Charting out the future agricultural trade and its impact on water resources

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Abstract

International agricultural trade triggers inter-dependency among distant countries, not only in economic terms but also under an environmental perspective. Agricultural trade has been shown to drive environmental threats pertaining to biodiversity loss and depletion and pollution of freshwater resources. Meanwhile, trade can also encourage production where it is most efficient, hence minimizing the use of natural resources required by agriculture. In this study we provide a country-level assessment of the future international trade for 6 primary crops and 3 animal products composing 70% of the human diet caloric content. We set up four variegate socio-economic scenarios with different level of economic developments, diets habits, population growth dynamics, and levels of market liberalization. Results show that the demand of agricultural goods and the correspondent trade flow will increase with respect to current levels by 10-50% and 74-178% by 2050, respectively. The largest increase in the amount of traded goods is expected under the Economic Optimism scenario that will see an average trade flow of 2830 kcal/cap/day (i.e., nearly doubling the current per-capita flow). Most of the increase will be driven by the trade of crops for animal feeding, particularly maize will be the most traded crop. The trade networks architecture in 2050 and 2080 will be very different from the one we actually know, with a clear shift of the trade pole from the Western toward the Eastern economies. The dramatic changes of global food-sources and trade patterns will jeopardize the water resources of new regions while exacerbating the pressure in those areas that will continue serving food also in the future.

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In spite of this, trade may annually save around 40-60 m^3 of water per person, compared to a situation where countries are self-sufficient.

Keywords: water-food nexus, virtual water trade, water footprint, agriculture, future scenarios

Introduction

Since 1980, the world agricultural trade has increased in volume by six times, with food trade contributing to 80% of the overall flow [1]. In particular, since 2000 agricultural trade has grown more strongly than in the preceding decade thanks to falling barriers [2] and boosted by lower transportation and transaction costs. At the same time, the agricultural market has become more "global": the food that consumers find in their local stores is increasingly made from a large spectrum of international products coming from different locations across the globe. For instance, wheat produced in Australia and Ukraine is processed into flour in Indonesia and Turkey, and then exported to make noodles in China, and bread in Africa. Currently, around one fourth of the food we consume is traded internationally and a large amount of global population heavily relies on the food trade for its welfare [3].

The study of agricultural trade patterns is key to (i) analysing the mutual inter-dependency between countries, (ii) food security (e.g., access to food) and national welfare [4], (iii) the understanding of economic indicators pertaining to national poverty (e.g., per-capita purchasing power), (iv) transportation planning, and (v) the investigation of the environmental threats (e.g., euthrophication [5] and groundwater depletion [6, 7]) induced by the increasingly complex and "global" supply chain of agricultural goods [8, 9].

In light of increasing demand for agricultural goods [10, 11], approaching yield-plateaus in some locations and boosting production practises in other ones [12], what role will agricultural trade play in the future? Where will the agricultural trade pole settle in the upcoming decades? Who will lead the future agricultural market? Addressing these questions is crucially relevant to monitor the evolution of the international economic relationships and to investigate the effects of trade on natural resources. Moreover, the impacts of climate change on agricultural production [13], which are expected to bring greater fluctuations in crop yields and local food supplies especially at lower latitudes [14], may increase the importance of international trade in supplying food in climate vulnerable locations. Importantly, trade agreements and international policies play a crucial role to tackle mitigation objectives and boost international cooperation to lessen the environmental pressure (i.e., the Water Footprint [15]) and impacts (i.e., the Carbon Footprint [16]) on the Earth system, as it has been recommended by the IPCC's fifth assessment report.

A number of long-term economic projections have been provided by the European Commission [17], the International Monetary Fund [18], and The World Bank [19]. However, these studies are mostly focused on the market as a whole and the separation across commodities and services is generally limited to few sectors and hardly look at single commodities. Similarly, the commercial partners are rarely represented at the country scale, but mostly aggregated into groups/regions as [20] pointed out.

