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Dependency on imported agricultural inputs—global trade patterns and recent trends

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Abstract

Industrial food production systems depend on inputs such as fertilisers, pesticides, and commercial animal feeds that are highly traded commodities in global markets. Disturbances in international trade can threaten the local food production if the imports of the key agricultural inputs were drastically reduced. However, despite the importance of the topic, a comprehensive analysis focusing on the import dependency of multiple agricultural inputs at the global level and thus revealing the vulnerability of regions and individual countries does not exist. Here, we analyse the temporal trends of agricultural input trade globally at the national scale from 1991 to 2020 by applying statistics of the use and trade of synthetic fertilisers (N, P, and K), pesticides and livestock and aquaculture feeds (grouped into oilseed feeds and other feed crops). The results show that the import dependency of agricultural inputs has increased over the past 30 years, but there is high variation between countries. Countries with high import dependency combined with high use of these inputs, such as many industrial agricultural producers in South America, Asia as well as Europe, show high vulnerability to trade shocks. Also, our findings highlight that potential agricultural intensification in Sub-Saharan African countries—currently with low use of the inputs per cropland area but high import dependency—can lead to higher dependency on imported agricultural inputs. Therefore, understanding of the past trends and current risks associated with the dependency on imported agricultural inputs should be highlighted to mitigate the risks and build more resilient and sustainable food systems.

1. Introduction

Global food production has more than quadrupled in value since the 1960s (FAO 2023a) along with the increasing demand driven by population growth and dietary changes. The production growth has been enabled by the rapid industrialisation of the food production that has led to increased use of agricultural inputs such as synthetic fertilisers, pesticides, agricultural machinery, and industrial compound feeds (Conforti and Giampietro 1997, Giampietro *et al* 1999, Pelletier *et al* 2011). While enhancing productivity, the use of often imported agricultural inputs has also made food production dependent on these (Zhou and Zhang 2013, Alia 2017, McArthur and McCord 2017).

If the supply of the key agricultural inputs is drastically reduced, domestic food production in many countries can be under threat. The recent regional and global crises, such as the Covid-19 pandemic and the war in Ukraine, have shown the vulnerability of the current—international trade based—food systems (Savary *et al* 2020, Hellegers 2022). The prolonged war in the Black Sea region, a critical supply and transit hub for fertilisers, can affect trade flows with impacts to global food security (Behnassi and El Haiba 2022, Arndt *et al* 2023, Lin *et al* 2023). Furthermore, the concentration in the production of the inputs can create risks in the food supply chain. For example, the five biggest producer countries supply 60%, 70% and 84% of the world N, P and K synthetic fertilisers, respectively (FAO 2023a). In a global simulation study, the availability of nitrogen (N), phosphorus (P) and potassium (K) fertilisers, as well as pesticides and agricultural machinery was reduced by 50%, and this resulted in a 26% drop in global maize production and 21% decrease in global wheat production, and in many countries the reduction of production was even more drastic (Ahvo *et al* 2023).

While there are many studies analysing the agricultural trade of food commodities (e.g. Josling *et al* 2010, Serrano and Pinilla 2010, Porkka *et al* 2013, D'odorico *et al* 2014, Tu *et al* 2019, Kummu *et al* 2020, FAO 2022a), studies focusing on global trade of agricultural inputs are rare. This aspect is, however, crucial since agricultural inputs are essential and the disruptions to their availability can have drastic impacts to food production. Although agricultural inputs have been included in many global trade models (e.g. Anderson and Strutt 2014, Anderson *et al* 2016, Martin 2018), studies analysing the physical trade flows and focusing solely on the input trade are less common. Niemi and Huan-Niemi (2012) analysed agricultural input trade in macro-regional scale but did not include differences between individual countries and did not further assess how the dependency on input trade has evolved. While the general trends of agricultural input trade have been analysed focusing on single input, for example pesticides (FAO 2022b), phosphorus (Barbieri *et al* 2022) or animal feeds (Wang *et al* 2018), these or any other global studies do not focus specifically on the import dependency of different agricultural inputs. The existing studies assess only a single country (e.g. Finland: Huan-Niemi *et al* 2021, Lehikoinen *et al* 2021 and France: Pinsard and Accatino 2023). Therefore, a comprehensive analysis covering trade patterns of multiple agricultural inputs at the global level and highlighting risks not visible when focusing on a single input—or a single country—is lacking. Furthermore, an overall scrutiny focusing on the import dependency of agricultural inputs at the global level and showing the vulnerability of regions and individual countries does not exist.

In this study we present a global perspective on the import dependency of varied agricultural inputs, addressing the above introduced gap in the existing knowledge. We provide a comprehensive analysis of international trade flows of N, P, K synthetic fertilisers, pesticides, and feed crops, covering 184 nations from 1991 to 2020. By identifying distinct global patterns of agricultural input trade and recognizing the countries or regions with heightened import dependency over these three decades, we shed light on potential vulnerabilities induced by sudden declines in input availability in trade networks. This unique insight is very important as disruptions in agricultural input trade could significantly jeopardise agricultural production, food security and the sustainable progression of food systems globally. With a focus on the evolution of dependency on import trade of multiple agricultural inputs over three decades and analysis of regional vulnerabilities, our study goes considerably beyond the scope of previous works, which have not focused on individual country differences, longer-term changes in import dependence or multi-input analyses at a global scale.

2. Methods and data

2.1. Data gathering and pre-processing

We gathered data on imports, exports and agricultural use of the most important fertilisers (N, P and K), pesticides and feed crops for 1991–2020 for 184 countries. Trade and agricultural use of nitrogen, phosphorus (expressed as P_2O_5) and potassium (expressed as K_2O) inorganic fertilisers, including the use and trade of both straight and compound fertilisers for 1991–2020, were retrieved from FAO (2023a). Concerning the agricultural use and trade of pesticides, we applied an aggregate indicator for total pesticides, covering insecticides, fungicides and bactericides (including seed treatments), herbicides, plant growth regulators, rodenticides, mineral oils, disinfectants and others used in agriculture for 1991–2020 from FAO (2023a). Linear interpolation was used to fill the gaps in data between the years. Exports can include fertiliser and pesticide products originating from both domestic and imported raw materials.

