Untapped power of food system by-products to increase global food supply

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Untapped power of food system by-products to increase global food supply

Abstract

Many animal feeds compete for resources with human food production. The current use of food system by-products and residues as feed could potentially be increased to reduce the competition. We gathered a harmonised global food system material flow database for crop, livestock and aquaculture production including the availability of food system by-products. This allowed us to analyse the potential to replace the food-competing feedstuff, here cereals, whole fish, vegetable oils and pulses, that currently account for 11% of total feed used globally, with available food system by-products. While considering the nutritional requirements in animal production, we found that the replacement could free food-grade feeds for human consumption and increase the current food supply in kcal by 11-17% (6-11% if the use of crop residues is not accounted for) and in terms of protein 11-15% (9-14%). Our results thus indicate that the increased feed use of by-products has considerable potential, particularly when used in combination with other measures, in the much needed transition towards more sustainable and circular food systems.

Keywords: circularity, sustainable food systems, livestock feed, aquaculture feed, by-products

1. Introduction

The current food system's structure results in suboptimal food availability as a large proportion of the resources used to feed livestock and aquaculture production, could be directly consumed by humans. Up to 40% of all arable land and more than 30% of cereal crops produced are used for animal feeds (Mottet et al., 2017; FAO, 2021) and approximately 23% of all captured fish are destined to non-food uses, mainly for fish and livestock feeds (FAO, 2020). This food-feed competition reduces the efficiency in food systems as the environmental and resource costs are higher when arable land is used as a feed producing resource in animal production instead of directly contributing to human consumption (Bowles et al., 2019; Foley et al., 2011; Godfray et al., 2010). While animal products are generally more protein dense and of different protein quality, total protein supply is reduced when animals convert human edible feedstuff into human edible animal products (Goodland, 1997).

Increasing the use of food system by-products such as crop residues, food processing by-products, and food waste, has been proposed as a solution to increase the efficient use of resources (van Kernebeek et al., 2016; Schader et al., 2015; Röös et al., 2017; van Hal et al., 2020), to reduce the food-feed competition (van Zanten et al., 2018) and to increase the circularity within food systems (Billen et al., 2021; van Zanten et al., 2019; van Hal et al., 2019). In addition, the use of food system by-products as feed can reduce the agricultural environmental pressure by minimizing environmental impacts such as climate change emissions and the need to occupy inputs such as arable land, fertilizers or water for feed production (van Kernebeek et al. 2018; van Zanten et al., 2019; Schader et al., 2015; van Selm et al., 2021; van Hal et al., 2019). Increasing the use of by-products and crop residues as feed can also be cost-effective since they are widely available and low-cost materials (Devendra & Sevilla, 2002). These non-competing feedstuffs, however, can have a relatively low quality and nutritional content (Van Hal et al., 2019), which should be considered when increasing their share in livestock and aquaculture diets as it may either limit their inclusion rate or reduce productivity. However, many feed experiment studies show the potential to reduce food-grade feed use by replacing part of their use with non-food-competing feedstuff without negatively impacting productivity (Ertl et al., 2015; Karlsson et al., 2018; Tables S6 and S7).

Since the different food production sectors, i.e. crops and both terrestrial and aquatic animals, are tightly interlinked via feed use, a systemic view of the food system is needed to achieve the goals of circularity (Korhonen et al., 2018; Van Hal, 2020). However, studying the potential use of by-products for animal feeds at global scale is challenged by the lack of harmonized datasets of both feed material flows as well as the availability of the by-products. While different models and reports provide data on livestock (FAO, 2017; Wirsenius, 2000; Herrero et al., 2013) or aquaculture feed use (Tacon et al., 2009; Tacon & Metian., 2015) these are not harmonized throughout the global food system. Only few studies have assessed the feed use in both systems, but they don’t account for country-level differences in feed use (Froehlich et al., 2018) or have only regional focus (Karlsson & Röös, 2019). Estimates of the material flows related to food system by-products, in turn, have only been reported sporadically in different studies (e.g. Scarlat et al., 2010; van Hal et al. 2019; Devendra & Sevilla, 2002, Wirsenius, 2000) and thus, no comprehensive understanding of those flows exists. Previous studies have assessed the feed use potential of individual by-products at specific production systems (Tables S6 and S7) as well as analysed scenarios of the livestock production that could be sustained restricting the feed use to only non-food-competing feedstuff (Schader et al., 2015; Karlsson et al., 2017; Röös et al., 2017; Van Zanten et al., 2018; Van Hal et al., 2019). However, an analysis of the potential to increase the feed use of the by-products within the current food system, including both livestock and aquaculture sectors, has not been presented at the global level.

In this study, we assessed the potential of improving the food system's circularity through increased use of by-products and residues in animal feeds. Combining data from various sources, we analysed both current feed flows in the entire global food system as well as availability and feed use of most common by-products (i.e., crop residues, crop processing by-products, livestock by-products and fisheries and aquaculture processing by-products, hereafter referred to as fish by-products; see full description in Methods) (Fig 1). We then estimated the potential of these by-products in replacing food-competing feedstuff including both the livestock and aquaculture sectors, in the current food system. The focus was on the feed use of food-competing feedstuff including cereals, oilseed oils, pulses and the whole fish used in fishmeal and fish oil production. Here, only selected food system by-products and residues were considered based on their current feed use and the potential to increase it (see Methods). The replacement potential considered the animal nutritional requirements, regulation of the animal by-products feed use and the regional availability of the by-products assuming that all by-products, currently not used as feed, are available (see Methods and Discussion). The replacement constraints were set to allow no reduction in animal productivity, with the only exception for cereal replacement with crop residues where reduced productivity was unavoidable (see Methods). We further estimated the increase of human food supply when applying the potential to replace the selected food-competing feedstuff with food system by-products.

