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REVIEW

Farmed animal production in tropical circular food systems

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Abstract
In the discourse about the development of farmed animal production (terrestrial livestock production and aquaculture) in the tropics, two important food system outcomes emerge: (1) to supply animal-sourced food (ASF) at a level that suffices healthy future diets, including for poor people, and (2) to contribute to climate change mitigation and minimize pollution with nitrogen and phosphorus. Livestock production and aquaculture contribute to food security directly by increasing producers' food diversity and availability, but also that of urban consumers, and indirectly through income generation and increased farm resilience. Recently, circularity has come to the fore as an integrated approach to food system development. Circularity has four cornerstones: (1) food crops have highest priority (which implies no food-feed competition), (2) avoid losses, (3) recycle waste and (4) use animals to unlock biomass that humans cannot eat. In this review, the role of farmed animals in circular food systems in the tropics is presented in four case studies and the impacts of circularity on food security and environmental impact mitigation are discussed. The cases are ruminants in grazing systems in West Africa and in Colombia, fish in pond aquaculture in general, and land-limited dairy production in Indonesia. Additionally, options for novel protein sources for use in livestock and fish feeding are presented. It is concluded that farmed animals are important in circular food systems because of their use of land unsuited for crop production, their upgrading of crop residues, and their supply of manure to crop production. Nevertheless, the increasing demand for ASF puts pressure on important characteristics of circularity, such as minimizing food-feed competition, maximization of use of waste streams in feed, and the value of manure for fertilization. Hence, in line with conclusions for Western countries, maximum circularity and sustainability of food systems can only be achieved by optimizing the population size of animals. Thus, a sustainable contribution of ASF production to global food security is complex and in not only a technical matter or outcome of an economic process balancing supply and demand. It requires governance for which public, private, and social actors need to partner.

Keywords Livestock production · Aquaculture · Climate change mitigation · Pollution · Farming systems

1 Introduction

Farmed animal production, which includes terrestrial livestock production and aquaculture, is part of food systems. A food system *encompasses the entire range of actors and their … activities involved in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture, forestry or fisheries, and parts of the broader economic, social and natural environments in which they are embedded* (Van Berkum et al., 2018).

Food system outcomes relevant for production of Animal Sourced Foods (ASF) are food security, and environmental impacts. Food security implies that ASF are supplied and accessible at a level that suffices healthy future diets,

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including for poor people (Oosting et al., 2014)). The rising demand for ASF in tropical regions is an important issue for food security and will be addressed in Sect. 1.1. Major environmental isues are greenhouse gas (GHG) emissions (Gerber et al., 2011; Özkan et al., 2015; World Bank, 2019), and many countries have included farmed animal production interventions in their Intended Nationally Determined Contributions (FAO, 2018), pollution with nitrogen (N) and phosphorus (P) and land- and water use (World Bank, 2019). Some background information about the environmental issues associated with ASF production is presented in Box 1. Section 1.2 will compare GHG emission and land use impacts among different ASFs and plant sourced foods.

One additional food system outcome for which farmed animals are important is inclusiveness. Farmed animals have many roles and functions in farming systems. Beyond food production, they have cultural and societal functions such as for dowry, and sacrifices during religious festivities; they have financial and insurance functions which are specifically important to the poor; they may provide regular small income to women and children in a household, and they may provide status (Moll et al., 2007; Oosting et al., 2014; Rao et al., 2021; Udo et al., 2011). Such functions of farmed animals are most important in subsistence farming systems. Development of farmed animal production into market-orientated production will impact such functions and consequently the vulnerable groups.

Box 1 Environmental issues and animal- source food (ASF) (adapted from World Bank (2019))

Environmental issues associated with production of animal-sourced foods (ASF) fall into three categories	
Land and water use	Within agriculture, ASF production is the largest user of land and water resources. The sector uses most of the world's grasslands and more than a third of the world's arable land for feed production, as well as the irrigation and rainwater used on those lands. Livestock uses these resources predominantly for feed production, with four broad impact pathways: (1) *Conversion of forests and other natural vegetation to feed-crop land and pasture* results in loss of biodiversity, depletion of aquifers, and GHG emissions (when soil organic matter turns into carbon dioxide and methane). (2) *Competition with food crops for land and water*. Of the world's two billion hectares of grassland, one third could potentially be used as cropland. Feed production uses about a third of agricultural water. Livestock production is generally less efficient than crop production in terms of production of human food per unit of arable land. This affects the efficiency of food systems and limits use for other potential functions. (3) *Terrestrial livestock production can cause land degradation*. Overgrazing affects vegetation cover and potentially results in productivity losses, soil erosion, carbon losses, and adverse impacts on biodiversity and water cycles. Land degradation can also be a long-term process, when nutrients extracted from the soil by grazing or feed production are not replenished, e.g., by fertilization. (4) *Pollution of water and land resources* by pesticides, chemicals and other unwanted substances such as metals and organic residues ending up in the ecosystem. These may affect flora and fauna, fisheries, recreation, and drinking water
Greenhouse gas emissions (GHG)	Emissions from ASF production have been estimated to contribute 14.5% of global anthropic emissions of GHG. The largest contributor is methane (about 44% when expressed in CO_2-equivalents), followed by nitrous oxide accounts (29%), and carbon dioxide (27%). Emissions from ASF production account for 44% of global anthropogenic methane, 53% of global anthropogenic nitrous oxide, and 5% of global carbon dioxide emissions. Four major sources of GHG emissions from livestock production occur: (1) *Emissions from the production, processing, and transportation of feed*, accounting for about 45% of all ASF-related GHG emissions. (2) *Enteric methane emission* from the rumen of cattle, sheep, and goats during the digestion of feeds (about 40% of emissions, 77% of which comes from cattle). (3) *Emissions associated with land use change* (see above) (< 10% of emissions). (4) *Emissions from manure storage and handling* that generate methane and more importantly nitrous oxide emissions (about 10% of all ASF-related emissions). Fishponds with anaerobic conditions in the sediment may also emit methane and nitrous oxide
Nitrogen (N) and phosphorus (P) pollution of land, water and air	N and P are important nutrients for crops, grassland, and livestock. In agricultural systems, these nutrients cycle from soil to crops and grass, to livestock via feed, and back to the soil via manure. Ideally, these nutrient cycles happen with minimal losses. When substantial, losses can cause N and P pollution that results in i) eutrophication (excessive growth of algae in water) that may lead to "dead zones" in aquatic systems; and ii) acidification of rain and soils that may affect vegetation and aquatic life. Most N and P losses from livestock production are either associated with animal manure management or with the fertilization of feed crops and grazing lands. They take place at three stages of the supply chain. (1) *Manure collection and storage* (for processing and/or recycling), when N and P may be lost as gaseous components or may leach away. The liquid part of manure occasionally is discarded into the environment, causing severe pollution of water, air, and soils. (2) *Processing of manure and slurry* (manure mixed with urine) through drying, composting, biogas production, mixing into compound fertilizers, incineration, and aerobic treatment. This can improve N and P recycling and thus be beneficial to the environment. Done improperly, processing contributes to N and P losses. (3) *Application of manure and synthetic fertilizer to crops and grassland* may result in N and P losses through leaching, runoff, and volatilization. Losses may result from high application rates and poor phasing with plant uptake.

1.1 Food security: rising demand for animal sourced foods

Farmed animal production contributes to human food security; for many people in low- and middle-income countries, milk, fish and eggs are frequent components of the daily diet. Meats, such as beef, pork, mutton, and poultry, often are consumed less frequently, e.g., only at festivities. Rising incomes shift consumption from plant-sourced food to ASF. ASF has a high income elasticity of demand (International Food Policy Research Institute, 2017), which implies that an increase in income brings a considerable increase in demand (Speedy, 2003). Specifically in low income countries, the rise in ASF consumption per unit increase in income is high, as illustrated in Fig. 1 for countries in Asia. With rising gross national product, the consumption of ASF increases, plateauing at a level of 50–60 g of animal protein consumption per capita per day.

Urban dwellers eat diets with a higher proportion of ASF than rural dwellers. As the rate of urbanization is high in many tropical regions, urbanization also increases demand for ASF and so does population growth (Pica-Ciamarra & Otte, 2011).