Regarding feed crop trade and use, we applied the data of feed use from the FAO Food Balance Sheets (FBS) (FAO 2023a) (old and new methodology) for 1991–2020. We took into account the 17 most important feed crops covering more than 80% of global feed use in 2020 including oilseeds (cottonseed, rape and mustard seed, soyabeans and sunflower seed) and other feed crops (wheat, rice, barley, maize, millet, oats, rye, sorghum, cassava, cereals other, beans, plantains and sugar cane). The feed use of oilseed meals is not reported in the FAO FBS data, and therefore we converted the amount of oilseeds processed to oils and cakes/meals (grouped here as oilseed meals) using the conversion factors from FAO (1996). The supply of oilseed meals was then corrected adding imports and subtracting exports of oilseed meals using trade data from UN COMTRADE (2023) and assuming that this supply corresponds to domestic use. The feed use of the whole oilseed crops and oilseed meals was then summed. Here, both the direct imports of oilseeds and oilseed meals, as well as the oilseed meals produced domestically from imported oilseeds were regarded as imported products. For the share of feed crops coming from domestic production vs. imports we applied data from Kastner *et al* (2014) updated until 2020 that uses the bilateral trade data from FAO (2023a) and connects the production to the consumption country through the intermediate re-exporting countries (Kastner *et al* 2011). Due to a lack of trade data differentiating feed and food crop use separately, we assumed that feed crops followed the same trade flows as food crops (Kastner *et al* 2014).

To assess the relative use of the crop inputs we gathered data of cropland from FAOSTAT (FAO 2023a) and intensively used pasture from HYDE 3.2 (Klein Goldewijk *et al* 2017) here grouped together under 'intensive agricultural land'. We chose to compare the use against intensive agricultural land instead of only croplands since fertilisers and pesticides are also applied intensively in some grasslands (Heffer *et al* 2017, Maggi *et al* 2019). The data for the pasture areas were linearly interpolated for the missing years (1991–1999) and the last data year (2017) from Klein Goldewijk *et al* (2017) was used for the most recent years in our study, assuming only minor changes in pasture areas from 2017 to 2020. For countries that did not exist for all the years studied (1991–2020) including Russia and the former Soviet Union countries, Croatia, Slovenia, Ethiopia and Eritrea, the data for use and agricultural area of the first available year (either 1992 or 1993) was used for the first years with missing data. For the relative use of inputs to animal production, we compared the use with the livestock and aquaculture protein production in the country. The protein production from the most important livestock categories including beef and buffalo meat, eggs, poultry meat, pig meat and dairy, were gathered from FAOSTAT (FAO 2023a). For aquaculture production, we used the production numbers from FAO FishStat (2020) and converted them to protein equivalents using average protein contents from FAO (2001).

The large dataset about the country-level data of use and trade of the different inputs assessed in this study can be accessed through an application (AgrInputExplorer) created for this purpose and available at: https://wdrg.aalto.fi/agri-input-trade/.

2.2. Methods

For the analysis, we applied the trade to use ratio as an indicator of trade dependency by dividing net trade (imports-exports) by agricultural use. This way we were able to show how much of the domestic use is imported or on the other hand how big are the net exports compared to the domestic use. We chose to analyse net trade, instead of just imports and exports separately, to take into account all the material flows, including the re-exports, for example in the case when exported products are produced with imported raw materials.

To estimate the trend from 1991 to 2020 we applied linear regression and showed the slopes with p-values lower than 0.05 indicating a significant trend in figures 3 and 4. In order to cluster the countries to similar groups based on the data from the most recent years (mean 2018–2020), we applied fuzzy c-means clustering (Bezdek 1981). We chose to make separate clustering for crop production inputs (N, P, K fertilisers and pesticides) and for animal production inputs (oilseed feeds and other feeds). For the clustering all the values of trade to use ratio over 1 or below -1 were assigned to 1 or -1 respectively. We scaled the values of relative use between 0 and 1 using the 5th and 95th percentiles, due to the large difference between the extreme values, so values less than 5 percentile were assigned 0 and values over 95 percentile as 1. We had seven clusters for crop inputs and five clusters for animal production inputs based on minimising within the sum of squares and the number of clusters (Davidson 2022). As an output, we got groups of countries with which similarity within clusters and dissimilarity between clusters are maximised grouping countries with similar characteristics together. For figure 6, we used the same scaling as for clustering and summed the scaled values separately for crop inputs and animal production inputs. All the data analyses were conducted in the *R* environment for statistical computing and visualisation (R Core Team 2022).

2.3. Data limitations and assumptions

The data applied in this study are the most comprehensive available, but these are, however, constrained by potential limitations. The use and trade data for fertilisers and pesticides as well as feed use was retrieved from FAOSTAT country level statistics (FAO 2023a). These data are based on national level questionnaires complemented with national publications when available or when official data are not available. When there are inconsistencies, missing values are imputed (FAO 2023a). However, this procedure also contains inconsistencies including countries reporting sales values as use value, countries not willing to report some of the detailed trade due to confidentiality, or countries not reporting data every year (FAO 2023a). For pesticides, the trade data can exceed those of the use data for multiple reasons: imports might have non-agricultural uses such as those in the public health sector, and the stock can be stored for use in subsequent years (FAO 2022b).

Because feed trade data is not reported separately from food trade in FAO or other national level statistics, we applied the data from Kastner *et al* (2014) where the trade flows between countries are modelled using FAOSTAT (2023a) bilateral trade data. Here, because of the lack of data separating the food and feed crop trade flows, we assumed that they are traded proportionally. However, in practice, crops used as feed are often of lower quality (FEFAC 2021) and most likely less traded compared to food crops suggesting that trade values of feed crops applied here, particularly in the category 'other feed crops' might be overestimated.

3. Results

3.1. Global patterns of agricultural input use and trade from 1991 to 2020

The use of synthetic fertilisers, pesticides and oilseed feeds has increased gradually both in relative terms (figures 1 and S1) as in total quantities (figure S2) at the global level between 1991–2020 in line with increased yields (figure S3) along with the intensification of global food production. However, the trends differ between regions in the world. Regions such as Latin America, Oceania and Asia show a rapidly increasing use of fertilisers and pesticides. On the other hand, there is a stagnant or even declining trend for some regions with previous high use, such as Europe with the exception of using oilseeds for animal feed (figures 1 and S1). For other feed crops, the use has increased more than 60% since the 1990s (figure S2(f)). At the global level, the relative use of oilseed feeds per animal (i.e. livestock and aquaculture) protein produced has increased (figure 1(e)) and the relative use of other feed crops has somewhat decreased reflecting the changes in in production efficiencies, regional composition of animal production and diets (figure 1(f)).