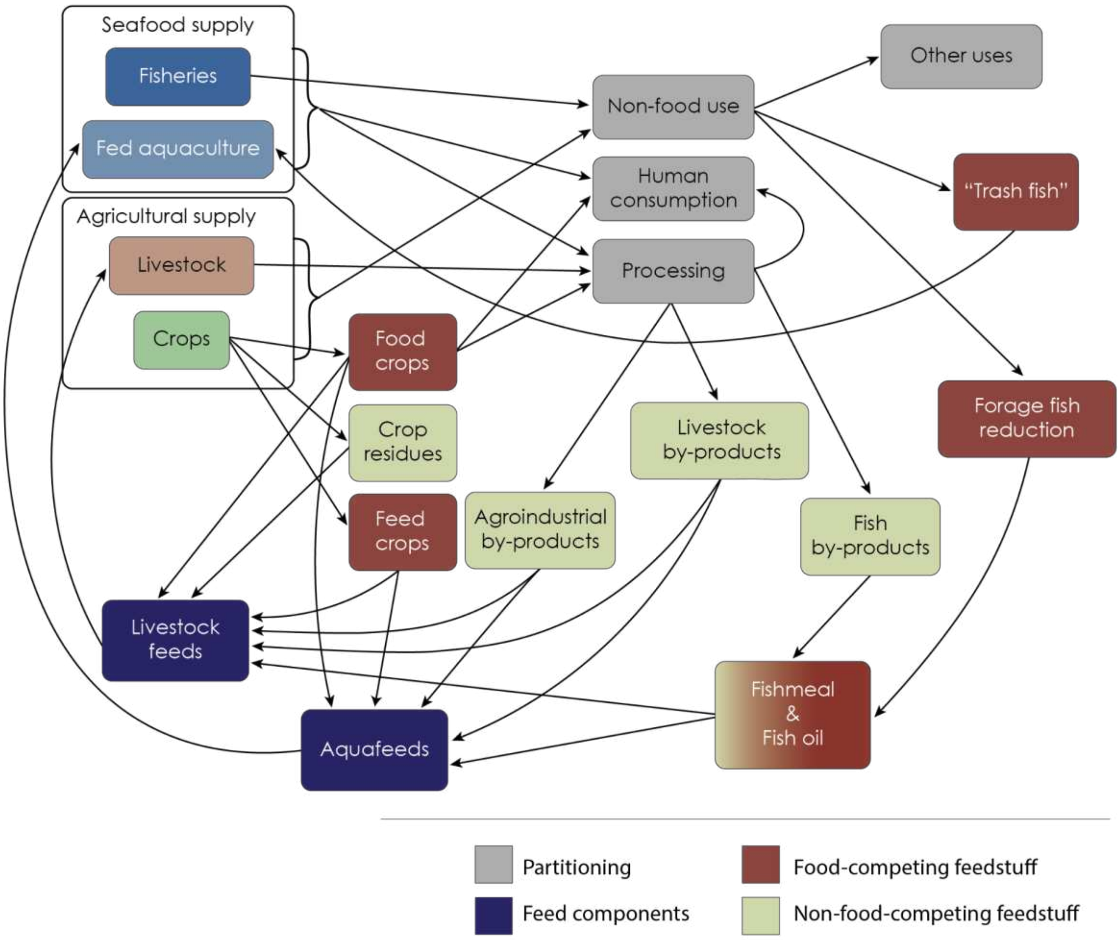

Figure 1. *Material flows in the global food system considered in this study. See methods for our quantitative interpretation of the flows.*

2. Results

2.1. Food-competing feedstuff use

Based on our harmonised global food system database, in 2016-2018 approximately 11% (in fresh weight) of feedstuffs used in livestock and aquaculture production consisted of the considered food-competing feedstuff that can potentially be directly used as human food (Fig 2). Here we assumed that cereals, oilseed oils, pulses, sugar crops and the whole fish used as feed in aquaculture or in producing fish oil and fishmeal were included in the food-competing feedstuff category (Table S2; see Methods for assumptions).

Animal production systems differ in their food-competing feedstuff use: at the global level, up to 42% of the feedstuff in aquaculture, 70% in poultry and 43% in pork meat production consisted of food-competing feedstuff while for cattle meat and dairy the ratio was only 3% (in quantities of feed in fresh matter). The low inclusion rate in cattle feed is mainly due to extensive grazing systems. These systems have high feed conversion ratios (kg feed/kg output) and hence consume high amounts of feed, which consists mainly of roughages such as grass and hay. The more industrialized cattle systems consume high amounts of food-competing feedstuff (e.g. in Northern America and Europe in the industrialized beef cattle systems the use of food-competing feedstuff is more than 70%) but on the other hand, these systems are highly optimized and efficient, having lower feed conversion ratios (Mekonnen & Hoekstra, 2012) and consequently lower total consumption of feed. There are also notable differences in regional variation in food-competing feedstuff use ranging from less than 3% in Africa and 6% in both Latin America and Oceania, 10% in Europe, 13% in Asia and almost 17% in Northern America. These differences reflect both the variation in animal production as well as the differences in the feed use.

At the global level, most of the feed use however, consists of materials not suitable for human consumption, mainly roughages such as grass foraged by cattle (Fig 2). From the food-competing feedstuff use, cereals form by far the largest group. Maize is the most important feed cereal followed by wheat, rice and barley (Fig 3a and 3d). Notably, fish has a considerable role when analysing the material flows in protein content (Fig 3b) and they can be particularly important for the supply of healthy fatty acids (i.e. EPA and DHA), while the importance of oilseed oils increases when looking at these from a fat content perspective (Fig 3c).

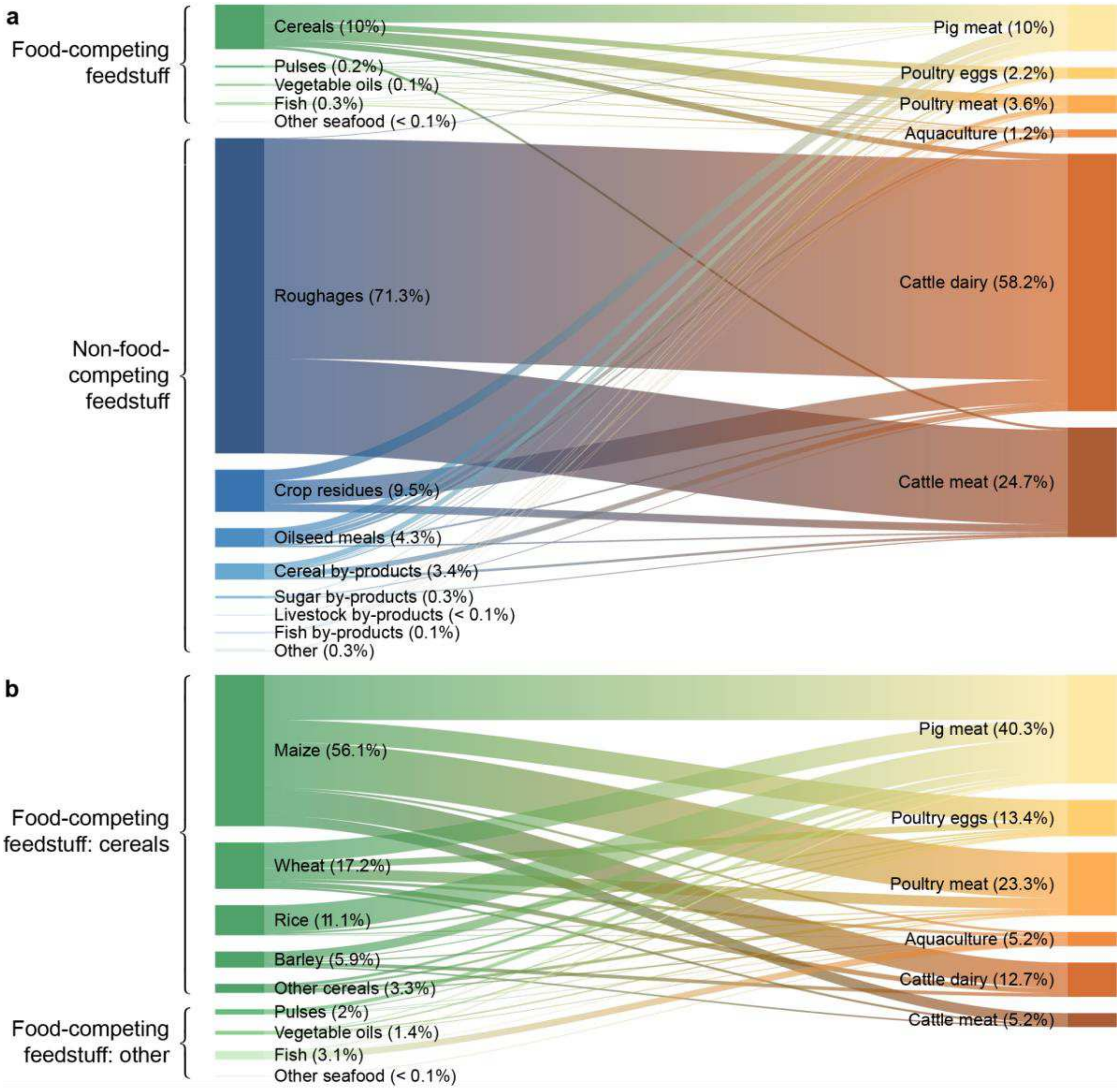

Figure 2. *Feed use material flows in the global food system (feed use in fresh weight). a) entire feed flows; b) only flows for food-competing feedstuff. The percentages refer to the share of the feed group (on the left) and the animal production group (on the right) of total feed use. See data sources used for combined feed database in Methods.*

