

## RESEARCH REVIEW

# Defining a land boundary for sustainable livestock consumption

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## Abstract

The need for more sustainable production and consumption of animal source food (ASF) is central to the achievement of the sustainable development goals: within this context, wise use of land is a core challenge and concern. A key question in feeding the future world is: how much ASF should we eat? We demonstrate that livestock raised under the circular economy concept could provide a significant, nonnegligible part (9–23 g/per capita) of our daily protein needs (~50–60 g/per capita). This livestock then would not consume human-edible biomass, such as grains, but mainly convert leftovers from arable land and grass resources into valuable food, implying that production of livestock feed is largely decoupled from arable land. The availability of these biomass streams for livestock then determines the boundaries for livestock production and consumption. Under this concept, the competition for land for feed or food would be minimized and compared to no ASF, including some ASF in the human diet could free up about one quarter of global arable land. Our results also demonstrate that restricted growth in consumption of ASF in Africa and Asia would be feasible under these boundary conditions, while reductions in the rest of the world would be necessary to meet land use sustainability criteria. Managing this expansion and contraction of future consumption of ASF is essential for achieving sustainable nutrition security.

## KEYWORDS

animal source food, greenhouse gas emissions, land boundary, land use, leftovers, livestock, recycling biomass, sustainable consumption, sustainable development goals

## 1 | INTRODUCTION

It is widely recognized that the food system generates a broad range of environmental impacts and that the contribution of livestock is significant (Bajželj et al., 2014; Bodirsky et al., 2015; Crist, Mora, &

Engelman, 2017; Foley et al., 2011; Godfray et al., 2010; Herrero et al., 2016; Popp et al., 2014; Wirsenius, Azar, & Berndes, 2010). Among these impacts, land use is a central concern as it is associated with critical processes affecting the functioning of the planet, such as climate change, biosphere integrity and biochemical flows

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**TABLE 1** Estimates of protein production from animal source food from food systems that limit livestock production based on the principle of low-cost livestock (i.e., avoiding feed-food competition)

Article	Diet	Input – leftover streams				Output – animal source food		
		Co-product	Food waste	Grass-land	Crop residue	Product Type	g/day	Protein g/day
Global scale								
Van Zanten, Meerburg et al. (2016); Van Zanten, Mollenhorst et al. (2016)	Nutritional	X	X	X		Pork	72	14
						Beef	27	5
						Milk	49	2
						Total		21
Smil (2014) <sup>a</sup>	Current	X		X	X	Pork	12	2
						Beef	9	2
						Poultry	14	3
						Total		7
Schader et al. (2015)	Projected	X		X	X	Pork	19	4
						Beef	7	1
						Milk	138	4
						Egg	2	0
						Total		9
Röös et al. (2017a,b)	Projected	X	X	X		Pork	26	5
						Beef	51	10
						Milk	275	8
						Total		23
Regional scale								
Röös et al. (2016) <sup>b</sup>	Nutritional	X		X		Pork	46	9
						Beef	10	2
						Milk	257	8
						Poultry	26	3
						Total		22
Röös et al. (2017a,b) <sup>c</sup>	Projected	X	X	X		Pork	22	4
						Beef	55	10
						Milk	519	16
						Total		30
Elferink et al. (2008) <sup>d</sup>	Projected	X				Pork	135	27
						Total		27
Van Kernebeek et al. (2016) <sup>d</sup>	Optimized	X	X	X	X	Beef	2	0
						Milk	208	6
						Total		7

Notes. <sup>a</sup>This study does not provide information on land use; it only provides protein production from low-cost livestock. <sup>b</sup>Based on the situation in Sweden, scenario with extensive milk production. <sup>c</sup>Based on the situation in Western Europe. <sup>d</sup>Based on the Dutch situation.

(Newbold et al., 2016; Rockström et al., 2009; Steffen et al., 2015). Livestock currently use about 70% of all agricultural land (arable land and grassland). Expansion of livestock production, therefore, has been a main driver of the conversion of forests and native grasslands into agricultural land, resulting in carbon emissions and biodiversity loss. Livestock currently also dominate human-generated greenhouse gas (GHG) emissions from the food system, being responsible for about 60% of the total (Gerber et al., 2013; Steinfeld, Gerber, Wassenaar, Castel, & De Haan, 2006).

About 40% of global arable land is used to produce feed (Mottet et al., 2017). No matter how efficiently animal source food (ASF) is produced, using arable land to produce feed for ASF production is less efficient than using it directly for plant source food production (Foley et al., 2011; Godfray et al., 2010). The increase in the global supply of animal proteins, from an average of 17 g per person per day in 1960 to 27 g per person per day in 2013 (FAOSTAT, 2017; Supporting information Appendix S1), has increased this so-called feed-food competition (Wilkinson & Lee, 2017). Globally,

monogastric animals (e.g., pigs and poultry) consume on average about 2 kg of human-edible feed protein to produce one kg of edible protein (Mottet et al., 2017) and, therefore they consume more human-edible protein than they produce. In a world with a growing population and finite land, their role in human food security, therefore, is open to challenge.