The increased use of the agricultural inputs is supported by the expansion of trade, thus increasing the import dependency on agricultural inputs globally (figure 2). At the global level, the share of imports in the use of fertilisers increased from 19% and 72% in 1991–1993 to 24% and 80% in 2018–2020 for N and K fertilisers, respectively (figure 2). For P fertilisers the share of domestic use coming from imports remained stable at 30% globally. For pesticides, the share of imports increased from 18% to 41%, and for oilseed feeds,from 29% in the 1990s to 51% in 2018–2020. For other feed crops, most of the usage comes from domestic production and the increase in the import share has been minor, from 12% in the 1990s to 15% in 2018–2020 (figure 2).

3.2. Global, regional and country level patterns of trade and recent trends—agricultural inputs for crop production

Our results show changes in import dependency between 1991 and 2020. In 1991–1993, a total of 84 out of the 184 countries included in the analysis were net importers of all four inputs analysed here for crop production (N, P and K fertilisers and pesticides) compared to 98 countries in 2018–2020. The share of global crop production taking place in countries importing more than 50% of all synthetic fertiliser and pesticide use increased from 7% in 1991–1992 to 31% in 2018–2020. Globally, the general increase in import dependency combined with the increased use of agricultural inputs has resulted in increasing vulnerability to disturbances in trade flows.

Many big crop producing countries in North and South America such as the USA, Brazil and Mexico, European countries such as Spain, France the UK as well as Asian countries such as India show an increasing trend towards higher import dependency of N fertilisers between 1991 and 2020 (figures 3(a)–(c)). Also, many Sub-Saharan African countries have increased their import dependency of N fertilisers (figure 3(c)), and many of them were net importers already in the beginning of the 1990s (figure 3(a)). On the other hand, Northern African countries, countries from the Middle East, and Russia were net exporters of N fertilisers. Among the net exporters, Saudi-Arabia shows a particularly strong trend in increasing N fertiliser exports (figure 3(c)).

For P fertilisers the global trends show relatively similar trends as for the N fertilisers (figures 3(d)–(f)). Nearly the whole North and South America shows a trend towards increased import dependency (figure 3(f)), with the exception of the USA which remains a net exporter of P fertilisers in 2020 (figure 3(e)). Also, most of the Sub-Saharan African countries, many Western European countries, such as Spain, France, and Germany as well as South and Southeast Asian countries, such as India, Indonesia and Malaysia have become net importers of P fertilisers in 2018–2020. The biggest net exporters of P fertilisers by total amounts in 2020 include countries such as Morocco, China, Russia and Saudi-Arabia (figure 3(e)). Interestingly, China has changed from being a net importer to a net exporter of both N and P fertilisers.

With K fertilisers, more countries were net importers with higher import dependency, i.e. higher trade to use ratio (figures 3(g)–(i)). Almost all countries in North and South America, with the exception of Canada and Bolivia, were net importers of K fertilisers and there is a trend towards higher import dependency. Most African countries as well as countries in Asia and Oceania were also net importers, although in some countries, such as India and China, import dependency has decreased in recent years (figure 3(i)).

With pesticides, most of the examined countries were net importers and the import dependency has been increasing with many South American countries, such as Brazil, moving from a net exporter to a net importer. Many European countries as well as Southeast Asian countries, Australia and Russia were net importers of pesticides showing an increasing trend towards higher import dependency (figure 3(l)). Many