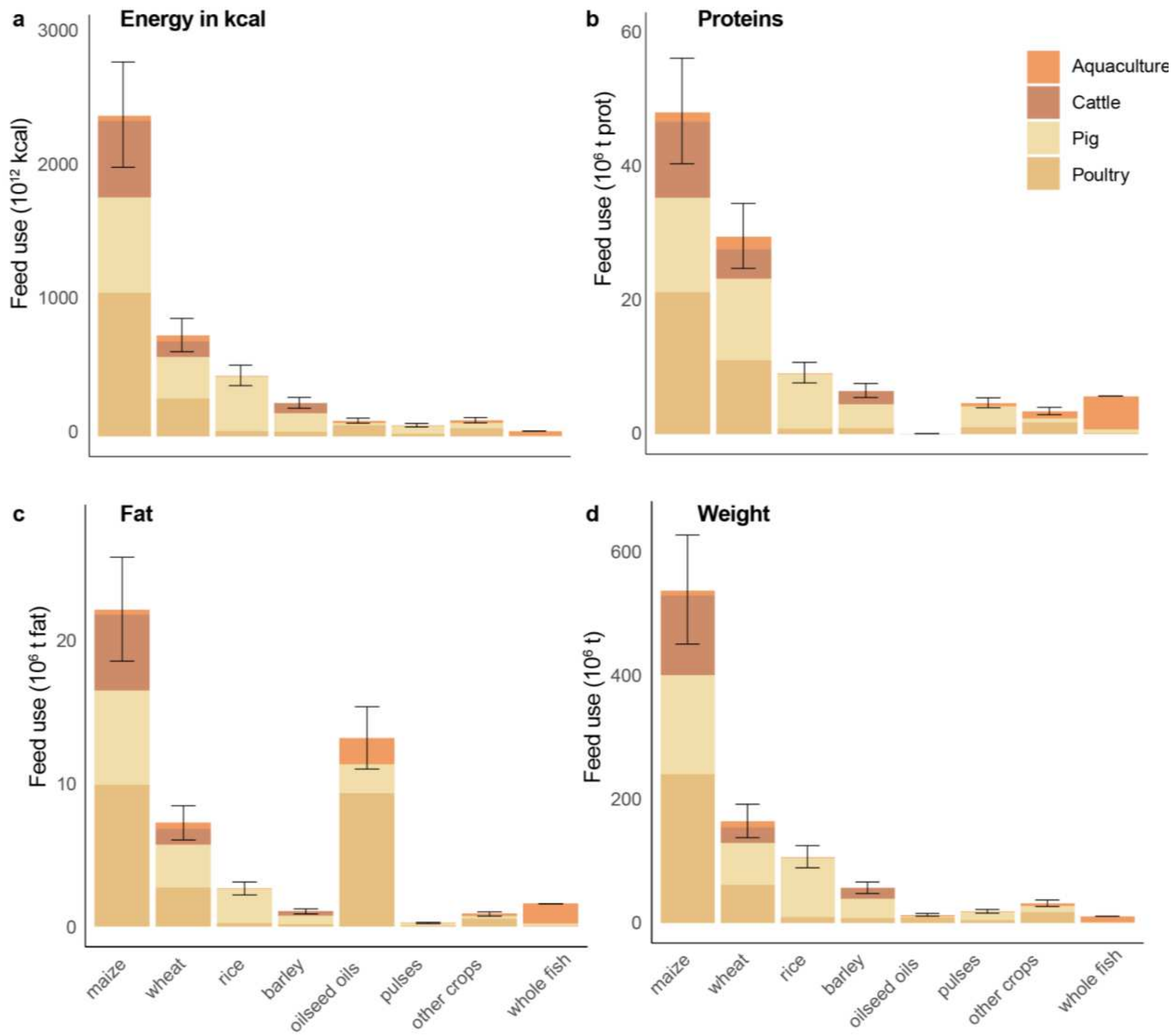

Figure 3. *Global feed use of food-competing feedstuff presented in a) energy content (kcal), b) protein content, c) fat content, and d) quantities (fresh weight). Error bars represent the total uncertainty range for different feedstuffs (see methods). The use of the feed is color-coded to each feed group.*

2.2. Availability of food system by-products

The total availability of food system by-products, including crop residues, selected crop processing by-products and livestock and fish by-products, was estimated by multiplying the production quantities from FAO (2021) and FishStatJ (2020) with the conversion factors for different by-products and residues (see Methods). The feed use of these by-products and residues was then reduced from their production to estimate the potential availability of materials not used as feed.

Only relatively small shares of crop residues and livestock by-products are used as feed currently while nearly all oilseed meals (i.e. oilseed meals and cakes, here grouped together under meals) and more than half of the total potential of crop processing by-products such as sugarbeet pulp and cereal bran are already in use (Fig 4). It should be noted that while only small shares of, for example crop residues, are used for feed, these resources also have other uses such as biofuels or bedding material for livestock. The use of crop residues in maintenance of soil quality was taken into account in sustainable harvest ratios (see methods), but other uses were excluded, assuming that all by-products not already used for feed would be available to replace the human-edible parts of feed. Despite the multiple uses, the largest absolute theoretical potential in utilizing by-products as feed still lies in crop residues and livestock by-products as their theoretical availability exceeds the availability of other by-products (Fig 5).

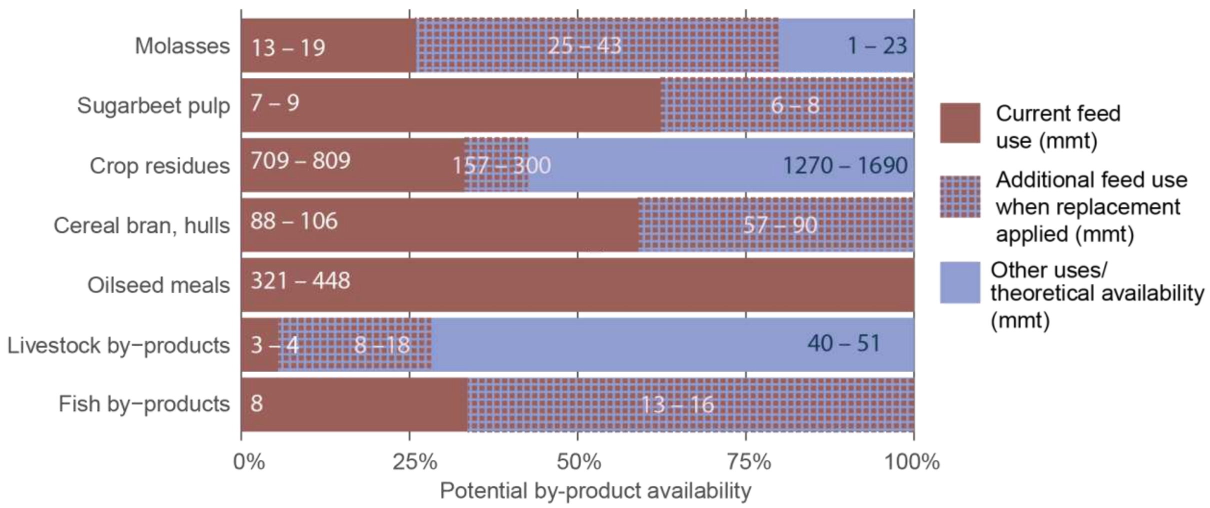

***Figure 4**. Feed use and theoretical availability of food system by-products. In addition, the increased feed use of by-products is shown when applying the replacement analyzed in this study (see Methods).*

The availability of crop residues and livestock by-products, with both high global production and relatively low feed use, is directly related to the crop and livestock production in a country, and hence larger countries with higher agricultural production show the highest potential availability (Figs 5a and 5e). For crop processing by-products such as cereal bran, with higher variation in their production and higher feed use, South Asia, Russia and North America show high availability while for sugar processing by-products especially Brazil and India show potential for increased feed use (Figs 5b and 5d). Oilseed meals are highly traded commodities in the global feed market and many of the countries actually present negative availability numbers, referring to a situation where the feed use exceeds the country-level production, indicating dependence on imports (Fig 5c). For fish by-products, the largest captured fish and aquaculture production countries, such as China and Indonesia, show the highest availability and the largest potential to increase the production of fishmeal and fish oil from by-products that can be used for local needs or exported to other countries (Fig 5f).