For these and other reasons, the future role of livestock in the food system is heavily debated. A central question is: what role could animals play in an environmentally sustainable food system? Some argue that to feed an increasing and wealthier population demanding more ASF, we have to produce more ASF with less impact and focus on reducing the environmental footprints of individual ASF products. This route is generally referred to as sustainable intensification or the production pathway (see text box; Alexandratos & Bruinsma, 2012; Cole & Mccoskey, 2013; Garnett, 2014; Garnett, Röös, & Little, 2015; Garnett et al., 2013). Others argue that consuming ASF is resource-intensive and, therefore, should be avoided or limited – also referred to as the consumption pathway (see text box; Garnett et al., 2013; Stehfest et al., 2009; Tilman & Clark, 2014). Besides the environmental argument, this pathway also stresses that the high consumption levels of ASF, especially red processed meat, in the western world are associated with the rise in noncommunicable diet-related diseases, such as obesity, heart diseases, and cancer (Tilman & Clark, 2014). Only a few recent studies focus on a third, alternative pathway and consider the role that ASF can play in feeding the world when production and therefore consumption are capped at levels that avoid food-feed competition and thus reduce the need for arable land (Elferink, Nonhebel, & Moll, 2008; Fairlie, 2010; Garnett, 2009; Peters et al., 2016; Röös, Patel, Spångberg, Carlsson, & Rydhmer, 2016; Röös et al., 2017a,b; Schader et al., 2015; Smil, 2014; Van Kernebeek, Oosting, Van Ittersum, Bikker, & De Boer, 2016; Van Zanten, Meerburg, Bikker, Herrero, & De Boer, 2016). Results of those studies show that by eating a small amount of ASF from livestock fed on “low-opportunity-cost feedstuff” (livestock fed with products that we cannot or do not want to eat directly and biomass from grasslands further referred to as “low-cost livestock”), we can feed the global population with lowest possible use of arable land.

The pathway in which feed-food competition is avoided (i.e., low-cost livestock) is a relatively unexplored area. Although it has started to gain increasing attention (Elferink et al., 2008; Fairlie, 2010; Garnett, 2009; Garnett et al., 2015; Peters et al., 2016; Röös et al., 2016, 2017a,b; Schader et al., 2015; Smil, 2014; Van Kernebeek et al., 2016; Van Zanten, Meerburg et al., 2016); Supporting information Appendix S2), the existing work has hitherto not been synthesized into a consistent review. The aim of our paper is to assess the potential contribution of livestock – fed with low-opportunity cost feedstuff – to food supply, while reducing arable land use. We reviewed, therefore, 8 studies that quantified the amount of ASF produced from low-cost livestock in different circumstances (Table 1). Our synthesis starts from a land-use perspective, as land is centrally coupled to many environmental impacts of livestock production. We can differentiate between arable land (cropland) and grassland, as feed sourced from the former directly competes with

food production, while feed sourced from the latter largely does not. While a considerable amount of grassland could in principle be used for crop production, such land use change would lead to adverse effects, such as soil carbon and biodiversity losses; therefore, this possible alternative use of grassland is not explored in any of the studies reviewed. We note that use of grassland for grazing precludes alternative uses, such as natural rewilding which may be preferable for biodiversity; a point we touch on further below.

We found that livestock – by recycling biomass unsuited for direct human consumption back into the food system – can potentially play a key role in feeding the future population. We show that, compared to no ASF, including ASF from low-cost livestock in the human diet frees up about one quarter of global arable land. The amount of ASF that can be provided by such livestock is limited by the quantity and quality of the leftover streams and grassland resources with low-opportunity costs available for livestock. This route can provide a significant amount (9–23 g) of our daily protein needs (~50–60 g). Consumption of animal products above this level would require feeding livestock human-edible crops or the conversion of grassland or uncultivated land, such as forests, to cropland – both causing environmentally damaging consequences.

**Production pathway.** Studies with their starting point in this pathway argue that meeting rising demands for ASF and minimizing livestock-associated environmental impacts necessitate action to reduce the environmental impact per kg of ASF product (i.e. reducing the environmental footprint of ASF products). Literature shows that reducing ASF footprints mainly implies increasing ASF yields per unit of resource used or emission produced. Examples include improved feed production methods (such as precision fertilization); increasing the life-time productivity of the herd (e.g., improving feed digestibility and efficiency, increasing reproductive rates and animal yields, and reducing diseases); and improving manure management (e.g., covering storage facilities or low-emission spreading of manure; De Vries & De Boer, 2010; De Vries, Van Middelaar, & De Boer, 2015; Herrero et al., 2016; Schader et al., 2015). The footprint concept, however, does not account for the competition for natural resources (e.g., land, water, fossil phosphorus) between feed and food production. Feeding more concentrates instead of roughage to cattle, for example, can reduce footprints of beef (De Vries et al., 2015), but at the same time increase feed-food competition. The production pathway, therefore, favours, a transition from grass-based to concentrate-based ruminant systems (Herrero et al., 2016).

