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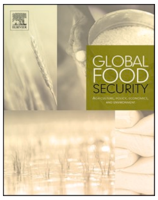

Quantifying food consumption supply risk: An analysis across countries and agricultural products

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ABSTRACT

Resource criticality is the field of study that quantifies supply risks for a set of resources. To assess the vulnerability of a country's food supply, whether domestically produced or imported, supply risk indexes for agricultural products have been developed by adapting a resource criticality method and a supply diversity model. These indexes take into account both the diversity of supply and the risks to which each sourcing option is exposed, such as climate or price volatility.

The results enable a comparison of the supply risk of food consumption between different countries and identification of the products with the highest risk of supply disruption for each country. When analysed by region, the results indicate that North America and Europe generally have lower supply risk across all products than the rest of the world, while African and Sub-Saharan countries tend to have the highest supply risk. Furthermore, the analysis of supply risks for four cereals - wheat, maize, rice, and sorghum - indicates that trade diversification can reduce supply risks for wheat and maize in many countries. However, for rice and sorghum, supply risk reduction will most likely be achieved through stockpiling, export redirection, and adaptation of agriculture to climate change. The results highlight the importance of supply risk indexes for decision-making, particularly when compared to self-sufficiency. Finally, limitations and new perspectives are discussed, including the need to adapt the index to nutritional data, consider competition for agricultural product usage, and refine climate or economic risk indexes.

1. Introduction

Food security is defined as the state "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 2009). The first dimension of food security is food availability, which deals with the supply component and is determined by the levels of food production, stocks and net trade (FAO, 2008). At a global level, agricultural production increased by 54% in tonnes between 2000 and 2020 (FAOSTAT, 2021). Although stock levels are difficult to assess, Laio et al. (2016) showed that global stock levels have remained constant for 50 years. Moreover, more than 20% of the food produced for human consumption is traded internationally (D'Odorico et al., 2014), with certain commodities, such as wheat, maize and soya, that are increasingly globalised (Macdonald et al., 2015). At the level of a country, food supply strategies can vary according to its biophysical production capacity (Fader et al., 2013, 2016) and to its political choices (e.g. cash-crop subsidies (Candel et al., 2014; Rosegrant and Cline, 2003)).

Whatever a country's food supply strategy, it is subject to a number of risks (Bernard de Raymond et al., 2021). Agricultural systems increasingly undergo production shocks (i.e. sudden loss of food production) due to environmental shocks (e.g. extreme weather events) or to societal shocks (e.g. armed conflicts) (Cottrell et al., 2019; Davis et al., 2021). In addition, global markets are exposed to economic risks (e.g. price instability) (FAO, 2021b), and can also convey production shocks from one country to another (Bren d'Amour et al., 2016; Marchand et al., 2016). In order to reduce their vulnerability, (i.e. the degree to which the system is susceptible to adverse effects and unable to cope with them) (McCarthy et al., 2001) and to ensure food security (Ericksen, 2008), it is thus crucial for countries to assess their food supply risks.

One of the first methods of assessing food supply risks at country level relies on the concept of self-sufficiency (i.e. the extent to which a country can satisfy its food requirements from its own domestic production) (Clapp, 2017). This type of assessment is based on the assumption that the more self-sufficient a country, the less vulnerable its food supply, since it is less exposed to external production shocks in supplier countries, (such as heavy yield losses), or sudden commercial restrictions. However, domestic production is not risk-free (Simelton, 2011). Indeed, Clapp (2017) explained that self-sufficiency can only reduce supply risks under certain conditions (e.g. when the supply of staple crops is controlled by a handful of suppliers), and that other strategies need to be implemented.

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Secondly, certain studies quantify the vulnerability of country food supply according to their trade connectivity (D'Odorico et al., 2014; FAO, 2022b; Porkka et al., 2013, 2017; Puma et al., 2015). They highlight the trade-off created by international trade. On one hand, trade ensures food supply when domestic production is not possible (Porkka et al., 2013, 2017), or in the event of a domestic production shock, while on the other hand it exposes countries to external production shocks (Bren d'Amour et al., 2016; Suweis et al., 2015).

Finally, a third type of assessment focuses on the diversity of the food supply: both the diversity of suppliers and the diversity of food products are considered, thus allowing for a combination of the first two types of assessments. These latter approaches are based on the principle that the greater the diversity in supplies, the greater the chance that one of the supply options would be available if the others become unavailable after a shock (FAO, 2021b; Kummu et al., 2020; Remans et al., 2014; Seekell et al., 2017; Wassénius et al., 2023). The more a country tends to rely on trade for its supplies, the more it becomes exposed to market risks (Kummu et al., 2020). Although self-sufficiency can offset these risks, it is often at the expense of supply diversity (Remans et al., 2014; Wassénius et al., 2023). Among these studies, the FAO model (FAO, 2021b) not only takes the import and domestic production balance into account, but also considers exports as a potential source of supply, as well as stocks, and the distribution of all these sourcing options through an index of food supply diversity. However, these assessments do not cover the different risks affecting food supply (i.e., environmental, geopolitical, or economic).

To address this issue, resource criticality methods can provide relevant insights. Resource criticality evaluates the economic and technical dependency on a certain resource, as well as the probability of supply disruptions, for a defined stakeholder group and within a certain time frame (Schrijvers et al., 2020). Criticality assessment methods first propose to quantify a supply risk index, which represents the possibility of supply disruption for a given material, depending on its geological, technological, economic, social, or geopolitical availability. Then, criticality assessment methods involve a second dimension related to the impact of supply restrictions, where the substitution and importance of the use of the studied material are analysed (Schrijvers et al., 2020). Criticality was initially intended for non-energetic mineral resources to help secure the supply of key resources for specific industries, such as renewable energy production systems (Graedel et al., 2012). However, the methods were later extended to water (Sonderegger et al., 2015), land (Deteix et al., 2023) and biotic materials such as wood (European Commission, 2020) or crop production for industrial uses (Bach et al., 2018). In particular, (Bach et al., 2017) proposed a criticality method applied to soybean and rapeseed for biodiesel production. This method takes into account the physical, socio-economic, abiotic, social and environmental constraints on the availability of these two types of crop. Recently, (Deteix et al., 2024) pointed out the significance of applying criticality thinking to the agricultural sector.

The aim of the present study is to enhance the indexes of food supply diversity proposed by FAO by combining them with resource criticality indexes in order to assess country food supply risks, and by developing supply risk indexes for agricultural products. The products considered in this study are raw agricultural products that have not been processed (e.g. soybean but not soybean oil nor soybean cake).

Section 2 details the adaptation of the FAO model and of the criticality method to the supply risk of agricultural products, as well as the consideration of environmental, geopolitical and economic risks. These new indexes are applied to national food consumption data to assess the potential food supply risk for a given year at a country scale. Section 3 compares food supply risks between countries, and analyses the supply risk of the most widely consumed products in 2 countries. An analysis of supply risk for four cereal products, across all continents, is also provided. Finally, the supply risk indexes for these products are compared with corresponding self-sufficiency indexes in order to discuss their main advantages and limitations.

2. Material and methods

The methodological developments carried out to compute supply risk indexes for agricultural products are described here. These indices are then analysed according to the annual consumption of agricultural products at the country level. The joint analysis of supply risk and apparent food consumption enable the comparison of food supply risk situations between countries. This approach is similar to food security studies at country level (FAO, 2021b; Kummu et al., 2020; Remans et al., 2014; Wassénius et al., 2023). In this study, data for the reference year 2018 are used.