More detailed forecasts of the future agricultural market have shown important insights about the impacts of cropland expansion and intensification on the agricultural market [21], the implications of trading more food for land use and GHGs emissions [22, 4], and the water resource system [23, 24]. To these aims, Partial Equilibrium (PE) models (e.g., IMPACT, GLOBIOM, MAgPIE) and Computable General Equilibrium (CGE) models (e.g., ENVISAGE, MAGNET) are the most used economic models applied to the agricultural sector to analyse trade responses to productivity and consumption changes under a spectrum of climatic and socio-economic scenarios [25]. However, PEs' and CGEs' estimations are poorly tested against historical data [26] and they are sensible to parameter-choices, resulting in very different outcomes for different parametrizations, as shown by [25]. Moreover, these models (e.g., IMPACT) do not allow a region to be both an exporter and an importer of the same commodity [27]. In many cases the models are available only at the regional scale (e.g., MAgPIE) and in some models (e.g., MIRAGE) the trade network architecture cannot change in the future: i.e., two partners cannot start trading in the future if they were not trading in the past [28].

We advance the present state of agricultural trade modelling by providing and validating an integrated methodology to forecast future agricultural domestic demand, production, and international trade considering time horizons 2020, 2050, and 2080. We focus our analyses on 6 key global crops and 3 animal products, composing 70% of the human diet measured in terms of caloric content [3]. We project domestic crop- and animal- demand at the country scale as a function of population dynamics [29] and diet habits [30] based on the income growth and environmental paths defined by the Shared Socio-economic Pathways (SSPs) narratives [31]. We disentangle demand into human food, feed for livestock, and other uses (e.g., seeds, inputs to manufacture), which are seldom disaggregated in the literature. Crop production is forecast as a function of the yield scenarios available from [32]. This study presents and validates a new trade model with country-level and commodity-specific details. This model includes a dynamic network structure where commercial partnerships can change over time depending on demand, supply, and market liberalization. Moreover, the model takes into account that a country can be at the same time both importer and exporter of a certain commodity (e.g., wheat), and that the commodity-specific trade networks are indirectly connected (e.g., the livestock trade network is connected to the maize trade network through feed demand). Finally, the model respects the balance constraint of production plus import equal to consumption plus export for each commodity at the country level, which is not guaranteed, e.g., by the gravity model [33].

1. Methods

In this Section, we provide information about the data and methods used to forecast the future agricultural demand, supply, and international trade flows by 2020-2050-2080. Four assorted scenarios are set-up for 34 plant-based products

(6 primary crops and 28 derived crops) and 3 animal-based products (Table S1). Products have been selected on the basis of their importance in human nutrition, international trade, and because of their pressure on natural resources.

1.1. Scenarios set-up

Scenarios are used to delineate future long-term narratives of human activities considering environmental, economic, and social aspects. In this study, we build on (i) the Special Report on Emissions Scenarios (SRES) developed in the 4th IPCC Assessment Report [34] to project future crop production based on crop yield scenarios provided by the GAEZ database [35] and (ii) the Shared Socioeconomic Pathways (SSPs) to project future crop demand as a function of population scenarios [31] and diet transitions [30]. The comparisons and reconciliation between the SRES and SSP scenarios has been proposed during the SSP development phase [36, 37], while the study by [38] found specific correspondences between the SRES scenarios families and the SSPs.

We frame our projections within four scenarios (Table 1), where each is identified through an archetype that has been derived from [38]. The Economic Optimism scenario (EO) is driven by the economic success of countries, which prompts a globalization of the western diet patterns ("Western high meat" scenario) with increased shares of animal products in the diets for developing countries and constant or decreased meat consumption in developed countries. In this scenario, protein consumption will reach 90 grams/cap/day on global average (all regions above 80 grams/cap/day). We associate this scenario with a liberalized market and the SSP5 population growth dynamics [29]. In the Regional Competition scenario (RC), the trade openness is restricted and subordinated to the national food security due to a faster population growth (SSP3), while the diet composition remains equal to the current one ("Current meat" scenario for year 2016). The Sustainable Development scenario (SD) projects a global shifting toward a more sustainable pathway (SSP1), accompanied by decreasing population from the middle of the century and diet shifts toward a lower meat diet ("Less meat" scenario, 70 grams/cap/day of protein) especially across

Western economies, but with high degree of globalization as in EO. Finally, the Baseline (BL) scenario is coupled with the SSP2, and the market openness and diet composition are kept constant to the 2016 values.