**Consumption pathway.** Studies with their starting point in this pathway argue that – to reduce food system environmental impacts – eating less or no ASF is the priority. They base their conclusions on comparing footprints of diets containing varying amounts and/or types of ASF. In Figure 1,

we display the relation between ASF content (in grams of animal protein) and land use or GHG emissions of the diets explored in consumption studies (more information can be found in Supporting information Appendix S3), indicating a vegan diet (no animal protein) has most environmental benefits. Consumption studies calculate dietary footprints by summing the environmental impact of all food products consumed, preferably on an annual basis (Van Kernebeek, Oosting, Feskens, Gerber, & De Boer, 2014). In this calculation, the environmental impact of each consumed product, for example milk, is determined by multiplying the amount of product (in kg) with the footprint per kg of that food product (e.g., milk). This implies that dietary footprints also rely on the footprint of individual food products and, thus, ignore feed–food competition. As a result, consumption pathway studies advice to eat meat or eggs produced by poultry fed with grains, instead of milk or meat from low-yielding ruminants that are only grass-fed. Footprints used in consumption studies also ignore linkages within the food system between, for example, between sugar and beet-pulp or between milk and beef, which explains why shifting to a vegetarian or ultimately a vegan diet has most environmental benefits (Aleksandrowicz, Green, Joy, Smith, & Haines, 2016; Hallström, Carlsson-Kanyama, & Börjesson, 2015). The footprint of a vegetarian diet including milk products, however, ignores the environmental impact of the production of associated meat from culled milking cows and surplus calves, or assumes that this meat is consumed by others in the population. Similarly, if everyone would become vegan, human inedible by-products like sugar beet pulp, currently fed to animals, are no longer recycled back into the food system. Thus, such footprint assessments are not able to adequately capture environmental benefits of using low-opportunity feedstuff as livestock feed.

## 2 | THE CONCEPT OF LIVESTOCK FED WITH LOW-OPPORTUNITY COST FEEDSTUFF

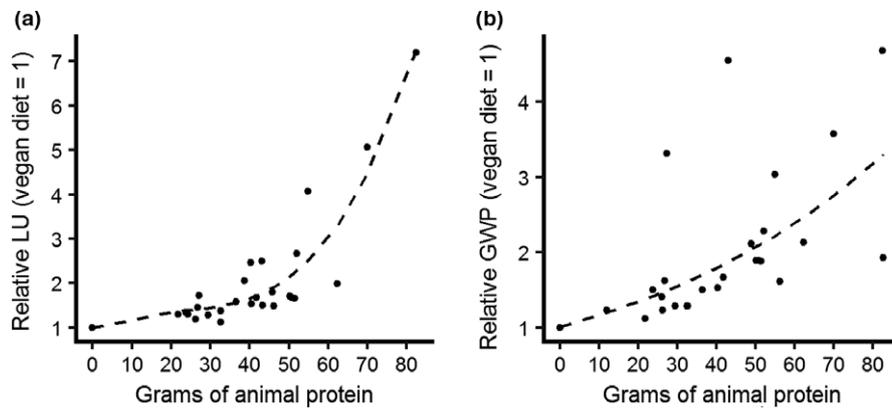
We suggest that the role of animals in the food system should be centered on converting biomass that we cannot or do not want to eat into valuable products, such as nutrient-dense food (meat, milk, and eggs) and manure (Figure 2). This approach has been examined by others too, both within and beyond the scientific community, and has been referred to as producing livestock on “ecological leftovers” (Garnett, 2009), “default livestock” (Fairlie, 2010), or as the “consistency narrative (Schader et al., 2015)”. It has been offered as a potential strategy to reduce the environmental impact of ASF production (Röös et al., 2016, 2017a,b; Schader et al., 2015; Van Zanten, Meerburg et al.,

2016; Wirsenius et al., 2010). Biomass that we cannot or do not want to eat consists of biomass from grassland and leftovers. Leftovers include crop residues left over from harvesting of food crops, co-products left over from industrial processing of plant source and ASF, and losses and waste in the food system. By converting these leftover streams, livestock recycle nutrients back into the food system that otherwise would have been lost in food production (Garnett et al., 2015). Ruminants can create nutritional value from grasslands by converting grass products into milk, meat, and manure. Therefore, by adopting this approach, arable land should be used primarily for production of food crops, rather than feed, so that livestock can contribute to nutrition supply without using arable land.