Moreover, thanks to this joint analysis, a more specific assessment can be made 1) for a given country, on the agricultural products that are most vulnerable to supply disruptions, and 2) for a given agricultural product, on the countries which are most vulnerable to supply disruptions. This second approach is closer to criticality studies, which often propose a criticality matrix that relates the resource supply risk to the impact of supply restriction (Schrijvers et al., 2020). This type of visualisation allows for resources to be compared between one another, and for the most critical ones to be identified.

2.1. *Defining agricultural product supply risk indexes based on supply diversity*

The FAO developed the Dietary Sourcing Flexibility Index (DSFI) for assessing the diversity of a country's food supplies for a given nutrient (FAO, 2021b). This index assesses the balance between different sourcing options, i.e. importing via several trade partners, sourcing from stocks or producing. The DSFI operates at the level of nutrients (e.g. kilocalories or proteins). It first assesses the diversity of products (e.g. wheat, rice, potatoes) that contribute to the supply of nutrients. However, in this study, the supply risk assessment is conducted at the agricultural product level, where a more detailed analysis of food consumption in different countries can be conducted. The developed index is identified as the Commodity Sourcing Flexibility Index (CSFI).

For a given agricultural product in a given country, the CSFI characterises the diversity of options for accessing it. The larger the choice in different sourcing options, the lower the Supply Risk (SR), since the plurality of options contributes to mitigate the effects of shocks such as extreme weather events or high price spikes (FAO, 2021b; Kummu et al., 2020; Remans et al., 2014; Wassénius et al., 2023). In the event that an option would become no longer available, the other options would ensure that access to the agricultural product can be maintained. Fig. 1 describes the different components of the CSFI.

In order to access a product, the first choice would be to source it domestically or to import it. If the product is imported, the second level of choice would depend on the number of available suppliers. If the product is of domestic origin, it could come from the previous year's stocks or from the current year's production. Finally, exports are considered as a SR buffering option, since these flows could be redirected for domestic consumption if required (FAO, 2021b).

The diversity of each option, represented by a node in Fig. 1, is evaluated by the Shannon equitability index (H) (Shannon, 1948). This index evaluates the number of elements in a set, and how evenly they are represented. This index has been employed for characterising the diversity of agricultural production or food supply at country level in several studies (FAO, 2021b; Kummu et al., 2020; Remans et al., 2014; Seekell et al., 2017; Wassénius et al., 2023).

The importance of each option is then evaluated by the share it represents. The CSFI is computed according to Eq. (1):

$$CSFI = p_1 * \left(H_{Domestic\ availability} + p_{12} * H_{Production}\right) + p_2 * H_{Import} \qquad (1)$$

With.

- p_1: share of Domestic availability (see Fig. 1)

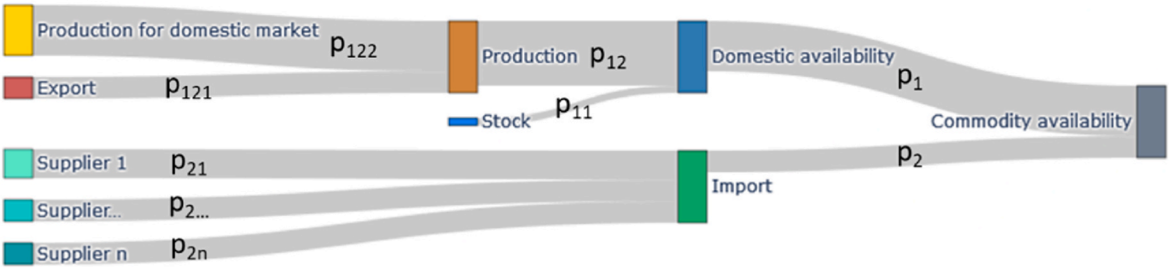

Fig. 1. Representation of the different options and the pathway to source an agricultural product in a country. P_x are the shares of each option.

- p_{12}: share of Production (see Fig. 1)
- p_2: share of Import (see Fig. 1)
- *H*: Shannon equitability index of the corresponding option (see Appendix A)

The CSFI is similar to the Herfindhal-Hirschman Index (HHI) (Herfindahl, 1950; Hirschman, 1945), used in criticality methods for assessing market concentrations and the associated supply risk, one of the dimensions considered in the supply risk for mineral resources (Schrijvers et al., 2020). These two indicators represent the risk associated with sourcing from a limited number of options. However, in the criticality methods, the HHI does not include exports or stocks, thus implying that the CSFI provides a more detailed description of the supply diversity.

To go further in the analysis, the FAO recommends the incorporation of the probability of supply disruptions, such as the inaccessibility of stocks or the unavailability of trading partners, thus quantifying the level of reliability of each supply option (FAO, 2021b). This approach is similar to criticality methods.

2.2. Consideration of other criticality dimensions

Among the many criticality methods (Schrijvers et al., 2020), the method of the Joint Research Centre of the European Commission (Blengini et al., 2017) has been recognised for its scientific robustness (data quality, uncertainty, peer-reviewing), transparency (traceability of modelling and documentation, reproducibility), applicability (technical feasibility, data availability, etc.) and high level of acceptance (by policy-makers, industry, academia) (Hackenhaar et al., 2022). This method has also been developed for biotic resources (natural rubber, natural cork, teak wood, sapele wood). In addition, it has been recognised by a public institution as an effective decision-making tool. The method is based on a short to medium-term temporal perspective (5–10 years) and was developed for the European Union (EU).

The JRC SR index comprises two parts. The first relates to the diversity of raw material supply, which is assessed by the HHI. The second part of the SR incorporates parameters that reduce the SR, i.e. recycling and substitution.

2.2.1. Integrating the risks affecting supply diversity

The HHI for raw material is equivalent to the CSFI for agricultural products. Indeed, both indexes quantify the risks associated with supply diversity.

Nevertheless, the JRC criticality method also considers the influence of geopolitical parameters (geopolitical stability of suppliers) and economic parameters (supplier trade restriction measures) on resource availability. These parameters are incorporated into the HHI to provide an HHI weighted by these risk parameters (Blengini et al., 2017). Similarly, the CSFI is weighted by the probability of supply disruption. For each agricultural product, this involves a quantification of the risks to which each supply option is exposed (trade, stocks, domestic production).

The considered risk parameters are the major threats for the supply of agricultural products, i.e. (i) geopolitical risk (assessed by political stability), (ii) climatic risk (assessed by the occurrence of extreme events) and (iii) economic risk (assessed by price volatility) (Cottrell et al., 2019).

The political stability of a country is crucial, both for its agricultural production (Asfew et al., 2023) and for the continuity of trade (Deaton and Lipka, 2015). To characterise the geopolitical risk of both domestic sourcing and imports, a Political Stability index is included in the CSFI. Climate is one of the major factors affecting the production of agricultural products (Lobell and Field, 2007). Extreme climatic events such as droughts, floods, storms or late frosts can cause agricultural production to become suddenly and instantaneously unavailable (Brás et al., 2021; Cottrell et al., 2019; FAO, 2015; Lesk et al., 2016). This mechanism can be accounted for by incorporating an index for the quantification of the extreme climate event risk of domestic supply in the CSFI. Finally, importing countries can suffer from the volatility of agricultural commodity prices (i.e. the variability of prices), as this creates supply instability. This risk is represented by a price volatility index, based on the prices of agricultural products in supplier countries, which is included in the CSFI. It characterises the economic risk of the import option. This risk index aims to reflect agricultural production disruptions within import countries due to diverse shocks including socio-economic and climatic events. Therefore, climate index of supplier countries is not taken into account.