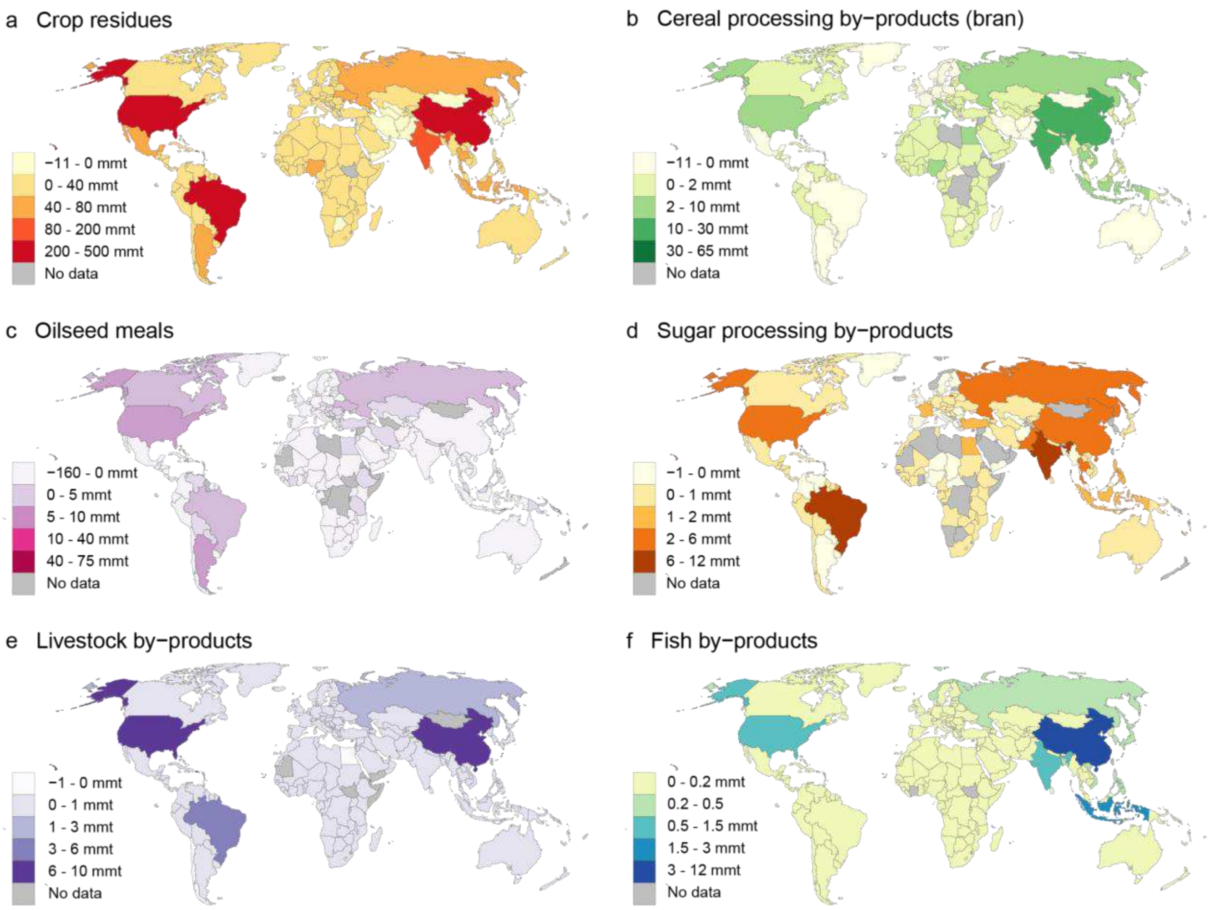

***Figure 5**. Theoretical availability of by-products and residues (computed by subtracting the feed use from potential production in a country) without considering trade. Here a) crop residues include residues from rice, cereals, sugar cane and pulses; b) cereal processing by-products include cereal bran and hulls; c) oilseed meals include rapeseed, soybean, sunflower seed, palm kernel, sesame seed and other oilseed meals; d) sugar processing by-products include molasses from sugar beet and sugar cane and sugar beet pulp; e) livestock by-products include only by-products from non-ruminant origin, including blood meal, hydrolyzed feather meal, meat meal from hogs and ovines and poultry by-product meal, f) fish by-products include by-products from processing of both aquaculture and capture fish.*

2.3. The potential for replacing food-competing feedstuff with non-food competing by-products and residues

To estimate the replacement potential of the food-competing feedstuffs with by-products and residues, we focused on five cases with high replacement potential owned to the similar nutritional profiles: 1) the replacement of cereals including maize, wheat, barley, cassava, sorghum, millet and rice with cereal processing by-products such as brans or hulls and sugar processing by-products such as molasses and sugar beet pulp and crop residues, 2) the replacement of oilseed oils with poultry oil and fish oil made from fish by-products, 3) the replacement of pulses with oilseed meals, livestock by-products and fishmeal made from fish by-products, 4) the replacement of fishmeal made from whole fish with processed animal proteins from livestock by-products, oilseed meals and fishmeal made from fish by-products, 5) and the replacement of fish oil made from whole fish with poultry oil and fish oil made from fish by-products.

Although the potential availability of some of the by-products or residues is much higher compared to the feed use (Fig 4), animals' nutritional requirements constrain their use in livestock and aquaculture feeds (Table S5). For example, although there is abundance of crop residues, their fibrousness, lack of protein and readily utilisable carbohydrates limit their inclusion potential while meeting the nutritional requirements to maintain animal productivity (Table S7). The same applies for other animal feeds. For example, there is a great abundance of livestock by-products to replace all fish use but due to the need to maintain the essential fatty acid profile required in aquaculture production (Monteiro et al., 2018), not all fish oil in aquafeeds can be substituted with processed animal fats from livestock (Tables S5 and S6). Here, the replacement potential was estimated based on literature on feed experiments, applying the maximum replacement ratios with no impact on productivity (Methods). The only exception was considered for the replacement of cereal feed use with crop residues in cattle production as the negative impacts on productivity are likely unavoidable even with low substitution rates (Tables S5 and S7).

When taking into account these replacement constraints (Table S5) and the total availability of the selected by-products, 14–17% of the selected food-competing feedstuff could be replaced with the by-products assessed in this study, without negatively impacting productivity, and even up to 30-35% when considering also crop residues and allowing some decrease in animal productivity (Table 1). The highest replacement potential lies in cereals, due to their major use as feedstuff in all animal production systems (Fig 2). However, the share of potential replacement is highest for fishmeal and fish oil made from whole fish indicating that nearly all whole fish used to produce fishmeal and fish oil could be replaced with by-products.