It could be questioned whether this rising demand should be met. Potentially, human beings can live without consuming ASF, though balancing nutrient supply from vegan diets requires knowledge and access to a diverse food basket. This is often not the case for poor people. Hence, many countries have included ASF in their National Dietary Recommendations (NDRs; FAO, 2018). The NDRs are country-specific dietary guidelines that address public health and nutrition priorities and accessibility of foods. Nutritional reasons to include ASF in NDRs encompass that ASF provide proteins with a high bioavailability and an amino acid profile meeting human requirements (Elmadfa & Meyer, 2017) and that they are important sources of micronutrients such as zinc, selenium, iron, vitamins A, B12 and folic acid (Beal et al., 2021; Biesalski, 2005), specifically for the world's poor (Adesogan et al., 2020). Aquatic ASFs are also a good source of highly unsaturated fatty acids. Meeting NDRs for a whole population will prevent nutrient deficiencies, including poor people. Aquaculture and livestock production may benefit food security of poor farmers either by direct provision of ASF to household consumption, but also indirectly as a source of income for which additional food can be purchased and by diversifying farms and thus increasing resilience of food production (Abu Hatab et al., 2019; Ahmed & Waibel, 2019; Fraval et al., 2020; Megersa et al., 2014).

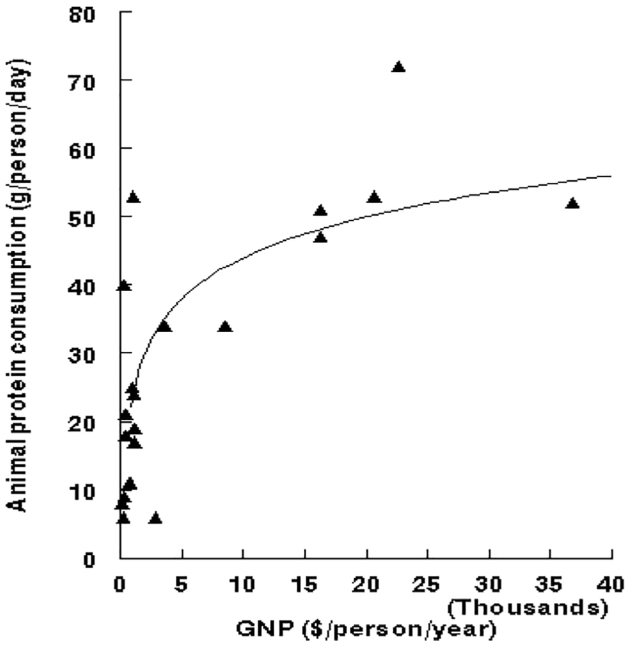


Fig. 1 Gross national product (GNP) and animal protein consumption in Asian countries (source FAO, 2020a)

On the other hand, ASF can be overconsumed. Matena (2018) compared actual daily consumption of dairy, eggs, and meat by diverse income strata and found that (i) poor strata consume considerably less than the NDRs in Africa and Asia, (ii) rich strata consume approximately according to NDRs in Africa (with overconsumption in some countries occurring), but they overconsume in all other continents. Over- and underconsumption of ASFs may occur concomitantly within the same country. Overconsumption of ASF is unhealthy, especially of ASF derived from terrestrial livestock, because ASF is rich in saturated fatty acids and high ingestion of such saturated fatty acids may cause hypercholesterolemia and cardio-vascular diseases (Muehlhoff et al., 2013). Hence, meeting NDRs with ASFs is partly a matter of distribution, though sub-Saharan Africa (SSA) and South and Southeast Asia (SSEA) have, on average, a considerable gap between actual average consumption and NDRs for dairy and eggs, and in some countries for meat. Therefore, future food systems in SSA and SSEA will require production of ASF at levels that are higher than those of today to meet nutrition security of many poor people. However, associated with this requirement a discourse developed about the sustainability of such future ASF production because of the impacts ASF production has on the environment and on the use of natural resources including land and water.

1.2 Environmental issues associated with farmed-animal species and their products

The environmental issues associated with ASF production, as outlined in Box 1, depend on the farming system and on farmed animal species kept. Table 1 presents GHG

Table 1 Greenhouse gas emissions and land use associated with production of protein rich foods (Source: Poore & Nemecek, 2018)

Protein rich foods	Greenhouse gas emissions (kg CO_2-e/100 g protein)		Land use (m^2/year/100 g protein)	
	Average	10th percentile	Average	10th percentile
Animal-sourced foods				
Beef	50	20	164	42
Lamb & mutton	20	12	185	30
Cheese	11	5.1	41	4.4
Pig meat	7.6	4.6	11	4.8
Fish (farmed)	6.0	2.5	3.7	0.4
Poultry meat	5.7	2.4	7.1	3.8
Eggs	4.2	2.6	5.7	4.0
Plant sourced foods				
Tofu	2.0	1.0	2.2	1.1
Groundnuts	1.2	0.6	3.5	1.8
Peas	0.4	0.3	3.4	1.2
Nuts	0.3	−2.2	7.9	2.7
Grains	2.7	1.0	4.6	1.7

emissions and land use associated with ASF and some plant sourced foods, as derived from a meta-analysis of published life cycle assessment studies of agricultural production by (Poore & Nemecek, 2018). Ruminant meat production has the highest mean GHG emission intensities (emission of GHG expressed as CO_2-equivalents per 100 g protein produced), followed by milk production (represented by cheese in Table 1), fish, pig and poultry production. All ASFs have higher GHG emission intensities than plant sourced food products. The variation in emission intensities (for which the difference between the mean and the 10th percentile is used as a proxy) for ASF is high, indicating that there are farms with low and farms with high emission intensities. This implies that there is room for GHG emission mitigation by addressing farms with high GHG emission intensities. One important determinant of GHG emission intensities within an ASF product is the production per animal. A high production per animal implies that the emissions associated with the animal's maintenance are diluted across many liters or kilos of produce (Gerber et al., 2011), which is not the case for animals with a low production. An example of the relationship between production per animal and GHG emission intensity for milk production is given in Fig. 3.

Land use is also higher for ruminant ASF than for plant-sourced foods, whereas fish, pigs, and poultry are at equal level with plant-sourced foods with highest land use (Table 1). It is important to realize that ruminant meat and milk are often produced on lands unsuited for crop production, whereas intensive fish, pig, and poultry production require relatively high quality feeds grown on crop lands that could have been used for human food crops directly.

1.3 ASF production in circular food systems

Recently, circularity has come to the fore as an integrated approach to develop food system sustainably. Circular food systems are food systems with four important cornerstones: they (1) use arable land and water bodies primarily to produce food for direct human consumption, (2) avoid or minimize food losses and wastes, (3) recycle by-products (such as crop residues, co-products from processing, manure, excreta), inevitable food losses, and waste streams back into the food system, and (4) use animals to unlock biomass with low opportunity costs for humans into value-food, manure, and ecosystem services. As a result, circular food systems apply practices and technologies that minimize the input of finite resources (e.g., phosphate rock, fossil fuel, and land), encourage the use of regenerative ones (e.g., wind and solar energy), prevent leakage of natural resources from the food system (e.g., of N and P), and stimulate recycling of inevitable resource losses in a way that adds the highest value to the food system (De Boer & Van Ittersum, 2018; Van Zanten et al., 2019).

Farmed animals have a role in circular food systems: waste stream biomass can be used as feed, and farmed animals provide manure and pond sediment which can be used as fertilizer to maintain or improve soil quality. The use of waste streams for feed may reduce the need for feed production with associated GHG, land and water use, and N and P pollution. Maximization of the use of manure and pond sediment for fertilization may prevent losses of these nutrients. Figure 2 illustrates the flow of biomass in a circular food system.

The increasing demand for ASF drives intensification of farmed animal production. Improved feeding is an important intervention to achieve this intensification. Hence, cultivation of feed crops such as maize and soybean, and of improved forages is increasing. This, however, often happens on land which is suitable for cultivation of human food crops. Since circular food systems should use arable land for production of human food crops and not for feed crops, intensification has a trade-off with circularity of food systems. This is being referred to as food-feed competition.