The CSFI weighted (CSFI_w) is defined according to Eq. (2):

$$CSFI\_w_{i,j} = p_1 * PS_j * \left(H_{Domestic\ availability} + p_{12} * (1 - c_k) * H_{Production}\right) + p_2 * PS_{imp,j} * \left(1 - v_{i,j}\right) * H_{Import} \tag{2}$$

With.

- PS_j: Political Stability of country j
- $PS_{impj,j}$: Political Stability of country j importers
- c_k: Climate index of sub-region k (to which country j belongs to)
- $v_{i,j}$: Import volatility of product *j* in country *i*

The CFSI_w is then linearly rescaled, so the higher the CSFI_w, the higher the SR (see Appendix A). The calculations of risk parameters (Political Stability, Climate index, Import volatility) are described in the following sections. Section 2.3 details the computation of the risk indexes (political stability, climate risk index and price volatility).

2.2.2. Integrating strategies to reduce agricultural products SR

Finally, the JRC SR also takes into account means of reducing the SR, i.e. resource recycling and resource substitution. In order to refine the SR index for agricultural products, these two parameters are adapted to the context of agricultural products. This approach follows that of Sonderegger et al. (2015) who adapted the criticality method from Graedel et al. (2012) to water, and from Deteix et al. (2023) who adapted the JRC criticality method to land.

For agricultural products, the rate of food loss and waste affects the SR, by increasing the quantity needed to provide a given level of supply for a country (Bajželj et al., 2020; FAO, 2019). In order to take this process into account, the FLW rate estimated by the FAO (FAO, 2019), and available at the agricultural product category (i.e. cereals, meat, etc.), is used as a parameter in the SR (see Eq. (3)).

In the initial JRC method for mineral resources, substitution is accounted for as a means to adapt to supply restrictions. In the case of agricultural products, countries can apply economic, organisational or technological solutions to thereby adapt to product access restrictions (FAO, 2021b; Pingali et al., 2005). The substitution index is thus replaced by an adaptation capacity index, which is represented by the Human Development Index (HDI) (UNDP, 2020). The HDI, defined by the United Nations Development Programme (UNDP 2020), was used in the food security assessment to evaluate the relationship between levels of development and food security (Conceicao et al., 2011; Eini-Zinab et al., 2020; Rosenbloom et al., 2008). The higher a country's HDI, the higher its level of food security. Indeed, a country could respond to product access restrictions thanks to its stronger capacity to purchase agricultural products from other countries, or to implement technological infrastructures (such as irrigation (Wrachien and Goli, 2021)) and organisational solutions (such as new land management (Haregeweyn et al., 2023)). The HDI has also been used in criticality assessments (Deteix et al., 2023; Sonderegger et al., 2015) to describe a country's capacity of adaptation to resource supply shortages.

The final agricultural product SR is obtained by following the original SR equation from the JRC method for resources (Blengini et al., 2017). All the parameters are multiplied. The SR for an agricultural product i in country j ($SR_{i,j}$) is given by Eq. (3):

$$SR_{i,j} = CSFI\_w_{\ i,j} * \left(1 + FLW_g\right) * \left(1 + \left(1 - HDI_j\right)\right) \tag{3}$$

- $CSFI\_w_{\ i,j}$: CSFI weighted by risk indexes for agricultural product i and country j
- FLW_g : Food Loss and Waste rate of product group g (to which product i belongs to)
- HDI_j: Human Development Index of country j

Fig. 2 recaps the computation of the SR.

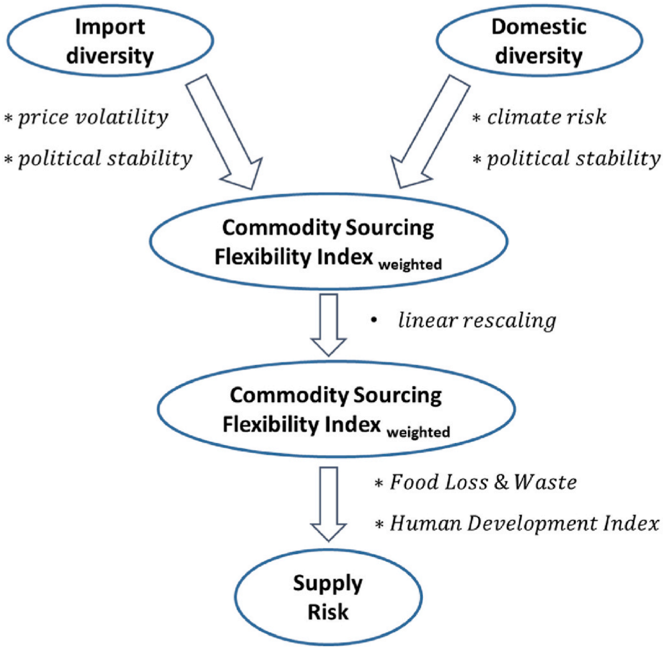

Fig. 2. Schematisation of the procedure to compute agricultural product Supply Risk.

2.3. Calculation of indexes

2.3.1. Political stability (PS)

This index is based on the Political Stability and absence of Violence/Terrorism index. It describes "the capacity of the government to effectively formulate and implement sound policies" (Kaufmann et al., 2010).

To assess the risk related to domestic sourcing, the PS of the country is used. Furthermore, in order to assess the risk related to imports, an average of the PSs of the importing countries, weighted by their import share, is used (Eq. (4)):

$$PS_{imp\ i,j} = \sum_s PS_s * p_{i,s_j} \tag{4}$$

With.

- •$HDI_jPS_{imSp\ i,j}$: import PS of product j in country i
- •HDI_jPS_s: PS of supplier s
- •HDI_jp_{i,s_j}: share of supplier s for the product j for the country i

The PS index ranges from 0 to 1, with 1 indicating the highest PS. The higher a country's PS, the higher its SR, therefore the PS is incorporated into the CSFI_w to reflect this relationship (see Eq. (2)). In the case where PS indexes are missing for the import PS, the average PS of the Sustainable Development Goal region is used (see Appendix A).

2.3.2. Climate risk

The quantification of the risk associated with extreme weather events remains a challenge (Sillmann et al., 2017), which is why a simple indicator has been chosen, i.e. the occurrence of extreme weather events (FAO, 2021a).

The climate risk is defined as the yearly mean occurrence of extreme climate events over the past 20 years per subcontinent (c_k) Eq. (5):

$$c_k = \frac{1}{S_k} * \left(\frac{1}{n} \sum_{y=1}^{n} N_{k,y} \right) \tag{5}$$

With.

- $N_{k,y}$: number of extreme climate events in subcontinent k, in year y.
- •S_k: Subcontinent area (km^2)

The climate risk index is rescaled with a quantile power function to range from 0 to 1, with higher values indicating a higher occurrence of extreme events and thus a higher SR. The index is incorporated into the CSFI_w to reflect this relationship (see Eq. (2)).

It is assumed that the climate risk index only affects domestic agricultural production, and not imports. Concerning imports, the price volatility index in supplier countries is considered also to be related to the shock to agricultural production in these countries.

2.3.3. Price volatility

This index is the FAO Indicator of Food Price Anomaly (IFPA) (FAO, 2022a). It highlights abnormal price spikes by comparing the current price with that of the previous year and with that of the previous four months. The index therefore detects price spikes due to seasonality (previous year) and to shocks (four previous months).

