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LETTER

The potential to increase food system resilience by replacing feed imports with domestic food system byproducts

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Abstract

Many key feed commodities used in livestock and aquaculture production are highly traded in global agricultural markets. The dependence on these imported inputs may create vulnerabilities for importing countries when disturbances in global trade flows occur. Replacing feed imports with domestic food system byproducts—i.e. secondary products from crop, livestock and aquaculture processing—offers a solution to decrease trade dependency, increase food system resilience, and contribute to environmental sustainability. The potential impacts of such replacements on global food-trade patterns—and consequently on heightened self-sufficiency—remain largely unexplored. In this study, we assessed the material flows in the global feed trade at the country level and estimated the potential to replace imported feeds with more efficient use of domestic food system byproducts. We focus on three key feed groups in both livestock and aquaculture production: cereals, oilseed meals and fishmeal. We show that, at the global level, 19% of cereal, 16% of oilseed meals, and 27% of fishmeal feed imports can be replaced with domestic food system byproducts without affecting animal productivity. The high-input animal production countries in East and Southeast Asia, Western Europe, and North America show the highest potential. This study highlights the commodities and areas with the most potential to guide and inform decisions and investments to build more local and circular livestock and aquaculture production that would be more resilient to several kinds of shocks. Replacing feed imports with food system byproducts can increase food system resilience. Nevertheless, larger sustainability strategies, such as dietary change and reducing food loss and waste, should be implemented to ensure a transition towards more sustainable food systems.

1. Introduction

Several key feed ingredients, such as soybean meals or fishmeal, are highly traded commodities in global markets (FAO 2023a). This has led to the spatial separation of livestock and aquaculture production from the associated natural resource utilisation and thus environmental stress linked to these products. The feed trade has increased exponentially during the past five decades, driven by increases in animal production and livestock density (Wang *et al* 2018). In 2017, the global trade of soybean, 80% of which is processed into soybean meal for use in animal feeds, was worth 58 billion US$, which is nearly three times greater than the global rice trade (20 billion US$) and more than 30% greater than the global wheat trade (43 billion US$) (De Maria *et al* 2020).

International trade has increased the supply of high-quality feed in many regions where their own production does not meet demand, contributing to increased food production and food security (Uwizeye *et al* 2020). However, the increase in the global feed trade has also created implications for food system resilience, by which we refer to the 'capacity of the food system to persist, maintain its core functionalities and adapt to change but also transform away from unsustainable social-ecological trajectories' (Nyström et al 2019). First, increased trade dependency has led to increased vulnerabilities to production countries if unexpected shocks or disturbances in trade flows occur. These shocks or disturbances can be produced by extreme weather events, geopolitical or economic shocks or global pandemics, with major implications for food system resilience. The Russian invasion in Ukraine portraits a recent example of food trade disturbances (Hassen and Bilali 2022). Second, the concentration of production amplifies the impacts of trade dependency on food system resilience (Tu et al 2019). For example, most soybean and maize trade occurs between a few exporting countries and an increasing number of importing countries (Wang et al 2018). If feed production and export flows in these few exporting countries are disturbed, food production in the importing countries will be threatened. Third, the spatial separation of animal production from feed production has obscured the environmental and resource costs of animal production (Naylor et al 2005, Fuchs et al 2019) and led to environmental problems such as aggravated global nutrient imbalances (Wang et al 2018).

Food system resilience has gained increasing attention with an increasing human population and worsening environmental problems, such as climate change leading to increased unpredictability in global trade flows, and the number of studies focusing on food system resilience is growing (e.g. Tendall et al 2015, Kamalahmadi and Parast 2016, Stone and Rahimifard 2018). Studies on food supply chain resilience have traditionally focused on enterprise operations management (Kamalahmadi and Parast 2016), for example, by suggesting diversification of feed trade flows to decrease the dependency and monopolies of certain producing regions (Rimhanen et al 2023). However, few studies have presented practical strategies and concrete actions to increase resilience at the national (e.g. Rimhanen et al 2023) or global scale (e.g. Fraser et al 2015).

In this study, we focused on increasing food system resilience by reducing the dependence of animal production on imported feeds. Although a reduction in global animal protein production and consumption, particularly in developed countries, is one of the most important actions for increasing food system sustainability (Van Kernebeek et al 2016, Poore and Nemecek 2018, Willett et al 2019), some levels of animal production continue to play an important role in producing nutritious food for the human population when it is produced under a circular paradigm (Röös et al 2017, Van Zanten et al 2018, 2019). Replacing feedstuff with alternative, potentially even domestically available, feed ingredients offers one possible practical solution to increase circularity and the capacity to maintain animal production. Food system byproducts and residues, referring here to all the secondary products derived from the production of primary human foods, offer one highly relevant possibility for use as alternative feeds (Sandström et al 2022). At the same time, replacing crops with food system byproducts can also reduce pressure on natural resources, such as land or water use, and increase food system circularity (Van Zanten et al 2019), which has been the target of many national-level (Ministry of the Environment, Finland 2021) and regional-level policies and strategies (EC COM/2020/98 2020). Reducing the use of crops or fishmeal as feed would also contribute to decreasing the environmental pressure caused by their production related to, e.g. soybean or palm oil production driving tropical deforestation (Vijay et al 2016, Song et al 2021) or the production of fishmeal from wild-caught fishes aggravating overfishing for many sea ecosystems already under high pressure (Cashion et al 2017, FAO 2022).

Many crop processing byproducts (e.g. cereal bran, distillers' grains, molasses and fruit pulps), livestock byproducts (e.g. processed animal protein from pig and poultry production) and fisheries and aquaculture processing byproducts (e.g. fishmeal produced from fish processing waste) have valuable nutritional profiles and are widely used as alternative feed materials in both livestock and aquaculture production without compromising animal productivity (Sandström et al 2022). Previously, the potential to replace food-grade feed materials with food system byproducts has been quantified at the global level, and it was found that this replacement could increase the human food supply by up to 13% (Sandström et al 2022).

