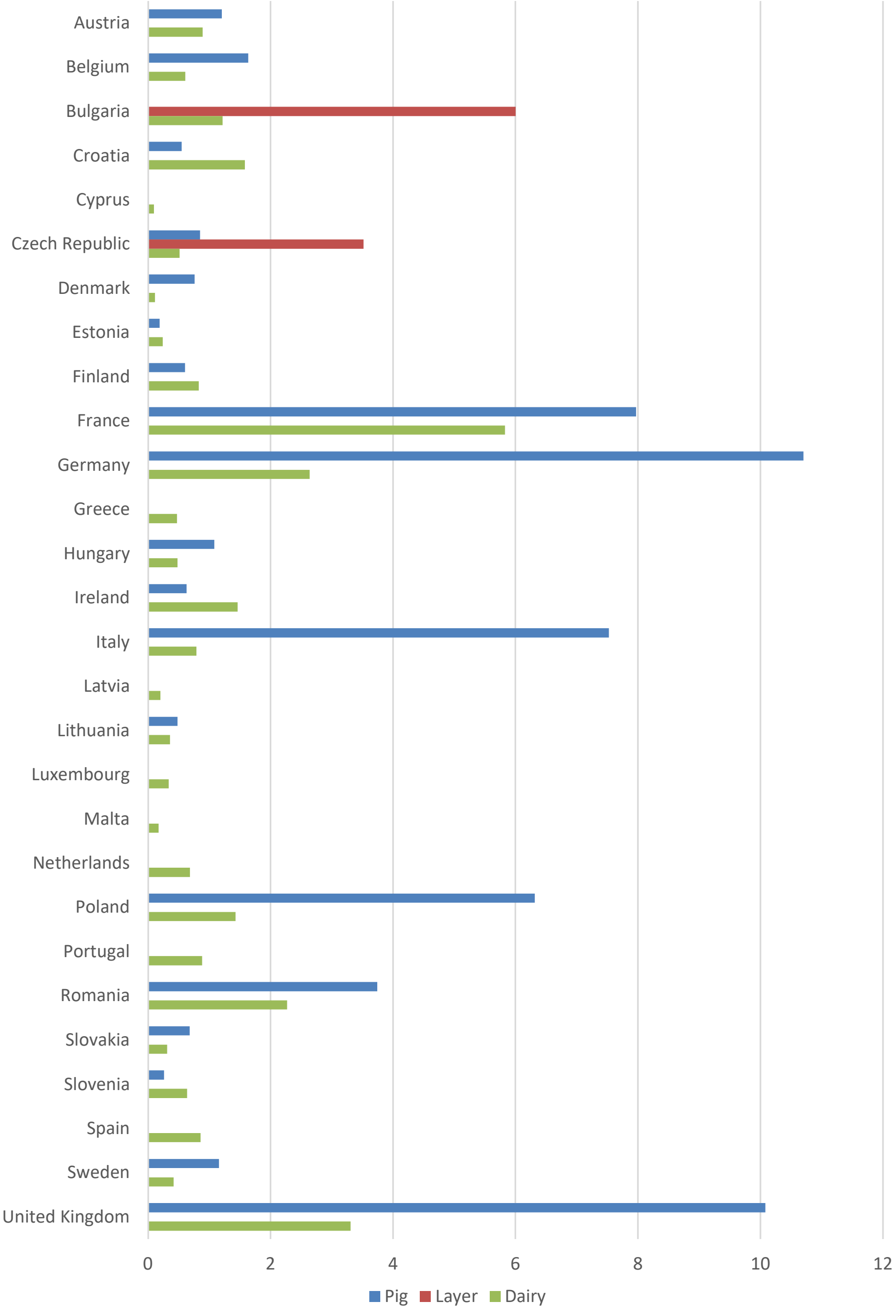


Figure A8 Number of producing animals of each livestock system x10^6 (pig, laying hen, dairy cattle) in each EU 28 country under optimal conversion of available low-opportunity-cost feed (LCF)

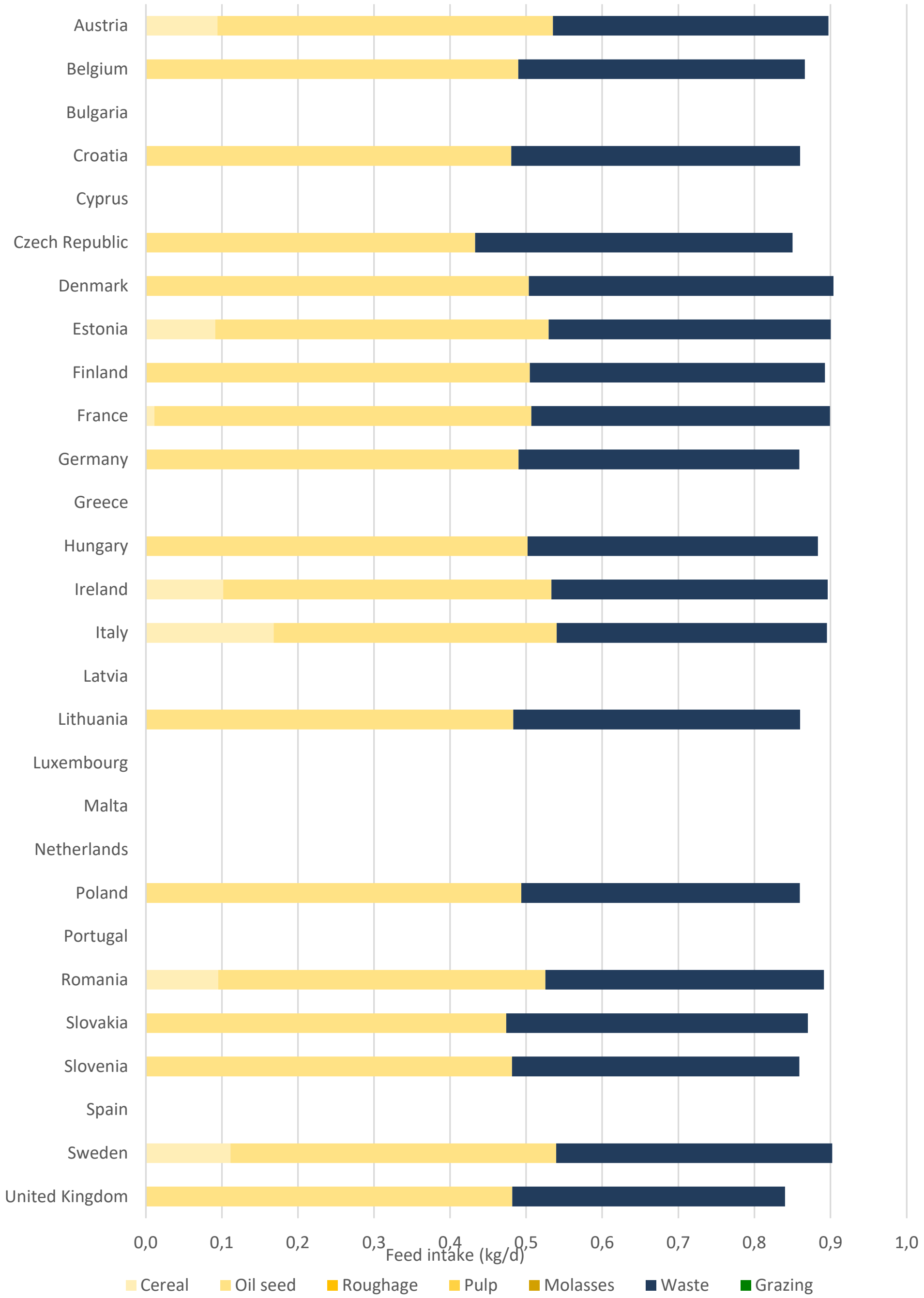


Figure A9 Proposed daily feed intake for pigs under the optimal use of low-opportunity-cost feed (LCF) for each country; expressed per production animal per day including related requirement of non-producing animals.

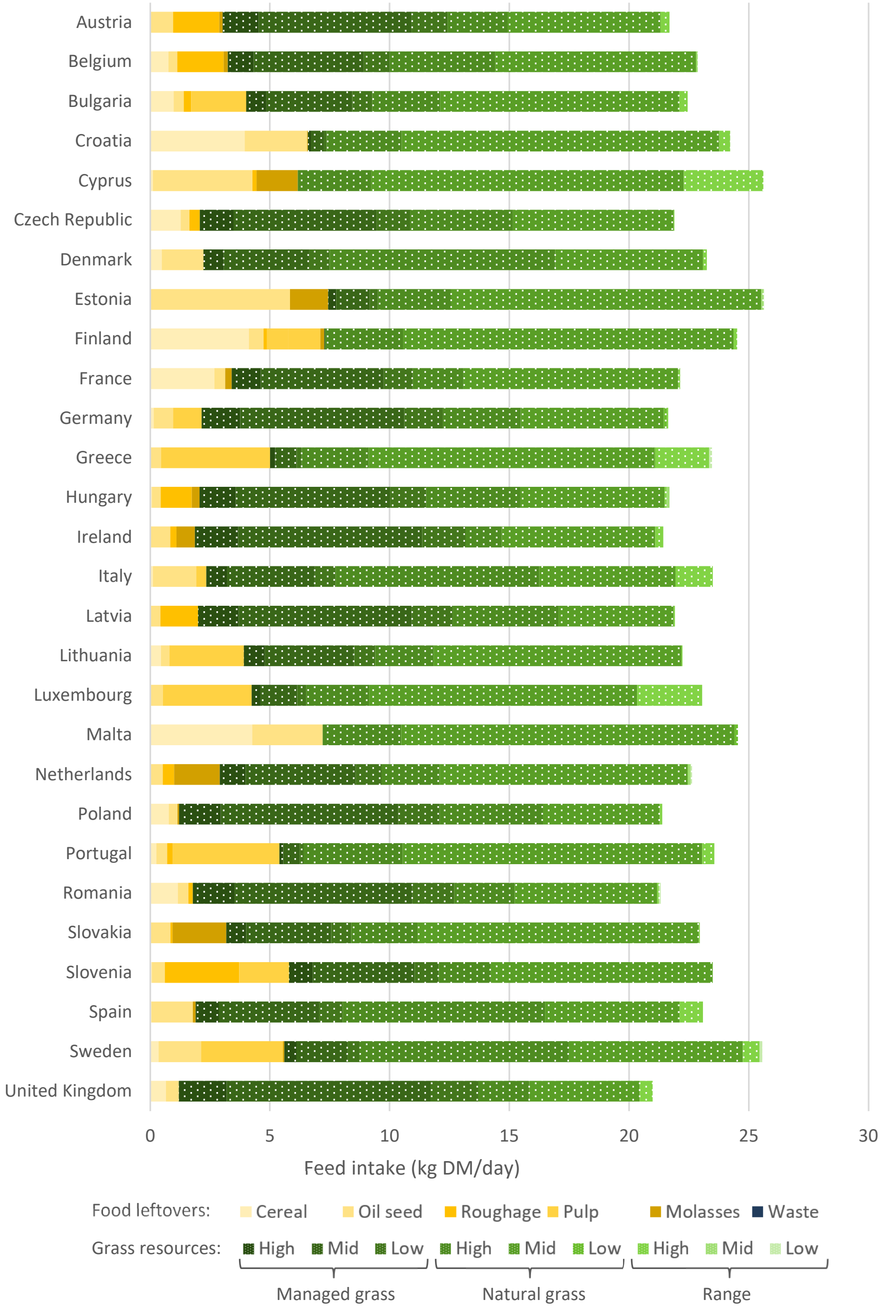


Figure A10 Proposed daily feed intake for dairy cattle under the optimal use of non-food-competing feed (LCF) for each country; expressed per production animal per day including related requirement of non-producing animals.

Appendix B

B1 - Fisheries assumptions

For simplicity, we focused on the limited fisheries species that currently provide the majority of landed biomass. To this end, we collected landings data for the 122 stocks of 24 species (ICES, 2018) that provided 90% of the 2016 landings in the Northeast Atlantic (7.1 of 8.4 Mtonne). Five of these species (blue mussels, chub mackerel, scallop, edible crab, Greenland halibut; 4,7% of total catches) were excluded because they did not have an ICES advice and could thus not be translated to MSY. Three additional species (beaked redfish, Atlantic redfishes and capelin; 2.5 % of total catches) were excluded as their ICES advise did not match geographically with fishing quota distributions.

Table B1 Current and sustainable fisheries landings (tonne) in the north east Atlantic by EU-28 of the 16 selected species and their current and sustainable fractional allocation to human consumption (Fish use).

		Fisheries landings			**Fish use**	
			Sustainable			
Fish species[1]		Current	MSY[2]	MSY0.8[3]	Current[4]	Sustainable[5]
Atlantic cod	*Gadus morhua*	130089	119517	213083	1	1
Atlantic herring	*Clupea harengus*	839837	487715	870792	0.74	1
Atlantic horse mackerel	*Trachurus trachurus*	75103	187150	299184	0.86	1
Atlantic mackerel	*Scomber scombrus*	456879	356308	323380	0.63	1
Blue whiting	*Micromesistius poutassou*	222434	131935	236988	0	1
European hake	*Merluccius merluccius*	108175	111181	95482	1	1
European plaice	*Pleuronectes platessa*	98349	215121	201089	1	1
European pilchard	*Sardina pilchardus*	73062	83721	155891	0.98	1
European sprat	*Sprattus sprattus*	444022	320817	567749	0.35	1
Haddock	*Melanogrammus aeglefinus*	85325	56115	110590	1	1
Ling	*Molva molva*	10740	11261	15589	1	1
Norway pout	*Trisopterus esmarkii*	23573	191812	96245	0	0
Norway lobster	*Nephrops norvegicus*	49583	35642	66528	1	1
Northern prawn	*Pandalus borealis*	13356	18163	13625	1	1
Pollock	*Pollachius virens*	34379	43513	72732	1	1
Sandeels	*Ammodytes sp.*	32463	106038	284911	0	0

1 Considering the most exploited species in 2016 (ICES, 2018)
2 MSY based on ICES advise (ICES, 2016)
3 Long term (2030) MSY with reduced fishing mortality (0.8) (Froese et al., 2018)
4 Fraction of landings of which edible yield is used for food; current post landing utilisation (EUROSTAT, 2016)
5 For all prime/food grade species (Cashion et al., 2017) the edible yield of full landings are allocated to food

The 16 species with 100 stocks finally included represented 6,8 Mt (or 81%) of catches Northeast Atlantic landings in 2016; 2.2 Mt of this volume were EU landings. These 2.2 Mt landed fish, here representing current EU landings, constitute 75% of total EU landings (EUROSTAT, 2019). Besides excluded species and stocks in the Northeast Atlantic, the other 25% of EU landings originates from stocks in the Mediterranean and Black Seas, fished under third-country agreements. Inclusion of these stocks, especially under MSY, is less relevant as many of these stocks is severely impaired (Froese et al., 2018). While the current landings assumed here are based directly on above described data, maximum sustainable yield (MSY), for the same stocks and species were obtained from (ICES, 2016) for the short term MSY and (Froese et al., 2018) for the long term MSY.