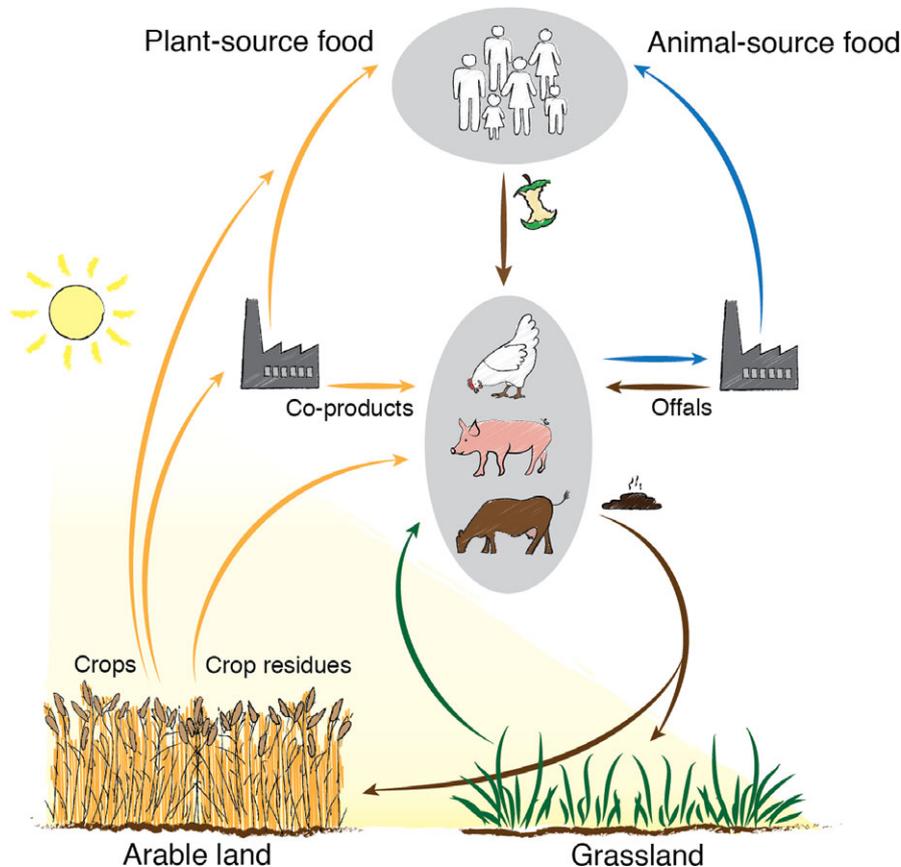
## 3 | DEFINING A LAND BOUNDARY FOR SUSTAINABLE LIVESTOCK CONSUMPTION

Diets containing animal protein from low-cost livestock use less arable land than a vegan diet and considerably less arable land than the current diets in high-income countries (Röös et al., 2017a; Schader et al., 2015; Van Kernebeek et al., 2016; Van Zanten, Meerburg et al., 2016). The curve in Figure 3a was illustrated previously for a hypothetical food system (Van Kernebeek et al., 2016). Van Kernebeek et al. (2016) used linear programming to determine the minimum amount of land needed to feed a fix population a diet in which 0% to 80% of the daily protein requirements was derived from terrestrial, domestic animals. A similar curve, however, can be derived from results of three global studies (i.e., Schader et al., 2015; Van Zanten, Meerburg et al., 2016; Röös et al., 2017a; Figure 3b). In a vegan dietary scenario (see Figure 3, zero gram of ASF as x value), crop residues stay on the field to feed the soil–food web; co-products from the food industry become a bio-energy source or are wasted; and grasslands are not utilized for food production. Because animals do not recycle these biomass streams back into the food system, additional crops have to be cultivated to meet the nutritional requirements of the vegan population. Based on the available global studies (Röös et al., 2017a; Schader et al., 2015; Van Zanten, Meerburg et al., 2016) we can conclude that eating no ASF compared to eating some ASF could free up about a quarter of global arable land (Figure 3b). This, however, largely depends on the plant source foods consumed and the amount of food wasted. Reducing the amount of co-products or food wasted will benefit the environment directly, but will reduce the amount of ASF produced from low-cost livestock.

As soon as the ASF consumption exceeds the level derived from low-cost livestock, we encounter direct feed–food competition and require additional arable land to cultivate livestock feed – or we need to take additional pasture land from currently uncultivated areas. Figure 3b shows that, in terms of food supply, consuming some ASF from low-cost livestock is the most efficient way of using arable land for food production, although it may preclude the use of grassland for other purposes, such as rewilding. This concept provides one approach to define thresholds for sustainable livestock production and consumption.