As with the PS (see Eq. (5)), the volatility index for a country is the average of the volatility of the importers, weighted by their share of imports, Eq. (6):

$$v_{i,j} = \sum_s v_{j,s} * p_{i,s_j} \tag{6}$$

With.

- $v_{i,j}$: import volatility of product j in country i

- $v_{j,s}$: volatility index of supplier s for product j
- p_{i,s_j}: share of supplier s for the product j for the country i

The volatility index $v_{i,j}$ is rescaled with a quantile power function to range from 0 to 1, with 1 indicating a maximum volatility. The higher the volatility, the higher the SR. The index is incorporated into the CSFI_w to reflect this relationship (see Eq. (2)).

If a supplier volatility index is missing due to lack of data, it is replaced by the world average volatility index of the product.

Additional data description as well as data sources are provided in Electronic Supplementary Material 1. Supply Risk indexes full dataset is available at: https://doi.org/10.57745/SKHTL7.

2.4. Implementation of agricultural product SR to national food consumption data

In addition to the SR, the JRC criticality method also includes a second criticality dimension called Economic Importance, which expresses the impact of resource supply restrictions on the EU economy. Here, the importance of an agricultural product in a country's food consumption is assessed by its Apparent Consumption. Apparent Consumption is defined in Eq. (7):

$$Apparent\ Consumption = Production + Import - Export \tag{7}$$

Apparent Consumption can be defined either at the product level (e.g. wheat Apparent Consumption) or at the country's consumption level (sum of consumption of all agricultural products).

A country's food supply is assessed using the SR of agricultural products to calculate an Apparent Consumption SR index. The consumption of each product is multiplied by the corresponding SR and the terms are summed (see Eq. (8)).

$$Apparent\ consumption\ SR_i = \sum_{j}^{N} AC_{j,i} * SR_{j,i} \tag{8}$$

With.

- N: the number of most consumed agricultural products included
- $AC_{i,j}$: the Apparent Consumption of agricultural product j in country i (in tonnes/year/inhabitants)
- $SR_{i,j}$: the SR of agricultural product j in country i

In this study, the top 20 most consumed products in mass per country are taken into account to quantify the Apparent Consumption SR. These 20 are chosen because in average they represent more than 90% of the country apparent consumption and more than 90% of the country Apparent Consumption SR (see Electronic Supplementary Material 1).

At the agricultural product level, the SRs are also analysed according to self-sufficiency, defined in Eq. (9).

$$Self - sufficicency = \frac{Production}{Production + Import - Export} \tag{9}$$

Detailed data are available in Electronic Supplementary Material file 2.

3. Results and discussion

The results of Apparent Consumption SR are first presented at country level. A more detailed analysis of the agricultural product SR and Apparent Consumption is then performed, first by focusing on comparisons between two countries and then by comparing four agricultural products (cereals). Finally, the SRs of the four cereals are compared to self-sufficiency indexes. Each result provides the opportunity to discuss the employed methodology, in terms of data, hypotheses and elements for decision-making. Research perspectives are identified from these discussion points.

3.1. Apparent consumption SR per country

The Apparent Consumption SR for the 20 most consumed products in each country has been calculated for 153 countries across the world. A clustering analysis by country was performed, taking into account the country-specific variables from the SR (HDI, PS, climatic risk index), as well as total Apparent Consumption per capita per year (i.e. the sum of Apparent Consumption of all agricultural products). This clustering analysis reveals three groups of countries. Fig. 3 illustrates the relationship between the Total Apparent Consumption and the Apparent Consumption SR per cluster.

The first cluster group consists of countries with a rather low consumption (Total Apparent Consumption <1.2 tonnes/person/year) and low Apparent Consumption SRs (between 0.2 and 1.5). These countries are mainly located in Sub-Saharan and Northern Africa, Central, Southern, Eastern and South-Eastern Asia. For this group, the low consumption levels mainly explain the low Apparent Consumption SR.

The second group consists of countries with medium to high Apparent Consumption levels (between 0.9 and 2.5 tonnes/person/year), and low to high Apparent Consumption SR values (1–2.8). These countries are mainly situated in Northern America and Europe, Oceania and Latin America and the Caribbean. This group presents the highest observed variability in the different Apparent consumption SRs. Countries such as Vanuatu and Hungary, which share similar Apparent Consumption levels (1.6 tonnes/person/year), have contrasting Apparent Consumption SRs (1.2 for Hungary and 2.6 for Vanuatu). This difference occurs because Vanuatu has a higher average SR than Hungary. Indeed, for supply, Vanuatu only relies on a few products, which are sourced domestically. Vanuatu also has an average HDI (0.6) and a high climate risk (0.66), which increases the SR of the products. In contrast, Hungary consumes a wider variety of products, and relies on both its own production and imports. Its HDI is higher (0.85) and its climate risk lower (0.14), which thus reduces the SR for domestic products. In addition, the diversity and political stability of its imports are quite high, leading to a reduction in the SR for imports.

Finally, the third group comprises countries with very high levels of Apparent Consumption (from 2.5 to 5.2 tonnes/person/year, due to high country apparent consumption and small population) and therefore high Apparent Consumption SRs (from 2.8 to 5.2). These countries are from Northern America and Europe, Oceania, Latin America and the Caribbean, as well as Eastern and South-Eastern Asia. Similarly to the countries in the first group (low Apparent Consumption level, low Apparent Consumption SR), the Apparent Consumption SR is explained almost entirely by the level of Apparent Consumption.

In this study, only raw agricultural products and not processed products are taken into account. However, some agricultural products are exported in a processed state, such as milk powder, soya cake or palm oil. As these products have not been accounted for, either on the import or the export side, the consumption levels in countries that import these products have been underestimated, while the consumption levels in producing and exporting countries are overestimated. This applies for example, for milk in New-Zealand or oil palm in Malaysia. Furthermore, no distinction is made between the agricultural products consumed, which are not all intended for human consumption. This is the case with maize, for example. In Africa maize is essentially used for human consumption, while in Europe 75% of supplies go to animal feed (Erenstein et al., 2022), and in the USA 40% of maize produced contribute to bioethanol production (Ramsey et al., 2023). Therefore, countries where maize represents a large proportion of the national human consumption are considered vulnerable because of agricultural products that are used for non-alimentary purposes.