B2 - Availability of low-opportunity-cost feeds

The LCF that are input to the model consider human inedible products associated to primary use of spatial resources and include crop processing by-products, animal processing by-products, plant-based manufacturing wastes and grass resources. The availability of crop processing by-products and grass resources was adopted from Hal et al. (2019) and are described in detail in Appendix A2. For grass resources, the availability of managed grass was corrected to a total of 89 Mt based as suggested by the authors of the underlying research Haberl et al. (2007) and Plutzar et al. (2016). The range of nutrient content of grass resources of each vegetation type, obtained from literature was assumed to be normally distributed over the available grass biomass. Below we describe the assumed availability of plant based manufacturing wastes and the data used to calculate available by-products related to processing yields of sustainable fisheries as well as animal by-products related to upcycling available LCF.

Manufacturing waste: former food stuff

To follow EU legislation (EU, 2017, 2018) only plant based former foodstuffs (FFS) –products intended for human consumption wasted during food manufacturing – were included as LCF. As studies on feeding food waste to animals focus on the potential of relegalising currently banned food waste (zu Ermgassen et al., 2016), no scientific data on the availability of FFS is available. EUROSTAT data on biomass lost during food processing and manufacturing, are unsuitable as it includes food co-products and their product composition in unknown (EUROSTAT, 2018). The European Former Foodstuff Processors Association (EFFPA), whose members process 3.5 million tonnes of FFS annually, estimates that in the EU a total of 5 million tonnes of FFS are processed into feed annually (EFFPA, 2019). While EFFPA indicates the majority of these FFS are cereal based (>70%) the exact product composition of EU FFS remains unknown (EFFPA, 2019). We, therefore, assumed the product composition of FFS, excluding by-products, of the UK (UKFFPA, 2019), Netherlands (VIDO, 2019) and France (Vernier et al., 2016) combined (Figure B1) and applied this to the estimated 5 million tonnes of EU FFS. The resulting 4.2 million tonnes of cereal based FFS comes close Caldeira et al. (2019) estimation of 4.9 million ton cereal based products wasted during product manufacturing in the EU. Each of the former food products was assumed to be processed into common FFS based feed ingredients, resulting in the available feed ingredients displayed in Figure B2, classified based on their nutritional properties.

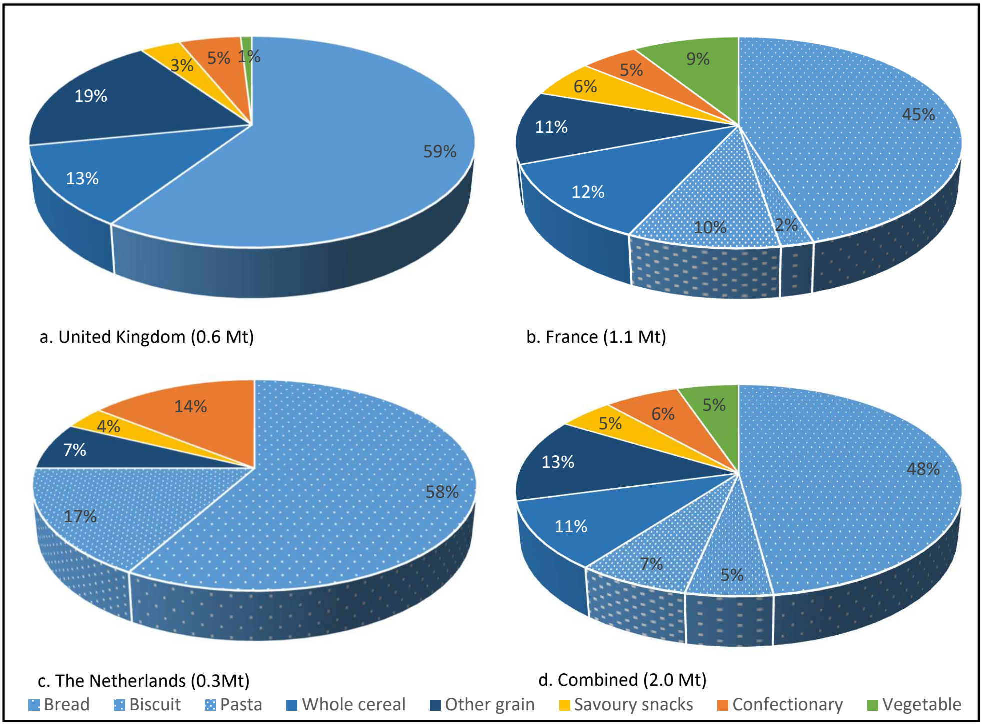
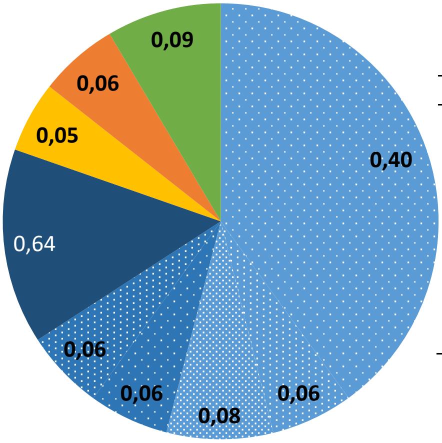


Figure B1 Combined (d) former foodstuff product composition based on that of the UK (UKFFPA, 2019), The Netherlands (VIDO, 2019) and France (Vernier et al., 2016) adapted to exclude animal based products and crop by-products.



Former foodstuff	Type	Classification
Bread meal	Fat enriched cereal	Enriched staple
Biscuit meal	Sugar enriched cereal	Enriched staple
Pasta meal	Cereal product	Cereal
Rice meal	Cereal product	Cereal
Mixed cereal	Cereal product	Cereal
Puffed rice	Cereal product	Cereal
Potato chips	Fat enriched potato	Enriched staple
Vegetable	Vegetables	Pulp
Molasses	Sugar syrup	Molasses

Figure B2 Available former food stuffs based ingredients (Mt) in the EU, assuming a total of 5 Mt (EFFPA, 2019) and the combined product composition in the UK, Netherlands and France (Figure B2) and their classification based on nutritional properties.

Animal by-products

Table B2 Edible yield fraction of fresh whole fish obtained from DanishFoodInstitute (2019), FAO (1989) and SwedishFoodAgency (2019); and oil and meal output from rendering fish and fish by-products in kg per kg input

	Slaughter yield	Render fraction		
Fish Species	fraction	Meal	Oil	Reference
Atlantic herring	0.52	0.20	0.04	(Cashion et al., 2016)
Atlantic Cod	0.35	0.17	0.02	(Cashion et al., 2016)
Blue whiting	0.46	0.20	0.02	(Cashion et al., 2016)
Atlantic mackerel	0.38	0.19	0.19	(Cashion et al., 2016)
European sprat	0.52	0.19	0.08	(Cashion et al., 2016)
Haddock	0.33	0.17	0.02	(Cashion et al., 2017)
Pollock (=Saithe)	0.39	0.17	0.02	(Cashion et al., 2017)
European plaice	0.33	0.17	0.02	(Cashion et al., 2017); Cod
European hake	0.42	0.17	0.02	(Cashion et al., 2017); Cod
Atlantic horse mackerel	0.54	0.19	0.19	(Cashion et al., 2017); Mackrel
Sandeels	0.00	0.20	0.04	(Cashion et al., 2017)
European pilchard	0.62	0.23	0.18	(Cashion et al., 2017)
Norway pout	0.00	0.20	0.12	(Cashion et al., 2016)
Norway lobster	0.42	0.16	0.00	(Cashion et al., 2016); Krill
Northern prawn	0.36	0.16	0.00	(Cashion et al., 2016); Krill
Ling	0.46	0.17	0.02	(Cashion et al., 2017); Cod
Atlantic Salmon	0.63	0.20	0.04	(Cashion et al., 2016); Herring
Nile Tilaptia	0.42	0.17	0.02	(Cashion et al., 2017); Cod

Table B3 Slaughter (and cutting) outputs for differnt livestock systems in kg per kg LW

Slaughter output	Pig[1]	Laying hen[2]	Broiler[2]	Dairy[1]	Beef[1]
Carcass	0.77[3]	0.61	0.72[4]	0.57	0.64
Meat, raw	0.64	0.38[5]	0.47[6]	0.47	0.53
Bone meal	0.12	0.22	0.23	0.09	0.10
Offals	0.08	0.07	0.05	0.06	0.05
Animal fat	0.04			0.13	0.11
Bloodmeal	0.01			0.01	0.01
Meat and bone meal	0.06	0.07	0.05	0.11	0.09
Feather meal		0.08	0.06		

1 Based on USDA slaughter reports (USDA, 2018b, 2018c)
2 Based on Damme & Ristic (2003), Haslinger et al. (2007) and Sams (2010; improved compared to van Hal et al. (2019)
3 Carcass output varied per productivity level as reported in van Hal et al. (2019)
4 Outputs of broiler breeder stock based on laying hens
5 Meat yield/kg carcass based on: Damme & Ristic (2003), Loetscher et al. (2015) and Zanders & Claessens (2018)
6 Meat yield/kg carcass based on: Denton & Mellor, (1990), Sams (2010) and USDA, (2018a)

Legislation on feeding of animal by-products

The strict EU regulations on feeding animal based products to food producing animals (Table B4) were implemented after the major BSE crisis to avoid transmission of diseases between animals, and specifically transmission of animal diseases to humans (EU, 2009). While, originally, these regulations banned feeding animal proteins to any food producing animals, a 2013 amendment has relegalised feeding these proteins (except from bovine origin) in aquaculture (EU, 2013a). With this relegalisation, aquaculture can upcycle human inedible outputs of fisheries, livestock production and even aquaculture itself, that livestock cannot consume. Proteins from bovine animals are, however, still banned as aquaculture feed. Additionally EU legislation forbids feeding farmed animals with proteins originating from farmed animals of the same species (EU, 2013a). Farmed salmon can, thus, not be fed with salmon meal originating from aquaculture. Salmon and tilapia in our model are, however, a proxy for multiple species with similar characteristics (e.g. rainbow trout, seabass and seabream for salmon) that are allowed to feed on each other's by-products. To reflect this we allow for intraspecies recycling of fish farming by-products, meaning we allow farmed salmon to eat salmon by-products, assuming salmon represents multiple species that could recycle each other's by-products.

Table B4 Allowance of animal by-products in feed of food producing animal species based on EU legislation (EU, 2009, 2013a).

Animal by-product	Pig	Poultry	Cattle	Fish
Meat&Bone meal	NO	NO	NO	YES[1]
Bone meal	NO	NO	NO	YES[1]
Blood meal	YES[1]	YES[1]	NO	YES[1]
Animal fat	YES	YES	YES	YES
Feather meal	YES[2]	YES[2]	NO	YES
Poultry by-product meal	NO	NO	NO	YES
Fish oil	YES	YES	YES	YES
Fish meal	YES	YES	NO	YES

[1] Allowed if not from bovine origin

[2] Allowed in EU but prohibited in many of its member states

B3 - Animal production systems

The animal production systems considered to upcycle available LCF, include the entire lifecycle of 5 livestock and 2 aquaculture species composed of food producing animals and associated parent and young stock. The livestock systems considering pig, laying hen, broiler, dairy, and beef production under 3 productivity levels, were adopted from van Hal et al. (2019); underlying assumptions, data and calculations are provided in Appendix A3 and A4. In contrast, aquaculture production systems were simulated specifically for this study and all underlying data is provided below.

Aquaculture production

We included carnivorous Atlantic Salmon, the most farmed fish in the EU, and omnivorous Nile Tilapia, the most consumed omnivore, considering the entire lifecycle (EUROSTAT, 2019; FAO, 2018b) comprised of food producing animals and associated non-food producing animals such as parent and young stock. For both species status quo performance for the entire lifecycle was based on optimal growth and related feed intake simulated with Skretting's AquaSim model, validated and adjusted based on literature.

Herd composition

The number of non-producing animals (e.g. alevin, fry, smolt and brood stock) needed to harvest one producing animal (e.g. Salmon grower) (Table B10) was based on species specific mortality and fertility data. Note that, due to death and selection, additional producing animals are needed to harvest of one producing animal. For Salmon, mortality in the early life phases was based on (McGeachy et al., 1995) and for growers on the average in Norway (EY, 2017). We assume salmon brood stock is selected from growers before slaughter, and to spawn only once (Sedgwick, 1982) after 32 days providing 9750 eggs (Eskelinen, 1989; FAO, 2018a), before being slaughtered at a slaughter weight of 6000 g. A male salmon brood stock was assumed to fertilise the eggs of 100 female brood stock (Cryogenetics, 2014). For tilapia, mortality throughout the production cycle is based on (Bhujel, 2014). We assumed Tilapia brood stock is selected as juveniles of 125 g to ensure optimal fertility. A brood stock set consists of one male and two females, where each female spawns 5000 eggs over a period of 9 months, before being slaughtered at 400 gram BW (TIL-AQUA, 2016).

Table B5 Occurence of each herd component relative to one harvested adult fish.

Animal type	Herd component	Occurrence
Salmon	Grower	1.19
	Male Brood stock	0.00
	Female Brood stock	0.00
	Alevin	2.15
	Fry	1.46
	Smolt	1.28
Tilapia	Grower	1.05
	Male Brood stock	0.00
	Female Brood stock	0.00
	Swim up fry	5.78
	Fry	1.73
	Fingerling	1.30
	Juvenile	1.17

Production performance

Atlantic Salmon

Optimal growth and feed intake during the lifecycle of the poikilothermic Atlantic Salmon was simulated assuming the sea water temperature curve of atlantic ocean surrounding the UK (SeaTemperatures, 2019), where the majority of the EU's salmon production is situated (EUROSTAT, 2019). The simulated optimal growth is in line with studies that assessed growth performance over (specific parts) of the growth cycle (Figure B5). The simulated fish, housed in sea cages, grow from 77 g to a slaughter weight of 5500 g in 490 days after a yearlong freshwater phase. The cumulative feed conversion ratio (FCR: kg feed needed per kg growth) over the life cycle of this simulation (1.16) is low compared to those observed in practice (1.2-1.5; (Fry et al., 2018; Tacon &

Metian, 2008). This is likely due to simulation models such as AquaSim assuming a healthy population while continuous health cannot be assured in practice, especially under the extensive exposition to external influences in sea cages (Føre et al., 2016). The simulated FI and growth in the sea water phase – where most handling and treatment occurs – were therefore adapted (both growing period and FI extended with 5%) to meet performance found in practice with a cumulative FCR of 1.22 and a 520 day long sea water phase (Main article; Table 2).