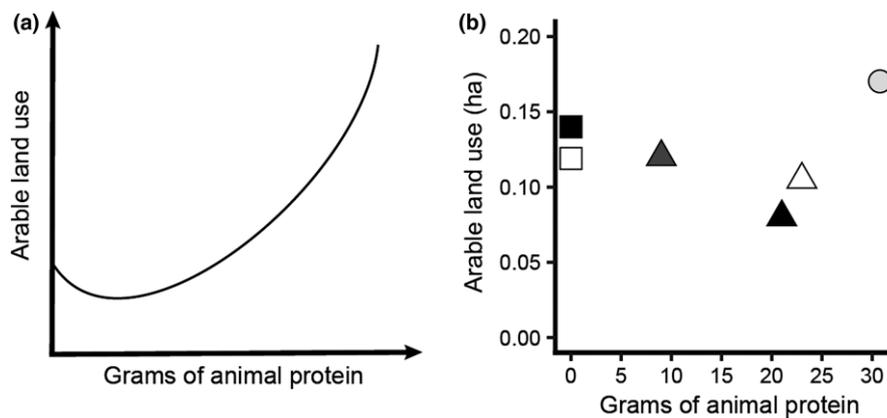
**FIGURE 1** (a) Relative reduction in land use per g of protein from animal source food (ASF) (polynomial fit; adjusted  $R^2$  of 0.85;  $p$ -value  $<0.00$ ) (b) Relative reduction in GWP per g of protein from ASF (exponential fit, adjusted  $R^2$  0.61;  $p$ -value  $<0.00$ ). Each dot represents a dietary scenario. Dietary scenarios were derived from peer reviewed studies that assessed the environmental impact of different diets based on footprint approaches that do not account for systemic aspects, such as feed-food competition or interconnectedness between food and feed via by-products, etc. (see Supporting information Appendix S3 for a more detailed description of the methodology)



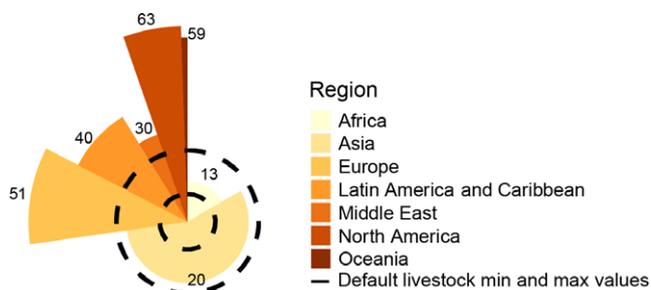
**FIGURE 2** The role of low-cost livestock in the food system. Livestock convert biomass that we cannot or do not want to eat into valuable products, such as animal source food and manure [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

What might the implications be for human nutrition? According to the World Health Organization, the average adult requires 50–60 g of (plant and/or animal) protein each day (Alimentarius, 2013). The current average global supply of terrestrial animal protein (excluding fish) per capita is 27 g per day (FAOSTAT, 2017), while large differences exist between countries. For example, the average European supply is 102 g of protein per day (of which 51 g is terrestrial

animal protein), while the average West African supply is 65 g of protein per day (of which just 8 g is terrestrial animal protein). The estimated global amount of daily per capita ASF protein that could be sourced from low-cost livestock ranges from 9 to 23 g; therefore, it could potentially fulfill a useful part of our daily protein needs – while enabling arable land to be dedicated to the cultivation of food crops.



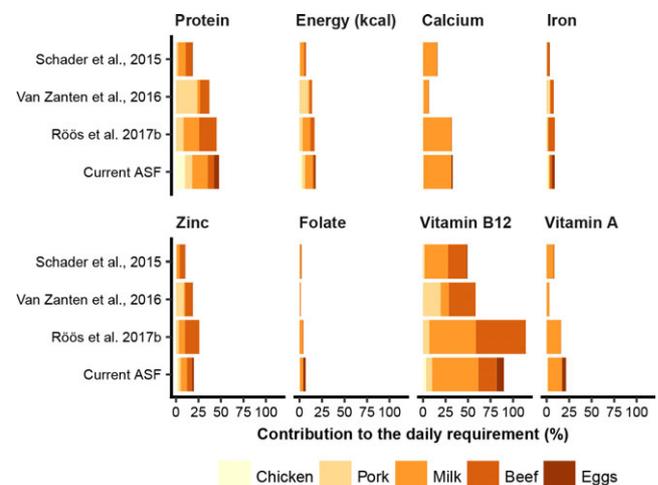
**FIGURE 3** (a) This graph illustrates the theoretical relation between the percentage of animal protein in the human diet and the total amount of arable land used to produce human food. This theoretical line was illustrated previously for a hypothetical food system (Van Kernebeek et al., 2016) (b) This graph is based on global studies assessing the principle of livestock with low-opportunity costs: Schader et al. (2015), dark gray; Van Zanten, Meerburg et al. (2016), black; and, Röös et al. (2017a) white. The squares represent a vegan diet; triangles represent the value of low-cost livestock; and the circle (light gray) represents a current diet. It clearly shows that arable land use is most efficient with a moderate consumption of protein from livestock with low-opportunity costs