Studies by Van Hal, 2020; Van Kernebeek et al., 2014; and Van Zanten et al., 2019, indicate that protein consumption from ASF could be maintained at levels between seven and 36 g per capita per day, if livestock and fish would only consume feeds from waste streams and from lands (and water bodies) unsuited for human food crop production. Present protein consumption from ASF is close to 60 g per capita per day in wealthy countries (see Fig. 1). Circular food systems will therefore imply reduced ASF consumption

Fig. 2 Flow of biomass in a circular food system (Muscat, 2021)

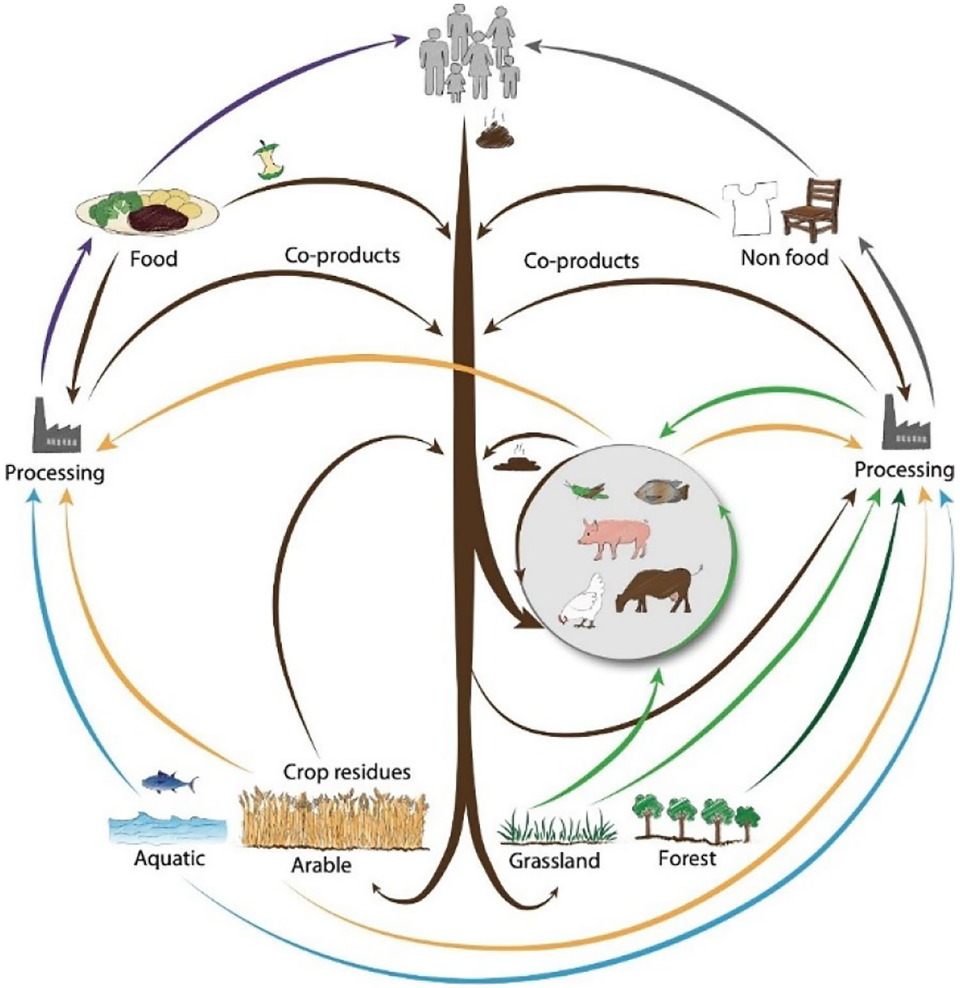
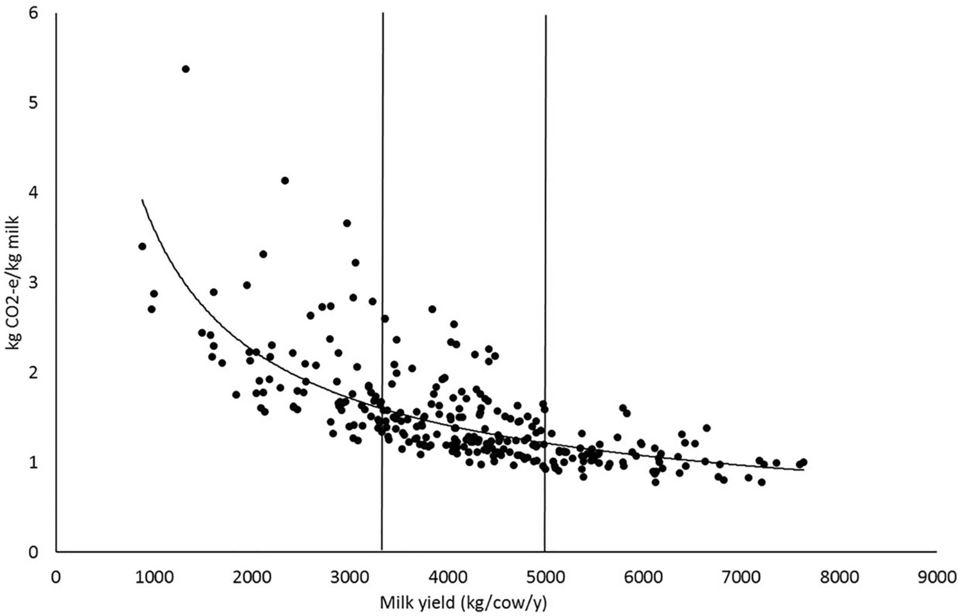


Fig. 3 Relation between GHG emission intensity (y-axis) and milk yield per dairy cow (x-axis) in the Lembang district Indonesia (Source: De Vries et al., 2019))



in wealthy countries, which complies with dietary adjustments proposed to achieve healthy diets in the EAT-Lancet report (Willett et al., 2019).

1.4 Objective of this paper

Under reduced ASF consumption scenarios, circular food systems with farmed animals have potential to meet the food system outcomes of sufficient ASF production, and minimal environmental impacts concomitantly (De Boer & Van Ittersum, 2018; Van Hal, 2020; Van Zanten et al., 2016). It is, however, yet to be explored to what extent production systems with farmed animals have this potential in the tropical regions of SSA, SSEA, and Latin America and the Caribean (LAC). The present review, will explore this potential. The dilemma will be presented between intensification of ASF production on the one hand to meet objectives of increasing ASF supply and climate change mitigation, and increased circularity. Since circularity of food systems implies avoidance and recycling of wastes, a circular food system will have limited N and P pollution. In addition, circular food systems will prioritize resource use for food crop production over other uses and therefore have limited food-feed competition.

In Sect. 2 we describe the major farmed animal species and the farming systems they are found in. In Sect. 3 we give examples of present and possible contributions of farmed animals and farming systems to circularity in food systems. In Sect. 4 we address the potential of novel proteins that support the role of farmed animals to meet the objectives of sufficient ASF production and minimal environmental impacts in circular food systems. Section 5 contains discussion and conclusions.

2 Farmed animal species and livestock farming systems in tropical regions

2.1 Major farmed animal species

Different species of farmed animals are found in different farming systems with different ASF output levels, and impacts on the environment. Development trends of farming systems affect the performance of farms regarding these objectives.

In this review we consider the following farmed animal species:

2.1.1 Cattle

Cattle are kept for meat production, referred to as beef cattle, and for milk production, referred to as dairy cattle. Cattle do, however, have important additional functions too: draught power for land preparation, production of manure for crop fertilization, capital asset, insurance, social and cultural functions, and status (Moll et al., 2007; Oosting et al., 2014). In SSEA, water and swamp buffaloes are equally important as cattle for milk production and tilling of rice fields, and the same is true for camels in parts of Africa and Asia (Hoffmann et al., 2014).

2.1.2 Sheep and goats

Sheep and goats, together referred to as small ruminants, are important livestock species for the poor (Udo et al., 2011), but the income derived from keeping them is relatively low. Therefore, they are mostly kept in extensive systems for meat production and they have a key role in religious festives, and are an important small capital asset to be sold for cash needs. Goat and sheep populations in Africa and Asia are growing by approximately 2.5–3.5% per annum for goats and 1.1% per annum for sheep, which is slightly higher than the growth of cattle populations in both continents (Mazhangara et al., 2019).

2.1.3 Pigs and poultry

Pigs and poultry are monogastrics, which implies that they need better quality feed than ruminants. Pigs and poultry are either kept in backyard systems where they scavenge their own feed, supplemented with household wastes, or in intensified systems, which require investments in housing, feed, and disease control. In low-middle income countries, intensive pig and poultry production are the most rapidly growing livestock sectors and are seen as the major future supplier of ASF (Herrero et al., 2013).

2.1.4 Fish

Aquaculture in inland ponds is a growing contributor to the world supply of ASF. Fish farmed in ponds consists mainly of herbivore, omnivore, and filter feeding species. This feeding behavior allows the inclusion of plant-based by-products in the feed (Hua et al., 2019). Ponds are not only production systems, but also complete ecosystems, in which algae and bacteria grow on nutrients and energy from waste streams and contribute to water purification, and supply natural foods. Today, the majority of fish in ponds are fed formulated pelleted feeds (Tacon, 2020), constituting the main source of waste, besides crop residues, livestock manure or kitchen waste applied to complement pelleted feed (Pucher & Focken, 2017). The sediment of fish ponds, where a large fraction of input nutrients accumulate, may be used as a crop fertilizer.