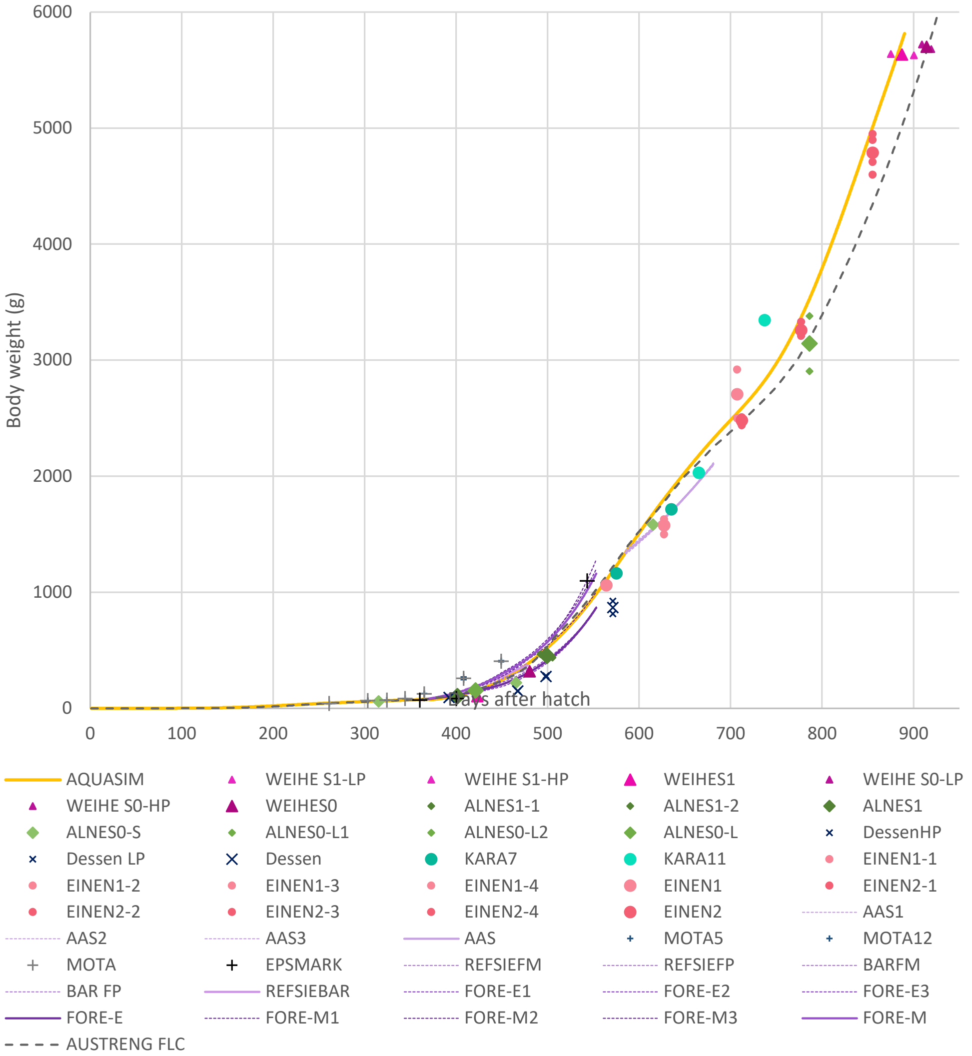


Figure B3 Optimal (temperature dependant) growth simulated with AquaSim compared to literature (Aas et al., 2015; Alne et al., 2011; Bar et al., 2007; Dessen et al., 2017; Einen & Roem, 1997; Espmark et al., 2017; Føre et al., 2016; Karalazos et al., 2011; Karalazos et al., 2007; Mota et al., 2019; Refstie et al., 2004; Weihe et al., 2018).

Nile Tilapia

For Nile Tilapia, optimal growth and feed intake during the entire lifecycle were simulated for a tank system with a constant water temperature of 28 degrees and controlled high oxygen levels and a slaughter weight of 750g as is typical of the European market (TIL-AQUA, 2016). The cumulative FCR of this simulated performance of 1.45 (Main article; Table 2) falls low in the range observed in practice (1.4-2.4; (Fry et al., 2018), that includes less efficient systems without oxygen level management. This FCR is attained by growing to a slaughter weight of 750 g in 200 days.

Nutrient requirements

Digestible energy (DE) and protein (DP) requirementto achieve the growth described above (Main article; Table 1), were calculated by multiplying the required feed intake with the DE and DP content of Skrettings' commercial feeds, tailored for each species and life phase. The nutrient content of these phase specific feeds is provided in Table S3.5.

Table B6 digestible energy and digestible protein content of the assumed common phase specific Skretting feeds

	Nutrient content	
	DE (MJ/kg)	DP (%)
Salmon		
Alevin	18.50	49.88
Fry	19.30	48.16
Fingerling	19.10	48.16
Parr	18.80	46.44
Smolt	18.40	41.28
Post-smolt	20.50	36.55
Grower	21.30	32.68
Brood	17.60	41.28
Tilapia		
Swim up fry	15.50	48.00
Fry	15.00	44.00
Fingerling	14.50	40.00
Juvenile	12.20	35.00
Grower (60-200g)	12.00	32.00
Grower (200+ g)	11.60	30.00
Broodstock	12.00	32.00

Protein digestibility (PD%)

Table B7 Protein digestibility of Tilapia and Salmon (and comparable carnivorous fish) obtained from literature used to overwrite IAFFD values where possible

	Tilapia										
Feed ingredient	1	2	3	4	5	6	7	8	9	10	**used**
Spring wheat						0.96					**0.96**
Wheat flour											**0.96**
Wheat middlings			0.84			0.84					**0.84**
Wheat bran						0.85					**0.85**
Wheat germ						0.94					**0.94**
Corn			0.93				0.93				**0.93**
Corn germ							0.89				**0.89**
Corn germ meal	0.89	0.91					0.97		0.83		**0.90**
Broken rice			0.83								**0.83**
Rice bran			0.87							0.84	**0.86**
Sorghum			0.77								**0.77**
Dried distillers grains										0.89	**0.89**
Pea				0.86	0.96						**0.91**
Chickpea					0.98						**0.98**
Faba bean					0.98						**0.98**
Soybean meal	0.87	0.92		0.91				0.97	0.87	0.92	**0.91**
Cottonseed meal		0.79									**0.79**
Canola meal				0.82						0.88	**0.85**
Flaxseed meal											
Dehulled flax				0.46							**0.46**
Sunflower meal										0.90	**0.90**
Meat and bone meal		0.78									**0.78**
Poultry by-product		0.90									**0.90**
Feather meal		0.79								0.87	**0.83**
Poultry meat meal									0.69		**0.69**
Hemoglobin meal									0.86		**0.86**
Anchovy meal	0.91										**0.91**
Pilchard meal											
menhaden meal											
Herring meal											
Capelin meal											
Jack mackrel meal											
Whitefish meal											
Gammarid meal	0.76										**0.76**
Krill meal											
Crayfish meal	0.71										**0.71**

1 Köprücü and Özdemir (2005)
2 Guimarães et al. (2008a)
3 Guimarães et al. (2008b)
4 Borgeson et al. (2006)
5 Magalhães et al. (2018)
6 Vidal et al. (2017b)
7 Vidal et al. (2015)
8 Vidal et al. (2017a)
9 Davies et al. (2011)
10 Tran-Ngoc et al. (2019)

Table B7 Protein digestibility of Tilapia and Salmon (and comparable carnivorous fish) obtained from literature used to overwrite IAFFD values where possible **(Continued)**

	Salmon									
Feed ingredient	5	11	12	13	14	15	16	17	18	**used**
Spring wheat						0.87			0.85	**0.86**
Wheat flour							0.91		0.82	**0.86**
Wheat middlings						0.86		0.92	0.69	**0.82**
Wheat bran										
Wheat germ										
Corn								0.95	0.68	**0.82**
Corn germ										**0.91**
Corn germ meal		0.95	0.87		0.89			0.96	0.92	**0.92**
Broken rice										**0.70**
Rice bran									0.72	**0.72**
Sorghum										**0.70**
Dried distillers grains					0.87			0.85		**0.86**
Pea	0.98			0.87	0.90		0.88			**0.91**
Chickpea	0.92									**0.92**
Faba bean	0.89							0.96		**0.93**
Soybean meal		0.88	0.77		0.83	0.77		0.96	0.89	**0.85**
Cottonseed meal									0.75	**0.75**
Canola meal		0.92			0.77	0.85		0.77	0.75	**0.81**
Flaxseed meal									0.7	**0.70**
Dehulled flax										
Sunflower meal										
Meat and bone meal								0.85		**0.85**
Poultry by-product					0.81	0.85			0.88	**0.85**
Feather meal					0.72	0.70			0.87	**0.76**
Poultry meat meal					0.85					**0.85**
Hemoglobin meal					0.71			0.99	0.91	**0.87**
Anchovy meal					0.94	0.92			0.97	**0.94**
Pilchard meal							0.83		0.89	**0.86**
menhaden meal		0.89				0.83		0.86	0.86	**0.86**
Herring meal		0.94				0.91		0.92		**0.92**
Capelin meal						0.94				**0.94**
Jack mackrel meal							0.83			**0.83**
Whitefish meal							0.73			**0.73**
Gammarid meal										
Krill meal							0.60			**0.60**
Crayfish meal										

11	Anderson et al. (1992)
12	Opstvedt et al. (2003)
13	Zhang (2011)
14	FAO (2018a)
15	Hajen et al. (1993)
16	Bransden et al. (2001), Carter et al. (1999)
17	Cho (1990)
18	Gaylord et al. (2008)

B4 - Nutrient content of animal sourced food

Table B8 Nutrient content of cooked ASF obtained from USDA (2019) and supplemented with (DanishFoodInstitute, 2019; FAO, 2016b; SwedishFoodAgency, 2019)

			PUFA		Vitamins			Minerals			
	DM	Protein	EPA	DHA	A	D	B12	Calcium	Iron	Zinc	Selenium
Product	kg	g	g	g	µg	µg	µg	mg	mg	mg	Mg
Pig meat	0.51	291	0.0	0.0	38	10	8	173	11	30	396
Pig offal	0.33	198	0.6	0.2	163	8	91	155	68	34	367
Cattle meat	0.41	293	0.0	0.0	20	1	31	129	28	69	307
Cattle offal	0.34	231	0.5	0.1	584	5	313	383	45	46	191
Milk	0.12	33	0.0	0.0	460	1	5	1130	0	4	37
Poultry meat	0.38	260	0.1	0.4	46	0	3	140	12	19	210
Poultry offal	0.32	272	0.1	0.3	18	0	94	140	70	42	596
Eggs	0.26	123	0.0	0.1	175	20	15	540	16	12	301
Salmon	0.35	254	6.9	14.6	690	140	40	150	3	4	414
Tilapia	0.28	262	0.1	0.8	0	37	19	140	7	4	544
Atlantic herring	0.36	203	12	15	54	54	141	740	14	13	468.0
Atlantic Cod	0.24	105	1	2	12	12	15	140	5	6	376.0
Blue whiting	0.25	116	3	5	18	18	26	620	4	5	411.0
Atlantic mackerel	0.47	262	9	14	209	209	190	150	16	9	516.0
European sprat	0.29	185	16	29	264	264	98	2028	15	13	208.7
Haddock	0.20	90	1	4	6	6	24	140	2	4	317.0
Pollock	0.28	118	2	5	13	13	37	770	6	6	468.0
European plaice	0.27	108	2	2	15	15	42	263	1	6	368.4
European hake	0.22	86	0	3	8	8	17	522	9	4	277.2
Atlantic h mackerel	0.38	201	8	14	114	114	65	290	15	9	468.0
European pilchard	0.34	172	9	18	55	55	86	649	20	9	653.9
Norway lobster	0.29	116	16	6	6	6	9	591	14	36	441.7
Northern prawn	0.26	99	2	2	6	6	167	700	5	16	193.5
Ling	0.26	111	1	2	12	12	7	440	8	10	468.0

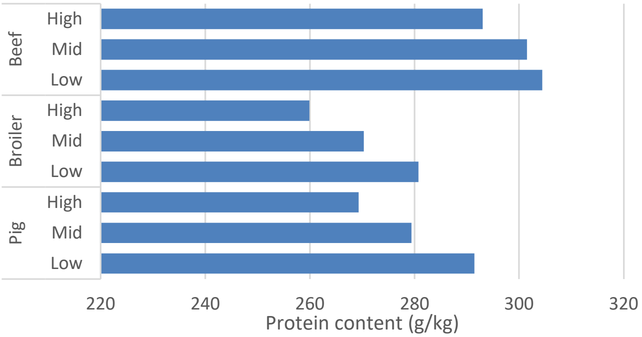


Figure B4 Human digestible protein content per kg cooked meat of pigs, broilers, and beef cattle adjusted for predicted variation in protein deposition under varying productivity

B5 - Additional results of Chapter 3

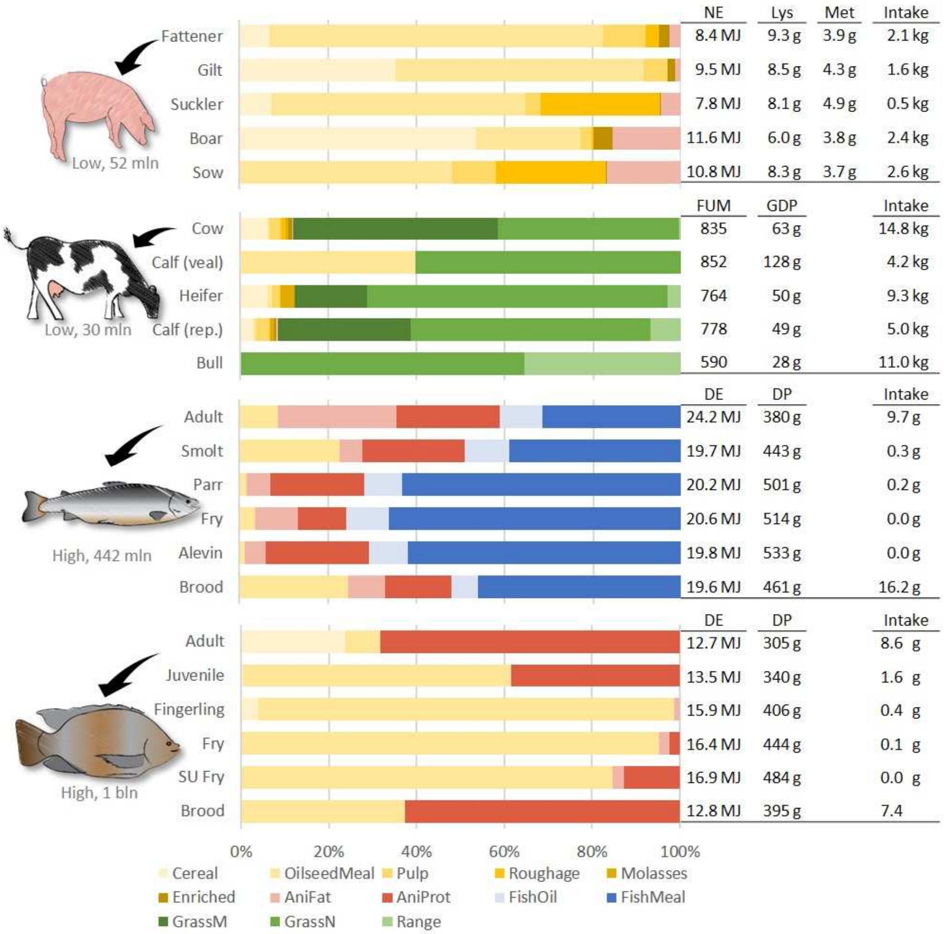


Figure B5 Required number of food producing animals, ration composition for each life phase of each animal production system and daily intake of this ration.