Replacing feed imports with domestically available byproducts could make the food system more sustainable and local, and it also offers a concrete action to potentially reduce the increasing dependency on trade. This, in turn, could improve the food system's resilience against possible trade shocks. Despite the importance of this topic, the potential impacts of such substitutions on global food-trade patterns—and consequently on increased self-sufficiency—remain largely unexplored. Our global study aimed to examine how imported livestock and aquaculture feeds could be replaced with domestic food system byproducts. Our objective is to identify countries and alternative feedstuffs that have the greatest potential for this transition, particularly those concentrating on three of the most used and traded feedstuffs globally: cereals, oilseed meals, and fishmeal. By analysing how much of the imported feed can be replaced with domestic food system byproducts, we are able to present a novel perspective on alternative feedstuff utilisation.

2. Methods and data

We analysed the replacement potential of imported feedstuff (cereals, oilseed meals and fishmeal) with domestic food system byproducts and residues. First, we collected data on feed use and feed trade flows to analyse how much of these feedstuffs are used and traded in different countries. Second, we analysed the potential availability, i.e. the nonfeed use of the food system byproducts available domestically. Third, we combined these two datasets and analysed how much of the feed imports could be replaced with domestically available byproducts, taking into account the nutritional restrictions in animal diets.

2.1. Feed trade flows

We gathered data on livestock and aquaculture feed use covering 168 countries (see the regional division of countries in supplementary figure S1). For livestock feed use, we applied the total country-level feed use quantities from the FAO Global Livestock Environmental Assessment Model (GLEAM) 3.0, including the feed use of beef and dairy cattle, chicken, and pigs for the reference year 2015 (FAO 2023b). The use of fishmeal in livestock feed was harmonised to match the global totals from Green and Pearsall (2016). For commercial aquaculture feed use, we applied the following approach, as in Sandström *et al* (2022). The production of different aquaculture groups (FAO 2023c) was first multiplied by the respective feed conversion ratios (FCRs) from Tacon and Metian (2015). The diet compositions for the aquaculture groups were obtained from Tacon *et al* (2011) and Troell *et al* (2014). The amount of fishmeal produced from fish-processing byproducts were estimated to be 25%–35% of the total quantities used (FAO 2020). Finally, livestock and aquaculture feed use totals were summed to obtain the total country-level feed use.

Feed trade flows (i.e. the share of imports, exports, and domestic production) were analysed using the method of Kastner *et al* (2011), which identifies the original production countries for the imported commodities. For crops, we based the calculations on FAO (2023a) production and bilateral trade flow data, and for fishmeal, we based the calculations on the FAO Fisheries and Aquaculture Statistics (2023b). We used the three-year mean of 2014–2016 to match the feed use data and to avoid yearly fluctuations in the data. According to the trade data for fishmeal, some countries presented higher export quantities than the sum of production and imports, possibly because of errors in reporting or categorising fishmeal into other categories. In these cases, we assumed that consumption was based on 100% domestic origin.

2.2. Nonfeed use of food system byproducts

Here, we considered three categories of food system byproducts that can be used to replace cereals, oilseed meals or fishmeal in feeds without affecting animal productivity:

1. crop processing byproducts, including cereal bran and middlings, citrus pulp, distillers' grains from beer brewing and corn ethanol production, molasses and sugar beet pulp,
2. livestock byproducts included processed animal protein from pig and poultry production, blood meal, hydrolysed feather meal, meat and bone meal and poultry byproduct meal,
3. fisheries and aquaculture byproducts processed into fishmeal.

In addition, we analysed an alternative scenario presented in the supplementary information, including crop residues in the replacement. We assumed that all the potential domestic production of the byproducts, excluding those already used as food and feed domestically, were available for use in the replacement analysis, here referred to as 'nonfeed use'. All the other uses, or exports to other countries, were not considered, assuming that the domestic feed use of these materials should be prioritised over, e.g. energy use (see Discussion).

First, we estimated the current production, or alternatively, the potential production of the byproducts when the current production values were not available, together with the modelled feed use of the food system byproducts. Additionally, the reported use of byproducts for food was removed when estimating the potential. The current quantities of cereal bran and molasses produced and used as feed and food were obtained from the FAO supply and utilisation accounts (FAO 2023a). The production of distillers' grains from corn ethanol production was estimated from Iram *et al* (2020), and the production of brewer grains from beer brewing was analysed by multiplying country-level beer production (FAO 2023a) by the conversion factor from Lynch *et al* (2016). The current feed used for distillers' grains was obtained from FAO GLEAM 3.0 (FAO 2023b). The potential production of sugar beet pulp was estimated by multiplying the amount of sugar beet processed (FAO 2023a) by the conversion factor (FAO 1996) and reducing waste and losses from processing (FAO 2011). Sugar beet pulp was obtained from FAO Gleam (FAO 2023b). Similarly, for citrus pulp, the potential production was estimated by multiplying the amounts of lemons, limes, oranges, tangerines, mandarins, clementines and satsumas processed with conversion factors from the FAO (1996). The current global feed use of citrus pulp is estimated to constitute 10% of the potential production (Bampidis and Robinson 2006). The nonfeed use of crop residues was estimated by applying the data from Smerald *et al* (2023), applying the country-level cereal crop residue production values and subtracting the animal usage (including animal feed and bedding) and the crop residues remaining in the field (to maintain soil organic carbon and avoid erosion (Scarlat *et al* 2010)) from the total production.