Applying the maximum potential of replacing the food-competing feedstuff with by-products would potentially free up altogether 530-890 $*10^{12}$ kcal and 22-33 mmt of protein for humans, corresponding to 14-17% and 6-11%, respectively, of current global food supply. More specifically, up to 146 mmt of cereals (~16% of their feed use), up to 5.0 mmt of vegetable oils from oilseeds (~39% of their feed use), 4.7 mmt of pulses (~25% of their feed use), and more than 4.2 mmt of fishmeal made from whole fish, corresponding to more than 21 million tons of whole fish (~13% of current seafood supply) could be directed to human food use. The current global food supply refers to the food supply for the global population on average in 2016-2018 (FAO, 2021) taking into account food losses and waste from the supply chain excluding the production and consumption stage (Kummu et al., 2011). When applying world average yields for the replaced feed crop groups, the replacement would free up to 48-90 million ha of cropland corresponding to 4-7% of the world total arable land use in 2018 (FAO, 2021).

The maximum replacement potential scenario would use most of the cereal processing and fish by-products available, in contrast to livestock by-products and crop residues for which the potential availability is much higher and even if applying the maximum replacement potential, still the majority would remain available for other uses (Fig 4).

Table 1. *Feed use, replacement potential and increased food supply when applying the replacement potential with selected food system by-products and residues, given replacement constraints and regional availability of by-products and residues (see Methods).*

Feedstuff	**Feed use**	**Replacement material**	**Replacement potential**	**Increased food supply**					
	Million t		**%**	**10^12 kcal**	**% of current supply**	**10^12 g of protein**	**% of current supply**	**10^9 g of fat**	**% of current supply**
Cereals	898 (753 - 1050)	Cereal bran and hulls; Sugarbeet pulp; Molasses	13 – 16%	420 – 728	4.9 – 8.6%	11 – 19	4.4 – 7.7%	2920 – 5060	1.2 – 2.0%
Cereals including replacement with crop residues *		Cereal bran and hulls; Sugarbeet pulp; Molasses; Crop residues	29 – 35%	825 – 1280	9.7 – 15%	16 –21	6.7 – 8.8%	-1570 – -4410	-0.5 – -1.7%
Oilseed oils	13.1 (11.0 - 15.3)	Poultry oil; Fish oil from fish by-products	30 – 39%	31 – 57	0.3 – 0.6%	0	0	3270 – 6060	1.2 – 2.3%
Pulses	18.7 (15.7 - 21.8)	Oilseed meals; Livestock by-products; Fishmeal from fish by-products	17 – 25%	11.6 – 23.7	0.1 – 0.3%	0.62 – 1.3	0.3 – 0.5%	37.1 – 76.0	0.01 – 0.03%
Fishmeal from whole fish	4.86 (4.10 - 5.66)	Livestock by-products; Fishmeal from fish by-products	87 – 98%	71.7 – 87.6 **	0.8 – 1.0%	10.5 – 12.8**	4.4 – 5.3%	3010 – 3672 **	1.2 – 1.5%
Fish oil from whole fish	0.57 (0.48 - 0.66	Poultry oil; Fish oil from fish by-products	90–99%	38.8 – 58.8 **	0.4 – 0.6%	5.7 – 8.6	2.4 – 3.6%	1630 – 2470 **	0.6 – 1.0%
Total ***	934 (783 – 1091)		13.8 – 17.2%	532 – 893	6.3 – 10.5%	21.9 – 32.8	9.1 – 13.6%	8920 – 14600	3.6 – 5.9%
Total (incl. replacement with crop residues) ****			29.7 – 35.2	935 – 1450	11.0 – 17.0%	27.3 – 35.4	11.4 – 14.7%	4420 – 5130	1.8 - 2.1%

*Estimates include the reduced productivity (40-80%) when replacing cattle meat and dairy production feed use of cereals with crop residues.
**Fishmeal and fish oil converted to whole fish to estimate the increased food supply using conversion factors 0.2 for fishmeal and 0.04 for fish oil (see Methods).
*** Since fishmeal and fish oil can be produced simultaneously from the same fish, the increased food supply from replacing fishmeal and fish oil alternatives is calculated by considering only the one with the higher replacement potential to avoid double-accounting, in this case fishmeal.
****The sum of the potential considering also the cereals replacement with crop residues taking into account the reduced impact on productivity.

3. Discussion

Earlier scenario-based assessments have found that it is possible to keep the global supply adequate, restricting livestock feed use to only non-food-competing feed combined with changes in livestock production levels (Schader et al., 2015; Karlsson et al., 2017; Van Zanten et al., 2018; Van Hal et al., 2019; Röös et al., 2017). Our findings complement those assessments by showing that there is considerable potential to increase the feed use of food system by-products already in the current food system, without assuming reductions in animal production. This would reduce the feed use of food-competing feedstuffs and consequently contribute to increased food supply without consuming additional natural resources. However, the access to the improved food supply is unequally distributed around the world since a large part of the replacement potential, and the food-grade feed use, lies in the developed countries while less unused potential and more need remains in certain parts of the global South (Fig 5).

We found that cereals present the highest potential for increased food supply, but the increased supply of whole fish, pulses and oils from oilseeds can also have an important contribution to human nutrition (Fig 3; Table 1). Many of the crop processing by-products, such as cereal bran, sugar molasses or oilseed meals, have high nutritional quality and are well suited as animal feeds (Table S7). However, their use as feed in the current food system is already high, and increasing the feed use could imply more production pressure for the primary product. Other by-products, such as fish and livestock by-products, that also present valuable nutritional qualities, show more potential to increase their feed use. The replacement potential could be increased even further by also considering other food system by-products, apart from those focused in this study, and implementing more feed experiments focusing specifically on replacing food-competing feedstuffs with by-products and residues.

3.1. Challenges with using by-products as feed

The prospects of replacing part of the feedstuff with by-products are faced by various challenges. For example, not only the production of alternative feed is limited by the availability of by-products and residues and by existing regulations, such as banning the intra-species feed recycling in farmed animal production, but the potential can also be limited by nutritional aspects. Some by-products are of lower nutritional quality and can contain antinutritive compounds or higher amounts of fibre limiting growth (Bindelle et al., 2008; Colovic et al., 2019). This is true particularly with crop residues, that shows the highest theoretical replacement potential. Replacing the higher quality feeds with these compounds can result in lower livestock and aquaculture productivity or reduced nutritional (e.g. fatty acids composition) content of the commodities produced (Fry et al. 2016; Cottrel et al. 2020). Processing by-products through e.g. fermentation or other chemical treatments or additives can, however, improve their nutritional value (Shi et al. 2017; Dawood & Koshio 2019; Pires et al., 2010). Yet, as shown in the different feed experiment studies reviewed here (Tables S6 and S7), particularly food processing and animal by-products, have valuable nutritional quality and they can replace food-grade feed use without an impact in productivity. Especially in cattle nutrition, it is possible to construct the diets entirely based on non-food-competing feedstuffs even on very high animal production levels, as was demonstrated by Karlsson et al. (2018). Thus, this shift in animal diets may favor ruminant based production over monogastric animal based production (van Selm et al., 2021). However, increasing ruminant production will result in increased greenhouse gas emissions, which together with other environmental impacts, should be comprehensively assessed and balanced with other measures, such as changes in diets, when trying to minimize environmental impacts from food production. Additionally, if some reduction in animal productivity is acceptable, the avoidance of food-competing feedstuff use can be further implemented by raising livestock breeds or herbivorous and omnivorous fish species that can consume lower quality feeds, such as crop residues, and enable the more efficient use of these low-quality resources (Zijlstra & Beltranena, 2013; van Hal et al., 2019).