**FIGURE 4** Current protein supply per person per day per region, based on (FAOSTAT, 2017) compared with the minimum global average value of low-cost livestock of Schader et al. (2015) of 9 g protein per person per day, and the maximum value of low-cost livestock based on Röös et al. (2017a) of 23 g protein per person per day [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 4 shows the current daily supply of protein per capita (g/person per day) in different regions against the range of ASF that could be produced through low-cost livestock. Overconsumption is evident in most high-income regions – in many cases by a factor of two or more. Our analysis also shows that the supply of ASF in Asia and Africa is still within the land-use boundary, allowing people in these areas – where people's nutritional needs are still not met to a significant degree – to maintain or even increase their ASF consumption, at least in the short term.

Protein is only one among many nutrients supplied by ASF. Besides protein, ASF also provides energy and highly bioavailable micronutrients, such as calcium, iron, and vitamin B12. So far, no studies to our knowledge have yet quantified the contribution of ASF from low-cost livestock to our daily recommended intake of essential micronutrients. Here, we perform this calculation (Figure 5; for calculation details, see Supporting information Appendix S4 and S5). We show that, on a global average, in addition to providing 35% of recommended protein intakes, ASF from low-cost livestock could



**FIGURE 5** Nutritional contribution of animal source food (ASF) from low-cost livestock and current ASF production to daily recommended nutrient intake. Figure is based on global studies assessing the principle of livestock fed with low-opportunity cost feedstuff (Röös et al., 2017a; Schader et al., 2015; Van Zanten, Meerburg et al., 2016) [Colour figure can be viewed at wileyonlinelibrary.com]

provide about 75% of the recommended intake of B12; about 20% of the recommended intake of calcium and zinc; about 10% of the recommended intake of energy, iron, and vitamin A; and less than 5% of folate (Figure 5). These results show the importance that low-cost livestock could make to global nutrient supply. The regional production potential of ASF from low-cost livestock obviously varies according to the availability of feed resources and productivity of animals within the region (Röös et al., 2017b). Clearly, trade in low-opportunity cost feedstuff will influence ASF production in regions involved, whereas trade in ASF will affect its consumption in regions involved.

## 4 | ENVIRONMENTAL IMPACTS OF EATING ANIMAL SOURCE FOOD FROM LOW-COST LIVESTOCK

The majority of the studies reviewed in this paper explored the role of low-cost livestock from a land-use perspective. (See Table 1). Only one study (Schader et al., 2015) also explored the consequences for nutrient losses (i.e., nitrogen and phosphorus), whereas two studies addressed GHG emissions (Röös et al., 2017a; Schader et al., 2015; other environmental impacts, for example, water use, eutrophication, acidification, and biodiversity are so far unexplored). Compared with projected FAO consumption patterns for 2050, eating only ASF from low-cost livestock reduced nitrogen losses by 40% and phosphorus losses by 46% (Schader et al., 2015). Similarly, those studies that address GHG emissions show that eating ASF from low-cost livestock reduces GHG emissions from livestock production by 19%–50%, compared with a business as usual scenario (Röös et al., 2017a; Schader et al., 2015), but one study also showed that eating no ASF at all (vegan diet) reduces emissions considerably more (Röös et al., 2017a). This result can be explained by the relatively large role of ruminants in the low-cost livestock scenario, which emit significant amounts of methane, as well as the influence of nitrous oxide emissions from manure management related to all animals. As long as there is a dearth of viable technical solutions for reducing methane production by cattle, ruminants will continue to emit significant amounts of this potent GHG. While it has been argued that methane emissions from the animals can be offset by carbon sequestration in grass-based ruminant systems, a recent comprehensive study found that – although there is potential for significant sequestration in certain localized situations – at an aggregate global level, the potential benefits from sequestration are substantially outweighed by the animal's methane and other emissions (Garnett et al., 2017). In the absence of a technological solution, this trade-off between grassland use and GHG emissions from ruminants will be unavoidable. It is important also to emphasize that a proper definition of a sustainable food system accounts for and addresses a multiple range of concerns. Biodiversity is clearly key here and as noted earlier, some grasslands, especially those that were once covered with forest, would benefit from being rewilded. As such there is an opportunity cost entailed in rearing livestock: not all biomass from grasslands can be considered “free” for livestock production. We suggest that defining a “biodiversity boundary” and the possibilities of rewilding for the world's grasslands are important topics for future research (Newbold et al., 2016; Svenning et al., 2016).