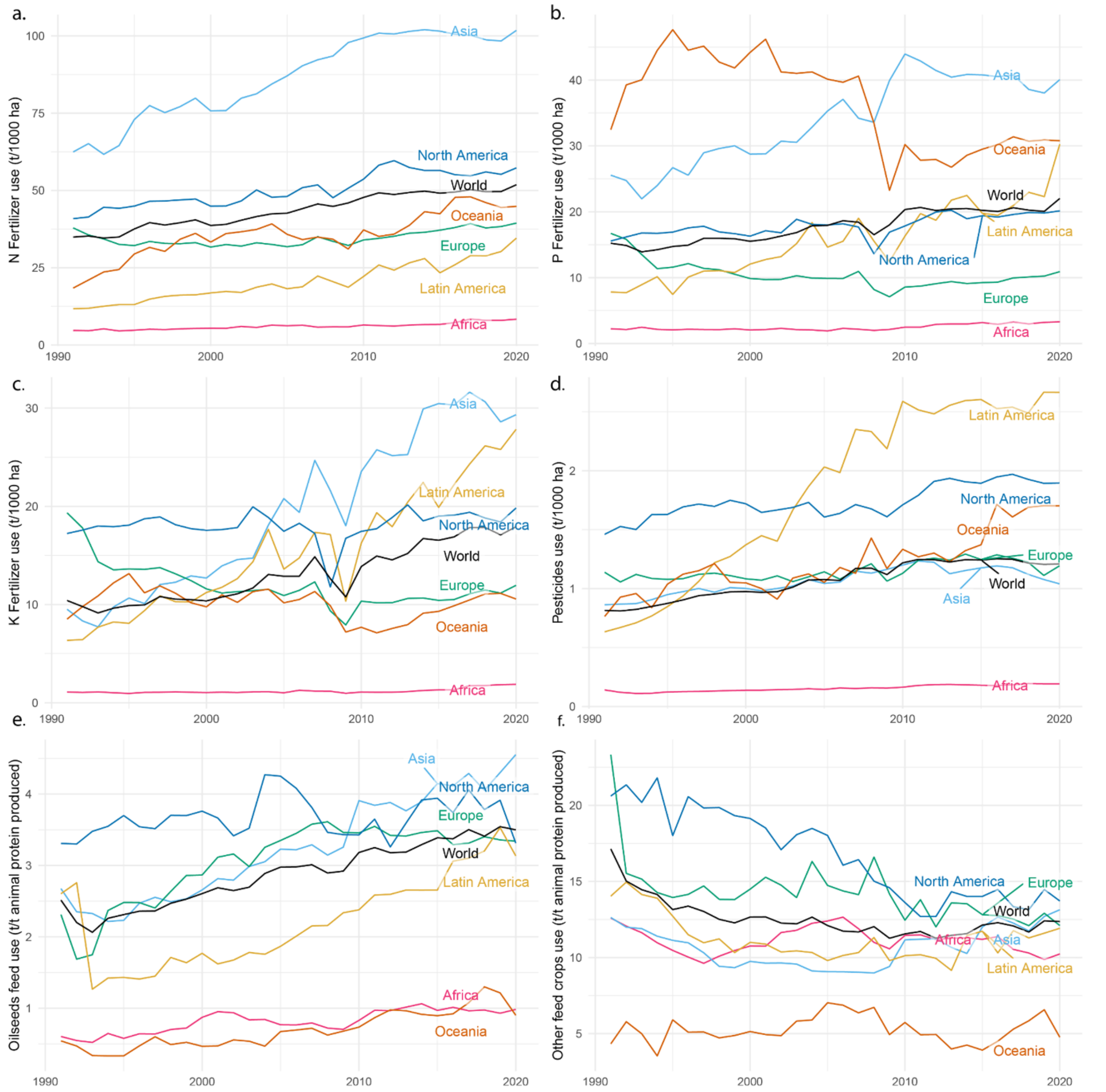

Figure 1. Change in agricultural input use per hectare for N, P, K fertilisers and pesticides (a)–(d), and input use per animal (i.e. livestock and aquaculture) proteins produced for oilseed feeds and other feed crops (e), (f).Please note different y-axis scales in each tile.

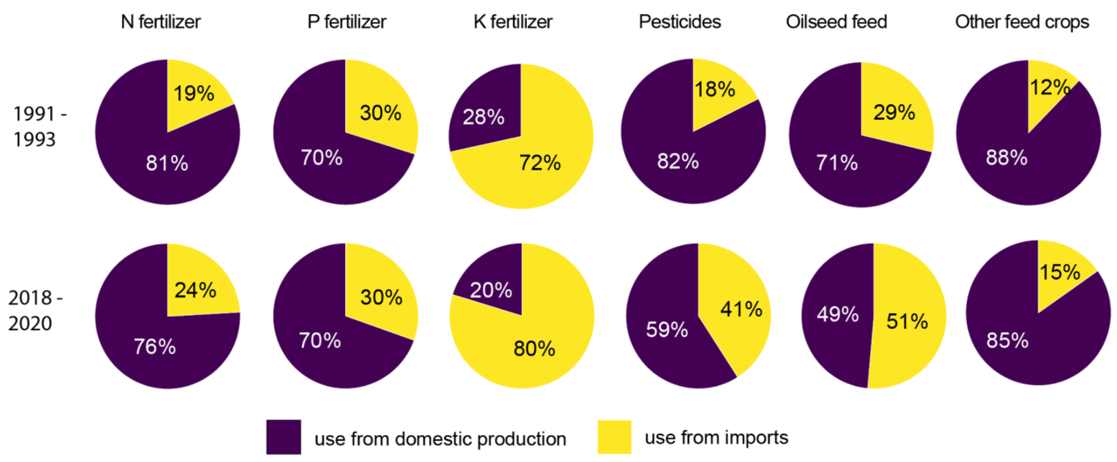

Figure 2. The share of imports of agricultural use. Global sums of imports in relation to agricultural use for 1991–1993 and 2018–2020. The global sum is computed by calculating the net imports (imports-exports) for each country, assigning all negative values, i.e. net exporter countries to 0 and consequently taking the global sums of use vs. net imports.