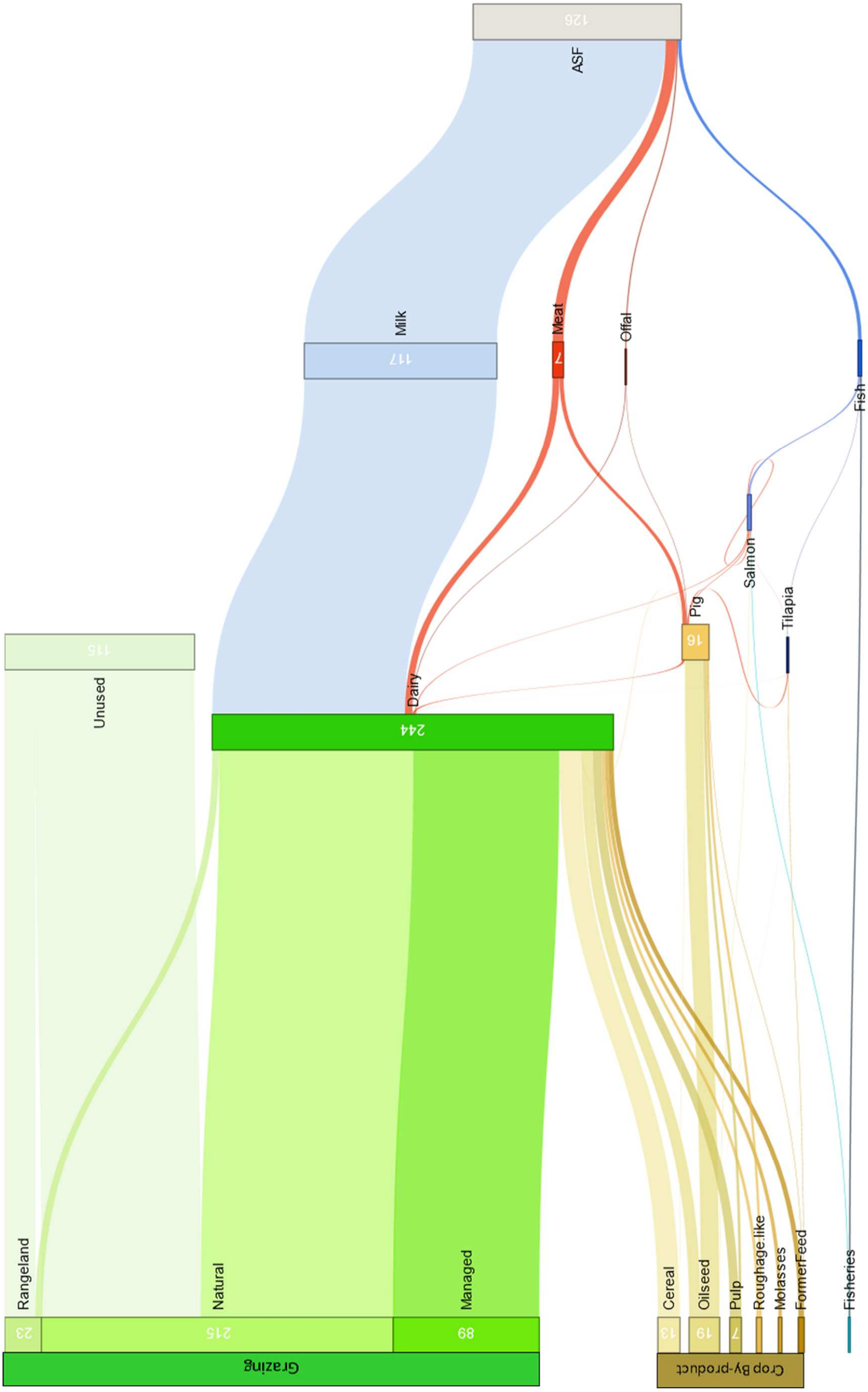


Figure B6 mass flow diagram of the baseline scenario in Mt dry matter for feed ingredients and in Mt fresh matter for food output

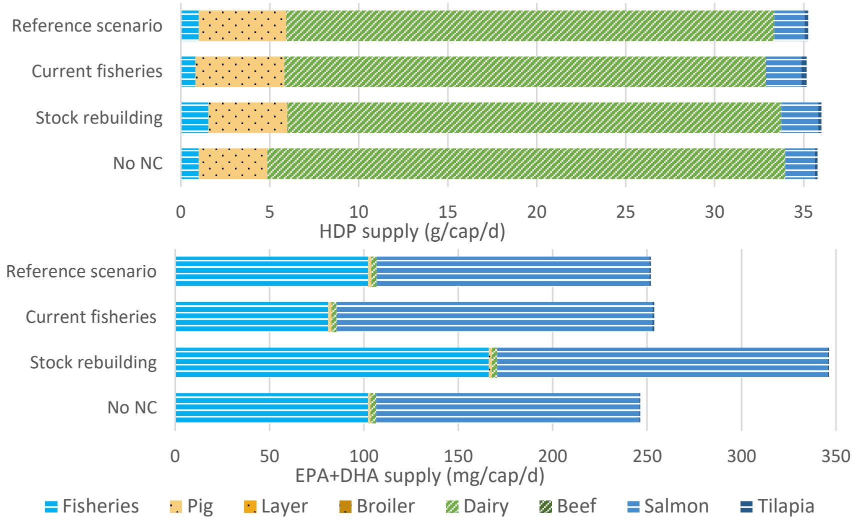


Figure B7 a. Human digestible protein (HDP) and b. essential ω3 fatty acid (EPA+DHA)) supply by fisheries and each animal production system in the reference scenario and under each scenario of the sensitivity analysis: Current fisheries, Stock rebuilding (fisheries) and No NC (excluding nutrient constraint regarding vitamin B12 and EPA+DHA)

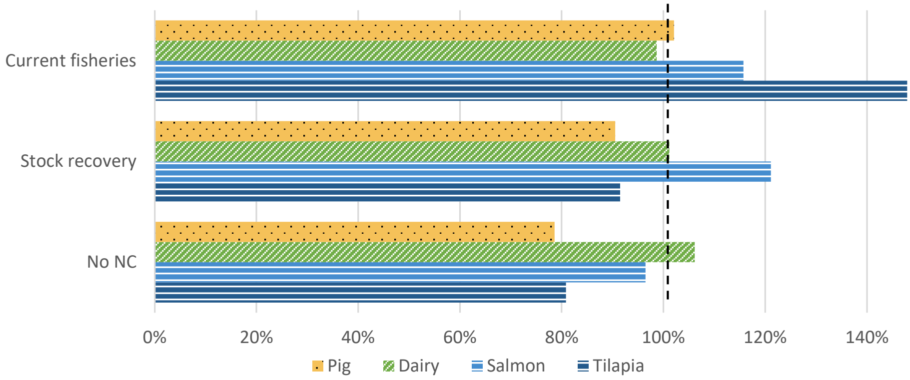


Figure B8 Number of animals of each production system under each scenario of the sensitivity analysis: Current fisheries, Stock rebuilding (fisheries) and No NC (excluding nutrient constraint regarding vitamin B12 and EPA+DHA), relative to animal numbers in the reference scenario.

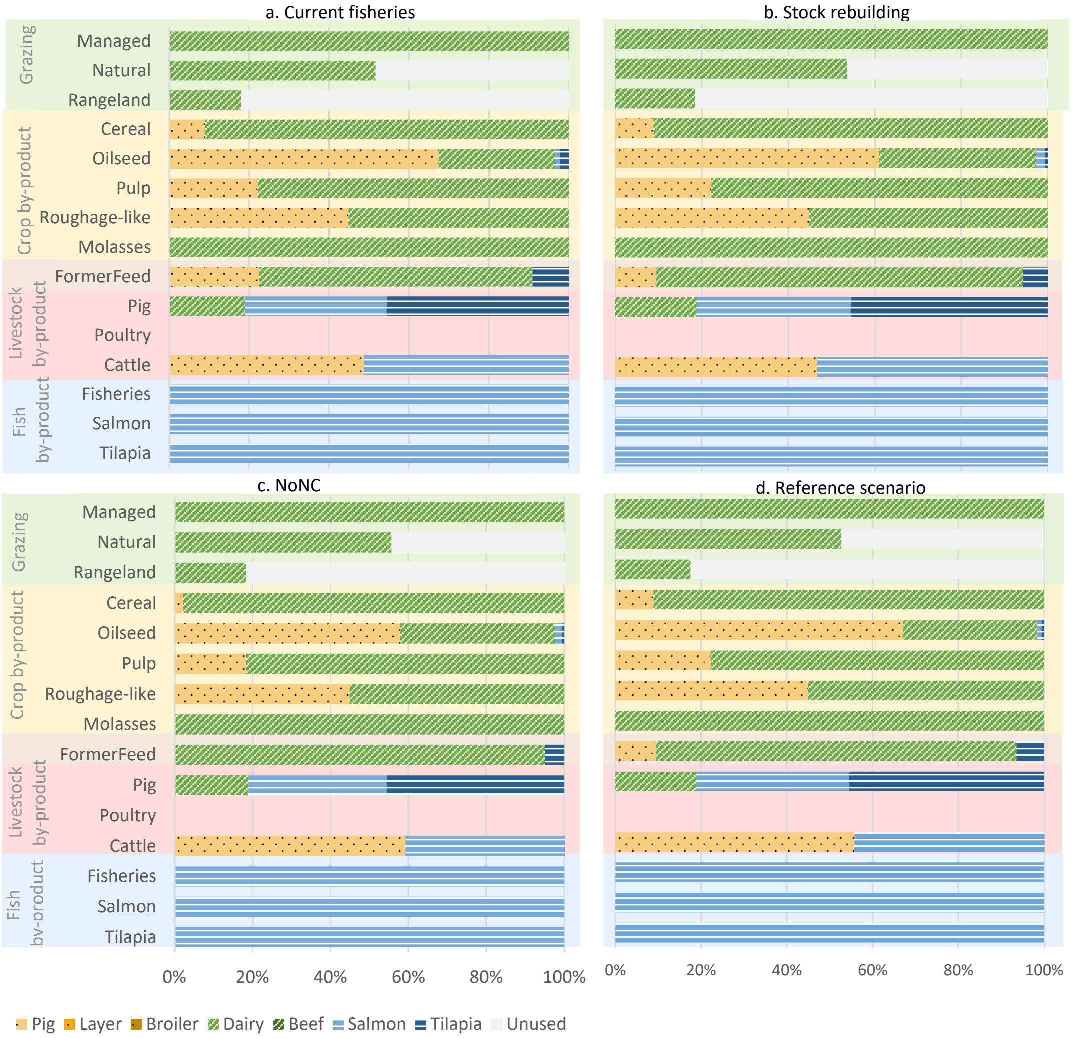


Figure B9 Feed allocation to the animal production systems (% of available feed) under alternative optimisations: a. current fisheries , b. Stock rebuilding , c. Exclusion of nutrient constraint d. Reference scenario

Appendix C

C1 - Availability of low-opportunity-cost feeds

The LCF that are input to the model consider human inedible products associated to primary use of spatial resources and include crop processing by-products, animal processing by-products, food wastes and grass resources. The availability of crop processing by-products and grass resources was adopted from Hal et al. (2019) and are described in detail in Appendix A2. For grass resources, the availability of managed grass was corrected to a total of 89 Mt based as suggested by the authors of the underlying research Haberl et al. (2007) and Plutzar et al. (2016). The range of nutrient content of grass resources of each vegetation type, obtained from literature was assumed to be normally distributed over the available grass biomass. Below we first describe the data used to calculate the availability animal by-products related to processing sustainable fisheries yields and animals by-products related to upcycling available LCF. Second we describe the assumed availability of food waste in each scenario.

Animal by-products

The strict EU regulations on feeding processed animal proteins (PAPs) to food producing animals were implemented after the major bovine spongiforme encepathology (BSE) and foot and mouth disease (FMD), to avoid future transmission of diseases between animals and to humans (EU, 2009). While, originally, this legislation banned feeding most livestock proteins to any food producing animals, a 2013 amendment has relegalised feeding these proteins (except from bovine origin) in aquaculture (EU, 2013a). Additionally EU legislation forbids feeding farmed animals with proteins originating from farmed animals of the same species (EU, 2013a). Farmed salmon can, thus, not be fed with salmon meal originating from aquaculture. Salmon and tilapia in our model are, however, a proxy for multiple species with similar characteristics (e.g. rainbow trout for salmon) that are allowed to feed on each other's by-products. To reflect this we allow for intraspecies recycling of fish farming by-products, meaning we allow farmed salmon to eat salmon by-products, assuming salmon represents multiple species that could recycle each other's by-products.

With the 2013 amendment, the EU showed to a willingness explore legislative change to aid and stimulate efficient use of resources in the food system. With legalisation at processing scenario we assess the ASF supply potential of possible future amendments that pose least risk to public health. With these amendments the use of PAPs to monogastric livestock, including those of ruminants, would be legalised, excluding high risk organs of the nerve system (EU, 2009). Similarly, PAPs from ruminants would be legalised as feed for farmed fish. Allowance of different PAPs in the feed of the food producing animals included in the model, under current and our adapted legislation is illustrated in Table C1. The ban on cannibalism would be maintained.

Table C1 Allowance of animal by-products in feed of food producing animal species based on EU legislation (EU, 2009, 2013a).