## 5 | WHAT DETERMINES THE POTENTIAL PRODUCTION OF PROTEIN FROM LOW-COST LIVESTOCK?

The greatest influence on the amount of ASF available from low-cost livestock is the quantity and quality of leftovers and grass resources available for livestock. Differences in quantity and quality of

leftovers and grass resources among studies can be explained by a number of factors as presented below.

First, the definition of the human diet used in the studies varies and thus the quantity of the leftover streams varies as well. Results differ significantly when the starting point is the current diet, computed using national per person food supply data (Elferink et al., 2008); nutritional adequacy in terms of energy and protein (Van Kernebeek et al., 2016); the nutritional guidelines (Van Zanten, Meerburg et al., 2016); or diets as projected by the FAO (Röös et al., 2017a,b; Schader et al., 2015). The quantity of the leftovers streams derived from diets in affluent countries, for example, is relatively high and can, therefore, produce relatively more ASF.

Second, the quality of the leftover streams depends also on the type of plant source foods included in human diets. For example, human diets can contain soy oil, yielding soybean meal as a co-product for livestock feed. Soybean meal has a higher nutritional value for livestock than do other oil co-products, such as rapeseed or sunflower meal. Feeding soybean meal to livestock (Van Zanten, Meerburg et al., 2016) yields more ASF than feeding rapeseed meal to livestock (Van Kernebeek et al., 2016). This example emphasizes the key role that dual purpose food-feed crops can play in nutrition security. Hence, it can be argued that if the goal is to minimize use of arable land, the value of a food crop should be ascertained on the basis not only of its food value for humans but also on the feed value of its co-products for livestock.

Third, the availability of food waste for livestock feed significantly impacts the amount of ASF produced. This is because the nutritional value of food waste is often high, especially in comparison with crop residues or co-products (Van Zanten, Meerburg et al., 2016). Reducing food-waste should remain our first priority, but unavoidable food waste can be valued as livestock feed. As pigs eat most foods also consumed by humans and can consume food with high moisture content, they are ideally suited for being reared on food waste. Currently the use of most food waste as feed is prohibited in many countries (including European countries) because of potential risks to human health (e.g., bovine spongiform encephalopathy). Evidence shows, however, that feeding food waste to livestock, especially to monogastrics, can be a safe alternative if food waste is heat-treated (Zu Ermgassen, Phalan, Green, & Balmford, 2016). Such practices are applied commonly in Japan, where about 35% of wasted food is fed to pigs (Zu Ermgassen et al., 2016).

Fourth, the availability of crop residues influences how much ASF is obtainable (Smil, 2014; Van Kernebeek et al., 2016). That said, compared to food waste and co-products, crop residues generally have a lower nutritional value and, thus make a lower nutritional contribution. Furthermore, the availability of crop residues as livestock feed is limited, because crop residues are often left on the field as fertilizer and to maintain soil organic carbon. Using crop residues to produce ASF, therefore, can result in trade-offs with e.g., climate and soil fertility and, therefore, needs careful examination before their use as livestock feed is stimulated.

Fifth, to what extent grasslands are used is important. Ruminants fed solely on existing grasslands could potentially produce about 7 g of protein/person per day (Schader et al., 2015; Van Zanten, Meerburg et al., 2016). By feeding them co-products in addition to grass, however, the productivity of grass-fed ruminants can be increased (Röös et al., 2017a,b). An important aspect influencing these estimates is the assumed grassland availability and quality, which is highly uncertain on a global level (Fetzel et al., 2017).

Finally, technological developments and cultural changes can affect the availability of leftover streams. Technology might shift the use of leftovers across species or make leftover streams suitable again for human consumption. For example, bio-refineries can separate grass into proteins and fibers. These proteins useful in cattle production are also very suitable for monogastrics and – if processed into foods – can be consumed by humans directly, thus reducing arable land requirements. Cultural changes may also change the availability of products that we “do not want to eat”. A widespread dietary shift from white toward brown bread, for example, will change the quantity of wheat middlings available.

## 6 | THE ROLE OF LIVESTOCK CHARACTERISTICS ON UTILIZATION OF LEFTOVERS

Animals differ in their ability to convert leftovers into valuable ASF. This ability is affected by the type of animal, the production system, and the productivity level (among other factors). Studies exploring the potential of low-cost livestock have heretofore considered a limited number of animal production systems (Table 1). Most studies included pigs and cattle; only a few also included poultry. Pigs were generally fed with co-products and food waste, whereas cattle were fed grass.

Besides the type of animal, the breed and the productivity level may affect the animal's ability to convert available leftover streams into ASF (Picard & Cuca, 1986; Van Zanten, Mollenhorst, Klootwijk, Van Middelaar, & De Boer, 2016). Animals bred to be highly productive may be less suited to using leftover streams, because their high productivity levels require high-quality feeds (Zijlstra & Beltranena, 2013). Less productive animals have lower daily nutrient and energy requirements, and can fulfill their requirements with lower quality feeds. Therefore, using different breeds in different livestock systems can enable an optimal use of leftover streams.