The potential production of byproducts from pork and poultry production was estimated by multiplying the production of pork and poultry meat (FAO 2023a) converted to live weight using dressing percentages from the FAO (2023c) by the conversion factors of processed products (van Hal 2020), including poultry byproduct meal, poultry oil, blood meal, hydrolysed feather meal and meat meal from pork meat production. Byproducts of egg production were analysed by estimating the number of slaughtered hens by dividing the number of laying hens (FAO 2023a) by the average age and weight at slaughtering (FAO 2023b). Here, we assumed that meat from laying hens was not destined for human consumption. Livestock byproducts currently used in aquaculture feeds were estimated following the approach described in '2.1 Feed flows'.

To estimate the potential production of fish and seafood processing waste, we multiplied capture fisheries and aquaculture production (FishStatJ 2020) by the ratios of human consumption and processing (FAO 2019). Then, we multiplied the processed quantities by the average ratio of non-human-edible waste (such as skin, scales, bones, heads and intestines). Due to the lack of estimates of fish processing waste for several fish species, we estimated a value of 41.5% for salmon (Stevens *et al* 2018), although we acknowledge that this value is most likely a conservative estimate for other species. We assumed that all other parts except blood (2%) could be used in fish meal production and accounted for 2% of the losses assumed at the processing stage (from Cao *et al* 2015). The amount of fishmeal produced from the available fish processing waste was estimated by using a conversion factor of 0.2 (Shepherd and Jackson 2013).

2.3. Replacement constraints

The potential of food system byproducts to replace cereals, oilseed meals and fishmeal in cattle, poultry, pork and aquaculture diets was estimated by applying minimum and maximum replacement constraints derived from a literature review of feed experiment studies from Sandström *et al* (2022), not allowing reduction in animal productivity (table 1). In addition to nutritional constraints, regulation also limits the replacement potential. Intraspecies recycling (feeding byproducts of animal species back to the same species) was assumed to be forbidden globally following EU legislation (EC 1069/2009 2009, EC 142/2011 2011, EC 1372/2021 2021). In addition, bovine-origin byproducts are not allowed for use in animal feed to avoid the spread of transmittable diseases (EC 1069/2009 2009, EC 142/2011 2011, FAO & IFIF 2020, US Food and Drug Administration 2020); therefore, they were not considered in this study.

2.4. Replacement potential

The potential to replace the imports of feed cereals, oilseed meals and fishmeal was quantified considering the range of replacement potential indicated in table 1 individually for the different byproducts. Second, the replacement potentials were corrected for the potential nonfeed use of the byproducts domestically. Last, to avoid double accounting, the combined replacement potential of the different byproducts was adjusted proportionally for all replacement materials, i.e. without prioritising, so that the total replacement could not exceed the imports of the feedstuff in question.

2.5. Uncertainty analysis

To assess the combined uncertainties related to the estimation of the nonfeed use of the food system byproducts, we took 500 randomly sampled values from the uncertainty range of each variable described in supplementary table S1. For most of the conversion factors, we applied an uncertainty range with a coefficient of variation (cv) of 0.1. This value was selected to represent the variation in the FAO technical conversion factor (FAO 1996) for most of the crop processing byproducts. The uncertainty ranges for the estimations of crop residue production, feed use, and remaining crop residues were retrieved from Smerald *et al* (2023). In addition, for the uncertainties of the feed replacement constraints, we applied 500 random samples of uniform distribution of the minimum and maximum values identified from the literature review of the feed experiment studies from Sandström *et al* (2022) (table 1). In the results, we present the median, 10th and 90th percentile values of the resulting distribution of Monte Carlo outcomes.

3. Results

3.1. Feed trade flows

We found that approximately half of all oilseed meal (54%) and fishmeal (47%) feed use globally comes from imports, while for feed cereals, the share of imports is much smaller, ca. 17% (figure 1). Therefore, the trade of these feedstuffs has a large importance for global livestock and aquaculture production, resulting in high dependencies on imports. Imports play a particularly important role in poultry and pig production since 32% and 30% of global oilseed meals are used for their feed, while fishmeal imports are most important for aquaculture production, where 68% of it is used (see supplementary figure S2).

We found, however, high variation in trade dependency between the countries (figure 1). In 2015, North and South America—especially the USA, Canada, Brazil and Argentina—as well as countries such as Russia and Ukraine were major exporters of both cereals and oilseed meals (figure 1). On the other

Table 1. Replacement constraints applied in this study.

Feed material	Replacement material	Dairy Cattle	Beef Cattle[a]	Pigs	Poultry	Aquaculture
Cereals	Crop residues[b]	100% but production decreased 40%–80%	100% but production decreased 40%–80%	2%–13% piglets	2%	0%
	Cereal bran, middlings	45%–55%	45%–55%	5%–16%	5%–39%	0%
	Distiller's grains and brewers' grains	26%–100%	26%–100%	10%–43%	4%–40%	0%
	Sugar beet pulp	70%–100%	70%–100%	10%–25% (up to 70% on sows)	2%–18%	0%
	Molasses	17%–30%	17%–30%	5%–10%	0%	0%
	Citrus pulp	34%–100%	34%–100%	13%–40%	0%–15%	0%
Oilseed meals	Pork meat meal	_	_	0%	33%–35%	75%–100%
	Poultry byproduct meal	_	_	75%–100%	0%	75%–100%
	Hydrolysed feather meal	_	_	12%–43%	0%	75%–100%
	Blood meal pig	_	_	0%	5%–36%	75%–100%
	Blood meal poultry	_	_	17%–50%	0%	75%–100%
	Fishmeal from fish waste	_	_	75%–100%	33%–35%	75%–100%
Fishmeal	Pork meat meal	_	_	0%	0%	27%–79%
	Poultry byproduct meal	_	_	0%	0%	27%–79%
	Hydrolysed feather meal	_	_	75%–100%	0%	27%–79%
	Blood meal pig	_	_	0%	75%–100%	27%–79%
	Blood meal poultry	_	_	75%–100%	0%	27%–79%
	Fishmeal from fish waste	_	_	75%–100%	31%–40%	75–100%