Table 1: Scenarios set-up. Four scenarios are adopted in this study: the Economic Optimism (EO), the Regional Competition (RC), the Sustainable Development (SD), and the Baseline (BL) scenario. Each scenario is identified by three main key features pertaining to the diet composition (western high meat, WHM, less meat, LM, current meat, CM), the market openness (restricted, current, liberalized), and the population growth (slow, medium, fast). Each archetype defined in this study is meant to reproduce one of the SSP narrative [39] following the indications provided in [38].

Scenario	diet	market openness	population growth	SSP	SRES
Economic Optimism	WHM	liberalized	slow	5	A1
Regional Competition	CM	restricted	fast	3	A2
Sustainable Development	LM	liberalized	slow	1	B1
Baseline	CM	current	medium	2	B2

1.2. Scenarios of future agricultural demand

The agricultural domestic demand, $D_{p,c}$ [ton], of product p in country c accounts for different uses: food for human consumption, feed for livestock, seeds, inputs to manufacture for food and non-food uses, and losses during storage and transportation. To obtain scenarios of future agricultural demand, first we project the per-capita domestic demand, $d_{p,c}$, and then we couple this projection with the future population scenarios, PP_c, derived from the SSPs' scenarios [29], namely $D_{p,c} = d_{p,c} \cdot PP_c$. Hereafter, we denote the per-capita variables with lower-case characters and national scale variables in capital letters.

First, we quantify the per-capita demand in 2016, using a 17-years (2000-2016) linear regression of the annual $d_{p,c}$ values. This allows us to obtain more robust results, given that the past annual $d_{p,c}$ values are affected by stocks' variations, which cannot be isolated due to high intrinsic uncertainties [40].

The annual $d_{p,c}$ values are obtained with a *top-down* approach using production, trade data, and population available from the [41], namely

$$d_{p,c} = \frac{P_{p,c} + I_{p,c} - E_{p,c}}{PP_c} \qquad [\frac{\text{ton}}{\text{cap}}] \tag{1}$$

where, $P_{p,c}$ is the national production of p, $I_{p,c}$ is the country import, and $E_{p,c}$ is the country export. In equation (1), import and export account for both the primary crops (e.g., barley) and their derived products (e.g., barley pearled, malt, and beer of barley, see Table S1).

In order to project the future demand for the ”western high meat” and ”less meat” diets, we split $d_{p,c}^{2016}$ into per-capita food demand ($fo_{p,c}^{2016} = l_{food}^{2016} \cdot d_{p,c}^{2016}$), per-capita feed demand ($fe_{p,c}^{2016} = l_{feed}^{2016} \cdot d_{p,c}^{2016}$), and per-capita demand for ”other uses” ($ot_{p,c} = l_{others}^{2016} \cdot d_{p,c}^{2016}$). These components are disentangled at the country scale according to the fraction of domestic demand used by each sector, l^{2016}, obtained with the FAOSTAT data available in the ”Food Balance Sheets”.

Food demand by 2050, $fo_{p,c}^{2050}$, is obtained by modifying the $fo_{p,c}^{2016}$ value according to the percentage variations shown in Tables 5 and 6 in the SI material, which have been calculated on the basis of the diet scenarios provided by [30] for 2050. Due to lack of data, we assign the $fo_{p,c}^{2016}$ value to the 2020 projection and the $fo_{p,c}^{2050}$ projection to the $fo_{p,c}^{2080}$. The $fe_{p,c}^{2016}$ value depends on the domestic and foreign demand for meat products. Given that the same crop can be fed to different animals, first we disentangle the crop-specific feed demand across the considered three animal products, namely

$$fe_{c,cr,m}^{2016} = \frac{Pr_{c,m}^{2016} \cdot K_m}{\sum_m Pr_{c,m}^{2016} \cdot K_m} \cdot fe_{c,cr}^{2016} \qquad [\frac{\text{ton}}{\text{cap}}], \tag{2}$$

where K_m indicates the caloric content of the animal product m, namely calories per tonne. Then, we project the crop-based feed demand by modifying the $fe_{c,cr,m}^{2016}$ value according to the rate of variation of m production ($rate_{c,m}^{2050,2080}$) with respect to 2016.

$$fe_{c,cr,m}^{2050,2080} = fe_{c,cr,m}^{2016} \cdot (1 + rate_{c,m}^{2050,2080}) \qquad [\frac{\text{ton}}{\text{cap}}]. \tag{3}$$