2.2 Farming systems with farmed animal species

Geographical distribution of farmed animal species and farms is not random. The World Bank (2019) considers different farming system-farmed animal species combinations, which are associated with different locations in the world. For the present review, the following four farming system-farmed animal species combinations are relevant (Oosting et al., 2014; World Bank, 2019):

2.2.1 Dryland grazing systems

In dryland regions, mobile grazing systems with pastoralists herding ruminants are dominant. Dryland regions are too dry for crop production and herding is the only agricultural activity supporting livelihoods. Because of the harsh conditions in dryland regions, human and livestock population densities are low. Pastoralist herding systems are extensive and have a low production per animal and, consequently, products come with a high emission intensity. In line with Udo et al. (2016), the emissions of pastoralist herding systems should not be allocated to the ASF produced by ruminants only but also to the other functions and services they provide, i.e., cultural (e.g. maintaining rare animal breeds), ecological (e.g. contribution to the dynamics of natural grasslands), and agricultural (provision of manure to crop farmers) (Ayantunde et al., 2011; Tamou et al., 2018). Traditionally, pastoralist systems exist in symbiosis with crop systems, in part because of exchange of food, but also because pastoralists require grazing on crop residues during the dry season, whereas crop-farmers benefit from manure deposited during grazing (Ayantunde et al., 2011; Tamou et al., 2018; Zoma-Traoré et al., 2020).

2.2.2 Semi-arid to semi-humid grazing systems

In regions with semi-arid to semi-humid conditions, animal rearing is generally limited to grazing ruminants for meat production. These regions could potentially be used for crops or were once covered by forests. Soil depletion after deforestation and use as crop land may have caused the current situation where extensive ruminant production on grassland is the only possible economic activity. Meat production is often a two-stage activity: first stage consists of a relatively long pre-fattening period with low growth rates on relatively poor pastureswith relatively high GHG emission intensities, and a second stage of intensive fattening at feedlots. Feedlots are landless systems where beef animals have a high growth rate, with relatively low emission intensities, but with high levels of nutrient accumulation and consequently high risk of N and P pollution. Moreover, fattening at feedlots requires high levels of feeds produced on land suitable for crop production (Poore & Nemecek, 2018; World Bank, 2019).

2.2.3 Mixed crop-livestock and aquaculture systems

Due to relatively favorable conditions, these systems are found at farms in relatively densely populated regions, where farms are small. High levels of integration between activities at a farm are observed; various species of livestock are kept to feed on residues of crop production and household wastes, in addition to collected grass or grazing on communal and public lands. Manure is used as nutrient input for fish production in ponds (Phong et al., 2010) of which the sediment may be used for fertilization. Animal productivity is low, hence the GHG emission intensity is relatively high, but part of the emissions should be allocated to non-ASF production functions of animals such as facilitation of crop production (manure, traction and store of cash) and livelihood support (store of wealth, status, insurance) (Moll et al., 2007; Udo et al., 2016). Intensification of mixed crop-livestock and aquaculture systems may lead to specialized farms which may be characterized as (semi-)industrial systems, since they import the inputs and no longer have crop and other activities at the farm to integrate with. Intensification of mixed crop-livestock and aquaculture systems often affects the feeding management. The required feed quality increases, which reduces the use of waste streams in and between farms.

2.2.4 (Semi-)industrial systems

(Semi-)industrial systems, often with poultry, pigs, aquaculture, and dairy, are found in densely populated regions with nearby markets and good infrastructure, allowing farms to source feed externally and market produce with limited transaction costs. Productivity is high, hence GHG emission intensities are relatively low. Industrial systems use high quality feeds (e.g. maize and soybean—often as soybean meal) and consequently land and water use for such systems compete with human food crop production. Deforestation in LAC to produce soybean for intensive farmed animal production in Europe and Asia goes beyond food-feed competition. It leads to loss of biodiversity in a global biodiversity hotspot, it releases sequestred soil-carbon into the athmosphere thus contributing to climate change, and the agricultural practices often result in soil degradation (Pacheco et al., 2021). Moreover, industrial farms have a risk of polluting the environment with N and P. Uwizeye (2019) reported that, with a contribution of 76%, feed production is the primary contributor to total N losses, whereas losses from pig housing and manure management contribute 22% to total N losses, and post-farm activities contribute only 2%.

3 Contribution of farmed animals to circular food systems

At present, farmed animals play an important role in circularity of food systems in tropical regions. Scarcity of feed inputs and fertilizers make crop residues, agro-industrial by-products, and manure valuable inputs in most farming systems. This section reviews the contribution of the farmed animals-farming system combinations described above to circular aspects of food systems, using several specific cases as examples. It focuses on ASF supply, GHG emissions, and on performance of these systems within circular food systems outlined above.

3.1 Ruminants in grazing systems (dryland, semi-arid, semi-humid)

3.1.1 Pastoralist herding systems

Traditional pastoralist herding systems are found in regions where production of human food crops is not possible for biophysical reasons. Hence, there is no direct competition for land use with human food crop production. Regarding avoidance of wastes, pastoralist herding systems exploit dryland grazing areas and the biomass growing there. If not grazed, the biomass will turn dry and not be utilized. Pastoralists have extensive traditional ecological knowledge about utilizing land and water in a way that is in line with the natural dynamics in these regions.

Regarding recycling of waste, in the dry season the pastoralists' herds provide manure to crop lands while grazing crop residues. Hence, pastoralist systems use animals for what they are good at, i.e., turning low-opportunity cost biomass into valuable food.

Present day developments, unfortunately, put enormous pressure on pastoralist systems. Crop land regions are being used more intensively, often through use of (subsidized) synthetic fertilizers, which severely reduces the value of manure for crop farmers. Grazing of crop residues either becomes unavailable or can only occur with payment (Rao et al., 2021). Traditional trekking routes become inaccessible due to expanded land use. As a consequence, conflicts between pastoralists and crop farmers become frequent, overgrazing of grassland regions occurs, and vulnerability to climate change increases (Ayantunde et al., 2011; Rao et al., 2021; Tamou et al., 2018). Prioritization of crop production near regions with pastoralism, therefore, may have negative effects on circularity of the combined food systems in the region and makes part of the food system unsustainable. Re-establishing the symbiosis between crop farmers and pastoralists could be a way to sustainable development.

3.1.2 Silvo-pastoral systems in LAC

In semi-arid to semi-humid regions, where beef production occurs on lands that could potentially be used for crop production or forest, land degradation is a risk. In many parts of the tropics, almost 80% of forests are cleared to establish extensive pasture dedicated to animal grazing with low stocking rates (McGroddy et al., 2015). For instance, in Colombia the expansion of agriculture for grassland was and is one of the main drivers of deforestation (Dávalos et al., 2014; Graesser et al., 2015). Cattle are managed in large-sized paddocks with a stocking rate of approximately 0.6 animals ha^{-1} (Teutscherová et al., 2021). Pasture productivity is low, and seasonal rainfall, continuous grazing and compaction of soils may result in land degradation (World Bank, 2019). Silvopastoral systems (SPSs) have been proposed as a sustainable alternative to traditional grassland systems (Somarriba et al., 2012; Tapia-Coral et al., 2005) in LAC. SPSs are a type of agroforestry considered by FAO as a climate-smart agricultural practice (Harvey et al., 2014) that also meet some of the circularity cornerstones: SPSs only minimally compete with food crop production since they are on land unsuited for crop production, or they even make food crop production possible on previously degraded land, they avoid wastes by making degraded land productive again, and animals are being used to unlock biomass unsuitable for direct human consumption.

SPSs combine cattle, fodder plants such as native or introduced grasses and legumes, and trees and shrubs (native, timber, fruit, legumes) for animal nutrition and complementary uses such as windbreaks, shade, timber, and fruit for household consumption or income generation (Murgueitio et al., 2011; Solorio et al., 2011). SPSs may have diverse settings such as dispersed trees, tree-alley pasture, fodder banks, and pasture with live fences and windbreaks. Under relatively favourable conditions SPS may include food crop production in a mixed crop-livestock system (Chará et al., 2019; Pezo et al., 2008). Compared with traditional grassland systems, SPSs present higher forage productivity that improves the quantity and quality of the diet, improving animals' welfare, productivity, and stabilizing reproductive parameters over time (Dagang & Nair, 2003; Yamamoto et al., 2007). Better nutritional conditions have been shown (Chará et al., 2009) to reduce methane (CH_4) enteric emissions by 21% and nitrous oxide (N_2O) emissions by 36%. At the same time, high-quality food available from SPSs throughout the year (Broom et al., 2013; Feliciano et al., 2018), could contribute to reduced need for land conversion and deforestation (Luedeling et al., 2014; Matos, 2011; Mbow et al., 2014).