Results (Fig. 3) indicate a strong correlation between Apparent Consumption SR and Apparent Consumption. Indeed, both indexes are based on the aggregation of individual products apparent consumption levels (see Eq. (8)). However, for average Apparent Consumption levels, the Apparent Consumption SR is found to be variable. This allows the

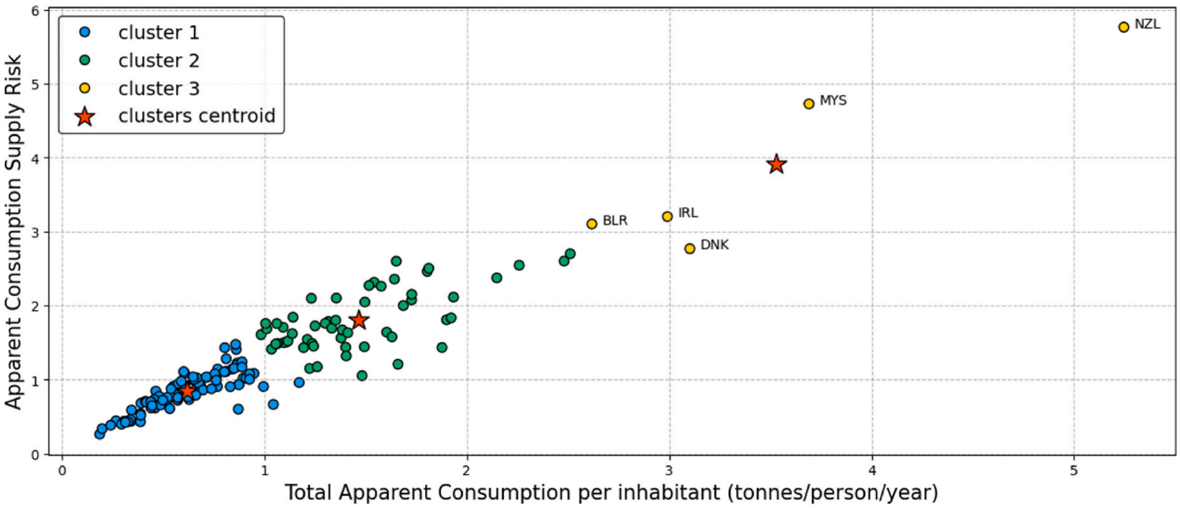

Fig. 3. Consumption Supply Risk and Total Apparent Consumption per country by cluster.

countries where supply is most at risk to be identified and for comparison of countries between one another. In order to fully understand and explain the mechanisms at play, analysis by country and by agricultural product enables further investigation and identification of the levers that can reduce SRs.

3.2. SR analysis comparing countries and products

In this section, the SRs are firstly analysed by country (i.e. analysis the SR of different products within a single country) and secondly by agricultural product (i.e. analysing the SR of a product across all countries).

Based on the JRC criticality matrix representation (European Commission, 2020), the most critical products are found to be those with both the highest SRs and the highest Apparent Consumption.

3.2.1. SR analysis by regions and countries

15270 SR indexes have been computed across 153 countries and for 108 products. The SRs range from 0 to 1.89, with an average of 1.35. Fig. 4 illustrates the SR distributions for agricultural products across the SDG regions.

Fig. 4 illustrates how, on one hand, countries in Northern America and Europe tend to have lower SRs than countries in other regions, and that countries from Sub-Saharan Africa tend to have the highest SR. This is due to the relatively high HDIs in Northern America and Europe and relatively low HDI in Sub-Saharan Africa. However, the SRs of the countries in regions can also vary greatly within a country (e.g. Canada or Finland). Other countries, on the other hand, have SRs with a low variability, for example Iran or Trinidad and Tobago.

For further in-depth analysis, the SRs of the most consumed products (Apparent Consumption >0.01 tonnes/person/year) in two countries (Czech Republic and Oman) are compared with their level of consumption (Fig. 5). These countries have been chosen for illustrative

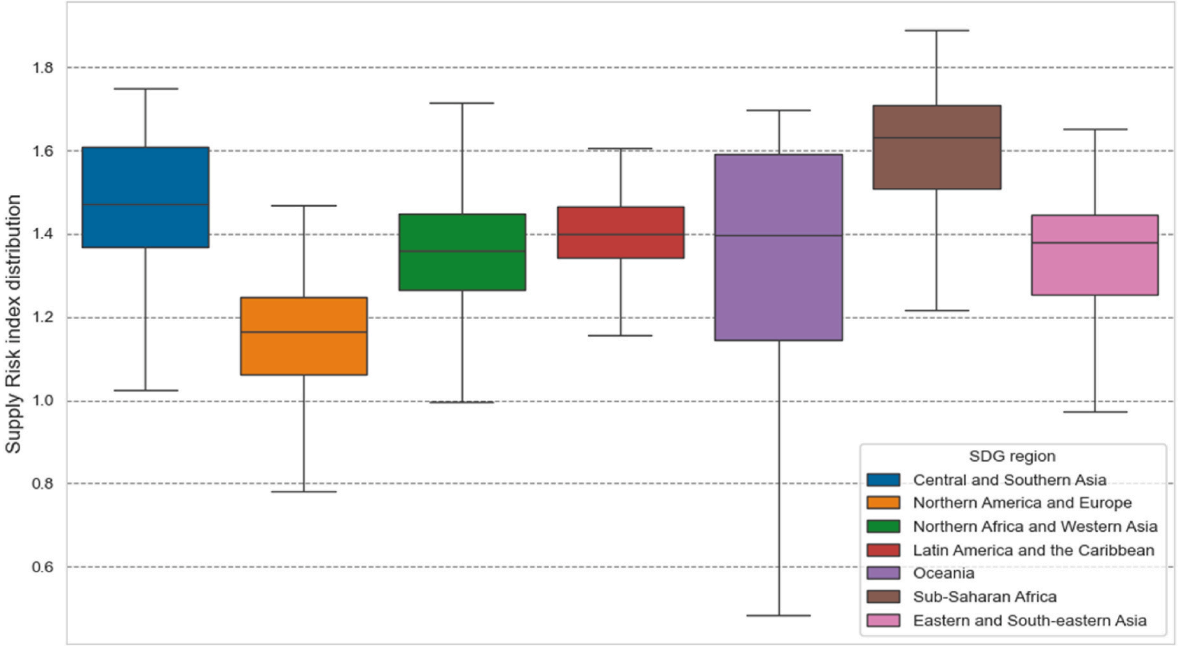

Fig. 4. Supply Risk index distribution per SDG region. The lines inside the rectangles are the median values of the SR, the lower limits of the rectangles are the 1st quartile and the upper limits the 3rd quartile. The maximum lower and upper limits correspond to 1.5* the interquartile range.

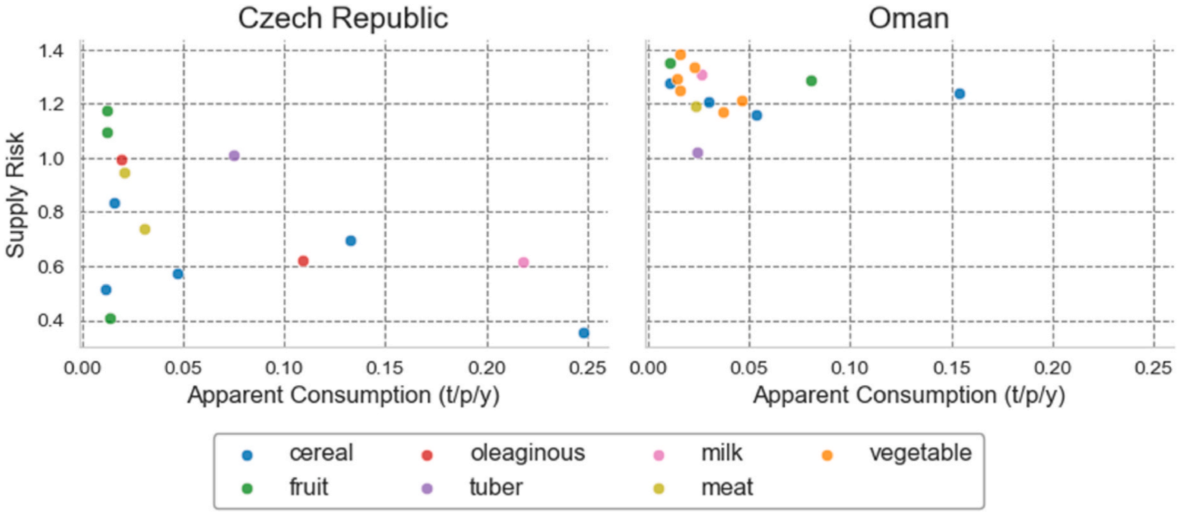

Fig. 5. Apparent Consumption and Supply Risk for the most consumed products in the Czech Republic and Oman, per product and product categories. t/p/y: ton per inhabitant per year.

purposes since they offer contrasting profiles.