To our knowledge, no scientific study has yet explored the allocation question: which leftovers are available where, and to what animals should we feed them in order to maximize the production of ASF? It is worth noting – although not discussed further here – that feed production in aquaculture and insect production also has a significant environmental impact (Parker, 2012; Van Zanten et al., 2015), so finding sustainable feed sources is a major focus of research across all animal production systems.

## 7 | CONCLUSION AND STEPS TOWARD LOW-COST LIVESTOCK

If we want to use livestock for what they are good at, namely converting leftovers from arable and grass products into valuable food and manure, we suggest that we should no longer focus on reducing footprints of ASF products per kg of product. The footprint concept (see text box above) does not account for the competition for natural resources (e.g., land, water, fossil phosphorus) between feed and food production; rather, it focuses on improving life-time herd productivity and, as such, stimulates the use of human-edible feed in livestock diets. Instead, we should focus on improving the efficiency with which livestock recycle biomass unsuited for human consumption back into the food system. The priority use of arable land is then human food production, whereas livestock mainly recycle nutrients in leftover streams from arable land and nonarable grassland back into the food system. This approach would require us to base decisions on outcomes from bio-physical models that account for the competition for natural resources between production of feed and food and that also include interconnections within the food system.

The low-cost livestock concept is based on decoupling of production of livestock feed from the use of arable land. Livestock then mainly convert leftovers from arable land and grass resources into food. Global production of ASF is thereby limited by the quantity and quality of these biomass streams. Thus, the availability of these biomass streams for livestock determines the boundary of livestock production and consumption. Respecting this boundary to sustainably feed a growing world population requires major changes in both consumption and production of ASF.

Our results show that low-cost livestock can supply a significant part (9–23 g) of global daily protein needs (~ 50–60 g). Current consumption patterns of ASF, however, differ largely across the world. This suggests that there are large differences in how consumption patterns in different regions could change in the near future. Africa and Asia – would still be within the land boundaries of sustainable livestock consumption, even if ASF consumption increases there, but significant reductions in consumption would be needed in all other regions. Identifying these differences is crucial to inform the sustainable development goal agenda on reducing all forms of malnutrition. The need to reduce the consumption of ASF, especially in Europe, the Americas and Oceania, is in line with the conclusion of the consumption pathway (see text box) but in contrast with it, we show that eating some ASF, instead of no ASF (a vegan diet), is the strategy that uses the least amount of arable land. Studies arguing for the consumption pathway arrive at their conclusion that a vegan diet makes the best use of the land, because they ignore interconnections in the food system. Producing wheat and then wheat flour for bread also yields straw and wheat middlings, which can be fed to animals without additional land requirements. The consumption pathway – by using footprint-based assessments to minimize environmental impacts – advocates eating poultry over beef, but, such reasoning again neglects systemic aspects. In the current situation, chicken eat grain, contributing to feed–food competition; while some

(though not all) beef cattle graze on marginal lands, thereby reducing feed–food competition.

Our reviewed studies show that a variety of ASF product can be produced if we feed livestock with low-opportunity cost feedstuff: 7–135 g of pork; 2–55 g of beef; 2–14 g of chicken; 138–519 g of milk; and 2–24 g of eggs per person per day, resulting together in 9–23 g of protein per person on a daily basis (Table 1). Nonetheless, it should be acknowledged that consumption of ruminant products (beef meat and milk) in the upper part of the range will give rise to considerable GHG emissions particularly in the form of methane. Thus, what might be sustainable from a land-use perspective might not be so, in terms of the climate impact. Nevertheless, the emissions from low-cost livestock still would be lower than in a business as usual reference scenario, since the reduction in animal numbers offsets increases in per kg product emissions. This may be one way of dealing with the trade-offs that are inherent in sustainable food systems.

We caveat this conclusion by observing that all the studies reviewed here assumed that all currently available grassland would be used for grazing. A large proportion of this land, however, was previously covered by forests and to reach biodiversity conservation targets it is probable that grazing would need to cease on some of this land. We recommend that a priority for research is to define a “biodiversity boundary” for livestock, including identifying which grasslands can be considered “available” for animals and which should rather be left for rewilding or other strategies to increase biodiversity (on some grasslands there may be opportunities for win–wins).

Finally, we note that this suggested approach is largely dependent on a credible transition of our livestock industries toward a more integrated, circular economy. This will require increased collaboration between governmental institutions and private industries for managing key resources, consumer education, and supporting policies and investment to ensure that livestock can contribute to meeting critical sustainable development goals in the near future.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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