Overall, it is worth noting that our approach attributes the (animal-specific) feed variation only to changes of meat production, while we assume constant feed mixes, production technology and management. We recognize the importance of these aspects causing a different impact on the environment [42], but to date this is the best approach due to lack of detailed projections about livestock systems. Finally, we evaluate scenarios for the "other uses" sector as a function of the food and feed scenarios and we assume that the ratio of other uses with respect to the total domestic demand remains constant in the future. In particular, we compute l_{others}^{2016} as the complement to 1 of the food and feed proportions, which have been previously obtained from the "Food Balance Sheet" data. With this assumption we can estimate the total per-capita domestic demand of each product, i.e.

$$d_{c,p}^{2050,2080} = \frac{fo_{c,p}^{2050,2080} + fe_{c,p}^{2050,2080}}{1 - l_{others}^{2016}}, \tag{4}$$

and, indeed, the demand for "other uses", as

$$ot_{c,p}^{2050,2080} = l_{others}^{2016} \cdot d_{c,p}^{2050,2080}. \tag{5}$$

1.3. Scenarios of future agricultural production

To model the future agricultural supply, we derive the yield scenarios from the GAEZ database [35] under four different SRES scenarios (A1-F1 for the Economic Optimism, A2 for the Regional Competition, B1 for the Sustainable Development, B2 for the Baseline). Each scenario accounts for land-resource availability, crop suitability, farm-level management, and crop production potentials that are a function of climate, technology, economic productivity, and other factors [32]. Accordingly, each scenario comes with 3 different implementation levels ("low input level" (LIL), "intermediate input level" (IIL), and "high input level" (HIL)) discriminating the technological advances of each country, considering how much agriculture is market-oriented, and accounting for the use of inputs and pesticides. To discriminate the best implementation level for each time-horizon, we firstly find the best input level for 2020 by comparing country

yield data of year 2016 (taken from [41]) with the projected yield in 2020 and assigning to 2020 the implementation level minimizing the difference. We then assume one-step increase in the implementation level for each following time horizon (i.e., 2050-2080). If a country already shows the highest implementation level, we keep it constant in the future.
As a first assumption, we keep the 2016 cultivated area constant in the future and we evaluate the relative attainable production only considering yield scenarios. Then we adjust the 2016 cultivated area of those crops showing a global production smaller/larger than the global demand. Indeed, at the global level we assume that production meets demand, as in [43, 44]). The crop-specific coefficient is defined as the ratio between global demand and global production of each crop and it is applied uniformly across countries.

Future scenarios of meat production are obtained as a function of the projected meat demand (Section 1.2). The global meat demand is distributed across producing countries according to their average production share over 2000-2016. For instance, on the basis of past data [41], we attribute to China 45% of the global pig meat production and to the US 20% of the global cattle meat production. We acknowledge that in the future the national production shares may change, especially under the Economic Optimism scenario due to the intense meat transition. However, other choices seem to be arbirtary.

1.4. Scenarios of future agricultural trade: a country-level and commodity-based approach

National demand for import and national opportunity for export are evaluated as a function of (i) the mismatch between demand (Section 1.2) and supply (Section 1.3) and (ii) the commodity-specific globalization degree expressing the market openness typical of each country (Table 1). The national import and export flows are then distributed over bilateral trade relations by means of the RAS algorithm ([45, 46] also called bi-proportional matrix balancing) in order to chart out the future evolution of the agricultural trade network.

1.4.1. National import and export

National imports and exports are estimated for each country considering one commodity at a time. This is very important, although rarely accomplished in the current literature [47], because each product has its own trade network, with specific topology and flow intensities.

In order to explore different levels of market integration, we define three levels of *market openness* ($f_{c,p}^{glob}$): (i) restricted, (ii) current, and (iii) liberalized. The restricted market assumes that each country focuses its economy primarily on its own needs as if it had some trade barriers that allow trade only in one direction: outflows of surpluses or inflows of lacking commodities. Hence, the market openness is zero. The current level of openness assumes that the future market will maintain a level of globalization equal to nowadays, with similar transportation margins, tariffs, and subsidies. Finally, the liberalized market mimics a world where trade barriers are reduced and countries tend to export more for economic reasons, rather than just to clear out surpluses.