Empty entries indicate not including the feed material in the diet.
Replacement constraints derived from a literature review detailed in Sandström *et al* (2022).
[a] Assumed similar replacement potential as for dairy cows if few studies have indicated lower substitution rates, as the nutrient and energy requirements of animals with identical live weights for growth are usually lower than those for milk production.
[b] Crop residues considered only for the alternative scenario shown in the supplementary information.

hand, many countries in Europe, Africa and South and Southeast Asia were net importers of both feed cereals and oilseed meals. For fishmeal, the largest net exporters were Peru, Venezuela, Denmark and Morocco. Interestingly, China appears to be a major net importer of all the feed groups studied here because of its livestock and aquaculture production, which are mostly consumed domestically.

Most of the cereals produced were consumed domestically (figure 1(a)) or within the same region (figure 2(a)). Interregional trade was more evident for oilseed meals and fishmeal than for feed cereals (figures 2(b) and (c)). For the oilseeds, North and Latin America were major exporters to East and Southeast Asia and Western Europe. Interestingly, East and Southeast Asia, although being major importers of oilseed meals, also exported them—mainly to South Asia, North Africa and Western Asia. East and Southeast Asia, especially China, was the largest user of fishmeal (figure 2(c)). Latin America, with large producers such as Peru and Chile, was a major fishmeal exporter, and its trade partners were located mainly in East and Southeast Asia.

3.2. Replacement potential

At the global level, 35 million metric tons (Mt) (23–46 Mt; 10th–90th percentile range), which is 19% (12%–25%) of cereal feed imports, 24 Mt, 16% (19–29 Mt, 13%–19%) of oilseed meals and 800 thousand tons, 27% (511–1117 thousand tons, 17%–39%) of fishmeal feed imports could be replaced with domestic byproducts. Countries with highly industrialised animal production and consequently high imports of feed materials, such as the USA, the EU-27 and China, also show high replacement potential (figure 3). The replacement potential is considerably lower and less important for many African countries, Western, Central and Southern Asia and Eastern Europe, which are also less dependent on imported feed crops and fishmeal in their animal production (figure 1). As China is one of the world's largest net importers of feed, China appears to be among the

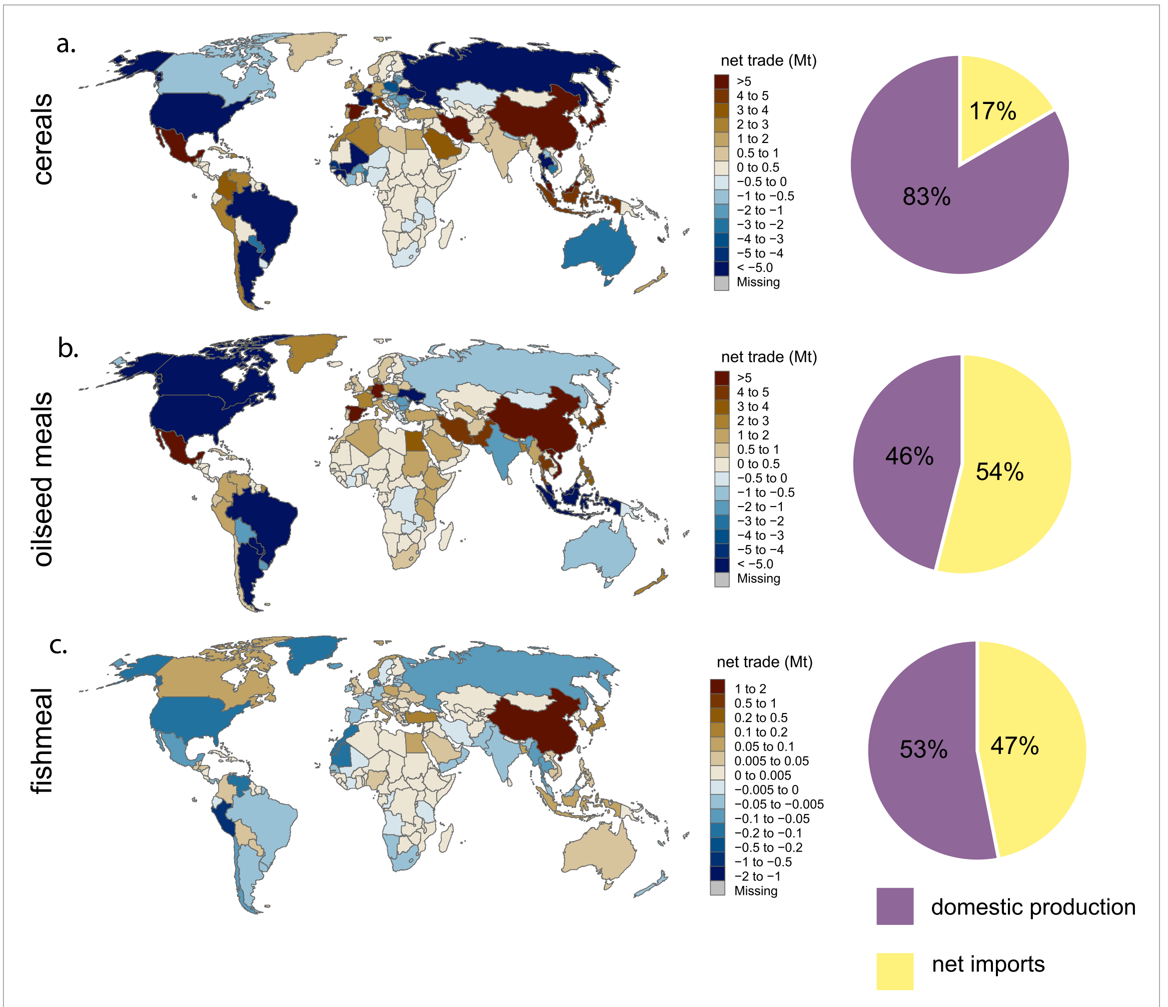

Figure 1. Net trade (imports-exports) for (a) cereals, (b) oilseed meals and (c) fishmeal used as feed for the world countries and the global sum of the feed from domestic production and net imports for 2015. The global sum is computed by calculating the net imports (imports-exports) for each country, assigning all negative values, i.e. net exporter countries, to 0 and consequently taking the global sums of use vs. net imports. Note the differences in the scales.

countries with the highest replacement potential in total quantities (figures 3(a)–(c)).