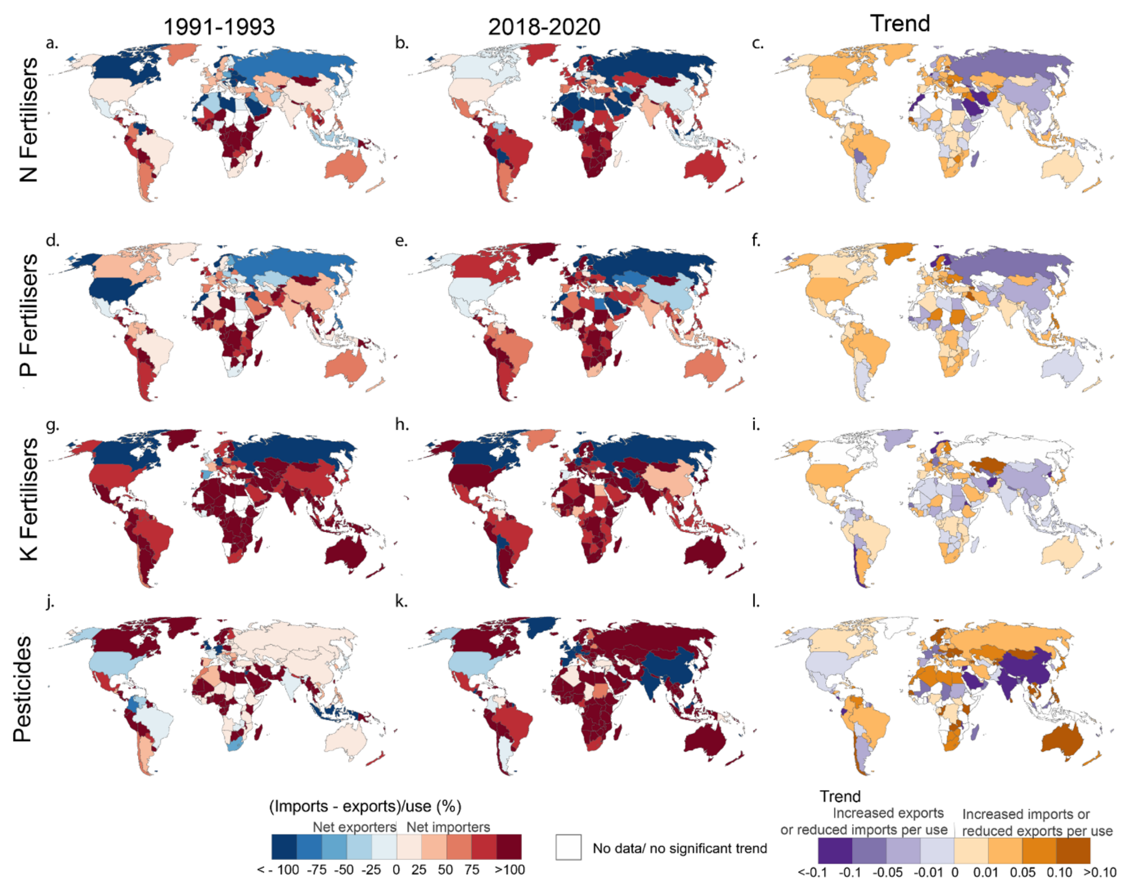

Figure 3. Trade to use ratio (=net trade (imports-exports)/agricultural use) for nitrogen fertilisers (a)–(c), phosphorus fertilisers (d)–(f), potassium fertilisers (g)–(i), total pesticides (j)–(l). The mean value for the indicator for 1991–1993 is shown in the first column, the mean value for 2018–2020 in the middle column and the slope indicating the trend estimated with the linear regression model in the third column. Only statistically significant trends with p-value less than 0.05 are shown. Increasing trend refers to a change to increasing import dependency or reduced exports compared to use, and decreasing trend refers to a change towards decreasing import dependency or increasing exports compared to use. See interactive map at AgrInputExplorer at https://wdrg.aalto.fi/agri-input-trade/.

African countries, with previously low use, have also increased their use of pesticides and become more dependent on imports. Noteworthy is the concentration of the net exporters for pesticides (figures 3(j)–(l)), which in 2018–2020 were mainly China, India, the USA, Argentina and some Western European countries.

3.3. Global, regional and country level patterns of trade and recent trends—agricultural inputs for animal production (i.e. livestock and aquaculture)

Concerning feed crops, the trend is somewhat different to that of food crops, showing less clear patterns of trade dependency. Only seven percent of global animal production took place in countries importing more than half of their feed crop use in the beginning of the 1990s, and this increased to 13% by 2020. Oilseeds were traded more compared to other feed crops (figure 2). Most of the European, South, East and Southeast Asian, Northern African and central American countries have become net importers of oilseed feeds by 2020 (figures 4(a)–(c)). Other feed crops, on the other hand, are mostly low-quality crops produced domestically, and therefore their use is less dependent on imports. Many African and Southeast Asian countries were net importers of these crops (figures 4(d)–(f)). Major net exporters in North and South America, such as the USA, Canada and Brazil have taken an even stronger role in the global feed markets, increasing their exports compared to domestic use (figure 4) exporting soybeans as well as other crops used as feed to global feed markets.

China shows a particularly interesting case in its changing role in the global agricultural input markets. China has changed from being a net importer of all fertilisers and pesticides to a net exporter of N and P fertilisers as well as a major exporter of pesticides (figure 3). On the contrary, China has changed from being a net exporter to a net importer of oilseed feeds and other feed crops. Currently, China is dependent on the imports of animal feed, especially oilseed imports, for livestock and aquaculture production (figure 4).

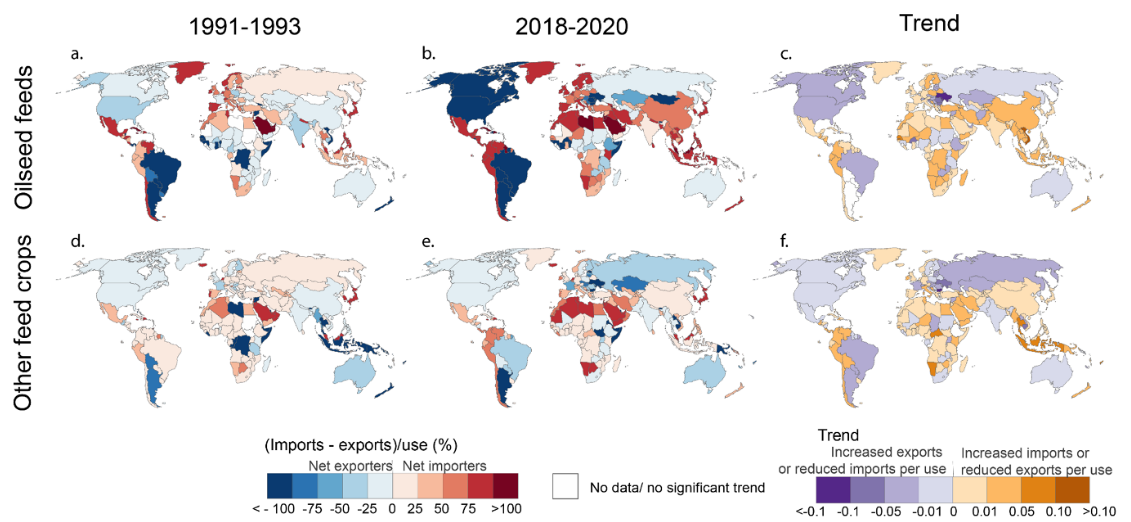

Figure 4. Trade to use ratio (=net trade (imports-exports)/agricultural use) for oilseed feeds (a)–(c) and other feed crops (d)–(f). The mean value for the indicator for 1991–1993 is shown in the first column, the mean value for 2018–2020 in the middle column and the mean value for 2018–2020 in the middle column and the slope indicating the trend estimated with the linear regression model in the third column. Only statistically significant trends with p-value less than 0.05 are shown. Increasing trend refers to a change to increasing import dependency or reduced exports compared to use, and decreasing trend refers to a change towards decreasing import dependency or increasing exports compared to use. See interactive map at AgrInputExplorer at https://wdrg.aalto.fi/agri-input-trade/.

3.4. Vulnerable countries with high agricultural input use and import dependency

When assessing the vulnerabilities against trade shocks, in addition to the import dependency, also the level of the domestic use of these agricultural inputs needs to be considered. Although many countries show high imports compared to domestic use, they differ greatly in the use of these agricultural inputs. For identifying the most vulnerable areas and countries, we clustered the countries into groups based on agricultural use and the trade to use ratio.