With this representation (Fig. 5), the most critical products are potatoes for Czech Republic and wheat and oranges for Oman.

Comparison between the two countries highlights the influence of HDI. The Czech Republic and Oman have an HDI of 0.90 and 0.81 respectively, which explains why the average SRs in the Czech Republic are lower than those in Oman. In addition, the FLW rate explains the differences in SRs between product categories. For example, the FLW rate for cereals is 4.6, while it is 6.9 for fruits and vegetables. This explains why a country's SRs for cereals tend to be lower than that for fruits and vegetables (see Eq. (1)). Nevertheless, within a single country, different mechanisms can explain the varying SRs between the different products.

The Czech Republic has contrasting SR values between products (ranging from 0.41 to 1.18). This country is mainly supplied with domestic products. Consequently, for these products, the parameters that most explain the SRs are the diversity of supplies between stocks and domestic agricultural production, the diversity between domestic production and exports (see Fig. 1), as well as the country's political stability and climate risk (see Eq. (4)). For these domestic products, the SRs of the Czech Republic remain rather low due to a high Political Stability (0.87) and low climatic risk (0.14). Concerning cereals, a significant proportion (20–30%) of supply originates from stocks, and for most products (wheat, maize, barley, rye), the proportion of exports is high, thus explaining the low SRs for cereals (0.35–0.84). Fruits (bananas, apples, grapes) present more contrasting results. For apples, the supply structure is similar to that of cereals (a high proportion of domestic sourcing, stocks and exports) and therefore the SR is very low (0.41). Bananas are imported, with an average import diversity, a high import volatility and a low political import stability, which explains the higher SR (1.18). Grapes are partly domestically sourced (63%) and partly imported (37%). For the domestic part, the stocks and exports are low, while the imported part has an average diversity of importers, volatility and political stability. All these mechanisms explain the higher SR for grapes (1.09).

Unlike the Czech Republic, the SRs of products in Oman have closer values (ranging from 1.02 to 1.38). Here again, however, different mechanisms explain these results. Half of the products are mainly imported (e.g. cereals, potatoes, chicken) while the other half are domestically sourced (e.g. sorghum, fruits and vegetables, milk). For products that are mainly domestically sourced, the SRs that are higher than for the Czech Republic result from a weaker political stability (0.66), a greater climatic risk (0.38), no stocks and very low export shares (<10%). Concerning the predominantly imported products, the combination of import diversity, import volatility and import political stability explains the similar SRs between products. For example, maize has a very low import diversity (0.27), which increases the SR. However, the average import volatility and political stability tend to buffer the effect of import diversity. Similarly, potatoes have a relatively high import volatility (0.59) and low import political stability (0.31), but a higher import diversity (0.47).

These results are in line with Wassénius et al. (2023), who demonstrated that food SRs are balanced between trade-related risks for food-importing countries and local risks for food-producing countries. Furthermore, this study makes it possible to identify which products in a country are most at risk of supply disruptions, the reasons for this, and whether or not the product is of major importance to the country's consumption.

3.2.2. SR analysis by products

This section analyses the SRs of wheat, maize, rice (sum of rice and broken rice), sorghum across all countries. These four cereals have been chosen because they are the most widely produced cereals in the world (FAOSTAT, 2021) and are the staple food for a large proportion of the world's population (Awika, 2011).

According to Fig. 6, the countries where wheat is most critical are mainly located in Northern Africa and Western Asia (Morocco, Tunisia, Algeria, Turkey, Azerbaijan). These countries have medium to high HDIs (0.74–0.82), and wheat import shares between 25% and 67%. Hence the risks affecting both domestic and external supplies explain the wheat SRs. Overall, these countries have a rather low political stability (<0.42), low stocks and do not export. Import diversity is medium to low (0.12–0.46), import volatility is high (>0.52), and import political stability is medium. The wheat SRs are therefore high for these countries.

Rice is critical for countries in Eastern and South-eastern Asia, Central and Southern Asia and Latin America and the Caribbean (i.e. Bangladesh, Cambodia, Indonesia, Nepal, Thailand, Viet Nam, Guyana). These countries have medium HDIs (0.59–0.72), and almost zero import shares. Therefore only the risks affecting domestic supply explain the SR values for rice. Political stability varies from country to country (0.14–0.50), while climatic risks are high for Asian countries (>0.62). Finally, these countries have low rice stocks and do not export, which explains their high SR.

Maize is most critical for Bosnia and Herzegovina, El Salvador, Mexico and South Africa. These countries have medium HDIs (0.67–0.78). However, the situation varies between countries, with

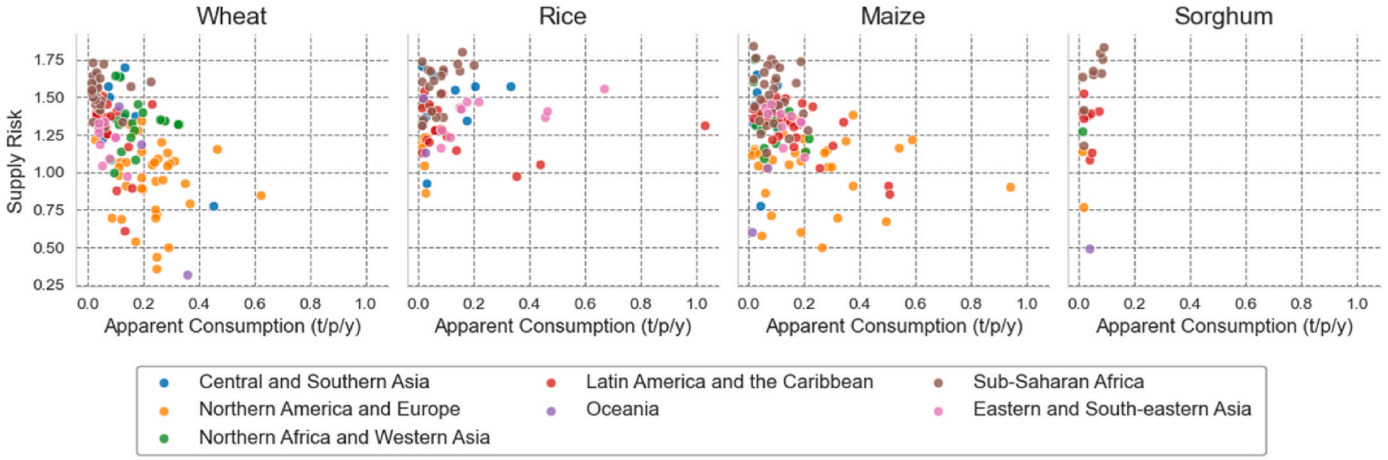

Fig. 6. Apparent Consumption and Supply Risk for four cereals, per country and world regions. t/p/y: ton per inhabitant per year.

some who import a large proportion of their maize (El Salvador) while others produce the majority (South Africa). Therefore, for this product, each country is exposed to specific risks, and no general trends can be drawn.