	Current legislation				Adapted legislation			
Animal by-product	Pig	Poultry	Cattle	Fish	Pig	Poultry	Cattle	Fish
Meat&Bone meal	NO	NO	NO	YES[1]	YES	YES	NO	YES
Bone meal	NO	NO	NO	YES	YES	YES	NO	YES
Blood meal	YES[1]	YES[1]	NO	YES[1]	YES	YES	NO	YES
Feather meal	YES[2]	YES[2]	NO	YES	YES	YES	NO	YES
Poultry by-product meal	NO	NO	NO	YES	YES	NO	NO	YES
Fish meal	YES	YES	NO	YES	YES	YES	NO	YES

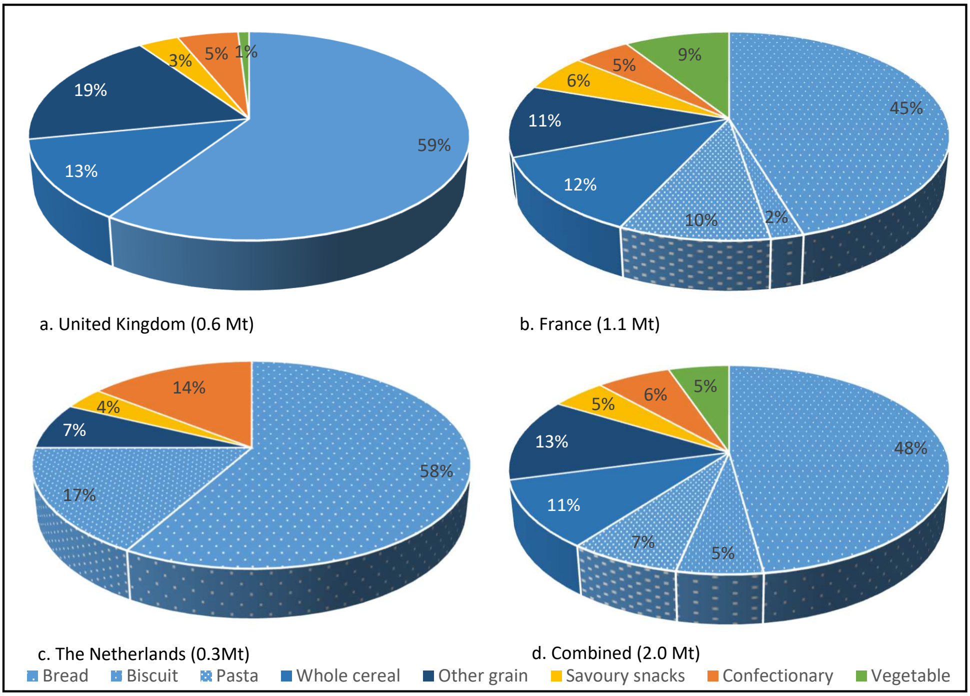
1: Allowed if not from bovine origin

2: Allowed in EU but prohibited in many of its member states

Manufacturing wastes

The European Former Foodstuff Processors Association (EFFPA), whose members process 3.5 million tonnes of FFS annually, estimates that in the EU a total of 5 million tonnes of FFS are processed into feed every year (EFFPA, 2019). While EFFPA indicates the majority of these FFS are cereal based (>70%) the exact product composition of EU FFS remains unknown (EFFPA, 2019). We, therefore, assumed the product composition of FFS excluding by-products of the UK (UKFFPA, 2019), Netherlands (VIDO, 2019) and France (Vernier et al., 2016) and combined (**Figure S3.3**) and applied this to the estimated 5 million tonnes of EU FFS. The resulting 4.2 million tonnes of cereal based FFS comes close Caldeira et al. (2019) estimation of 4.9 million ton cereal based manufacturing waste currently used as feed. Each of the former food products was assumed to be processed into common FFS based feed ingredients, resulting in the available feed ingredients assumed in the reference scenario (Table C12).

Processors of FFS have joined forces in an association to improve the recovery of FFS as feed, and estimate an additional 2 Mt per year could be recovered (EFFPA, 2019) which we assume to have the same composition as currently fed FFS in the improved recovery scenario (Table C12). Legalisation at manufacturing includes plant based FFS that are possibly contaminated with PAPs available. We assume this would only make additional cereal based FFS available, of which in total 7.4 Mt fresh matter is wasted per year (Caldeira et al., 2019). We assume the additional cereal based FFS has the same composition as the cereal based FFS already included in previous scenarios (Table C12). Safe use of these possibly contaminated FFS as feed requires standardised treatment guidelines even if they are still of food quality.



a. United Kingdom (0.6 Mt)

b. France (1.1 Mt)

c. The Netherlands (0.3Mt)

d. Combined (2.0 Mt)

Figure C1 Combined (d) former foodstuff product composition based on that of the UK (UKFFPA, 2019), The Netherlands (VIDO, 2019) and France (Vernier et al., 2016) adapted to exclude animal based products and crop by-products.

Table C2 Available former food ingredients (Mt) in the EU, under current recovery (5 Mt total) improved recovery (7 Mt total) and legalisation (7.4 Mt cereal based) assuming product composition in the UK, Netherlands and France (Figure C4).

	Current	Improved recovery	Legalisation
Bread meal	1778981	2490573	4232027
Biscuit meal	270843	379180	478863
Pasta meal	351383	491936	621261
Puffed rice	262944	368122	464898
Rice meal	262944	368122	464898
Mixed cereal	643679	901150	1138053
Potato chips	234836	328771	415202
Fruit waste	260933	365306	461342
Sugar syrup	378544	529962	669283

Retail and consumption waste

Table C13 shows the available plant based feed ingredients and available plant based household waste in the EU, both calculated from (Caldeira et al., 2019). Processing of of retailing waste considers drying of of bread and pastry into bread and biscuit meal. Processing of consumption waste considers the boiling and/or fermenting household food waste into swill.

Table C3 Available plant based feed ingredients from retail and available household waste (Mt) in the EU.

Waste product	Retail	Consumption
Wheat flour	43877	523893
Bread	0	5021781
Pastry	0	1083111
Bread meal	1230084	0
Biscuit meal	568534	201526
Pasta meal	21620	335588
Beer	180938	1980371
Mixed cereal	129406	698011
Rice grain	12616	327032
Fruit waste	800000	10100000
Vegetable waste	900000	14400000
Potato	300000	5700000
Sugar syrup	400000	1600000
Sunflowerseed oil	100000	1700000

Classification of ingredients

Table C14 shows the classification of LCF based on their origin and nutritional properties.

Table C4 Classification LCF based on their origin and nutritional properties

	Classification	
Product	Allocation	Ration
Crop by-products		
Wheat bran	Cereal by-products	Cereal product
Wheat germ	Cereal by-products	Cereal product
Wheat feed meal	Cereal by-products	Cereal product
Barley by-product	Cereal by-products	Cereal product
Barley rootlet	Cereal by-products	Cereal product
Spent brewers grain	Cereal by-products	Cereal product
Maize bran	Cereal by-products	Cereal product
Maize germ meal	Oilseed meals	Oilseed meals
Rye bran	Cereal by-products	Cereal product
Oat offal	Cereal by-products	Cereal product
Oat hulls	Roughage like	Roughage like
Rice hulls	Roughage like	Roughage like
Potato peel (steam)	Pulp	Pulp
Sweet potato peel (steam)	Pulp	Pulp
Sugarbeet toptails	Roughage like	Roughage like
Sugarbeet molasses	Molasses	Molasses
Sugarbeet pulp	Pulp	Pulp
Soybean hulls	Roughage like	Roughage like
Soybean meal	Oilseed meals	Oilseed meals
Groundnut shell	Roughage like	Roughage like
Groundnut meal	Oilseed meals	Oilseed meals
Sunflower seed meal	Oilseed meals	Oilseed meals
Rapeseed meal	Oilseed meals	Oilseed meals
Cottonseed meal	Oilseed meals	Oilseed meals
Copra meal	Oilseed meals	Oilseed meals
Sesameseed meal	Oilseed meals	Oilseed meals
Palm fiber	Roughage like	Roughage like
Palm effluent	Oilseed meals	Oilseed meals
Palm kernel meal	Oilseed meals	Oilseed meals
Olive residue	Oilseed meals	Oilseed meals
Citrus pulp	Pulp	Pulp
Grape pommace	Pulp	Pulp
Coffee husk	Roughage like	Roughage like
Cocoa husk	Roughage like	Roughage like
Processsing by-products		
Pig blood meal	Pig products	Livestock protein
First choice grease	Pig products	Livestock fat
Pig meat and bone meal	Pig products	Livestock protein
Lard	Pig products	Livestock fat
Pig plasma	Pig products	Livestock protein
Beef blood meal	Cattle products	Livestock protein
Tallow	Cattle products	Livestock fat
Beef meat and bone meal	Cattle products	Livestock protein
Poultry by-product	Poultry products	Livestock protein
Feathermeal	Poultry products	Livestock protein
Fisheries meal	Fisheries products	Fish meal
Fisheries oil	Fisheries products	Fish oil
Salmon meal	Salmon products	Fish meal
Salmon oil	Salmon products	Fish oil
Tilapia meal	Tilapia products	Fish meal
Tilapia oil	Tilapia products	Fish oil

Table C4 Classification LCF based on their origin and nutritional properties (continued)

	Classification	
Product	Allocation	Ration
Manufacturing waste		
Bread meal	Processing waste	Enriched staple
Biscuit meal	Processing waste	Enriched staple
Pasta meal	Processing waste	Cereal product
Puffed rice	Processing waste	Cereal product
Rice meal	Processing waste	Cereal product
Mixed cereal	Processing waste	Cereal product
Potato chips	Processing waste	Enriched staple
Fruit waste	Processing waste	Pulp
Sugar syrup	Processing waste	Molasses
Retail waste		
Wheat flour	Retail waste	Cereal product
Bread	Retail waste	Enriched staple
Pastry	Retail waste	Enriched staple
Bread meal	Retail waste	Enriched staple
Biscuit meal	Retail waste	Enriched staple
Pasta meal	Retail waste	Cereal product
Beer	Retail waste	Cereal product
Mixed cereal	Retail waste	Cereal product
Rice grain	Retail waste	Cereal product
Fruit waste	Retail waste	Pulp
Vegetable waste	Retail waste	Pulp
Potato	Retail waste	Pulp
Sugar syrup	Retail waste	Molasses
Sunflowerseed oil	Retail waste	Vegetable oil
Consumption waste		
Wheat flour	Consumption waste	Swill
Bread	Consumption waste	Swill
Pastry	Consumption waste	Swill
Bread meal	Consumption waste	Swill
Biscuit meal	Consumption waste	Swill
Pasta meal	Consumption waste	Swill
Beer	Consumption waste	Swill
Mixed cereal	Consumption waste	Swill
Rice grain	Consumption waste	Swill
Fruit waste	Consumption waste	Swill
Vegetable waste	Consumption waste	Swill
Potato	Consumption waste	Swill
Sugar syrup	Consumption waste	Swill
Sunflowerseed oil	Consumption waste	Swill

Appendix C4 - Additional results

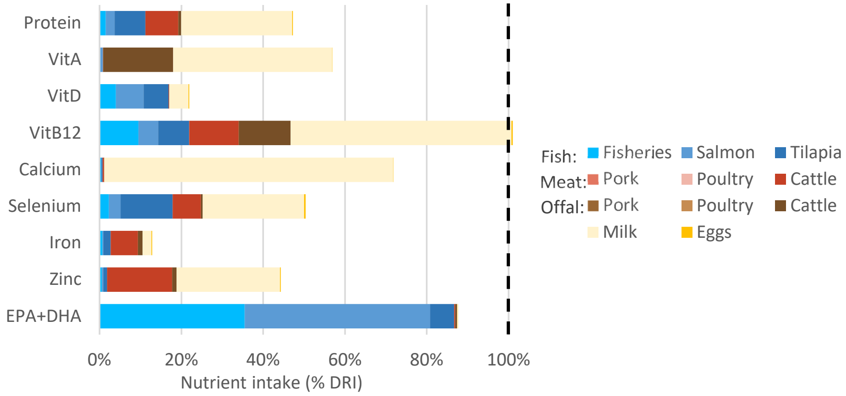


Figure C2 Nutrient intake from animal source food in the reference scenario expressed as % of daily recommended intake (DRI) fulfilled

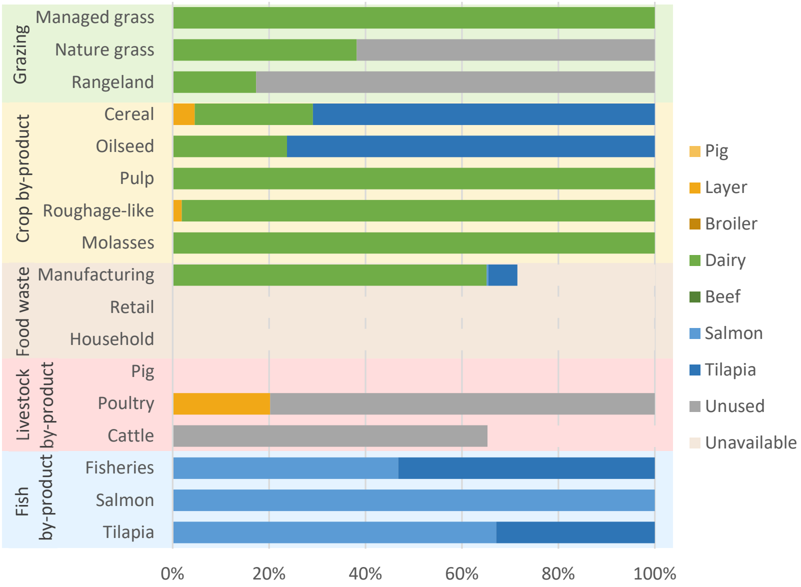
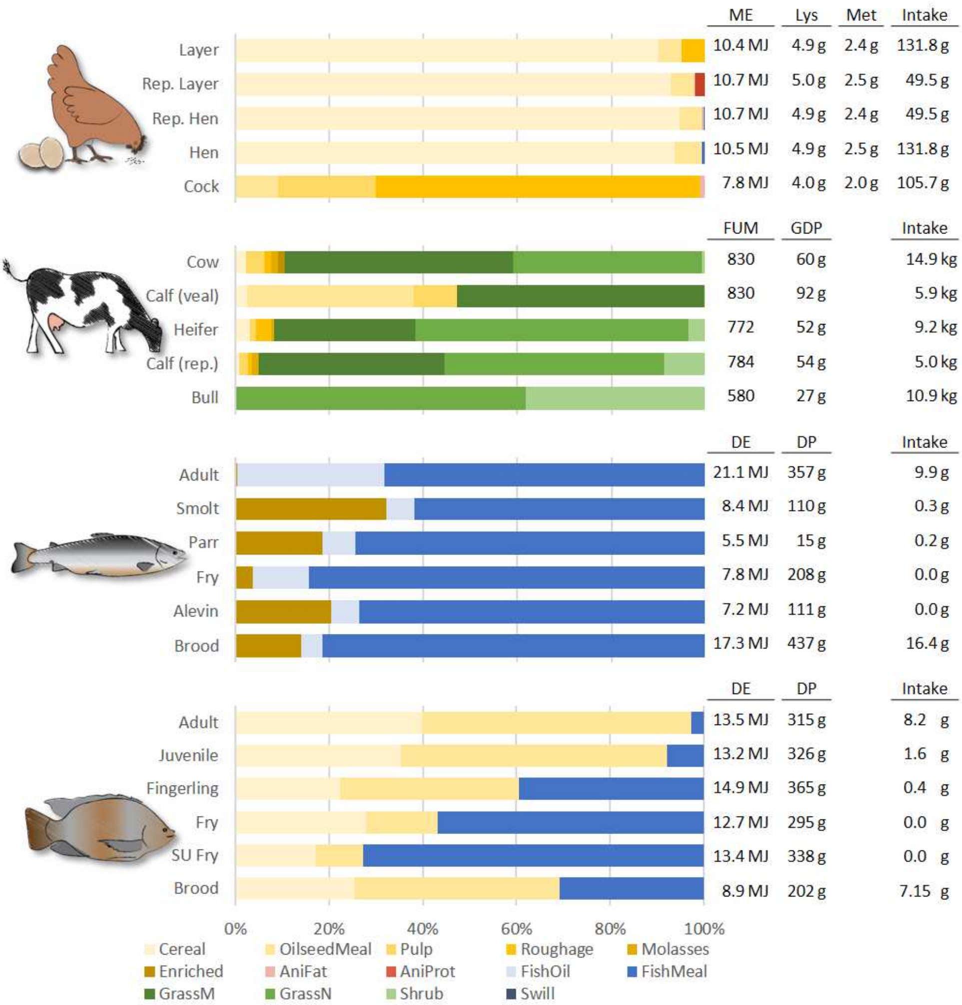


Figure C3 Feed allocation to each animal production system (% of available feed) the reference scenario.