3.3. Replacement materials

When assessing the byproduct sources that are most important in the replacements, we found that distillers' grains and brewers' grains are most relevant for replacing cereal feed imports in Northern and Latin America, Western Europe and East and Southeast Asia (figure 4), as they are produced in large quantities there (based on our findings). Sugar beet pulp shows potential, particularly in North America and Western Europe, as does molasses for Latin America and Western Europe. Cereal bran and middlings show the most replacement potential for North America and East and Southeast Asia. Although at the global level, citrus pulp does not have as large a production quantity as the other byproducts assessed here, at the local level, it shows relevant potential. For example, for Latin America, citrus pulp could replace almost 840 thousand tons of imported cereals, mainly for cattle and pig diets, representing 12% of the total replacement potential analysed here, and in Northern Africa and Western Asia, 380 thousand tons, representing 23% of the total replacement potential.

Livestock byproducts and the processed animal protein derived from them show high potential to replace the imports of oilseed meals and fishmeal in East and Southeast Asia, North America and Europe (figure 4). In addition, increasing the feed use of fishmeal from fisheries byproducts also shows high potential, particularly in East and Southeast Asia.

3.4. Potential changes in trade flows

Replacing feed imports with food system byproducts would reduce trade flows and can consequently reduce the environmental pressure in the original production country. In a hypothetical scenario in which we replaced feedstuff with byproducts and kept the shares of trade flows between countries the same, the major feed trade flows from North and Latin America to East and Southeast Asia would be most impacted (see supplementary figure S3). In East and Southeast Asia, oilseed meal imports could be reduced by 12 Mt, and fishmeal imports could be reduced by 420 thousand tons.