Countries with the highest risk are those that have high use of the agricultural inputs combined with high import dependency. These include countries in cluster CropA such as Brazil and Chile from Latin America, Vietnam and Japan from Asia and New Zealand from Oceania, indicating risk for their crop production if the import flows of agricultural inputs are disturbed (figure 5(a)). Furthermore, high import dependency with lower use can be observed for countries in cluster CropG including Australia from Oceania, Thailand and Turkey from Asia as well as Italy and Finland from Europe, along with Argentina and Mexico from Latin America (figure 5(a)). The import dependency of crop production inputs is particularly high for many Sub-Saharan African and Central and South American countries in cluster CropE. The use of agricultural inputs in these countries is at a much lower level compared to the more industrialised agricultural systems in Asia, Europe, and North America (figure 5(a)). However, cluster CropE countries may be more vulnerable compared to countries in cluster CropA because cluster CropE countries are relatively poor and may have more difficulties in coping with trade crisis.

There is high variation between countries even within the same cluster as shown in supplementary figure S6. Therefore, although figure 5 shows the average values of the clusters, it is good to remember that countries behave differently even within clusters. Countries in cluster CropC (e.g. Algeria, Libya and Iran), cluster CropD (e.g. Spain, France, the UK, India and Colombia), and cluster CropF (e.g. Saudi-Arabia, Egypt, Russia and Morocco) have on average high agricultural use and high import dependency but also are exporters of one or two of the inputs studied here. Countries in cluster CropB are also mainly exporters of multiple agricultural inputs such as the USA, Canada, China and Germany.

Concerning the inputs for animal production, the clusters look different. Countries in cluster AnimB and cluster AnimD consist of countries in North Africa, Middle East and Andean region as well as countries such as China, Indonesia, Turkey, and also Germany, Sweden, and Norway from Europe along with Mexico from Latin America. All these countries have high import dependency combined with high use (figure 5(b)). Countries in cluster AnimA including Russia, India, Australia and many countries in Africa have low use of inputs on average for animal production, and these countries are also exporting both oilseeds and other feed crops. The biggest exporters of both oilseeds and other feed crops are countries in cluster AnimC including Brazil, Argentina, the USA and Canada (figure 5(b)).

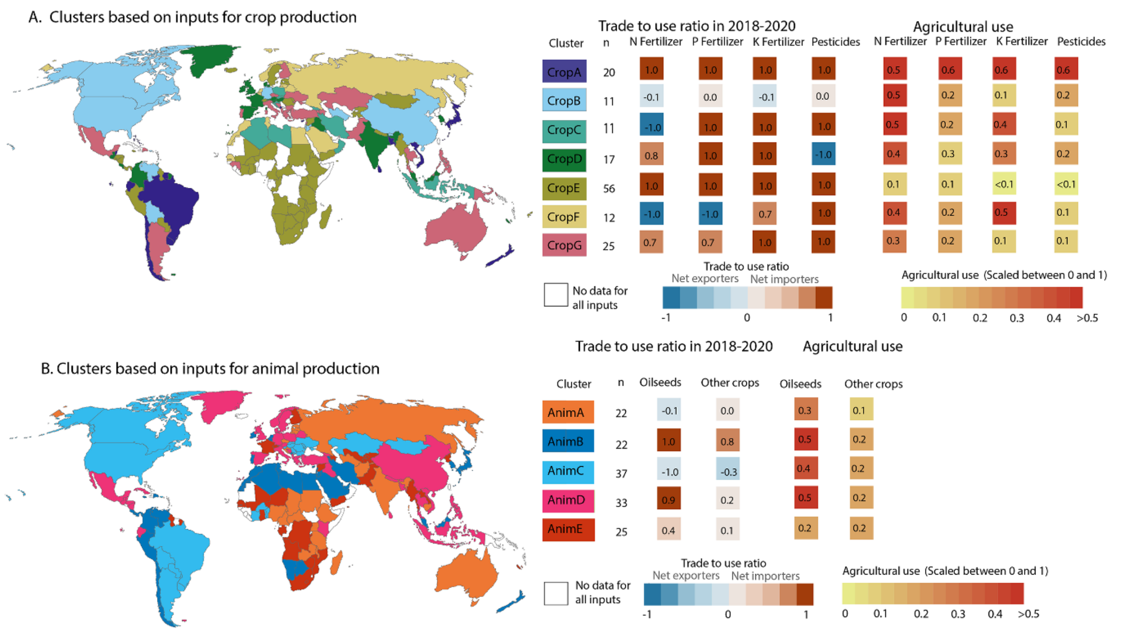

Figure 5. Country clusters based on trade to use ratio (imports-exports)/use) and relative domestic agricultural use in 2018–2020 (see also figures S4 and S5) for (a) inputs for crop production, and (b) inputs for animal production. Values in the tables refer to the cluster medians (see the within cluster variation in figure S6 in SI). The input values over 1 or below −1 for trade to use ratio were assigned to 1 and −1 respectively. The input values for agricultural use were scaled between 0 and 1. For clustering, fuzzy c-means clustering was used (see Methods). Only countries with data for all the indicators are shown here.

In this paper, vulnerable countries against trade shocks in agricultural inputs for crop production and animal production are examined separately. However, one of the biggest exporters of oilseeds in cluster AnimC such as Brazil has the highest risk in cluster CropA with high use of the agricultural/crop inputs combined with high import dependency on fertilisers and pesticides. Therefore, countries with high animal feed imports can also be affected by the trade disturbances for crop inputs such as fertilisers and pesticides used for feed crop production.

To identify the individual countries that are most vulnerable to potential shocks related to trade of multiple agricultural inputs (i.e. those with the highest use as well as import dependency) (figure 6(a); upper right corner), we combined trade dependency data with the relative use of all the different inputs for crop production. These countries include Japan, Vietnam, Bangladesh, Brazil, New Zealand and Oman. Interestingly, many African countries are in the upper left corner, indicating high import dependency but with relative low use. Countries with the lowest vulnerability (low use combined with low import dependency) are, for example, Russia, Germany, Belarus, Saudi-Arabia, and Jordan (figure 6(a); lower left corner).

When looking at the agricultural inputs for animal production, the general patterns are different (figure 6(b)). Contrary to the inputs for crop production, the lower use of feed crops can reflect the composition of animal production in the country, or it can also be a sign of efficiency in production. The countries with the highest trade dependency and use of animal feeds include similar countries that are also dependent on inputs for crop production, such as Asian countries Bangladesh and Vietnam and in addition, many other countries such as Portugal, China, Thailand, Saudi-Arabia, Greece, and Denmark (figure 6(b)). African countries have on average low relative use and are both net importers and exporters of feed crops. Countries with the lowest trade dependency and relative use of animal feeds include the USA, Brazil, Russia, Ukraine, Slovenia and Bulgaria.