	ME	Lys	Met	Intake
Layer	10.4 MJ	4.9 g	2.4 g	131.8 g
Rep. Layer	10.7 MJ	5.0 g	2.5 g	49.5 g
Rep. Hen	10.7 MJ	4.9 g	2.4 g	49.5 g
Hen	10.5 MJ	4.9 g	2.5 g	131.8 g
Cock	7.8 MJ	4.0 g	2.0 g	105.7 g

	FUM	GDP	Intake
Cow	830	60 g	14.9 kg
Calf (veal)	830	92 g	5.9 kg
Heifer	772	52 g	9.2 kg
Calf (rep.)	784	54 g	5.0 kg
Bull	580	27 g	10.9 kg

	DE	DP	Intake
Adult	21.1 MJ	357 g	9.9 g
Smolt	8.4 MJ	110 g	0.3 g
Parr	5.5 MJ	15 g	0.2 g
Fry	7.8 MJ	208 g	0.0 g
Alevin	7.2 MJ	111 g	0.0 g
Brood	17.3 MJ	437 g	16.4 g

	DE	DP	Intake
Adult	13.5 MJ	315 g	8.2 g
Juvenile	13.2 MJ	326 g	1.6 g
Fingerling	14.9 MJ	365 g	0.4 g
Fry	12.7 MJ	295 g	0.0 g
SU Fry	13.4 MJ	338 g	0.0 g
Brood	8.9 MJ	202 g	7.15 g

Figure C4 Ration composition for each life phase of each animal production system and daily intake of this ration in the reference scenario.

Appendix D

D1 - The environmental impact of free range broiler production

The environmental impact per kg free range broiler meat were calculated from literature (Table D1) Four studies have assessed the environmental impact of free range broiler production using life cycle assessment (LCA). Each of these studies expressed the environmental impact per kg carcass weight, except for (Da Silva et al., 2014) that expressed it per kg of live weight. These impacts were transformed with the assuming a carcass yield of 69% as introduced by (Da Silva et al., 2014) themselves. For all studies the environmental impacts where then transformed to per kg meat assuming a meat yield of 68% (USDA, 2018a), after which the average impact per kg meat was calculated.

Table D1 Global warming potential (GWP), energy use (EU) and land use (LU) per kg of free range broiler production, expressed per kg carcass and per kg fresh meat, obtained from literature

	Study	GWP	EU	LU
per kg carcass weight		kg CO_2-eq	MJ	m^2
	Williams et al. (2006)	5.48	14.5	7.30
	Leinonen et al. (2012)	5.13	25.7	7.20
	Leinonen et al. (2014)	4.42	28.0	
	Da Silva et al. (2014)	4.02	44.0	5.83
	Average	**4.76**	**28.0**	**6.78**
per kg meat				
	Williams et al. (2006)	8.06	21.3	10.74
	Leinonen et al. (2012)	7.54	37.7	10.59
	Leinonen et al. (2014)	6.50	41.2	
	Da Silva et al. (2014)	5.92	64.7	8.57
	Average	**7.01**	**41.2**	**9.96**

D2 - Feed composition and impact of ingredients

Table D2 Feed compositions for each feed scenario (S1-S3) and rearing feed for female (f) and male (m) chicks, and GWP (CO_2-eq), EU (MJ) and LU (m^2) per kg of each feed ingredient, under economic and food-based allocation.

	Feed composition					**Impact (/kg ingredient)**					
	Egg production			Rearing		Economic allocation			Food-based allocation		
Ingredient %	S1	S2	S3	f	m	GWP	EU	LU	GWP	EU	LU
Animal fat	-	2.80	-	-	1.06	820	12.4	0.00	820	12.4	0.00
Biscuit sand	6.95	-	-	-	-	12	0.2	0.00	12	0.2	0.00
Breadcrumbs	4.85	-	-	-	-	12	0.2	0.00	12	0.2	0.00
Candy syrup	-	-	-	-	0.5	12	0.2	0.00	12	0.2	0.00
Crispbread	-	6.90	5.00	-	-	12	0.2	0.00	12	0.2	0.00
Dough melange	3.00	-	-	-	-	12	0.2	0.00	12	0.2	0.00
Eggshells	9.41	9.00	9.32	-	-	12	0.2	0.00	12	0.2	0.00
Insect meal	-	-	21.53	-	-	770	9.3	0.03	420	6.6	0.01
Limestone	1.50	1.50	1.50	1.04	1.18	19	0.2	0.00	19	0.2	0.00
Lysine 78%	0.31	0.30	0.45	0.63	0.73	6030	119.2	2.37	6030	119.2	2.37
Maize	-	-	-	33.71	30	604	5.2	1.29	604	5.2	1.29
Maize gluten	-	-	-	-	5.1	997	1.3	11.41	37	0.5	0.00
MCP	0.64	9.00	1.44	0.88	0.87	1170	17.7	0.31	1170	17.7	0.31
Methionine	0.09	0.15	0.36	0.20	0.10	5490	90.9	0.01	5490	90.9	0.01
Natriumbicarb.	-	-	-	-	0.31	1050	3.5	0.02	1050	3.5	0.02
Oat	-	-	-	2	-	448	2.6	1.54	448	2.6	1.54
Oat hulls organic	-	5.00	11.00	-	-	227	1.6	0.64	16	0.3	0.00
Premix	0.50	0.40	0.40	1.15	0.88	2000	0.8	0.00	2000	0.8	0.00
Treonine 50%	-	-	-	0.31	0.2	8489	59.6	1.19	8489	59.6	1.19
Rapeseed meal	12.00	5.00	-	3	10.7	456	3.4	1.25	16	0.2	0.00
Rice waffle	8.40	8.00	8.00	-	-	12	0.2	0.00	12	0.2	0.00
Rusk	25.00	41.90	41.00	-	-	12	0.2	0.00	12	0.2	0.00
Fish oil	-	-	-	0.25	-	940	13.0	0.01	940	13.0	0.01
Salt	-	-	-	0.18	0.17	180	3.5	0.02	180	3.5	0.02
Soya lecithin	2.39	-	-	-	-	3190	20.9	4.37	3190	20.9	4.37
Soybean meal	-	4.70	-	13.7	-	636	4.9	3.32	112	1.5	0.00
Soybean oil	-	-	-	0.95	-	1830	12.0	3.90	4067	26.6	8.76
Sunflower oil	-	0.85	-	-	-	2207	19.7	18.59	2759	24.7	23.24
Sunfl. meal HP*	19.97	-	-	-	-	572	4.5	3.78	20	0.2	0.00
Sunfl. meal HP	-	-	-	6	13	549	5.6	3.83	138	0.6	0.00
Sunfl. meal LP	-	12.00	-	6	1.3	479	4.9	3.18	138	1.9	0.00
Waffle syrup	5.00	-	-	-	-	12	0.2	0.00	12	0.2	0.00
Wheat	-	-	-	30	33.9	329	2.9	1.14	329	2.9	1.14

* origin Ukraine

D3 - Calculation of emissions related to manure management

Table D3 shows the equations to calculate CH_4 emissions, and direct and indirect N_2O emissions with the related parameters calculated using the tier 2 approach (IPCC, 2006).

Table D3 Equations to calculate CH_4, direct and indirect N_2O emissions with the related parameters.

General information

		Egg production	Rearing female	Rearing male
Approach		Laying hen	Rearing hen	Rearing hen
Avergage animal number (N)	animals/round	23063	6175	6192
Round duration	d/round	469	119	119
feed intake	g/d	118		

Equations

CH_4 emission = N * (VS * d) * (B0 * 0,67kg/m^3 * (MCF / 100))

Direct N_2O Emission = N * (NEX / 365 * d) * EF3 * 44 / 28

N_2O leaching = N * (NEX / 365 * d) * (FracLeach / 100) * EF5 * (44 / 28)

N_2O volatilisation = N * (NEX / 365 * d) * (FracGas / 100) * EF4 * (44 / 28)

CH4 emissions

		Egg production	Rearing female	Rearing male
Volatile solid excretion (VS)	kg/animal/day	8.5	4	4
Potential CH_4 Production (B0)	m^3 CH_4/kg VS	0.34	0.34	0.34
CH_4 Conversion Factor (MCF)	kg CH4/animal/day	0.015	0.015	0.015
CH4 emission	**kg/round**	**3141.58**	**395.86**	**396.90**

N2O emissions

		Egg production	Rearing female	Rearing male
Nitrogen excreation	kg N/year	0.75	0.35	0.35
Emission Factor 3 (EF3)	kg N2O/kg N	0.001	0.001	0.001
Direct N2O emission	**kg/round**	34.9	4.4	4.4
Leaching fraction (Fracleach)	kg N2O-N/kg N		0.13	0.13
Emission Factor 5 (EF5)	kg N2O/kg N		0.0075	0.0075
N2O leaching	**kg/round**	0	0.04	0.04
FracGas	kg NH_3+Nox-N/kg N		0.40	0.40
Emission Factor 4 (EF4)	kgN2O-N		0.010	0.010
N2O deposition	**kg/round**	0	0.17	0.18

D4 - Calculation of the land use ratio

The LUR was selected over the, more commonly used, protein conversion ratio as better accounts for the feed-food competition avoid by feeding only low-opportunity-cost feedstuffs. The protein conversion ratio compares the human digestible protein in a kg animal source food (ASF) with the human digestible protein (HDP) in the feed required to produce this kg of ASF. The LUR, alternatively compares it to the plant-based HDP that can be derived from the land used to cultivate feed required to produce this kg of ASF. Only the LUR, therefore, accounts for indirect feed-food competition by considering the amount of HDP that could be produced by a range of food crops on the land related to feed crop and energy rich food crop production.

Methods to calculate the LUR were based on van Zanten et al. (2016b) and consists of four steps. The first step quantified the country specific land occupation related the amount of each feed ingredient needed to produce one kg of ASF (eggs and meat), considering both the rearing and the laying phase. To do so feed intake (Main article; Table 1) and feed composition (Main article; Table 2) were linked to the land use (Vellinga et al., 2013) and country of origin and yields of each ingredient (Bongards, 2017; Heuvelmans, 2017; Lemmens, 2017; Vellinga et al., 2013). The second step assessed the suitability to produce the five major food crops (i.e. maize, wheat, potatoes (white and sweet), soybeans and rice) for each of these countries of origin based on the Global Agro-Ecological Zones (GAEZ) database (IIASA/FAO, 2012). This database classified land from 'not suitable' to 'very suitable' based on to what extend soil and climate conditions match requirements of each crop, under defined input and management circumstances. The crop suitability was assessed for current cultivated land in a situation of high input levels, optimal water supply and baseline climate conditions (1961-1990) (IIASA/FAO, 2012). Land was considered suitable for cultivation of a specific crop if the suitability was good, high, or very high (suitability index >55).

Table D4 Country average yields (kg/ha) of five major food crops for the year 2014 (FAO, 2017b). An empty cell implies a country was considered unsuitable to cultivate that crop (i.e. suitability index <55) (IIASA/FAO, 2012).

Country	Maize	Wheat	Sweet potato	White potato	Soybeans	Rice (wet)
Argentina	6841	2667	14660	29411	2774	6504
Belgium	-	9413	-	54000	-	-
Brazil	-	-	13243	-	2866	5201
China	5809	-	-	16924	1787	6812
France	10050	7353	-	47978	2999	-
Germany	-	8630	-	47415	-	-
The Netherlands	-	9170	-	45660	-	-
Ukraine	6159	4012	-	-	-	-
United Kingdom	-	8578	-	41922	-	-
United States	10733	2938	-	47151	3198	8492

The third step calculates potential human-digestible protein production from the five food crops by multiplying their yields (Table D4) by their protein content and digestibility (Table D5). Country-average yields for crop production (FAO, 2017b) were used, as information about exact location and soil type were missing. Afterwards, the highest HDP for each area of land was chosen and summed across all land areas required to produce 1 kg of ASF, giving the numerator of the land use ratio. The last phase calculates the amount of HDP in 1 kg of ASF (i.e. eggs and meat) by multiplying with its protein content and its protein digestibility. The composition of one kg of ASF was based on Kipster's annual output of each product (i.e. eggs, laying hen meat and male laying hen chick meat) calculated from the outputs per round (Table 1) of the main paper.

Table D5 Dry matter (DM) and protein contents of products and protein digestibility (PD) by humans (van Zanten et al., 2016b).

Product	Code[a]	DM %	Protein g/kg DM	PD[b] %
Eggs	01123	24	527	97
Chicken meat	05001	34	545	94
Maize	20014	90	105	85
Wheat	20074	90	125	87
Sweet potatoes	11507	23	69	76
White potatoes	11354	18	91	80
Soybeans	16108	91	399	78
Rice	20052	87	75	89

[a] Product code in USDA database (USDA, 2018a) from which DM and protein content were derived

[b] Protein digestibility, source: (Gilani et al., 2005) except white potatoes (Eppendorfer et al., 1979; Khan et al., 1992; Kies & Fox, 1972), and sweet potatoes (Ravindran et al., 1995).