In these SPSs, animal welfare is improved. The incorporation of shrubs and trees reduces air temperature by 2–3 °C and soil surface temperature by as much as 13 °C (Cubillos et al., 2016). Shade of the trees has many beneficial effects: cattle skin temperatures and less sun exposure reduce sun-burn, cancer, and photosensitisation (Rowe, 1989). Increased biodiversity and number of natural predators lowers the populations of ticks, harmful insects, and the incidence of diseases which leads to a reduction of use of insecticides and antibiotics.

SPSs have a positive effect on carbon sequestration and consequently on GHG emission mitigation since they increase above and belowground biomass and they reduce soil erosion (Lorenz & Lal, 2014). In dry tropical conditions in Mexico, López-Santiago et al. (2019), reported that SPSs contained more aboveground biomass (approximately 40 Mg DM ha^{-1}) than grass systems (< 10 Mg DM ha^{-1}), and greater belowground biomass (approximately 16 Mg DM ha^{-1}) than deciduous tropical forest and grass systems (approximately 8.4 and 1.4 Mg DM ha^{-1}, respectively).

Pruning, N-binding through leguminous trees and forages and other management practices may contribute to build-up of soil organic matter (SOM) (Murgueitio et al., 2007). Besides contributing to C-sequestration, a higher SOM improves soil water holding capacity, among other properties such as cation exchange capacity, porosity, and infiltration.

SPSs can provide benefits to farmers by enhancing nutrient cycling, fodder production for animals, and diversification of income (Ibrahim et al., 2011; Yamamoto et al., 2007). The incorporation of leguminous species such as *Leucaena leucocephala* or fodder banks with legumes, enhances symbiotic N fixation (from 52 to 400 kg N ha^{-1} $year^{-1}$ depending on the variety, density, and environmental conditions; Cubillos et al., 2016; Murgueitio et al., 2007). N-fixation, SOM contribution, and a homogeneous distribution of animal excreta and urine contribute to increasing the efficiency of the system in the use and recycling of nutrients. Intensive rotational grazing management practices in SPSs, results in a better use of the available forage species and the development of denser sprouts with a higher proportion of leaves and lower fiber content (Senra et al., 2005). As a result, SPSs could increase system productivity, i.e., SPSs enhanced livestock productivity up to four times compared to conventional, extensive livestock systems (Montagnini et al., 2013). In addition, because of the integration and recycling in the system, SPSs are relatively independent on external agricultural inputs such as inorganic fertilizer and concentrates (Anguiano et al., 2012; Yamamoto et al., 2007). In summary, SPSs is a circular restoration intervention, with positive effects on food production and environmental impacts.

3.2 Fish in pond aquaculture

Pond aquaculture may have three manifestations of circularity at three scale levels: within the pond, within the farm (often mixed crop-livestock systems with fish), and within the broader food system. Inland and coastal ponds are the major fish farming systems in SSEA and contribute more than 75% to global farmed fish and shrimp production (FAO, 2020b).

Fish farming in ponds may not directly compete with human food crop production. Many ponds are fertilized with left-overs, manure, and kitchen waste. An example are the semi-intensified systems in Bangladesh (Belton & Azad, 2012) that produce fish by application of a combination of organic fertilizer, kitchen waste, home-made feed from local agricultural by-products, and commercial feed (Henriksson et al., 2018; Jahan et al., 2016; Mamun-Ur-Rashid et al., 2013). Commercial feeds produced in Bangladesh account for ~ 2 million metric t (Mamun-Ur-Rashid et al., 2013) and 90% of the ingredients are by-products from other agricultural activities (Kabir et al., 2017; Mamun-Ur-Rashid et al., 2013). Food-feed competition, therefore, is still rather limited. However, when aquaculture systems intensify more, recycling of waste streams in the ponds still can provide 40–60% of the nutrients required for growth of fish (Kabir et al., 2019). The remainder has to be imported and, if aimed for high productivity, should be of high quality (Boyd, 2015), which increases risk of feed-food competition.

Examples of recycling of left-over and waste streams are found in the integrated farming systems of the lower Ganges delta in Bangladesh, and the lower Mekong delta in Vietnam. Here, unique systems have developed in which rice, fish, and shrimps are grown in a circular way (Berg et al., 2012; Bosma et al., 2012; Faruque et al., 2017), sometimes combined with vegetable production on pond- or paddy dikes (Karim et al., 2014). At such farms, 30–40% of the farm area is dedicated for trenches to store water that helps in dry season irrigation water management. This water area is used for fish production. Depending on the location, such farms can include freshwater shrimps along with fish. Dissolved/run-off fertilizer from the fields enters the trench and allows growth of algae and other natural food, which is the main nutrient of the fish. During the wet season the fish encroaches in the paddy section and the fecal waste released in the paddy field works as fertilizer for the rice. At the end of each culture cycle, the bottom sludge of the trench is taken out and used in the vegetable beds on the dikes of the farms. When vegetables are harvested, the roots are often worked into the soil of the paddy field by ploughing; next to nutrients, water resources are shared too in this integrated rice-aquaculture system. The inter-crop dependency improves food quality and safety. For example, farmers in Vietnam are now careful in using pesticides in the rice crop to avoid the risk of mortality of fish or shrimps (Berg et al., 2017), while in Bangladesh vegetables grown on the pond dikes are produced free of chemicals (Faruque et al., 2017). This circularity not only brings efficiency in resource use but also improves product quality and safety.

Some of the production models from SSEA have been piloted in several SSA countries. A pilot of a rice-aquaculture model in the inland valley swamp of Sierra Leone enhanced circular use of agricultural waste and by-products; fish was produced as an additional animal protein, which increased profitability(Sankoh et al., 2018). However, vegetable production on the pond-dike was not successful, as the pond water level quickly dropped with the summer heat, making it difficult to provide enough moisture for vegetable production (Siriwardena et al., 2017).

The projected increase in global fish consumption drives intensification of pond farming, since an increase in pond area will be at the expense of potential human food crop land or waterbodies with fragile biotopes. In such intensified pond systems, feed is formulated based on the nutritional requirements of the fish. The nutrient composition of fish waste is not always ideal for complete mineralization of the waste through natural cycling. Not all the nutrients are utilized and accumulation of N in the pond may result in poor water quality and emmision of N_2O. In addition, accumulation of organic carbon and nutrients like N and P may occur in intensified fish ponds and eventually lead to pollution when discharged without treatment. By paying attention to the waste composition resulting from feeding during feed formulation, the recycling of nutrients within the pond can be enhanced, which leads to a higher nutrient use efficiency within ponds, reducing nutrient requirments and contributing to circularity (Kabir et al., 2020).

Presently, the aquaculture feed industry is increasing the use of low-cost, locally sourced non-edible parts of food crops that provide less nutrients and are less digestible. The loss in essential nutrient (e.g. minerals, trace elements, vitamins, essential fatty acids and amino acids) availability is compensated by directly including the deficient nutrients as additives in the feed (Boyd et al., 2020). Together, with the recycling of wastes through the pond food web, this allows pond farming to reduce nutrient losses and recycle by-products, unlocking biomass humans do not eat.

During the last decades, aquaculture became better integrated into the global food system (Naylor et al., 2021) and made significant contributions to reducing malnutrition by providing essential amino acids and fatty acids (Castine et al., 2017). Aquaculture also responded to public pressure to improve its environmental performance, by reducing pollution, including less fish meal and fish oil (Hua et al., 2019; Naylor et al., 2021) and re-using food wastes in aquaculture feeds. By becoming better integrated, aquaculture also made significant contributions to food security, bringing people out of poverty and developing smallholder inclusive value chains (Hernandez et al., 2018; Pant et al., 2014; Toufique & Belton, 2014). In addition, aquaculture is highly diverse, culturing more than 450 species, providing highly diverse foods and nutrition, often imbedded in the local food culture (FAO, 2020b).