4. Discussion

4.1. Increased import dependency on agricultural inputs

The dependency on agricultural inputs for food production is a critical aspect of modern agriculture. Agricultural inputs play a vital role in enhancing productivity, ensuring food security, and meeting the growing global demand for food. The trend towards increased dependency on agricultural input trade follows the general globalisation and increased connectivity of the food systems (D'odorico *et al* 2014, Tu *et al* 2019) and shows similarities when analysing direct food imports. For most of the global population, the dependency on food imports has increased between 1987 and 2013 (Kummu *et al* 2020). The population

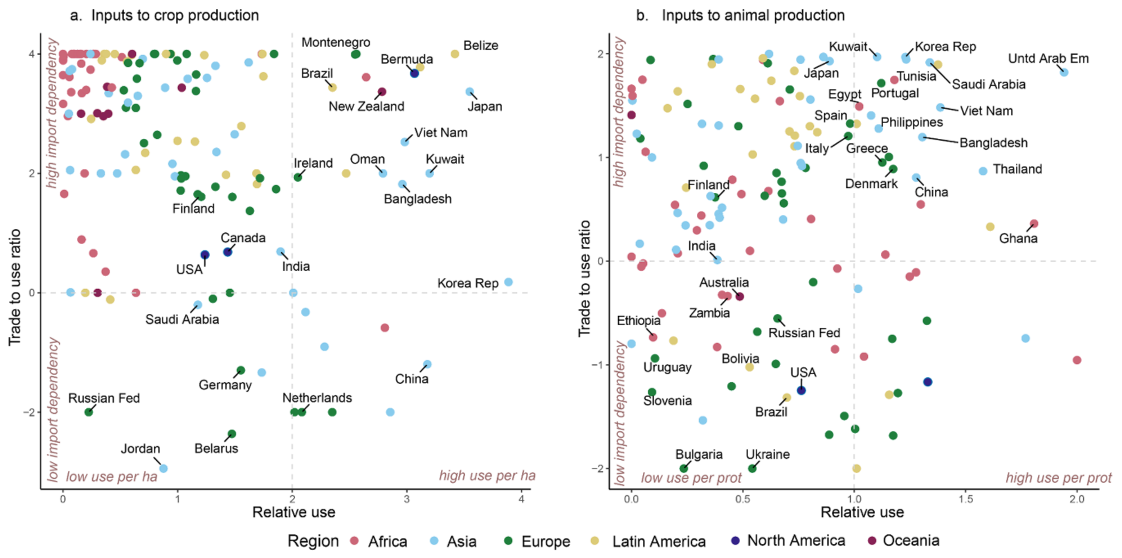

Figure 6. Trade to use ratio (imports-exports/agricultural use) and the relative use for (a) inputs for crop production including N, P, K fertilisers and pesticides per ha of intensive agricultural land; and (b) inputs for animal production including oilseed feeds and other feed crops per produced protein. The mean values for 2018–2020 for all inputs have been scaled and summed together (i.e. the range for trade to use ratio is from −4 to 4 or −2–2, and for relative use from 0 to 4 or 0–2 for crop and animal production inputs, respectively).

living in net food importing countries more than doubled from 1965 to 2005 (Porkka *et al* 2013). Consequently, the past food crises (e.g. 2007–08) have motivated several countries to increase their awareness in food self-sufficiency and buffer themselves from the volatility in the world food markets by increasing domestic food production (Timmer 2010, Ghose 2014, Brookings Institution 2023). Direct food imports are, however, more evident compared to the inputs imported for domestic food production, and the crucial role of agricultural input trade for food production remains often ignored. The existing studies have identified an increasing trend in the trade volumes of individual agricultural inputs, including fertilisers (Barbieri *et al* 2022), pesticides (FAO 2022b), and commercial animal feeds (Wang *et al* 2018). Our results validate these findings (figures 3 and 4). However, our analyses and conclusions extend beyond the scope of individual trade volumes by (a) including multiple inputs in a comparative manner and (b) for the first time, globally assessing the import dependency of these agricultural inputs. Through this comprehensive approach, we could reveal new insights into the evolution of import dependency for these inputs. Consequently, we have been able to identify countries where the import dependency of most inputs has significantly increased, intensifying their vulnerabilities to disruptions in agricultural input trade. This information is essential in steering countries towards more resilient food production and food security.

Major food producing countries in North and South America such as the USA and Brazil as well as countries in Europe, Asia, and Africa such as Spain, China, and South-Africa show high self-sufficiency in their food production (Kummu *et al* 2020, Wassénius *et al* 2023) but are still dependent on imported agricultural inputs for their domestic agriculture, as shown in this study (figures 3 and 4). Finland is a good example of a country with relatively high food self-sufficiency but also heavily and increasingly reliant on imported chemical and energy inputs required for food production as well as high dependence on the imports of supplementary protein feed for livestock production as shown in this study (figure 4) and discussed earlier in Huan-Niemi *et al* (2021) and Lehikoinen *et al* (2021).

High import dependency combined with high input use poses risks for agricultural production if the input supply through imports is reduced. Some countries in North and South America (e.g. Brazil and Argentina) as well as Europe (e.g. France and Ukraine) practise high-input agriculture and have increased their import dependency of N, P, K fertilisers and/or pesticides since the 1990s (figure 3). Many of these countries were already net importers of fertilisers in 1991–1992, and the share of imports has increased even more in recent years. Since these countries are also major exporters of food and feed, the impacts of reduced availability of imported fertilisers and pesticides for their agrifood systems may potentially have wide cascading effects for food and feed importing countries.

Disturbances in global agricultural input trade can increase agricultural input prices, which will consequently increase food production costs and put pressure on domestic food prices. Therefore, a reduction in the global agricultural inputs supply would have dire consequences for the net food importing countries. The majority of Africa's low-income countries had been net food importers, mostly in

Sub-Saharan Africa where two-third of its population lives (Rakotoarisoa *et al* 2012). Okou *et al* (2022) showed that Sub-Saharan African countries are highly vulnerable to fluctuation in global food prices with direct transmission (estimated close to unity) of high global prices to local food prices for vastly imported staples. Transmission of high food prices have pushed more households into poverty. Therefore, Sub-Saharan African countries may be more vulnerable compared to South American and European countries in dealing with disruptions in agricultural input trade.