D5 - Break-down of results

In this appendix we provide a break-down of the results as presented in Figure 3 of the main paper. Table D6 provides an overview of the made and avoided impacts in each phase, which together add up to the results presented in Figure 3 of the main paper. Tables D7-D9, give insights in how the made impacts in each phase, as presented in Table D6 were calculated, while Tables D10 & D11 give insights in the avoided impacts due to the use and supply of solar energy.

Table D6 Made, avoided (-) and net global warming potential (GWP) energy use (EU) and land use (LU) per kg Kipster egg, in each phase

	GWP (kg CO2-eq)	EU (MJ)	LU (m2)
Rearing female			
Rearing	0.21	2.54	0.50
Total	0.21	2.54	0.50
Rearing male			
Rearing	0.26	3.20	0.55
Meat output	-0.18	-1.06	-0.26
Total	0.08	2.14	0.30
Egg production			
Egg production	1.10	9.59	2.44
Meat output	-0.17	-0.99	-0.24
Solar energy output	-0.09	-1.42	-0.002
Total	0.83	7.18	2.19
Total	**1.13**	**11.86**	**2.99**

[1]: detailed calculations found in Tables D7-D9

[2]: avoided impact due to supply of solar energy as calculated in Table D11

Table D7 Global warming potential (GWP; kg CO_2-eq) related to each process or input of each phase of Kipster egg production.

Global warming potential (GWP; kg CO_2-eq)			
Rearing female		(/round)	(/kg egg)
On-farm	Manure management	12298	
	Gas use	7688	
	Electricity use	6212	
	Total	26198	0.05
Off-farm	Diesel use	7	
	Litter	25	
	Feed[1]	88322	
	Total	88420	0.17
Total			**0.21**
Rearing male		(/round)	(/kg egg)
On-farm	Manure management	12331	
	Gas use	7688	
	Electricity use	6196	
	Total	26214	0.05
Off-farm	Litter	25	
	Feed[1]	115121	
	Total	115212	0.22
Total			**0.26**
Egg production		(/round)	(/kg egg)
On-farm	Manure management	97220	
	Electricity use	21302	
	Total	118521	0.22
Off-farm	Litter	143	
	Feed[1, 2]	467233	
	Total	467315	0.87
Total			**1.10**

[1]: Assuming solar energy; under average grid electricity
- Rearing female: 11862 kg CO_2-eq
- Rearing male: 85508 kg CO_2-eq
- Rearing egg: 22519 kg CO_2-eq

[2]: impact of feed under economic allocation

[3]: impact of baseline (S1) feed

Table D8 Energy use (EU, MJ) related to each process or input of each phase of Kipster egg production.

Energy use (EU, MJ)			
Rearing female		(/round)	(/kg egg)
On-farm	Gas use	133238	
	Electricity use	202339	
	Total	335577	0.63
Off-farm	Diesel use	7526	
	Diesel production	102	
	Gas production	142564	
	Electricity production	73652	
	Litter	278	
	Feed[1]	798403	
	Total	1023446	1.91
Total			**2.54**
Rearing male		(/round)	(/kg egg)
On-farm	Gas use	132888	
	Electricity use	201809	
	Total	334697	0.63
Off-farm	Gas production	142190	
	Electricity production	73458	
	Litter	279	
	Feed[1]	1159403	
	Total	1376248	2.57
Total			**3.20**
Egg production		(/round)	(/kg egg)
On-farm	Electricity use	540000	
	Total	540000	1.01
Off-farm	Electricity production	196560	
	Litter	1609	
	Feed[1, 2]	4389897	
	Total	4587524	8.58
Total			**9.59**

[1]: Assuming solar energy; under average grid electricity

- Rearing female: 171593 MJ
- Rearing male: 31530 MJ
- Egg production: 298000 MJ

[2]: impact of feed under economic allocation

[3]: impact of baseline (S1) feed

Table D9 Land use (LU, m^2) related to each process or input of each phase of Kipster egg production.

Land use (LU, m^2)

Rearing female		(/round)	(/kg egg)
Off-farm	Gas production	8	
	Electricity production	0	
	Litter	2	
	Feed[1]	268000	
	Total	269446	0.50
Total			**0.50**
Rearing male		(/round)	(/kg egg)
Off-farm	Gas production	8	
	Electricity production	541	
	Litter	2	
	Feed[1]	293058	
	Total	295041	0.55
Total			**0.55**
Egg production		(/round)	(/kg egg)
Off-farm	Electricity production	1447	
	Litter	10	
	Feed[1]	1300195	
	Total	1302920	2.44
Total			**2.43**

[1]: Assuming solar energy; under average grid electricity
- Rearing female: 221 m^2
- Rearing male: 41 m^2
- Egg production: 384 m^2

[2]: impact of feed under economic allocation
[3]: impact of baseline (S1) feed

Table D10 Production, use and supply (to the grid) of solar electricity by Kipster

	kWh/round	kWh/egg	
Solar electricity produced	385479	0.72	
On farm electricity use	305003	0.57	-
Surplus of solar energy	80476	0.15	

Table D11 Avoided global warming potential (GWP), energy use (EU) and land use (LU) by the use and supply of solar energy per kg Kipster egg

	GWP (kg CO2-eq)	EU (MJ)	LU (m2)
Avoided by supply	0.09	0.25	0.00
Avoided by use	0.36	4.62	0.00
Rearing female	0.07	0.99	0.00
Rearing male	0.07	0.99	0.00
Egg production	0.23	2.64	0.00
Avoided total	0.45	4.87	0.00

[1]: Calculated by multiplying the difference in impact between production of solar electricity and Dutch average grid electricity (Appendix D1) with the supply of (surplus) solar electricity by Kipster (Table D10)

[2]: Calculated as the difference in impact of each phase when assuming solar electricity use (Tables D7-D9) and when assuming average grid electricity (see note 1 of Tables D7-D9)

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Summary

The food system faces the challenge of feeding a growing world population while limiting environmental impacts and resource use. The European Union (EU) aims to address this challenge by shifting to a more circular food system, as increasingly proposed by scientists. A central principle of a circular food system is to prioritise the use of resources for direct food supply to avoid feed-food competition. This implies arable land should be used to cultivate food crops, and the edible yield of sustainably caught fish should be used for direct human consumption. This food production and consumption, however, results in food leftovers that are unsuitable or undesired for human consumption, such as food processing by-products and food waste. Farm animals can contribute to a circular food system by upcycling these food leftovers and grass resources (so-called such low-opportunity-cost feeds; LCF) into valuable animal-source food (ASF) that contains essential nutrients for humans. A diet containing a small amount of ASF from animals fed only LCF appears most resource efficient, because if everyone would become vegan these LCF are no longer upcycled in the food system. Previous studies show that animals fed only LCF can provide 7-30 g human digestible protein (HDP) per capita per day. While these studies illustrate that farm animals can have a role in a circular food system, they give limited insight in how different animals can contribute to the efficient use of LCF. This thesis, therefore, aims to evaluate the potential of various farmed animals in upcycling LCF in a circular food system, using the EU-28 as a case study.

In **Chapter 2** we explored what combination of livestock systems (pigs, laying hens, broilers, dairy cattle and beef cattle), differing in productivity level (low, mid and high), optimally convert the LCF available in the EU-28 into HDP. To this aim, we developed an optimisation model that allocates available plant-based LCF to that combination of animals that maximises HDP supply. We found that optimal conversion requires a variety of both livestock systems and productivity levels. Dominant livestock systems were those that have a high conversion efficiency (laying hens, dairy cattle), were best able to valorise specific LCF (dairy cattle for grass; pigs for food waste), and could valorise low quality LCF because of their low productivity. We conclude that under the assumed availability of LCF, livestock could supply 31 g HDP per EU capita per day, but that this result was sensitive to assumptions regarding the availability and quality of LCF, especially grass.

While Chapter 2 focussed on livestock, aquatic animals also can make a valuable contribution to food supply. Fish are, for example, currently our only natural source of the essential eicosapentaenoic (EPA) and docosahexaenoic (DHA) ω-3 fatty acids. In **Chapter 3** we explored the contribution of capture fisheries and fish farming (salmon and tilapia), to a circular food system

in an EU-28 case study. Similar to Chapter 2, we maximised HDP supply but in addition demanded that human requirements of nutrients currently only obtained from ASF are met (i.e. vitamin B12 and EPA/DHA). We demonstrated that, under the circular paradigm, fish provide nutritious food via both capture fisheries and fish farming. Capture fisheries should increase their food supply by rebuilding fish stocks and prioritising edible fish for human consumption. Sustainable fisheries, however, can fulfil only about 40% of the EPA/DHA requirement and, therefore, additional farmed fatty fish, such as salmon, are needed. These fatty fish, however, depend on fisheries by-products to meet their EPA/DHA requirements and on livestock slaughter by-products to meet their high requirements of other nutrients, such as energy and protein. Optimal use of LCF requires a combination of livestock and farmed fish and – given the assumed availability of LCF –can supply 35 g HDP per capita per day. A circular food system, therefore, requires a combination of co-dependent animal production systems (e.g. fish farming requires capture fisheries and livestock by-products) to achieve balanced healthy diets with respect for our planet.

While Chapters 2 and 3 illustrate how different animals can contribute to a circular food system, literature shows large variations in the estimated amount of ASF that can be produced when feeding only LCF. To a large extent, this variations is caused by differences in the assumed availability and quality of LCF. The availability of food leftovers as LCF is currently restricted by legislation and other barriers. To address the ongoing debate on what products can be considered LCF, we explored the potential of food leftovers currently not used as LCF due to legislation and other barriers (**Chapter 4).** To this aim, we compared the optimal use of currently used LCF with various scenarios that add food leftovers currently banned or not fully recovered as feed. Our results showed that of the considered food leftovers, household waste and livestock by-products had most potential to increase animal protein supply. Optimal use of currently used LCF (given their assumed availability) provides an intake of 27 g HDP per capita per day. Reintroducing household swill can increase this intake with 12%, while using livestock by-products in fish feeds increased protein intake with 18%, and is essential to meet human requirements of EPA/DHA ω-3 fatty acids. Feeding swill, however, requires legislative change while feed quality and safety remain difficult to safeguard even with the development of a collection and processing system. In contrast, livestock by-products are allowed in fish feed, but not used currently, indicating other barriers to the transition towards a circular food system. We concluded that improved use and legalisation of inevitable food leftovers can improve the resource use efficiency of both current and future circular food systems.

While the food systems approach, used in Chapters 2-4, provides valuable insights into the role of different animals in a circular food system, it provides little direction to farmers in achieving sustainability and circularity objectives. At present, food system actors base their sustainability strategies on farm or product-level life cycle assessments (LCA), which do not consider interlinkages in the food system. To divide the environmental impact between multiple outputs (e.g. flour and middlings) of a process (e.g. wheat milling), an LCA commonly uses economic allocation. As economic allocation does not consider whether the outputs are suitable for human consumption, it does not account for feed-food competition. In **Chapter 5**, we proposed that a "food-based" allocation – assigning no environmental impact to feed products unfit for human consumption – may better account for food-feed competition. To evaluate the impact of accounting for feed-food competition on LCA results, economic and food-based allocation were compared in an LCA of a novel egg production system that feeds only products unsuitable or undesired for human consumption. Using economic allocation, the global warming potential (GWP) of 1.13 kg CO_2-eq, energy use of 11.86 MJ, land use (LU) of 2.99 m^2, and land use ratio (LUR) of 1.70 per kg egg of the case study farm, were all lower than that of free range or organic eggs. Avoiding feed-food competition on this farm halved GHG emission, and reduced energy use, LU and the LUR with about one third compared to free range laying hens fed a conventional diet. With our food-based allocation methods impacts per kg egg further reduced with 57% for GWP to 0.49 kg CO_2-eq, 40% for energy use to 7.19 MJ, 96% for LU to 0.11 m^2, and 88% for LUR to 0.30. This illustrates that our improved LCA better captures the complexity of the food system.

To conclude **(Chapter 6),** optimal use of LCF requires a combination of livestock and farmed fish. Animals in a circular food system should be tailored to available LCF and the nutrients we wish them to supply, and the unique role of each animal depends on its feeding characteristics and the nutrients in the ASF it provides. In the simulated circular food system, where all LCF were allowed, livestock and fish provide an HDP intake up to 39 g per capita per day, and fulfil the full requirements of EPA/DHA and vitamin B12. While this HDP intake is significantly lower than the current supply of animal protein (61 g per capita per day), it fulfils up to 65% of total protein requirements. A circular food system, thus, requires a reduction in ASF consumption, and a change in the type of ASF we consume, where fish and milk become more prominent. Besides the discussed changes in farming systems and consumption patterns, the paradigm shift needed for the transition towards a circular food system requires that industries redesign their production systems and policy makers value social and economic aspects within the ecological boundaries of our planet. This way, farm animals can contribute to the resource use efficiency of the entire food system.

Samenvatting

In de toekomst moet ons voedselsysteem meer mensen voeden terwijl milieu-impact en gebruik van schaarse grondstoffen moeten worden beperkt. De Europese Unie (EU) wil daarom een meer circulair voedselsysteem, zoals in toenemende mate voorgesteld door wetenschappers. Een kernprincipe van een circulair voedselsysteem is dat agrarische grondstoffen, waar mogelijk, gebruikt worden voor directe voedselvoorziening om zogenaamde voer-voedselcompetitie te vermijden. Akkerland wordt dan gebruikt voor teelt van voedselgewassen en ook eetbare, duurzaam gevangen vis wordt gebruikt voor menselijke consumptie. Deze voedselproductie en -consumptie resulteren echter in voedselresten (d.w.z. bijproducten en afval) die mensen niet kunnen of willen eten. Productiedieren kunnen bijdragen aan een circulair voedselsysteem door deze voedselresten en gras (zogenaamde low-opportunity-cost feeds; LCF) om te zetten in dierlijk voedsel dat essentiële nutriënten voor mensen bevat. Een dieet met een klein aandeel dierlijk product, geproduceerd met enkel LCF, lijkt grondstoffen het meest efficiënt te gebruiken. Indien iedereen veganistisch wordt, worden LCF namelijk niet langer gewaardeerd in het voedselsystem. Voorgaande studies laten zien dat dieren enkel gevoerd met LCF 7 – 30 g humaan verteerbaar eiwit (HVE) per capita per dag kunnen leveren. Hoewel deze studies illustreren dat productiedieren wel degelijk een rol spelen in een circulair voedselsysteem, geven ze beperkt inzicht in de bijdrage van verschillende dieren in het efficiënt gebruik van LCF. Het doel van dit proefschrift is daarom om de potentie van verschillende productiedieren in het verwaarden van LCF in een circulair voedsel systeem te evalueren in een EU-28 casestudy.