3.3 Land-limited dairy production in Indonesia

A case study of dairy farming in Lembang subdistrict in West Java illustrates aspects of circularity in small-scale semi-industrial systems, focusing on feed and manure management. Situated on the densely populated island of Java, dairy farming mostly takes place on small-scale, specialized commercial farms in a peri-urban context. The average farm in Lembang has four stall-fed dairy cows and 0.3 ha of land for production of forage and sometimes food crops. Annual production is about 4500 kg per cow per year. The feed ration consists of about 55% agro-industrial by-products (mainly tofu waste, cassava pomace, imported wheat pollard, palm oil meal, and corn gluten feed), about 15% crop residues (mainly rice straw), particularly in the dry season when grass is scarce (De Vries et al., 2019) and grass. Grass, the only primary crop in the ration (25% of total DM intake), is collected from roadsides (about one-third), grown in state-owned forest areas (half), or on slopes too steep for food crop production. Only 15–20% of grass intake (less than 6% of DM intake) is grown on land potentially suitable for cultivation of food crops. In this system, food-feed competition for land thus is limited and use of by-products and crop residues is relatively high. Moreover, the peri-urban localition of dairy farms leads to short transportation times, enabling low post-harvest losses of milk. Developments of the sector towards intensification, however, as supported by the Indonesian policy agenda to increase self-sufficiency in dairy production, will increase demand for more and better-quality forages and feeds, potentially threatening food-feed competition.

While dairy cattle in Lembang play a large role in recycling by-products and crop residues, the picture for waste management is less positive. Although most farmers acknowledge that manure disposal is a problem, practical and economic barriers hamper its utilization. Most dairy farmers in Lembang sub-district (84%) are disposing at least part of the manure into the environment, causing pollution of ground and surface waters, potentially leading to eutrophication of aquatic ecosystems and contamination of drinking water sources (e.g. Budisatria et al., 2007). Only a limited amount is utilized as fertilizer, mainly because dairy farmers have too little land to apply the manure and because transportation of manure to their own far-away fields or to other farms involves significant labour and expenditures. Amounts applied to lands near cow barns are extremely high, resulting in high run-off and leaching (De Vries & Wouters, 2017). Due to the relatively low nutrient content of cattle manure and heavy subsidization of synthetic fertilizers for small scale farmers in Indonesia, manure is less competitive in terms of macro-nutrients. Thus, while feeding of crop-residues and by-products unlocks significant amounts of biomass, converting these into high-value dairy products, current manure management practices lead to loss of nutrients and organic matter from the soil–plant-animal cycle.

With regard to GHG emissions, including relatively high-quality by-products in dairy cow rations generally leads to relatively low emissions from feed production and preservation, as most emissions primarily are allocated to the primary product (e.g. grain), a smaller part to the crop residues (e.g. straw), and the agro-industrial by-products (e.g. pollard). However, feeding of by-products may reduce the productivity of cows, as they often have a lower nutritional value than primary products, potentially causing a net increase in total GHG emissions per kg milk. This is illustrated by Fig. 3 from De Vries et al. (2019), in line with Gerber et al. (2011), showing that lower milk yields resulted in higher GHG emissions per kg of milk. Also, some crop residues and by-products have high embedded emissions from production or processing. For example, De Vries et al. (2020) showed that maize gluten feed (CGF) as an ingredient of compound concentrate feed increased milk yield but had a high carbon footprint related to energy use for drying CGF. With regard to manure disposal, increasing the use of manure could result in higher GHG emissions, since GHG emissions from manure dissolved in water are lower than when it is stored and applied on-field. Overfertilization of land close to cow barns causes elevated GHG emissions from N_2O (De Vries et al., 2020).

To enhance the contribution of Indonesian dairy farming to circular food production, manure management should be improved. Locally suitable, low-cost solutions to manage the manure, however, are still mostly lacking. Coupling livestock to land is a proposed solution to increase on-farm manure application (World Bank, 2019), but land on the densely populated island of Java is scarce and fragmented. Use of cattle manure in other agricultural sectors is being explored (e.g. Al Zahra et al., 2021; Pronk et al., 2020). In this context, reducing subsidies on artificial fertilizer may be an incentive for increased use of manure as crop fertilizer. With regard to feeding, in the quest for higher quality forages and feeds, possibilities to utilize or upgrade by-products need to be explored; for instance using technical solutions to improve the nutritional quality and digestibility of (rice) straws (Gerber et al., 2013). In addition, more efficient use of current feed resources can enhance the contribution of dairy farming to circular food production. This can be achieved through improved forage production and forage conservation, better feeding practices (e.g. drinking water provision) and feeding according to individual animal's nutritional requirements ('balanced rations'). More efficient feeding has no trade-offs, and will benefit both GHG emissions and the efficiency of resources such as land and nutrients.

The land-limited character and high use of crop residues and by-products results in a relatively high productivity of ASF per ha, with relatively low GHG emissions per kg of milk. The smallholder character of dairy on Java points at its inclusiveness for smallholders, provided asset conditions are met (Aune & Bationo, 2008; Udo et al., 2011). Strong cooperatives and peri-urban location enable linking of smallholder farms to input and output markets. Moreover, the number of female and young farmers is relatively high. The main weakness in the circularity of the current system is the poor manure management, resulting in loss of nutrients and ecosystem pollution. Food-feed competition may be threatened when the dairy sector develops towards using more and better-quality forages and feeds.

4 Novel protein sources

Novel protein sources, such as insects, micro and macro algae, can contribute to future food supply (Parodi et al., 2019). In line with biomass utilization from waste streams, novel protein foods should be prioritized for direct human nutrition and waste streams of novel protein production should be used as feed for farmed animals. Nevertheless, novel protein sources have not yet been incorporated in human nutrition to a large extent, which implies that at present, the benefit of novel proteins could be that they provide new and sustainable sources of farmed animal feed. The examples in this chapter will shed light on aspects of use of novel protein sources as ingredients of high-quality feeds in semi-intensive and intensive farmed animal production. Production of novel protein sources for such feeds could be based on recycling of waste streams, with limited land use, and low GHG emissions and N and P pollution. Hence, novel proteins could be a means to meet the triple objective of increased ASF output through intensification of production, environmental impact mitigation, and minimal food-feed competition.

4.1 Production of insect protein for feed in East Africa

As a novel protein source, insects are potential contributors to circular food systems because they can convert wastes from many sources into food and feed. Insects require limited water, nutrients, space, and energy, while GHG emissions associated with their production are low (Parodi et al., 2019).

Human consumption of insects is common in various countries in SSEA and SSA, e.g., Uganda. Odongo et al. (2018) found that edible insects are in high demand and that prices were higher than those of beef, pork, and poultry. Insect marketing in Uganda is built on extensive supply chain networks of collectors and traders. In Tanzania, insects have traditionally been eaten in the north-west, in the areas around Lake Victoria, where the local population appreciates the longhorn grasshopper (*Ruspolia differens*) as a delicacy (Mmari et al., 2017). In the western part of Kenya, people eat termites and other insects.

Farming of insects can be important for livelihoods of smallholders, because it may increase food supply and generate cash income for households and communities, and may create employment opportunities for the poor (Ayieko et al., 2016; Kelemu et al., 2015). Experiences in commercially growing of crickets for human consumption have been gained in the Flying Food project in Western Kenya (Flying Food, 2020).

There is potential for use of insect protein in concentrate feed for intensifying the livestock sector. The demand for concentrate feed in Africa is growing. Total concentrate feed production has risen by almost 30% in 4 years, from 31 M t in 2013 to 39 M t in 2017 (Alltech, 2018), making Africa the fastest growing continent for feed production in the world. Concentrate feeds are fed in semi-intensive and intensive pig, poultry, aquaculture, and dairy production. Concentrate feed production depends on the land area available for production of energy (maize and other grains) and protein ingredients (often soybeans or soybean meal after oil extraction), or on fish stocks, since fish meal is part of the concentrate feed ingredients. Because of biophysical conditions, Kenya has limited potential for crop production as compared to Tanzania and Uganda. Therefore, Kenya imports approximately 80% of concentrate ingredients, mostly from Tanzania and Uganda (Githinji et al., 2009; Vernooij et al., 2018). Nevertheless, Kenya is the leading producer of concentrate feeds in East Africa. with an annual production of approximately 1 million metric t in 2020 (Alltech, 2018). Companies and organizations in Kenya, therefore, attach high importance to alternative feed ingredients that can be produced in Kenya itself. Insect protein can be such an ingredient to replace fishmeal or soybean meal. It is produced in the form of larvae that grow from fly eggs inoculated on waste products. Larvae are harvested before they turn into flies (Parodi et al., 2019).