Countries with large populations such as China and India are worth paying special attention. India reveals an increasing trend towards higher import dependency of N fertilisers for crop production and China is very dependent on imported feeds for their livestock and aquaculture production. Food production in China and India is therefore vulnerable to potential shocks in agricultural input trade, and this can affect the large populations in these countries. The disruption in food production may have a wide effect for food security not only in China and India, but also globally by affecting global food trade and prices.

4.2. Risks for domestic food production

Dependency on imported inputs for domestic agriculture is often overlooked and can therefore cause unexpected risks for food production. These risks may include reduced availability due to sudden shocks in the global input markets, such as the war in Ukraine or the Covid-19 pandemic. After the Russian invasion of Ukraine, fertiliser and energy prices rose sharply across the world, and the FAO Food Price Index reached an all-time high in March 2022 (FAO 2023b). Rising input prices increase food production costs, which puts pressure on domestic food prices and food security. Countries must balance the risks associated with excessive reliance on trade with the costs involved in increasing self-sufficiency in food production (Clapp 2017).

The import dependency is notably high for many Sub-Saharan African countries that are net importers of inputs essential for agricultural production, especially concerning fertilisers and pesticides (figure 3). Although having high import dependency, the use of these inputs is currently at a much lower level in comparison to the industrialised agricultural systems in Asia, Europe, and America (figure 6(a); supplementary figure S4). However, with increased agricultural intensification, the use of synthetic fertilisers and pesticides can increase (Sheahan and Barrett 2017). Sustainable intensification is a process devised to achieve higher agricultural yields while at the same time decreasing the negative impact of farming on the environment. Pretty *et al* (2011) analysed 40 projects in 20 African countries during the 1990s–2000s and found that food outputs by sustainable intensification have been fruitful with increased yields per hectare by combining the use of agricultural inputs with agroecological farm management. However, there are concerns that it might be used to industrialise agriculture in Africa by adopting high-input agriculture, thus sustainable intensification has become a debated issue (Garnett *et al* 2013, Kuyper and Struik 2014, Godfray 2015, Rockström *et al* 2017, Haggar *et al* 2021). Without domestic production of the agricultural inputs, agricultural intensification will increase the countries' reliance on imported inputs. For example, our results show that in Ethiopia, agricultural intensification and recently industrialised agriculture (Haggblade *et al* 2017) increased their pesticides use and imports by 10-fold from 1994 to 2020 (see our AgrInputExplorer at https://wdrg.aalto.fi/agri-input-trade/).

The risks associated with the dependency on imported agricultural inputs should thus be highlighted when discussing sustainable food systems to further plan and investigate strategies and policies to mitigate the risks involved. Countries that have become more vulnerable to trade disturbances can strengthen their resilience, for example, by focusing on having strong reserve stocks (Lassa *et al* 2019) or invest in more diversified production and supply networks (Clapp and Moseley 2020) along with alternative ways to replace the imports of the agricultural inputs, for example, through nutrient recycling (Adegbeye *et al* 2020) or alternative feed sources (Sandström *et al* 2022).

4.3. Limitations and way forward

In this study, we assessed the trade patterns and the import dependency of fertilisers, pesticides and feed crops. In addition, agricultural machinery, energy, seeds, and vaccines are also vital inputs for the intensification of agriculture, but these are not analysed in this study due to the lack of available data relating to the use and trade of these inputs at the global level. The risks related to their supply from global markets should be investigated in future studies. Moreover, we did not cover the interprovincial trade within countries, which can also be an important factor in creating risks for input supply and merits more investigation particularly in large countries such as the USA, China, India, and Brazil. Most fundamentally, our results are influenced by the quality of the input data used, and particularly for pesticides trade and agricultural use there are a lot of inconsistencies as discussed in 2.3. Data limitations and assumptions. Therefore, findings from this study should be complemented with future studies for a more comprehensive view of the vulnerabilities related to the agrifood systems.

5. Conclusions

Industrial agriculture lays the foundation for an open through-flow system with continuous supply of inputs such as fertilisers, pesticides, and animal feeds to override ecological limits and expand agricultural production (Anlauf 2023). Industrial agricultural production for both food and other purposes (such as biofuels, bio-plastics and other products based on biomass) is heavily reliant on agricultural inputs and the sudden shocks or shortages in input supply can have cascading impacts to food and other products availability. Therefore, the dependency of agricultural production on imported inputs should be scrutinised.

Our results draw attention to countries and regions that have become more vulnerable to shocks in agricultural input trade by analysing the development of trade and use of the inputs from 1991 to 2020. Our findings shed much needed light on the interconnections in the global food system and establish the base to create solutions for more resilient and sustainable food systems.

We show that the import dependency of agricultural inputs has increased over the past 30 years, but there is high variation between countries. Countries with high import dependency combined with high use of these inputs, such as many industrial agricultural producers in South America, Asia as well as Europe, show high vulnerability to trade shocks. In addition, our findings highlight that agricultural intensification in Sub-Saharan African countries, which have high import dependency already with relatively low usage of the inputs, can lead to even higher dependency and thus increase the vulnerability of the food production.

The increasing import dependency of agricultural inputs, as identified here, and thus vulnerability to sudden shocks, calls for actions to increase the resilience of these countries. These include, for example, investments and innovations to increase domestic manufacturing and production of the inputs where it is possible. Additionally, diversifying the supply sources is essential, as dependency only on very few trade partners increases the vulnerability. Moreover, wider use of the sustainable agricultural practices, such as nutrient recycling and the use of alternative feed sources, allow farmers to reduce the dependency on many of the shocks. Furthermore, building strategic reserves of the essential agricultural inputs would smoothen the possible shocks. Specific attention should be given to Sub-Saharan Africa, where agricultural production intensification is necessary to bridge the yield gap and increase self-sufficiency. However, this region is particularly vulnerable to availability or price fluctuations of these inputs due to its relatively weak economies compared to other regions.

Data availability statement

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

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Conflict of interest

The authors declare no competing interests.

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