Finally, for sorghum, consumption levels are lower than for the other three cereals. Fig. 6 depicts that Sub-Saharan African countries present the highest SR (Burkina Faso, Cameroon, Djibouti, Ethiopia, Mali, Niger, Tanzania). These countries have rather low HDIs (<0.56). Their sorghum supply is based exclusively on their own local production, the political stability is very low (<0.26), climatic risks are variable (0.19–0.57) and they do not stock or export. Consequently, the SR is relatively high. One exception concerns Djibouti, where almost all the sorghum is imported. However the import diversity being low (0.22) and volatility being high (0.69), the SR remains high.

As in the previous section, these results point out that SRs are balanced between trade-related and domestic production risks, depending on the sourcing balance, and in agreement with recent food security literature (Kummu et al., 2020; Wassénius et al., 2023). It is therefore worthwhile to compare the SR of these products with the self-sufficiency index, which is often used as an indicator of food security.

3.3. Comparison with self-sufficiency

Fig. 7 illustrates the SRs of the same cereals as a function of the self-sufficiency of the countries for these cereals.

According to Fig. 7, for a given product, SR does not correlate with self-sufficiency. For example concerning wheat, countries with a self-sufficiency level of 1 can have SRs that range from 0.7 to 1.7. The SR index developed in this study indicates that even in the case of self-sufficiency, domestic production may not be accessible, due to various risks. This is consistent with Wassénius et al. (2023), who stressed that self-sufficient countries are not exempt from SR. Furthermore, the model suggests that for certain countries with high imports (i.e. low self-sufficiency level), the SRs are not necessarily high. This is in agreement with the work of Remans et al. (2014), Kummu et al. (2020) and Wassénius et al. (2023), who highlighted the trade-off between supply diversity and self-sufficiency.

Concerning wheat, Northern America and Europe have a wide range of SRs (between 0.26 and 1.26) and self-sufficiency levels (from 0.2 to more than 1). Some countries from these areas have self-sufficiency levels that are well above 1, thus indicating that they are very large wheat producers and exporters. Sub-Saharan Africa, North Africa and Western Asia tend to have high SRs (>1.25) and medium to low self-sufficiency (<0.8). Finally, Central and South Asian countries tend to be self-sufficient, but have high SRs.

Concerning rice, countries from Eastern and South-eastern Asia and Central and Southern Asia have self-sufficiency levels close to one, but with SRs varying from 0.9 to 1.62. Countries from Sub-Saharan Africa and Latin America and the Caribbean have self-sufficiency levels varying from low (near 0) to high (near 1), but then again the SRs cover a wide range (from 1 to 1.75).

For maize, results are similar to wheat for North America and Europe, i.e. variable SRs and self-sufficiency levels. On the contrary,

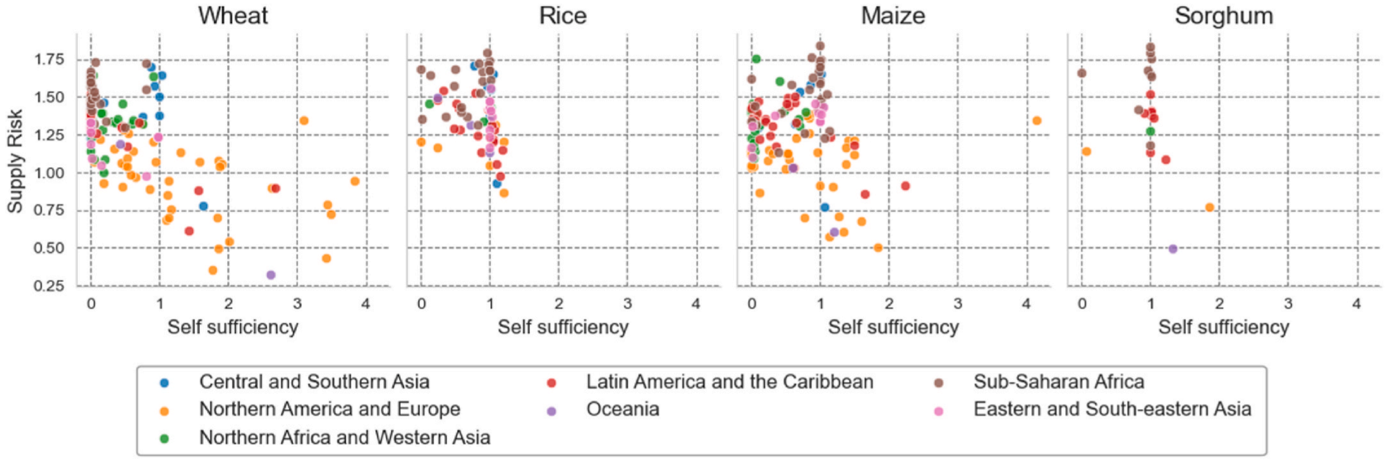

Fig. 7. Supply Risk as a function of Self sufficiency for 4 cereals, per country and world regions.

Sub-Saharan countries are more self-sufficient in maize than in wheat, but also have high SRs (1.12–1.77).

For sorghum, consumer countries tend to be self-sufficient. In addition, the SRs for sub-Saharan African countries are still higher than those for Latin American and Caribbean countries.

Results indicate that the strategies for reducing SRs differ from one crop to another, as observed by Puma et al. (2015) for wheat and rice. On one hand, wheat and maize are commodities produced and traded by many countries. Therefore, the countries that produce low amounts of these crops but consume large amounts, could reduce their SRs by diversifying the number of suppliers and by trading with politically stable countries. This analysis is in agreement with Bren d'Amour et al. (2016), who suggested that the diversification of trading partners can reduce vulnerability to supply disruptions, and Deaton & Lipka (2015) who showed the positive effect of trading with politically stable countries on food security.

Rice and sorghum, on the other hand, are widely grown for domestic consumption. Sorghum, in particular, is rarely traded. For countries where these crops account for a large proportion of the food consumption, means of reducing SRs include stockpiling, redirecting exports (if any) towards domestic consumption, and adapting agriculture to climate change. Once again, the analysis is consistent with the work of Laio et al. (2016), who highlighted the role of food stocks in offsetting the impact of crop losses. In addition, Puma et al. (2015) observed the tendency of large exporting countries to restrict exports in the event of food crises, while Anwar et al. (2013) stressed the importance of adapting agriculture to extreme climatic events.

All the aforementioned studies suggest that greater diversity, which reduces SR, could be achieved by increasing the share of trade in supply. The SR index developed here is also in line with the work of Clapp (2017) who demonstrated that food self-sufficiency is only beneficial for countries with certain situations including: a high exposure to volatile prices, a concentration of supplier countries, political tensions over trade and unexploited potential for biophysical production. However, the present study goes a step further by also distinguishing situations according to products, i.e. for a given country, the SR reduction strategies may vary according to the products considered.

3.4. Contribution to decision making

The developed indexes can be used to assess the risk of supply of countries for agricultural products. Analysis can be carried out at both country and agricultural product level, providing a more detailed picture of the risks and underlying causes. They enable differentiation between situations among countries and agricultural products, and identification of countries and products where the supply is potentially at risk, and the reasons why. One approach to reducing SR is to adapt crops to climate change, whether through infrastructure (e.g. irrigation) or agronomic practices (e.g. growing drought-resistant or later varieties to protect against late spring frosts). This strategy plays on one of the parameters of SR index: climate risk.