Furthermore, many by-products, especially those generated in livestock and fish processing, have high water content, are highly perishable or their production is seasonal (as is the case with crop residues) and hence, they require proper infrastructure and know-how for collecting, transportation, storage and processing (Colovic et al., 2019). The optimization of by-product based diets for maintaining high animal performance requires also knowledge of composition of feed resources and understanding of animal nutrient requirements. Thus, the realization of this dietary shift will likely require the education of animal producers and support of rural advisory services. Mixed farming systems (farms with both crop and animal production) would be logistically better suited for circulating material flows, e.g. when feeding crop residues to cattle produced in the same farm, but the ongoing trend towards more specialized farms will increase the need for transportation, storage and cooperation between farms when considering the feed use of by-products and residues. However, the large-scale infrastructure for logistics and storage is currently lacking in many parts of the world constraining their use (Rustad et al. 2011). The transporting and processing costs might thus be higher compared to the cost of conventional feeds especially in areas where investment in infrastructure would be needed. Further, social and cultural issues, related to the public acceptance of using by-products and residues in feed, especially related to livestock and aquaculture by-products, have to be considered (Hua et al., 2019; Rustad et al., 2011, Scarlat et al., 2010). In addition, when increasing the feed use of the food system by-products and residues, it is important to consider the impact of reduced raw materials available for other competitive uses, such as bioenergy, pharmaceuticals or fertilizer production. Yet, even when applying the maximum replacement potential shown in this study, much of crop residues and livestock by-products would remain available for other uses (Fig 3), therefore the issue of competitive uses is most critical for the other by-product groups. It can be, however, argued that food production should be prioritized over other uses of these biomass flows, as the other uses can typically utilize multiple alternative materials, while food can only be produced within food systems (Van Zanten et al., 2019; Muscat et al., 2020). All these aspects would require a broad systems perspective (Herrero et al., 2020) and further research, to fully understand the replacement potential, practical challenges and trade-offs related to realising it.

3.2. Challenges in directing current feed to human food

Increasing the consumption of the food-grade feedstuff also presents challenges. First, not all feed cereals meet the quality standards set by manufacturers or government agencies to be used as food, and changing from production of feed crops to food crops might require additional inputs such as increased fertilization. Second, the cultural, taste and consumer preferences need to be considered. For example, the whole fish used in the fishmeal and fish oil industries (i.e. from forage fish) consists mainly of bony and small pelagic fish species, or other low value by-catch fish or juvenile individuals, that are often not preferred for direct human consumption and they might require processing and preserving e.g. in canned, cured or dried form, for wider acceptance and uses in human diets (Tacon & Metian, 2009). However, these small fish are often low-cost and highly nutritious and they can serve as valuable dietary additions, especially in regions where more expensive fish products are not accessible for many people (Cashion et al. 2017).

In addition, the impacts of our current economic system on the food system structures should be considered; often it might be more beneficial to produce feed than food, as is the case with producing soybean meal or fishmeal for feed vs. using the raw materials directly as human food (Goldsmith, 2008; Cashion et al. 2017), an aspect that might restrict the transition. Also, the increasing use of by-products in feeds might result in added value in animal production that can result in rebound effect implying an increase in livestock production.

3.3. Limitations of the approach

The data in this study was gathered using various sources, databases, reports and models, each of which contain limitations of their own. An uncertainty analysis was performed for the estimation of livestock and aquaculture feed use as well as the potential availability of different by-products (see methods). Despite the uncertainties involved, our estimates for livestock and aquaculture feed use as well as the availability of by-products were compared to previous studies and they were found to be in line and in accordance with them (see comparison in SI). An important limitation of the study is that only selected food system by-products and residues were considered in our analysis. The by-products of cereal processing from alcohol and bioethanol industries are also used as major feedstuffs at the global level (Schingoethe et al, 2009; Klopfenstein et al., 2008), but our focus was on the by-products from food production and therefore these industries were omitted. Moreover, our database could not cover by-products from e.g. bakery or dairy industries as the feed use of those is not reported in our data sources. Therefore, while our study provides preliminary quantifications, a wider range of by-products and their replacement potential should be assessed in future studies. Also, some of the food-competing feedstuff categories excluded in this study, such as roots and tubers, might present additional replacement opportunities and deserve consideration. Another limitation is the spatial resolution applied in this study. The feed use and by-product availability was assessed at country-level and the replacement potential at regional level. However, to quantify the practical potential and assess in more detail the costs of transportation etc., a higher resolution spatial analysis would be needed.

Furthermore, estimating the replacement potential constraints from an animal nutritional perspective is challenging, since animal nutritional needs differ in different growing stages and production levels. The estimates used in this study were mostly based on feed experiment studies considering each replacement material individually (see Methods). In practice, the animal diets would likely be designed to include several different replacement materials simultaneously (e.g. brans, sugarbeet pulp and an oilseed meal). Their combined effect would, however, need more careful consideration as it could have effects on the nutritional value of the final product or impact animal health. Based on these limitations, the results of this study should be considered as theoretical potential of a biophysical change and the application of the results should be combined with more local level studies on the practical replacement potential taking into account also the social and economic considerations.

3.4 Concluding remarks

This study shows the considerable potential for more efficient use of food system by-products and residues for increasing the global food supply. In addition to the challenges related to the practical application of the replacement potential, harnessing the untapped potential of the by-products and residues would require a paradigm shift, from not only primarily pursuing higher productivity in food production but to also value more the efficient use of materials and the capacity of livestock and aquaculture sectors to circulate non-food-grade biomass back to food systems through feed use. Policy interventions and regulation would be needed in managing the feed resources and to provide incentives for feed industries to develop and innovate solutions for increased use of the materials most unused as feed, highlighted by this study. The more efficient use of food system by-products and residues can reduce the food-feed competition and improve food security without increasing the use of valuable natural resources. This, in combination with other measures, are urgently needed actions in the transition towards more circular and sustainable food systems for feeding the growing global population.

Methods

Material flows including the potential by-products and residues in the global food system were first mapped to understand the links and dependencies between the three subsectors of crop, livestock and aquaculture production (Fig 1). The total production of these sub-sectors was combined with the feed use data. The replacement potential was then analysed combining both the regional availability of the by-products and residues, and the replacement constraints (Table S5). Finally, the potential increase in global food supply was calculated assuming that all feedstuffs freed by this replacement were redirected to human consumption. The analysis was performed for a three-year average of 2016-2018 to avoid yearly fluctuations in the data.

Here, the focus was on replacing the human edible feed use, including cereals, oilseed oils, pulses, sugar crops and the whole fish used in producing fish oil and fishmeal, with by-products and residues. Although some of the terrestrial feedstuffs are produced with varieties classified as not suitable for human food, e.g. fodder maize, and not all of them meet the quality criteria for food use, we allocated them all in the food-competing feedstuff category since they are produced on arable land that instead can be used for production of varieties suitable for human consumption. While some unprocessed oilseeds, (e.g. soybeans) are consumed by humans, here all oilseeds were converted into meals/cakes and oils, of which only the oil was considered human edible. Roughages, crop residues and food processing by-products, such as oilseed meals or cereal bran, were not considered food-competing (Table

S3). Although some of them (e.g. brans) can also be used as food, they are considered as co-products of primary food commodities (e.g. flour), therefore they were not considered to be in direct competition with food use. Also some of the non-food-competing feedstuff, such as grass and other roughages may compete indirectly with food production when produced on arable land. This indirect competition was not, however, assessed in this study.