For the current production of concentrate in Kenya, 160,000 metric t of protein ingredients are needed, corresponding to approximately 350,000 metric t of insects (with a protein content of 40–60%). With an assumed efficiency of 2 kg of organic waste needed to produce 1 kg of insect biomass, this would require 700,000 metric t of organic waste annually. The total amount of waste produced in Nairobi is close to 900,000 metric t. Hence, if Nairobi separate organic and inorganic waste, then a considerable part of the insect protein for feed could be produced from its city waste. Production of insects on waste streams and its subsequent use as a feed protein source will substantially lower the use of agricultural land for production of feed ingredients for protein (Mulia & Doi, 2019). Comparing insect production to soybean production, by replacing the annual protein need for concentrate feed in Kenya (160,000 metric t of soybean), approximately 200,000 ha of land could be spared and used for human food production. When replacing fish meal as a protein source in concentrate feeds, use of insect protein would reduce pressure on fish stocks.

Insect production in Kenya is still in an initial stage (Ssepuuya et al., 2017), but several training and development projects have been launched to provide farmers with small scale equipment to produce insects for their own farm animals or for sale to farmers in the immediate neighborhood. For example, simple buckets have been developed to store food waste on which Black Soldier Fly eggs grow into larvae, which are usually fed to chicken or pigs (Food and business knowledge platform, 2020). Over the past five years, approximately 20 insects farms have started to grow insects in medium-scale industrial production systems. Efforts to process city waste into valuable protein are undertaken, e.g., in Dar es Salaam, Tanzania (Biobuu, 2020) and are in preparation in Kampala, Uganda (Proteen, 2020). A few projects for commercial production have been started so far, such as Biobuu Ltd. (Biobuu, 2020).

Constraints for insect production for feed include: (1) limited diversity of insect species for insect protein production; currently mainly black soldier flies, common houseflies and mealworms; (2) knowledge gap regarding feeding of insect larvae during cultivation; (3) controlled housing and climate conditions for insect production; (4) high production costs, and (5) regulations—Kenya since 2017 has legislation on use of insect protein in animal feed and use of manure is allowed (which is not the case in Europe). Kenyan regulations focus on producing feed ingredients without heavy metals, microbial or mycotoxins contaminants.

The environmental impacts of protein production from insects is subject of ongoing research but Van Huis and Oonincx (2017) and Parodi et al. (2019) concluded that GHG emissions associated with insect protein production are low.

4.2 Novel proteins in fish feeding

Aquaculture is the fastest growing ASF sector and is expected to contribute significantly to the ASF protein requirements of a growing world population. A major challenge of doubling aquaculture production by 2050 is the limited availability of fish meal. Soybean meal, the most popular alternative for fish meal, is also an edible protein for humans and other farm animals, all competing for the same limited land and water resources. Some of the potential ingredients that could minimize the pressure on the use of conventional protein ingredients are microalgae, macroalgae, yeast, microbial protein, and insects.

4.2.1 Microalgae

Microalgae are microscopic algae found in fresh water and marine environments. It is estimated that there are between 200,000 and 800,000 species of microalgae. Microalgae are at the base of the aquatic food chain, responsible for half of the world's primary production and supporting the supply of 90 million metric t of seafood per year through capture fisheries (FAO, 2020b; Muller-Feuga, 2000). In addition, microalgae drive the production of mollusks, mainly oysters and mussels, which extract nutrients from the sea, including nutrients deposited into the sea from land due to human activity (Cranford et al., 2013; Reid et al., 2013). Smaller contributions from microalgae include larvae culture of numerous fish and shrimp species. If large-scale production of microalgae at an affordable cost becomes possible, microalgae can be a replacement for fishmeal and fish oil. Currently, most microalgae are produced in industrially operated bioreactors that consume high amounts of energy and water. Microalgae can also be grown on wastewaters from agro-industrial and industrial sources, which have significant organic matter and nutrient contents, in this way bringing wastes back into food production system. Treatment of such waste streams comes with additional costs, for instance to remove toxins that otherwise will bioaccumulate in microalgae (Mohd Udaiyappan et al., 2017), while energy use and possible GHG emissions should be considered.

Replacing conventional protein in fish feed with microalgae from 0 to 100% consistently increased feed efficiency for carps and catfish, while for more carnivorous freshwater species, the feed utilization efficiency decreased with increasing microalgae inclusion level. The replacement of fishmeal with microalgae in shrimp diets had no effect on production. In salmon diets, 50% of fishmeal could be substituted by microalgae protein, while for other marine fish up to 40% replacement did not have a negative consequence on production or feed efficiency (Cottrell et al., 2020; Gamboa-Delgado & Márquez-Reyes, 2018; Hemaiswarya et al., 2011; Shah et al., 2018).

Microalgae are produced in large scale photo-bioreactors. The land area needed to produce fish feed was 10% less for fish feed with microalgae than for a reference diet (Taelman et al., 2013). However, GHG emissions by microalgae produced in a photo-bioreactor is high, as compared to a fishmeal-based diet, due to high use of fossil fuel (Taelman et al., 2013). When rearing microalgae in waste waters, there will be a trade-off between the energy required for conventional wastewater treatment versus microalgae production and processing.

4.2.2 Macroalgae

Macroalgae, also known as seaweed, are macroscopic, multicellular marine algae. The protein content in the dry matter of macroalgae varies from 5 to 50% (Wan et al., 2019). The red seaweed *Pyropia* sp. has a protein content of 50% (Wan et al., 2019), and can replace fishmeal in fish diets. Macroalgae have high levels of highly unsaturated fatty acids. Macroalgae containing less protein might be used as an energy source, replacing terrestrial carbohydrate sources. Seaweed is a popular human food in SSEA and one should carefully consider which species can be included as a feed ingredient in fish diets and which species should be consumed by humans. Advantages are that macroalgae are grown entirely in brackish or marine water bodies, and that they can strip excess nutrients from waste waters. So, macroalgae do not compete with arable land, for fresh water, or for ingredients used in animal feeds. Because no external nutrient inputs are needed, seaweed will reduce GHG emissions by replacing terrestrial plant sources otherwise used in fish feeds.

Inclusion of seaweed up to 25% in diets for carp, shrimp and non-salmonid marine fish either improved or maintained the feed conversion ratio, compared to a conventional diet. Including more than 25% reduced the feed utilization efficiency. For other aquaculture species, inclusion of macroalgae in the diet reduces the feed efficiency (Cottrell et al., 2020; Wan et al., 2019).

One major constraint with macroalgae is the presence of non-starch polysaccharides, which cannot be directly digested by fish, only indirectly by micro-organisms present in the gut (Wan et al., 2019). In addition, nutrient content shows seasonal variation and some species accumulate toxins from waste discharge (Wan et al., 2019). Therefore, there is a need to develop production methods resulting in safe-to-use macroalgae for fish diets. More research is needed on maximum inclusion levels of seaweed in fish diets, considering higher degree of variation in quality and presence of heavy metals and other contaminants.

Attention should be paid to mass extraction of seaweeds from the ocean. The stores of N and P in the ocean are limited. Mass extraction of seaweeds, might reduce nutrient availability for micro-algae, which are at the base of the marine food web. If there are less microalgae, production at higher trophic levels at sea might decline. Better insights in marine nutrient balances at local or regional level are needed before extracting large amounts of nutrients through seaweed farming (Van der Meer, 2020).

4.2.3 Yeast

Yeasts are co-products from the brewing industry. Yeasts contain 45–55% crude protein and can replace fishmeal up to 75% in fish diets without compromising growth

(Gamboa-Delgado et al., 2016; Pongpet et al., 2016). Yeasts can also be included in low concentrations as a catalyst in fish diets, improving the utilization efficiency of plant protein (Li & Gatlin III, 2003). Inclusion of yeast increased feed efficiency (Gamboa-Delgado & Márquez-Reyes, 2018; Pongpet et al., 2016) and enhanced fish immunity against bacterial diseases (Iwashita et al., 2015). Despite its high potential as a replacement of fishmeal, the price of yeast is still a major challenge.

4.2.4 Microbial (bacterial) biomass

Bacterial biomass is a popular alternative protein source not competing with human food. It can be grown by using agricultural wastes such as fruit pulp and maize stover effluents (Mahan et al., 2018), and even manure (Patthawaro & Saejung, 2019). Therefore, microbial protein can play a substantial role in circular food systems and reduce nutrient losses. Microbial protein does not require much land, as it is produced industrially (Ringpfeil, 2016). For carp, catfish and salmonids, replacing up to 30% of conventional protein with microbial protein either improved or had no effect on the feed utilization efficiency (Cottrell et al., 2020; Gamboa-Delgado & Márquez-Reyes, 2018).