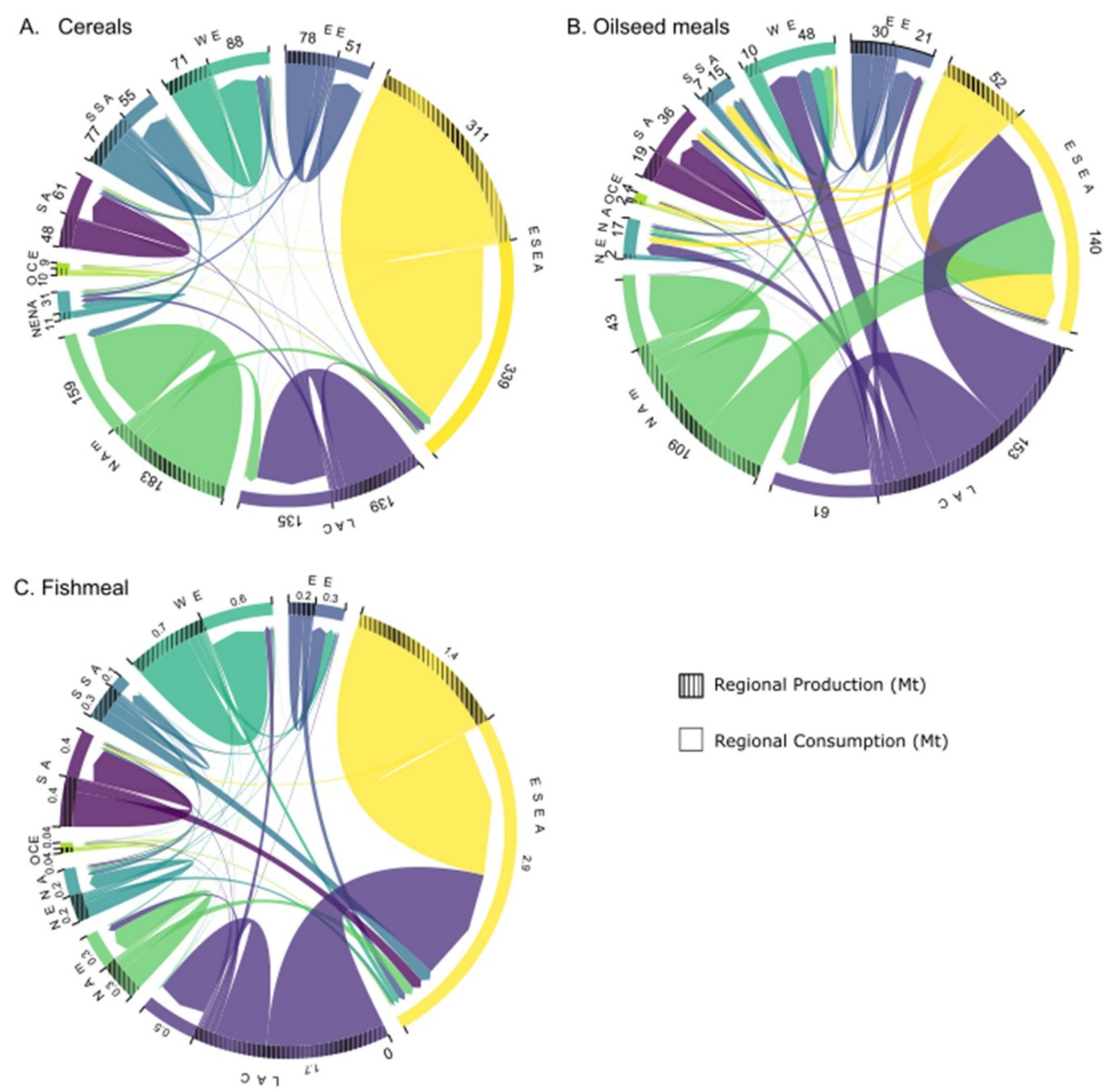

Figure 2. Feed production, consumption and trade flows within and between the regions in 2015. Both the total regional feed production and consumption are presented. The within-region arrows represent both the trade between nations (within a region in question) and domestically used feedstuff. Unit: million metric tons (Mt). WE= Western Europe, EE = Eastern Europe, ESEA = East and Southeast Asia, LAC = Latin America and Caribbean, NAm = North America, NENA = North Africa and Western Asia, OCE = Oceania, SA = South and Central Asia, SS = Sub-Saharan Africa. The countries in the regions are shown in supplementary figure S1.

4. Discussion

4.1. Increasing the feed use of food system byproducts can support more resilient and sustainable food systems

Recent events, such as the COVID-19 pandemic and the Russian invasion in Ukraine, are examples of major events that have caused disruptions in regular patterns of production and trade. These disruptions led to a decreased supply of various fundamental ingredients for livestock production in the importing countries (Rahimi *et al* 2022). In addition, reduced and disrupted trade flows led to increasing costs of animal feed ingredients impacting producers (Elleby *et al* 2020, Jagtap *et al* 2022). Thom *et al* (2024) found in a simulation study that reduced animal feed imports to the EU lead to an increase in domestic prices, consequently reducing domestic animal production and expanding domestic feed crop production. Feeding animals domestic food system byproducts could smooth and buffer the negative impacts of trade reductions.

In theory, replacing commercial feeds with byproducts could also lead to decreased pressure on natural resources if reduced imports lead to decreased feed production. For example, the reduced trade flows of oilseed meals and fishmeal from Latin America could reduce the pressure on South American tropical forests, which have been under high deforestation (Song *et al* 2021), and the Southeast Pacific fishing area, which currently has a very high percentage (67%) of stocks fished at unsustainable levels (FAO 2022). Alternatively, the reduced use of human-food-grade feed materials could contribute to an increased food supply without increasing agricultural production (Sandström *et al* 2022). However, the case might

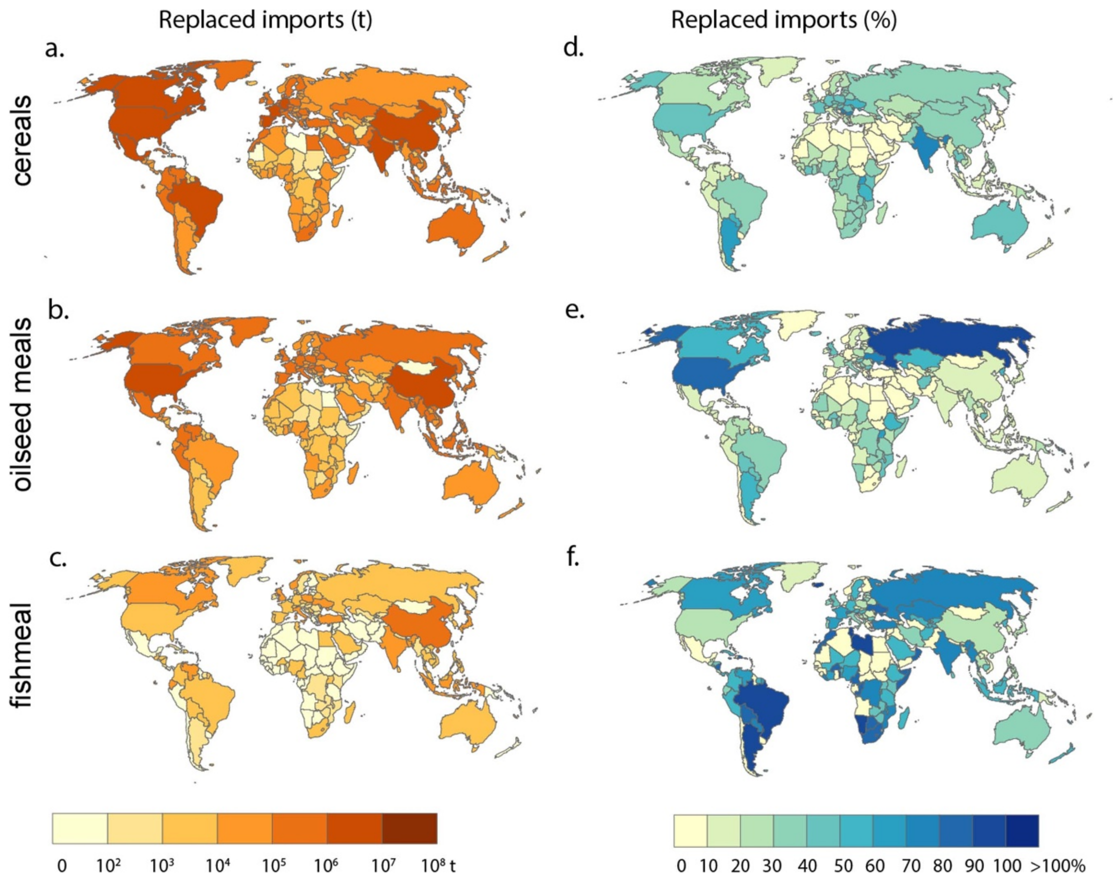

Figure 3. The potential to replace imports of cereals, oilseed meals and fishmeal with domestic food system byproducts was determined in 2015. Note the logarithmic scale in a-c. The first column indicates the total quantities replaced in metric tons, and the second column indicates the share of replaced imports of total imports of the specific feed material. The median values of the uncertainty range are shown here (see a map of the coefficient of variation in supplementary figure S4).