A second approach to reducing SR is to diversify supplies, as previously highlighted by the results in section 3.2 and 3.3. Diversification addresses several sources of risk - climatic, socio-economic and geopolitical – by spreading supply options, and is therefore a more far-reaching strategy. To encourage diversification of supply, governments can introduce economic measures such as import taxes, production quotas, export subsidies or restrictions, etc.

On a more global level, another approach to reducing risk could be to change diet. Encouraging the consumption of products with lower supply risks can reduce the SR of apparent consumption for a country. Therefore, the SR indexes could be integrated into agricultural and food policies aimed at ensuring food security. One interesting aspect of this approach is that it considers both food supply and demand, which is a major challenge for transforming food systems (Garnett, 2014). However, it is important to ensure that any changes to the diet are in line with the nutritional needs of the population and are socially accepted. Therefore, governments have different tools at their disposal to influence diets compared to those used to diversify supplies. These tools can include information measures such as labels, information campaigns, and guidelines, as well as public procurement for collective catering.

3.5. Data quality and validity

The agricultural data for the study, (production, imports, exports, stocks, and prices) are sourced from the FAOSTAT database. Although these data may be somewhat inaccurate due to being reported by states or estimated by the FAO, the database offers the advantage of providing harmonised data for all countries worldwide and is updated yearly. In this study the indexes were developed for the year 2018, but it is important to note that criticality is a dynamic concept (Ioannidou et al., 2019). Therefore, time series for SR could be created, as has been done in some studies on food self-sufficiency (Goswami and Nishad, 2018; Kummu et al., 2020; Porkka et al., 2013).

By conducting time series analysis of the SRs, it would be possible to observe their sensitivity to variations in the input data. Furthermore, time series analysis could facilitate the observation of emerging SR trends for specific countries or products. This would enable monitoring of the sensitivity of SR to cyclical effects, such as economic risk, or structural effects, such as changes in country supply strategies. By combining the SRs with data on food prices during the same time periods, it would be possible to empirically verify the accuracy of the SRs. This could be achieved by observing whether they detect sharp price increases, as suggested by (Frenzel et al., 2017) for the validation of criticality assessments.

Uncertainties could be propagated into the SR index from its parameters. However, in criticality, uncertainties arise more from the choice of parameters and aggregation methods than from the uncertainties of the parameters themselves (Cimprich et al., 2019). To examine the sensitivity to parameter aggregation, Electronic Supplementary Material 1 presents a local sensitivity analysis of the HDI aggregation formula. It demonstrates that while the absolute values of the SR indexes can be modified when the HDI aggregation formula changes, the ranking of the points varies very little. To delve deeper, a global sensitivity analysis would enable the weight of all factors to be considered.

3.6. Limitation and perspectives for the SR index

Although the developments proposed in this study provide a relevant assessment of food supply risks, there are some limitations, which open up prospects for future research.

Firstly, in this study, only the quantity of products consumed is taken into account, and not the nutritional content. However, the level of consumption does not indicate whether the quantity of food is sufficient to meet the dietary needs of the population, or whether nutritional requirements are being met. Some studies have assessed the diversity of supply at nutritional levels, although they do not allow for a more disaggregated analysis, and therefore provide less detailed information (Kummu et al., 2020; Wassénius et al., 2023). One way to improve the study would therefore be to integrate nutritional data as a "lower level" in the CSFI computation, as for the Dietary Sourcing Flexibility Index of the FAO (FAO, 2021b), which consider the diversity of agricultural product to nutrient supply. By analogy, a "higher" level to consider is the use of agricultural products, distinguishing between food, feed, and industrial or energy uses. This distinction would enable better consideration of competing uses for biomass of agricultural origin, which the SRs do not capture in this study. For instance, maize is used for food, feed, and biofuel production, creating competition between uses that can influence the supply risk for this product. Taking these mechanisms into account could greatly improve the relevance of the indexes for decision making.

Secondly, the index was designed on a country-by-country basis. However, food systems can be very diverse within a single country (Gaitán-cremaschi et al., 2019), and therefore they might not be exposed to the same SRs. Future research could thus focus on the adaptation of the SR index to finer territorial scales, such as regions, provided the data are available. Similarly, SRs could be downscaled at the company level, as companies can have very diverse agricultural product sourcing strategies facing various risks and are important players in the criticality field. In order to adapt the indexes to companies, however, certain indexes should be revised. For example, the HDI may reflect a country's ability to adapt, but other indexes should be found to assess a company's ability to adapt to a supply disruption.

Thirdly, risk indexes can be improved to better reflect the relationship between the assessed risk and the inaccessibility of agricultural products. For example, climate risk only takes extreme weather events into account. However, long-term climate trends such as decreasing rainfall or temperature variations are not considered, although they also affect the availability of agricultural products. In addition, climatic events do not affect all agricultural products in the same way. Therefore, broadening the scope of this index and differentiating climatic risk indexes for different crops could also help to improve the proposed SR. Along the same lines, the economic risk was solely assessed in terms of price volatility, which is assumed to transfer all production shocks from supplier countries. Once again, a more detailed characterisation of the mechanisms generating an economic risk of unavailability of agricultural products could be included in the SR. Examples of such mechanisms are export restrictions or subsidies, import taxes and quotas, etc.

Finally, one of the main hypotheses of the SR index is that diversity reduces SR, in line with the principles of resilience (Cabell and Oelofse, 2012) and with the field of study of resource criticality (Schrijvers et al., 2020). However, highly diverse systems are also potentially more exposed to external disturbances (Marchand et al., 2016; Puma et al., 2015) and less efficient (Cabell and Oelofse, 2012). This may increase the SR. Therefore, an improvement would be to determine the 'right level' of diversity needed in order to minimise the risk of food supply disruption while still providing sufficient amounts of food.

4. Conclusion

The SR indexes for agricultural products developed in this paper can be used for assessing the SRs of a given product in a given country. The novelty of this index is that it takes into account geopolitical, environmental and economic risks, as well as the structure and diversity of the food supply. In addition, the inclusion of the concept of resource criticality for agricultural products helps to fine-tune the index, and make it more relevant for decision-making purposes. Comparisons can be made between countries and between products, highlighting the different strategies that have been implemented for different countries and products to ensure a secure food supply.

A comparison of the SR index with the self-sufficiency rate indicates that these two metrics are distinct. The self-sufficiency rate quantifies production capacity in relation to consumption, while the SR index assesses the various risks that may affect the supply of agricultural products. The SR index is therefore more relevant for decision support concerning the food security of countries. The index also highlights the opportunities to reduce those risks, such as supply diversification, but also diet change or agricultural adaptation to climate change. However to effectively assess such strategies, the SR index needs to provide more accurate information on the nutritional content of food products, competition between biomass use or climate change agricultural adaptation strategies. These three research gaps provides interesting perspectives for the development of food security risk indexes.

CRediT authorship contribution statement

Lazare Deteix: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thibault Salou:** Validation, Supervision, Methodology, Investigation, Conceptualization. **Eleonore Loiseau:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

All data generated or analysed during this study are included in this published article and its supplementary information files.

- Electronic Supplementary Material 1 provides additional data description, data sources for the Supply Risk indexes and sensitivity analysis.
- Electronic Supplementary Material 2 provides data for the computation of the Apparent Consumption Supply Risk per country.
- Supply Risk indexes full dataset and data sources are available at: https://doi.org/10.57745/SKHTL7

Data availability

All the data used in this manuscript are available at the data repository or in supplementary materials

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2024.100764.

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