In **hoofdstuk 2** verkenden we welke combinatie van veehouderijsystemen (varkens, leghennen, vleeskuikens, melkkoeien en vleeskoeien), verschillend in productieniveau (laag, midden, hoog), beschikbare LCF optimaal omzetten in HVE. Daarvoor hebben we een optimalisatiemodel ontwikkeld dat beschikbare plantaardige LCF toewijst aan de combinatie van dieren die het meeste HVE levert. We demonstreerden dat de optimale omzetting van plantaardige LCF een combinatie van veehouderijsystemen en productiviteitniveaus behoeft. Prominente veehouderijsystemen hebben een hoge voerefficiëntie (leghennen en melkkoeien), zijn in staat specifieke LCF te verwaarden (gras door melkkoeien, voedselafval door varkens) en kunnen laagwaardige LCF verwaarden door hun lage productiviteit. We concludeerden dat, onder de aangenomen beschikbaarheid van LCF, vee 31 g HVE per capita per dag kan leveren. Dit resultaat is echter gevoelig voor aannames betreffende de beschikbaarheid en kwaliteit van LCF, in het speciaal gras.

Hoewel we ons in Hoofdstuk 2 richtten op vee, kunnen ook waterdieren een waardevolle bijdrage leveren aan voedselvoorziening. Vis is, bijvoorbeeld, momenteel onze enige natuurlijke bron van de essentiële ω-3-vetzuren eicosapentaeen (EPA) en docosahexaeen (DHA). In **hoofdstuk 3** verkenden we daarom de bijdrage van visserij en kweekvis (zalm en tilapia) aan een circulair voedselsysteem. Net als in hoofdstuk 2 maximaliseerden we HVE, maar vereisten daarbij dat de behoefte aan nutriënten die mensen momenteel enkel uit dierlijk product opnemen (d.w.z. vitamine B12 en EPA/DHA) moet worden vervuld. We demonstreerden dat in een circulair voedselsysteem zowel visserij als viskweek voedzame vis leveren voor menselijke consumptie. Visserij dient de voedselopbrengst te verhogen door het visbestand te herstellen en menselijke consumptie van eetbare vis te prioriteren. Duurzame visserij kan echter maar aan 40% van de EPA/DHA-behoefte voldoen waardoor aanvullende kweek van vette vis nodig is. Deze vette vis is echter afhankelijk van visserij bijproducten om te voldoen aan hun eigen EPA/DHA-behoefte en veehouderij bijproducten voor hun hoge behoefte aan vet en eiwit. Optimaal gebruik van LCF behoeft een combinatie van vee en kweekvis die – gegeven de aangenomen beschikbaarheid van LCF – 35 g HVE per capita per dag kan leveren. Een circulair voedselsysteem behoeft daarom een combinatie van, van elkaar afhankelijke, dierlijke productiesystemen (b.v. kweekvis is afhankelijk van visserij en veehouderij) om te komen tot evenwichtige gezonde diëten met respect voor onze planeet.

Terwijl hoofdstukken 2 en 3 demonstreerden hoe verschillende dieren kunnen bijdragen aan een circulair voedselsysteem, variëren schattingen van de hoeveelheid HVE dieren enkel gevoerd met LCF kunnen produceren sterk in de literatuur. Veel van deze variatie is veroorzaakt door verschillen in de aangenomen beschikbaarheid en kwaliteit van LCF. Momenteel wordt de beschikbaarheid van voedselresten als LCF beperkt door wetgeving en andere barrières. In het licht van het aanhoudende debat over de geschiktheid van voedselresten als LCF, verkenden we in **hoofdstuk 4** het potentieel van voedselresten die momenteel niet als LCF gebruikt worden. We vergeleken daartoe het optimale gebruik van momenteel gebruikte LCF met scenario's die voedselresten toevoegen die momenteel verboden of niet (volledig) herwonnen worden als LCF. Van de overwogen voedselresten hebben huishoudelijk voedselafval en dierlijke bijproducten de meeste potentie om de toevoer van dierlijk voedsel te verhogen. Optimaal gebruik van momenteel gebruikte LCF (gegeven hun aangenomen beschikbaarheid) levert een inname van 27 g HVE per capita per dag. Herintroductie van huishoudelijk voedselafval kan deze inname met 12% verhogen, terwijl het gebruik van bijproducten van veehouderij in visvoer HVE inname met 18% verhoogde en essentieel is om de menselijke behoefte aan EPA/DHA te voldoen. Het voeren van huishoudelijk voedselafval behoeft echter wetswijziging terwijl voerkwaliteit en veiligheid moeilijk te waarborgen zijn, zelfs met de ontwikkeling van een verzamel- en verwekingsinfrastructuur. Bijproducten van veehouderij zijn daarentegen al toegestaan in visvoer, maar worden momenteel niet gebruikt; een indicatie van andere beperkingen in de transitie naar een circulair voedsel systeem. We concludeerden dat verbeterd gebruik en legalisering van onvermijdbaar voedselafval als LCF, zowel in ons huidige als in een circulair voedselsysteem, de efficiëntie waarmee grondstoffen worden gebruik kan verbeteren.

Hoewel de voedselsysteembenadering, gebruikt in hoofdstukken 2 – 4, waardevolle inzichten biedt over de rol van verschillende dieren in een circulair voedselsysteem, geeft het boeren weinig richting in het behalen van hun duurzaamheids- en circulariteitsdoelstellingen. Momenteel baseren actoren in het voedselsysteem hun duurzaamheidsstrategieën op levenscyclusanalyses (LCA's) op voedselketenniveau. Deze LCA's houden geen rekening met onderlinge verbanden tussen de verschillende ketens waaruit het voedselsysteem is opgebouwd door gebruik te maken van economische allocatie. Economische allocatie verdeelt de milieu-impact van processen die resulteren in verschillende producten (bijvoorbeeld: het malen van tarwe resulteert in meel en zemelen) namelijk op basis van hun relatieve economische waarde. Deze allocatie houdt geen rekening met de geschiktheid van producten voor humane consumptie en negeert daarmee voer-voedselcompetitie. In **hoofdstuk 5** stelden we voor dat voer-voedselcompetitie beter wordt gevangen door een "voedselallocatie", waarbij geen milieu-impact wordt toegekend aan voer ongeschikt voor humane consumptie. Om het effect van rekening houden met voer-voedselcompetitie in LCA te evalueren, hebben we economische- en voedselallocatie vergeleken in een LCA van een nieuw eierproductiesysteem dat enkel LCF voert. Onder economische allocatie was het aardopwarmingsvermogen (GWP) van 1.13 kg CO_2-eq, energieverbruik van 11.86 MJ, landgebruik (LU) van 2.99 m^2, en landgebruikratio (LUR) van 1.70 per kg ei van de casestudy, allemaal lager dan dat van vrije uitloop en biologische eieren. Het vermijden van voer-voedselcompetitie op deze boerderij halveerde broeikasgasemissies en verminderde energie en landgebruik met een derde in vergelijking met vrijeuitloophennen gevoerd met een conventioneel dieet. Met onze voerallocatie verminderde de impact per ei verder met 57% voor GWP tot 0.49 kg CO_2-eq, 40% voor energie gebruik tot 7.19 MJ, 96% voor LU tot 0.11 m^2, en 88% voor LUR tot 0.30. Dit illustreert dat onze verbeterde LCA de complexiteit van het voedselsysteem beter vangt.

In conclusie (**hoofdstuk 6**): optimaal gebruik van LCF behoeft een combinatie van vee- en kweekvissystemen. De dieren in een circulair voedselsysteem moeten worden afgestemd op de beschikbare LCF en gewenste nutriëntvoorziening; en de unieke rol van elk dier is afhankelijk van de voergewoonte en nutriënten die ze leveren. In het gesimuleerde circulaire voedselsysteem, waar alle LCF zijn toegestaan, leveren vee en vis samen 39 g HVE per capita per dag en vervullen ze de behoefte aan EPA/DHA en vitamine B12. Hoewel deze HVE inname significant lager is dan de huidige toevoer aan dierlijk eiwit (61 g per capita per dag) vervult het 65% van de totale eiwitbehoefte. Een circulair voedselsysteem behoeft niet enkel een afname in de consumptie van dierlijkvoedsel, maar ook verandering in welke dierlijk voedsel we eten, waarbij vis en melk prominenter worden. Naast de bediscussieerde veranderingen in boerderijsystemen en consumptiepatronen, behoeft de paradigmaverschuiving voor een circulair voedselsysteem herinrichting van de verwerkingsindustrie en dat beleidsmakers sociale en economische aspecten waarderen binnen de ecologische grenzen van onze planeet. Op deze manier kunnen dieren bijdragen aan de efficiëntie waarmee grondstoffen worden gebruikt in het voedselsysteem.

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About the author

Ollie van Hal was born in IJsselstein in 1989. In 2013 she obtained a BSc in Animal Husbandry from Hogeschool HAS Den Bosch (cum laude), where her graduation project, commissioned by AgentschapNL, addressed the environmental implications of welfare enhancing measures in pig production. In 2015 she obtained her MSc in Animal Sciences at Wageningen University (cum laude, 2015). In her thesis at the Adaptation Physiology group she assessed environmental influences on eliminatory behaviour of piglets with the ultimate aim to direct this behaviour to improve housing and reduce environmental impacts. In her second thesis at the Animal Production Systems group, she explored the potential of livestock on leftovers in the Spanish province Aragon. From September 2015 onwards, Ollie continued in this research domain with her PhD at the Animal Production Systems group, that explored the role of animals in upcycling biomass, such as food leftovers and grass, in a circular food system. This PhD was part of the "sustainable food and nutrition security (SUSFANS)" project and funded with a Horizon 2020 grant. For this PhD, Ollie developed an optimisation model to explore the role of different production animals (livestock and fish) in the efficient use of biomass unsuitable for human consumption. Findings of this thesis were presented at international conferences and published in peer-reviewed scientific journals. Since completing her PhD thesis in 2020, she has been working as Researcher Sustainable animal husbandry & agrobiodiversity at the Louis Bolk Institute. As a nature enthusiast, Ollie spends most of her free time outside gardening and exploring the countryside.

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van Hal, O., de Boer, I.J.M., Muller, A., de Vries, S., Erb, K.-H., Schader, C., Gerrits, W.J.J. and van Zanten, H.H.E. (2019). Efficiently upcycling food leftovers and grass resources through livestock. *Selected Abstracts of Aligning the Food System for Improved Nutrition in Animal Source Foods. Davis, California, USA.* https://nasfc.ucdavis.edu/abstracts

van Hal, O., de Boer, I.J. M., Ziegler, F., Schrama, J.W., Kuipers, K., & van Zanten, H.H.E. (2020). The role of fisheries and aquaculture in a circular food system. *Abstracts of the WIAS Annual Conference 2020: Frontiers in Animal Sciences p. 46.* https://edepot.wur.nl/517927

van Hal, O., van Zanten, H.H.E., Schader, C., Muller, A., Gerrits, W.J.J. and de Boer, I.J.M. (2017). Valuing leftover streams through livestock: impact of livestock system and productivity level. *Digital book of abstracts of the 3rd International Conference on Global Food Security Conference - Cape Town, South Africa*. https://edepot.wur.nl/431970

van Hal, O., van Zanten, H.H.E., Schader, C., Muller, A., Gerrits, W.J.J., de Vries, S. and de Boer, I.J.M. (2018). Valuing leftover streams through livestock: impact of livestock system and productivity level*. Abstracts of the WIAS Science Day 2018: Impact in Science and Society. p. 35.* https://edepot.wur.nl/445870

van Hal, O., Weijenberg, A. A. A., de Boer, I. J. M., & van Zanten, H. H. E. (2019). Avoiding feed-food competition in practice; Environmental impact assessment of a novel egg production system. *Abstracts of the WIAS Science day 2019, Keeping the balance p. 42-43*

van Zanten, H.H.E., van Hal, O. & de Boer, I.J.M. (2016). How much animal-source food can we produce while avoiding feed-food competition? *Book of Abstracts of the 67st Annual Meeting of the European Federation of Animal Science, Belfast, Ireland.* Wageningen Academic Publishers, EAAP vol. 22, p. 102.

Scientific reports

van Zanten, H. H. E., van Hal, O. & de Boer, I. J. M. (2016). Report on T4.1: Deliverable No. 4.1: The drivers of livestock production in the EU. *SUSFANS Deliverable No. D4.1, 66p.* http://susfans.eu/system/files/public_files/Publications/Reports/SUSFANS%20D4.1_V1.pdf?_ga=1.220584016.995999759.1483713582

van Zanten, H. H. E., van Hal, O., Ziegler, F., Hornborg, S., Latka, C., Parodi, A., Achterbosch, T. J., Bianchi, M., de Boer, I. J. M., Borthwick, L., Burgstaller, E., Heckelei, T., Leip, A. & Valin, H. (2019). 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. *SUSFANS Deliverable No. D5.4, 84p. https://edepot.wur.nl/476875*

Education certificate

Completed training and supervision plan[1]

Basic package	**3 ECTS**
WIAS introduction day	2015
Essential skills	2015
Philosophy of science and ethics	2016

Disciplinary competences	**15.2 ECTS**
Quantative analysis of land use systems	2016
Writing research proposal	2016
Rundveevoeding	2016
Environmental impact assessment of livestock systems	2017
Workshop food safety & food waste (UC Davis)	2019

Professional competences	**1.8 ECTS**
Project and Time management (PTM)	2018
Brain friendly working and writing	2020

Presentation skills	**4 ECTS[2]**
Poster, WIAS science day, Wageningen, The Netherlands	2016-2019
Theater, LCA Food, Dublin, Ireland	2016
Theater, SUSFANS stakeholder meeting, Vienna, Austria	2017
Poster, Global Food Security, Cape Town, South Africa	2017
Theater, LCA Food, Bangkok, Thailand	2018
Poster, Aligning the food system, Davis, California, USA	2019
Theater, WIAS annual conference, Lunteren, The Netherlands	2020

Teaching competences	**6 ECTS[2]**
Thesis supervisor, 3 BSc theses	2016-2017
Thesis supervisor, 4 MSc theses	2018-2019
Project supervisor, Introduction animal sciences	2017
Lecturer, Future food systems	2018-2020
Practical supervisor, Global sustainable animal production	2016-2017
Practical supervisor, Sustainability assessment of animal systems	2016-2019

Education and training total	**30 ECTS**

[1] With the listed activities, the PhD candidate complied with the educational requirements of Wageningen Institute of Animal Sciences (WIAS) a Wageningen University & Research graduate school. One ECTS equals a study load of 28 hours.

[2] Listed activities provided more ECTS than granted by WIAS regulations

Colophon

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