be different for oilseed meals compared to cereals and fishmeal, since oilseed meals, with the exception of soybean meal, can be considered as byproducts of oilseed oil production. Therefore, reducing oilseed meal imports would not directly lead to reduction of oilseed production, unless vegetable oil demand would change as well. In addition, attention should be given to avoid unintended rebound effects. For example, halting soybean feed imports to the EU would potentially reduce cropland demand by 11–14 million hectares outside the EU, mainly in South America (Karlsson *et al* 2021). However, if vegetable oil and/or oilseed meal demand would not change, reduced soybean production in South America could increase the production of other vegetable oils, especially palm oil, in Southeast Asia (Karlsson *et al* 2021). This could be, actually, a more efficient use of resources as palm oil is the most efficient oil crop in terms of land use (Murphy *et al* 2021), but specific attention should be put to environmental and social impacts of the production, as large scale palm oil cultivation in Southeast Asia has been one of the main drivers of biodiversity loss and ecosystem destruction (Vijay *et al* 2016). These findings underline the importance of the systems approach when analysing large-scale changes in food systems.

The findings of this study show the potential to replace feed imports with domestic food system byproducts, particularly for high-input industrialised animal production systems in North America, Europe and Eastern Asia (figures 3 and 4). However, for many developing countries, such as countries in sub-Saharan Africa with high import dependency and critical food security challenges, the use of imported feeds in industrial animal production systems and the potential production of feed-grade byproducts are lower, and consequently, the potential to increase the feed use of food system byproducts is minor. However, at the local level, it may still be relevant.

Many of the food system byproducts, such as those from crop, livestock and fish processing assessed in this study, have high-quality nutritional value, and replacing traditional feed materials with these products would not impact animal productivity (Sandström *et al* 2022). Therefore, the direct economic impacts on production would remain minimal; however, the indirect impacts on the feed industry and other actors in the supply chain should be assessed in future studies. The processed protein feed from livestock and fisheries byproducts—which, in many parts of the world, are still underutilised feed resources with valuable nutritional properties

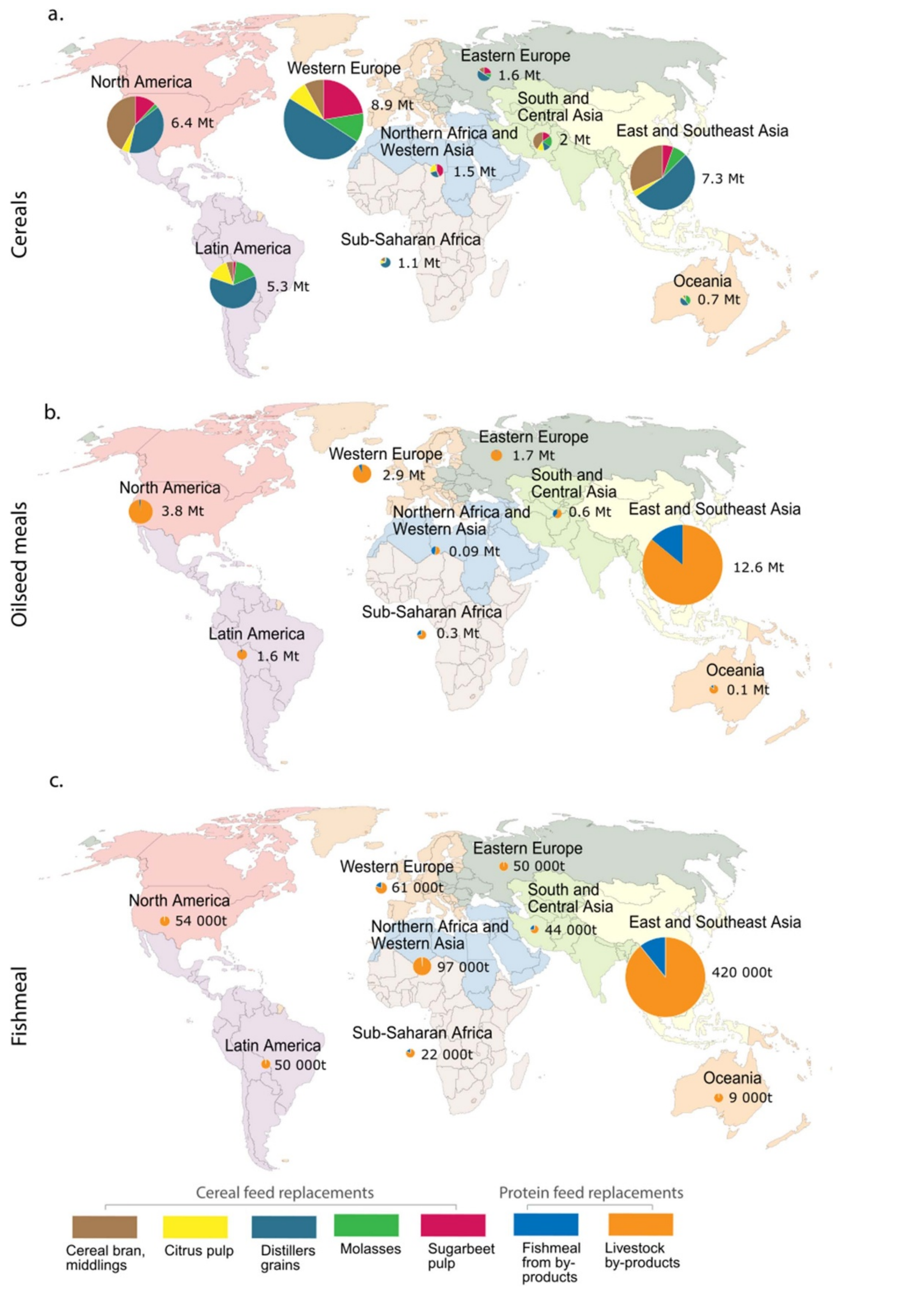

Figure 4. Regional potential of the different food system byproducts to replace the imports of cereals, oilseed meals and fishmeal. For the replacement analysis, the nonfeed use of the byproducts and the nutritional replacement constraints of the byproducts were considered (see Methods). Note the different scales in the figures. Regions with replacement potentials less than 1 million metric tons for cereals and oilseed and less than 50 000 tons for fishmeal are shown with equal sizes for visualisation purposes.