4.2.5 Insect meal

The feed efficiency for all important commercial fish species is improved or is not affected by inclusion of insect protein in the feed. Only for non-salmonid marine fish species did inclusion above 60% as protein source result in a decline of utilization efficiency (Cottrell et al., 2020). Limiting amino acids are histidine, lysine, and tryptophan, which could be supplemented (Sánchez-Muros et al., 2014), either in the feed or through the pond's ecosystem. Therefore, insect meal is a potential alternative to conventional protein ingredients. Another advantage is that rearing insects requires minimal land areas, therefore only marginally competing for land use by crops. Its biggest challenge is the price. The cost of insect meal is higher compared to the conventional protein ingredients used in fish diets.

5 Discussion and conclusions about the role of farmed animals in circular food systems

We have reflected on the role of farmed animal species and farming systems in tropical regions based on the characteristics set for circular food systems, i.e., (1) using arable land and water bodies primarily to produce food for direct human consumption, hence limiting feed-food competition, (2) avoiding or minimizing food losses and wastes, (3) recycling by-products, inevitable food losses, and waste streams back into the food system, and (4) using animals for unlocking biomass with low opportunity costs for humans into value food, manure and other ecosystem services. In the examples, we have given attention to the contribution of divers in farming systems and their expected developments to the food system outcomes of food security and environmental impacts.

The review shows that in relatively traditional systems, such as pastoralist systems and mixed crop-livestock systems, feed-food competition is limited, waste streams are highly utilized, and livestock is used for what they are good at. It also shows that ASF production in tropical regions faces the need to produce more to feed more people, to provide essential nutrients to the poor, or to meet the demand of the increasing population of urban dwellers (Adesogan et al., 2020; Oosting et al., 2014). To meet this increasing demand, production is intensifying, indicating higher production per unit of land or per fishpond. This has multiple implications:

(1) For pastoralist grazing systems, intensification implies that traditional exchanges between crop farmers and pastoralists come under pressure. The future of ASF production in regions with pastoralism seems to be in relatively intensive systems in the crop production areas, with seasonal grazing of cattle in the cropping season in the dryland regions, by contracted herders. This situation has important social consequences, such as conflicts between herders and crop farmers and lack of future perspectives for pastoralists. Collapse of the pastoralist system would mean that part of the dryland regions may become underutilized. Whether the process of increasing crop farming and marginalization of pastoralism is affecting the total food output of the pastoralist and crop regions together, in terms of both quantity and diversity, is unknown. Mottet et al. (2017) presented the grassland regions of the world as a basis for livestock production without food-feed competition. They optimistically conclude that a modest improvement in feed use efficiency in such regions could mean a great contribution to future food supply because the grassland regions cover a considereable part of the globe. Ayantunde et al. (2011) and Oosting et al. (2014), however, argued that the unfavorability of conditions, i.e. seasonal rainfall, risk of droughts, aggrevated by climate change and the expansion of crop farming and associated sociertal disconnects, make it very difficult to achieve increased feed use and land use efficiency in many grassland regions. Tamou et al. (2018) reported that when technological interventions (i.e. fertilization and/or irrigation) are possible in grassland regions, such interventions result in increased cash and food crop production and not increased animal production.

However, under the more favorable conditions (such as in LAC), systems with internal diversity, with good management may restore grasslands and even mimick forest systems, contribute to circularity of food systems. These may make higher contributions to food security and mitigation of climate change than the traditional pasture-based beef production. Nevertheless, the scope for large scale regenerative, agro-ecological approaches to agriculture for SSA and SSEA have yet to be explored.

(2) For mixed crop-animal systems, intensification implies that farms specialize, be it towards dairy, pig or poultry production or aquaculture (Oosting et al., 2014; Udo et al., 2011). Traditional within-farm circular pathways may disappear; the value of crop residues (insufficient quality for the desired production level) and manure (lower fertilization value than, often subsidized, synthetic fertilizer) decreases to the extent that they are regarded as wastes. Crop residues may still have value in intensive farms providing carbon to soils, but manure may be discharged, causing environmental problems such as in the Indonesian example. Intensification in mixed crop-livestock systems generally implies that the systems move in the direction of industrial systems. Use of high-quality feeds to achieve high animal productivity is a characteristic of intensified mixed crop-livestock and industrial systems. Agro-industrial by-products can be sourced to be constituents of such high-quality feeds. However, with increasing intensification and higher total ASF production, the need arises to cultivate feed crops, such as maize and soybean, and forage crops, such as grasses and legumes, on lands that are suitable for human food crop production. Hence, intensification may result in increased feed-food competition.

Since intensification most often results in increased productivity of farmed animals, the emissions of GHG per kg of product will reduce (Fig. 3). Risk of pollution of the environment by N and P, organic residues and heavy metals may increase under intensification, due to the accumulation of these substances in farms and fishponds and lack of land to apply it on. Proper waste management and recycling are options to prevent pollution, but the example of dairy farms in Indonesia shows that recycling of manure faces constraints. World Bank (2019) proposed coupling of livestock production and aquaculture to land on farm or regional level to reduce transportation costs and to make application of manure to land more likely. In mixed crop-farmed animal systems, animals have multiple functions, many of which are crop orientated (i.e. provision of manure, draught power, and store of small cash for seed and other crop inputs), while other functions (status, income provision, ASF, store of wealth) are livelihood supporting social and economic functions (Moll et al., 2007; Oosting et al., 2014; Udo et al., 2011). To meet such functions, having a high number of animals is often better than having animals with a high productivity. If mechanization and development of financial institutions could replace some of these functions, there will be less need for smallholders to keep a high number of animals and a reduced animal population could produce the ASF (Oosting et al., 2014). Reducing the size of the animal population is one of the best means to reduce environmental impacts.

Intensification of ASF production is often not limited to individual farms. Production clusters and value chains are likely to develop. Organizing the supply of high-quality feeds based on agro-industrial waste products and novel protein sources, and of fertilizers produced from wastes, including manure, can be done in such clusters and chains (Van der Lee et al., 2018). To reduce food-feed competition due to intensification of farmed animal systems, novel protein sources could replace traditional ones in concentrate feeds, such as soybean meal and fish meal. This substitution will reduce the food-feed competition for land and water and reduce the pressure on fish stocks. Production of such novel protein sources in itself is land- and water-efficient, but energy requirements for production can be high. The production of novel proteins is still in the innovation stage, and costs are still high, meaning that economic competition with other protein sources is still difficult.

Mixed crop-animal systems traditionally, and most so when subsistence-orientated, have an important role for the poor and for women. For the poor this farming system provides a livelihood with limited external inputs, and a high internal diversity, which creates a resilient environment for the farming household. Animals play an important role in these farms. Generally poultry is the type of livestock that is easily accesible to poor people, with small but essential benefits to them, be it for household nutrition, economy or social relations. Smallholder poultry production is therefore very essential for food security and livelihoods of many poor people in the world (Alders et al., 2019; Udo et al., 2011).

The role of farmed animals for women depends on social, cultural and economic factors and on the farmed animal species. Cattle are often owned by men, whereas smaller animals are kept by women. Women are often responsible, including decision making, for milking and processing of the milk, feeding and watering, and caring for young and sick animals. Marketing is often a male task (Rota & Sperandini, 2010).

Stepping-out of poverty is often associated with moving up the livestock ladder (i.e. via small ruminants, and pigs to cattle; Udo et al., 2011) or with intensification and specialization of the farming system. These steps up the livestock ladder and intensification and specialisation imply that more inputs are required and that farms become more market orientated (Oosting et al., 2014; Udo et al., 2011). Consequences are that women and a considerable part of poor households may become excluded from the development of farmed animal production. Circularity of food systems supports the subsistence roles of farmed animals and consequently inclusion of poor people and women. Intensification, and other forms of farming aimed at higher food output and less environmental impacts, on the other hand, have the risk of exclusion.

In conclusion, in tropical regions farmed animals are important in circular food systems because of their use of land unsuited for crop production, their upgrading of crop residues, and their supply of manure to crop production. Nevertheless, the increasing demand for ASF puts pressure on important characteristics of circularity, such as minimizing feed-food competition, maximization of use of waste streams in feed, the value of manure for fertilization, and on inclusion of the poor and women. Hence, in line with conclusions for Western countries (Van Kernebeek, 2020; Van Zanten et al., 2019), maximum circularity and sustainability of food systems can only be achieved by optimizing the population size of animals. Hence, achieving sustainable contribution of ASF to global food security is not only a technical issue or the result of a process driven by economic supply and demand. It is also a governance issue. Public, private and social actors should partner to define and implement policies and practices to achieve sustainable development of farmed animal production within the broader food system (Breeman et al., 2015).

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Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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