Feed use

For the total feed use in livestock production, we first multiplied the national yearly cattle (meat and dairy), poultry (meat and eggs) and pork (meat) production from the Food and Agriculture Organization of the United Nations statistics (FAO, 2021) with the regional feed conversion ratios (FCR) (kg dry matter feed/kg output) from Mekonnen and Hoekstra (2012). While over the last decade, FCRs have improved as the production systems have become more efficient, the FCRs from Mekonnen and Hoekstra (2012) for 2000 were applied here, as more up-to-date regional data on the FCRs was not available. The development of the FCRs since 2000 can be assumed marginal (e.g. for example in the EU the FCRs for finishing pigs improved 1% between 2013-2019 (ADHB 2015; ADHB 2019), and therefore the impact to our results would be marginal. The country-level feed use was then multiplied with the ratio of different feedstuff from Global Livestock Environmental Assessment Model FAO GLEAM 2.0 (FAO, 2017). These feed use data are presented for different production systems for ten world regions. This procedure resulted in overestimation of fishmeal use in poultry and pig production compared to Jackson (2009) which was corrected with applying the fishmeal inclusion rates for pig and poultry from Froehlich et al. (2018). In addition, the aggregated feed use categories in ruminant feed were divided into individual commodities (oilseed meals to rapeseed, soybean and cottonseed meals; grains to maize, wheat and barley) based on global feed use ratios of these materials. Also, the use of whole oilseeds (soybeans and rapeseed) was divided into oilseed oils and oilseed meals. However, since the replacement potential was estimated for aggregated categories (e.g. cereals) this division into individual commodities did not affect our results.

For the total feed use in aquaculture, both for commercial and farm-made feeds, we multiplied the feed production for each fed aquaculture production group (carps, tilapias, catfishes, other freshwater fishes, salmons, trouts, milkfish, eels, other marine fishes, shrimps, other freshwater crustaceans) with their respective FCRs. FCRs for commercial feeds were derived from Tacon & Metian (2015) and FCRs for farm-made feeds were assumed to be 50% higher than commercial ones based on Hasan et al. (2013). For highly carnivorous high value fed aquaculture groups (other marine fishes and shrimps), the percentage of global production not fed on commercial feeds, was assumed to feed on whole raw fish ("trash" fish) and their FCRs were estimated according to reported conversion ratios for these groups (Funge-Smith et al. 2005; De Silva & Turchini 2009; Hasan 2012; Cashion et al. 2017). Diet composition for the major fed aquaculture groups were taken from country-specific survey data from Tacon et al. (2011) and extrapolated to country level diet according to Troell et al. (2014). Diet composition data were provided in ranges of inclusion for each ingredient (min, max, average) and to estimate a diet composition that sums up to 100%, the proportion of each ingredient for the average diet composition was used to scale the diet to it, as explained in more detail in SI. This procedure resulted in an overestimation of the use of fishmeal and fish oil, as a) the survey data represented countries with notably higher inclusion rate of these ingredients than the global averages reported in Tacon et al. (2015) and b) the data represented diet composition for year 2010, while inclusion of fishmeal and fish oil has decreased since then. To adjust for this, we assumed the actual use of fish oil and fishmeal in each aquaculture group in 2015 and rescaled the rest of the diet to match this. (See SI methods for details). The amounts of fishmeal and fish oil produced from fish by-products were estimated to be 25-35% of the total fishmeal and fish oil produced (FAO, 2020).

The dry matter feed use was converted to fresh weight using the dry matter contents of the different feedstuff (FAO, 2017; Feedipedia, 2021; Feedtables, 2021). The combined feed use from livestock and aquaculture production was compared and harmonized with the estimates of global feed use from FAO Supply and Utilization Accounts (SUA) (FAO, 2021) for the years 2016-2018 for the feed groups for which the data was available (cereals, pulses, vegetable oils, molasses). Comparisons between our feed use estimates and published data is available in the SI.

Availability of by-products and residues

To estimate the availability of food system by-products and residues, we first estimated their potential production quantities and then reduced their current feed use from the totals. In this study we considered four different categories of food system by-products: 1) crop residues, 2) cereal and sugar processing by-products, 3) livestock by-products and 4) fish by-products processed into fishmeal and fish oil. The focus was on the by-products of primary crop and animal production and crop processing by-products already used as feed in important quantities at global scale and therefore, e.g. food waste from retail or consumption was not considered here.

To estimate the potential availability of crop residues, the yearly crop production (FAO, 2021) was multiplied with crop-specific residues-to-production ratios from Ronzon et al. (2015) originally from Wirsenius (2000). Here we considered only crop residues from cereals, rice, sugar cane and pulses that are most used as feedstuff (Davendra & Sevilla, 2002; Gertenbach & Dugmore, 2004). Crop residues left on fields have an important impact on soil fertilization and moisture retention (Scarlat et al., 2010). Therefore, we accounted for the crop residues that will be left on field by multiplying the crop production with the ratios of maximum sustainable harvest ranging from 0-50% (Ronzon et al. 2015; Scarlat et al., 2010).

Crop processing by-products refer to the co-products that result from a multifunctional process that is driven by the demand of the main product. The by-products considered in this study included cereal bran, molasses from sugar cane and beet processing, sugar beet pulp and oilseed meals. The quantities of cereal bran and molasses produced on average between 2016-2018 were taken from FAO Supply and Utilization Accounts (FAO, 2021). The amounts of sugarbeet pulp and oilseed meals were calculated from the amounts of sugarbeet and oilseed meals processed on average between 2016-2018 and multiplied with the conversion factors (FAO, 1996) reducing the amounts of waste created in the processing stage (FAO, 2011).

To estimate the potential availability of livestock by-products we first converted the production quantities of end products (cattle, pig and poultry meat) from FAO (2021) to live weight using dressing percentages from FAO (2017) and then multiplied those with the ratios of the processed by-products (poultry by-product meal, poultry oil, blood meal, hydrolyzed feather meal, meat meal from pork meat production, poultry oil) from van Hal et al. (2020). To estimate the poultry by-products from egg production first the amounts of slaughtered hen were calculated. This was estimated by dividing the numbers of laying hens from FAO (2021) with the average age at slaughtering and multiplied with their average weight at the end of the laying period (FAO, 2017). Here, the meat from laying hens was not assumed to be consumed by humans.

To estimate the availability of by-products from fish production we first gathered the aquaculture production and capture fisheries data from FishStatJ (2020). The fisheries production was multiplied with the average ratios of human consumption and non-food use from FAO Fisheries Yearbooks (FAO, 2010; FAO 2019) that presented the average ratios for developed and developing countries separately. The data was corrected for certain captured fish species for which literature indicates higher ratio going to non-food use (Shepherd and Jackson, 2013; Cao et al., 2015). The amounts of fish destined to non-food uses were then multiplied with the ratios going to reduction, i.e. fishmeal and fish oil production, and the ratios of fish fed directly to aquaculture (FAO 2010; FAO 2019). The amounts of potential fish by-products were estimated by multiplying the amounts of fish for human consumption from capture fisheries and aquaculture with the ratios processed (FAO 2010; FAO 2019) and multiplying the processed quantities with the average ratio of 41.5% of fish consisting of by-products (trimmings etc.) (Stevens et al., 2018), reducing 2% blood that is not used in reduction, and finally assuming 2% losses at primary fish processing stage (Cao et al., 2015). The share of by-products in fish varies among different fish species and even among the same species. The value applied in this study (41.5%) was estimated for salmon (Stevens et al., 2018) which most likely is a conservative estimate for most other fish species. However, it was applied here as a proxy, to avoid overestimating the fish by-products availability. To account for the uncertainty inherent in applying these conversion factors, we performed a sensitivity analysis (see below). The amounts of fishmeal and fish oil that could be produced from these by-products were then estimated by using the conversion ratios of 0.2 for fishmeal and 0.04 for fish oil, values a bit lower than the conversion ratios for fishmeal and fish oil from whole fish (Shepherd & Jackson 2013). Comparisons between our estimates and assessments from previous studies for food system by-product availability is available in the SI.