(Sandström *et al* 2022)—shows high replacement potential for oilseeds and fishmeal (figure 4). For example, poultry byproduct meal contains a more favourable amino acid profile than soybean meal and is therefore a highly relevant replacement material for fishmeal in aquaculture diets (Woodgate *et al* 2022).

4.2. Limiting factors for the replacement potential

The estimates for replacement potential applied in this study were derived from a review of feed experiment studies that analysed each replacement individually (Sandström *et al* 2022). In practice, animal feeds are formulated with various replacement materials combined. Therefore, the results of this study should be considered as a theoretical potential, followed by more careful consideration of their combined potential in animal feeds.

There are also additional food system byproducts not considered in this study, including byproducts from the dairy or bakery industries, that can be used in animal feeds (Liu *et al* 2018, Pineda-Quiroga *et al* 2018), and more research is needed to analyse their potential at the global level. Additionally, food waste fed to livestock or upgraded by feeding to insect larvae and using the protein produced as feed has important potential (Pinotti *et al* 2019). Furthermore, crop residues (i.e. straw, leaves and other fibrous inedible parts of crops removed at harvest) are widely produced feed materials, and they can be used instead of cereals in ruminant diets, either unprocessed or supplemented with additives (Duncan *et al* 2016, Koul *et al* 2022, FAO 2023b). Replacing high-energy feed cereals with them would, however, lead to an unavoidable drop in production (Duncan *et al* 2016); therefore, in this study, crop residues as replacement feedstuff were excluded from the main analysis. However, in a crisis situation where cereal feed imports and supply are disturbed, crop residues can serve as a valuable backup feed material. Therefore, we ran an alternative scenario, including crop residues as potential feed materials replacing feed cereals in cattle diets, taking into account the fraction of crop residues left in the field for soil amendment (see Methods). The results of the alternative scenario show that including crop residues in the replacement analysis would increase the potential, with an additional 6.7 Mt of cereal imports replaced, representing up to 23% (16%–29%) of total feed grain imports compared to 19% (12%–25%) without crop residues (see supplementary figure S5). Their relevance is particularly high for North America, Latin America and Western Europe (figure S5).

The replacement potential shown in our results, however, is constrained by various practical challenges, and for a more in-depth understanding of these challenges, this global view should be followed by more local-level practical case studies. In this study, to estimate the potential availability of byproducts for use in the replacement analysis, we excluded only the current domestic food and feed uses from the total availability of the byproducts. However, in addition to current food and feed use, these byproducts have many other uses, e.g. as bioenergy, pharmaceuticals or fertiliser (Rashwan *et al* 2023). If some of the resource flows are shifted from these industries to feed use, alternative materials would be needed. For example, biofuels are produced from fish processing waste, and if these waste streams are reduced, local biofuel industries would need to reduce production or obtain raw material from other streams (Stevens *et al* 2018). Therefore, the impact on other industries or local uses should be carefully assessed. However, according to the food recovery hierarchy (Stevens *et al* 2018, US Environmental Protection Agency 2024), food and feed use should be prioritised over other industrial uses. Furthermore, some of these byproducts are exported to other countries for use as feed. However, since they are often low-value side streams, their exports can be assumed to be marginal. For example, for molasses, which is one of the most commonly used byproduct, exports account for less than 10% of the total production at the global level (FAO 2023a). Due to the lack of global-level trade data for many of the byproducts and residues produced, we were not able to take this into account. This should, however, be assessed more carefully in future research. In addition, in many countries and regions, feed use regulation and legislation constrain the use of food system byproducts, mainly those of animal origin, in animal feeds (Woodgate *et al* 2022). Often, the supply of food system byproducts and potential users, such as livestock and aquaculture producers, are separated, and the lack of access can hinder their use. In addition, most of the byproducts considered here require collection, transportation, processing and storage before they can be used as animal feed, and this infrastructure does not exist in all countries. In addition, all the processes of the supply chain consume additional resources, such as energy, which were not considered in this study.

5. Conclusions

Replacing feed imports with domestic byproducts can support the transition towards more sustainable and resilient food systems by reducing the dependency on increasingly concentrated global feed markets and reducing the risk for food security due to unexpected shocks in international trade flows. This replacement could therefore contribute to more local food systems and shorten the spatial separation of production and consumption. However, it must be embedded in larger sustainability strategies, such as dietary change and reducing food loss and waste, to ensure a transition towards more circular and overall sustainable food systems. In addition to decreasing food-feed competition, domestic food system byproducts and residues can provide a buffer against unexpected disturbances in global trade flows and increase national resilience and food system circularity. More research and innovation are needed on the development and processing of feed materials from food system byproducts. However, the initial results quantified by this study can guide decision-makers and feed industries to focus on the materials with the most potential to develop their production chain. Their utilisation as feed can be supported, for example, by providing a platform or an interactive tool for suppliers to meet the potential users of their leftover materials or where policy and business could interact to develop solutions for more circular and resilient food systems.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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