Replacement potential

The replacement potential of cereals, fishmeal and fish oil with food system by-products and residues was estimated by taking into account 1) the potential availability of the replacement materials within the 19 world regions (see Table S4 about the division of the countries to subregions) and 2) the replacement constraints including the nutritional requirements of livestock and aquaculture as well as regulation of the use of different animal derived by-products and residues in livestock and aquafeeds (Tables S5-S7). The replacement constraints were derived from reviewing literature on feed experiments assuming no reductions on productivity. The only exception for this was the replacement of cereals with crop residues in cattle feeds which reduced productivity by 40-80%. This reduced productivity was taken into account later when estimating the increased food supply.

Since the selected by-products are typically low value commodities, inter-regional trade of by-products and residues was excluded, but materials were assumed to be freely traded within each region. Oilseed meals and fishmeal are an exception being highly traded and valued products in the global feed markets. Here, as we did not account for inter-regional trade, the feed use of these highly traded commodities exceeds the potential production for some regions. In those regions the replacement potential is assumed to be zero for the by-products with negative availability.

Legislation and regulation constrain the use of livestock by-products as feed. A comprehensive review of animal by-product regulations in all countries was out of scope for this study, and in order to follow a precautionary approach and avoid overestimating the by-products availability, we applied the EU regulations globally, since they can be considered among the most strict ones. Feeding farmed animals on materials originating from the same species is forbidden (EC, 2009; EC, 2011; EC, 2021) and in addition, processed by-products from bovine animals are banned to use in livestock or aquaculture feed to avoid the spread of transmittable diseases (EC, 2009; EC, 2011). The safety issues regarding the feed use of by-products from ruminant origin are also acknowledged in US regulations (US FDA, 2020) as well as the more broad feed use recommendations by FAO (FAO & IFIF, 2020). Therefore livestock by-products from bovine origin were not considered as feed replacements in this study. However, animal-derived protein from non-ruminant origin is allowed for pig and poultry diets, considering the intra-species recycling ban (EC, 2021).

Fishmeal and fish oil are included in livestock feeds and aquafeeds because of their protein content, favourable amino acid and fatty acid profile, effect on growth and immune system and high digestibility (Cho & Kim, 2011). However, they are not essential to pig and poultry and here we assumed that 75-100% of the fishmeal in pig and poultry feeds are replaceable with oilseed meals, fishmeal made from fish by-products or livestock by-products from non-ruminant origin (blood meal and hydrolyzed feather meal) without impacting negatively their productivity (Frempong et al., 2019; Zier et al., 2004) (Table S5).

Based on previous alternative feed experiments for various fish species, 27 – 79 % of the fishmeal (dry matter) and 51 – 79% of the fish oil in aquafeeds can be replaced with processed by-products from livestock production (see Table S6). Fishmeal and fish oil made from fish by-products differ from the ones produced from whole fish as they on average contain less protein and have higher ash content (Hua et al., 2019). Despite this, they provide essential fatty acids and they have been successfully applied in aquafeeds (Hua et al., 2019). Here we assume that they are viable alternatives and can replace 75-100% of the fishmeal and fish oil made from whole fish in aquafeeds.

Crop processing by-products, such as cereal by-products (bran, hulls) and sugar by-products such as sugarbeet pulp or molasses were considered here as potential replacements for cereal use and oilseed meals as potential replacements for pulse use in livestock feed. Cereal by-products, such as bran have been applied in pig feeding (Table S7). They typically contain less starch and more fibre, compared to whole cereals, due to endosperm removal during processing (Woyengo et al., 2014). Although the high fibre content of these feedstuffs can produce satiety and have beneficial impacts on gut health in pig production, their inclusion is sometimes limited because of a reduction in the digestibility of dietary energy and protein, which can reduce the overall production performance (Jarret and Ashworth, 2018). Sugarbeet pulp contains readily digestible fibre such as pectin, has low lignin concentration and thus has high energy value for ruminant nutrition (Fadel et al., 2000), making it a well suited substitute of cereals (Karlsson et al., 2018). The nutritive value of sugarbeet pulp can be further improved with added molasses (Fadel et al., 2000). Crop residues (straws and leaves) are high in fibre and applicable as potential replacement materials for cereals in ruminant feeding taking into account their negative impact on productivity (Tables S5 and S7). However, the potential use of crop residues for monogastric animals such as pigs or poultry is much lower due to limited ability of monogastrics to digest feedstuffs with high fibre concentration and low digestibility (Yang et al., 2021) (Table S5). Oilseed meals and cakes derived from e.g. soy and rapeseed are high-quality protein feeds with balanced amino acid composition and high nutrient digestibility for livestock (Feedipedia, 2021). The animal production responses of oilseed meals and cakes are typically superior or less often equal to pulses (e.g. faba bean, pea, lupin and lentils) in diets of lactating dairy cows (Puhakka et al., 2016; Ramin et al., 2017; Lamminen et al., 2019), pigs (Zijlstra et al., 2008; Degola and Jonkus, 2018) and poultry (Koivunen et al., 2014; Koivunen et al., 2016). The use of oilseed meals and cakes as protein feed in livestock diets is currently the prevailing practice, whereas pulses are considered as the alternative. For ruminants, only the mixed and feedlot production systems (FAO, 2017) that contained cereals in their feed were considered in the replacement, since the ruminant diets in grazing systems are mainly based on forages and typically contain no or only low amounts of cereal-based concentrates.

The maximum and minimum total replacement potential was calculated considering both the availability of replacement materials as well as the replacement constraints (Table S5). First, the feed use of each of the food-competing feedstuffs selected was multiplied with the replacement constraints to estimate the maximum and minimum replacement potential for each animal production group and replacement material individually. Second, the maximum and minimum replacement potentials were corrected with the availability of the selected replacement material in the region. Third, the combined replacement potential of the different replacement materials for one animal production group was estimated by summing the individual replacement potentials and normalizing them so that the total could not exceed the feed use of the animal production group in a region. Finally, the combined potential of the different replacement materials and animal production groups were summed to derive the total replacement potential (see SI for more detailed description of the method).

The increased food supply was estimated by multiplying the replaced food-competing feedstuff amounts with their energy (kcal), protein and fat contents (FAO, 2001; Feedipedia, 2021; Feedtables, 2021). It is important to note that since fishmeal and fish oil can be produced simultaneously from the same fish, the increased food supply from replacing fishmeal and fish oil alternatives was not summed to avoid double-accounting, but only the one with the higher replacement potential was considered.

For the replacement of cereals in feed use two cases were estimated. One applying only the replacement materials (cereal bran, sugarbeet pulp and molasses) and constraints with no estimated impact on productivity (Table S5) and a second case adding crop residues as potential replacement material in addition to the first case. With the latter case, the replacement with crop residues implies a 40-80% decrease in cattle meat and dairy production (Table S7), which was then calculated proportional to the share of feed replaced and reduced from the estimated increase in the food supply.

Sensitivity analysis

To assess the associated uncertainty with the input variables, we performed Monte Carlo simulations for the input data for both the feed use and the availability of by-products and crop residues. Livestock and aquaculture feed use were first calculated by taking 500 randomly sampled values from uniform distributions of feed-conversion ratios with mean value the reported FCRs (described in the feed use section) and a coefficient of variation (CV) of 0.1. Next, a similar approach was followed to derive the uncertainty intervals for the availability of by-products and residues. Five hundred randomly sampled values were taken from uniform distributions of different conversion factors with the CV of 0.1. This CV was chosen because it represented the variation in the FAO technical conversion factors (1996) for many of the crop processing by-products and for lack of more detailed data, the same distribution was assumed to represent the uncertainty also in the availability of crop residues and livestock by-products.

Data availability

All the data used in this study are publicly available, see methods about a description of the source data. Supplementary data produced in this study provided with the submission.

Code availability

The analysis was performed using R studio (R version 4.0.5) (R Core Team, 2021). The code is available upon request from the first author.

Competing Interests

The authors have no conflicts of interest to disclose.

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