We define the market openness in year 2016 as the portion of production that is traded to meet the market demand, regardless the availability of production surplus, i.e.

$$f_{c,p}^{glob} = \frac{E_{c,p}(P_{c,p} < D_{c,p}) + I_{c,p}(P_{c,p} > D_{c,p})}{P_{c,p}}, \tag{6}$$

where, the term $E_{c,p}(P_{c,p} < D_{c,p})$ represents the amount of commodity that country c exports although its production is not sufficient to satisfy the domestic demand, while the term $I_{c,p}(P_{c,p} > D_{c,p})$ quantifies the amount of product that is imported, despite production surplus, and re-exported. The denominator quantifies the total national production of p. We evaluate the $f_{c,p}^{glob}$ for each commodity and country using the trade and production data of year 2016 available from [41].

National export is evaluated as the sum of the portion of production that is exported to meet the demand of the globalized market and the portion of production that exceeds the domestic demand and needs to be disposed, i.e.

$$E_{c,p} = f_{c,p}^{glob} \cdot P_{c,p} + \max[0, (1 - f_{c,p}^{glob}) \cdot P_{c,p} - D_{c,p}] \qquad [\text{ton}]. \tag{7}$$

National import is obtained by solving the national balance among demand, supply, and export,i.e.

$$I_{c,p} = D_{c,p} - P_{c,p} + E_{c,p}, \tag{8}$$

where, $D_{c,p}$ is the national domestic demand projected as described in Section 1.2 and $P_{c,p}$ is the national supply projected according to Section 1.3. In equation (8), we do not account for national stocks because we are projecting average future trade scenarios.

By substituting equation (7) in equation (8), the national import reads

$$I_{c,p} = \max[0, D_{c,p} - (1 - f_{c,p}^{glob}) \cdot P_{c,p}]. \tag{9}$$

According to equation (9), a country imports the amount required to match the domestic demand $D_{c,p}$, previously diminished by the portion of production $(1 - f_{c,p}^{glob})$ that is used to satisfy the global market demand. We notice that while trade projections come separated for each commodity, commodities are inherently connected to one another through demand and supply. For instance, a country increasing its meat production will increase the demand of crops for feeding; this translates into an increase of crops import when domestic supply is not sufficient. With the proposed approach we are able to consider this inter-connection.

1.4.2. Network topology reconstruction at the country and regional scale

The national import and export projected in Section 1.4.1 are used to reconstruct the network topology, namely the adjacency matrix, $\mathbf{A}$, expressing the existence of a relation between any couple of countries. We define an adjacency matrix for each commodity trade network, scenario and time horizon. Accordingly, $a_{i,j} = 1$ if the two countries trade the commodity, $a_{i,j} = 0$ otherwise. The matrix's rows represent the export flows, while the matrix's columns represent the import flows: we assign 1 to all the elements of the matrix that are found at the cross of a non-zero column sum ($I_{c,p} > 0$) and a non-zero row sum ($E_{c,p} > 0$).

The adjacency matrix represents the unweighted network of each future trade scenario. We adopt the RAS algorithm [45, 46] to obtain the bilateral trade flows of each commodity. The RAS algorithm is a balancing method widely adopted in the context of input-output tables [48], which allows one to estimate the trade flow departing from country c_1 and reaching country c_2 using as input variables the national imports and exports (namely, the columns' and rows' sums). In practice, the initial adjacency matrix is progressively modified through an iterative procedure of bi-proportional adjustment that distributes the row and column sums over each matrix element. In order to obtain more precise estimates of the bilateral flows, we previously adjusted **A** with the inverse of the geographical distance between the couples of countries. Hence, the initial bilateral trade flow, $f_{i,j}$, reads

$$f_{i,j} = \frac{1}{d_{i,j}} \cdot a_{i,j} \qquad \left[\text{ton}\right]. \tag{10}$$

The initial bilateral trade matrix, **F**, is then adjusted with two coefficients, a row factor (r_i) and a column factor (s_j), which are obtained with an iterative procedure that progressively updates the initial matrix to obtain the final bilateral trade matrix, **F'**, that satisfies the equations

$$\sum_i f'_{i,j} = E_i \quad \text{and} \quad \sum_j f'_{i,j} = I_j. \tag{11}$$

The iterative procedure alternatively evaluates the row and the column factors as follow. At step n=1, s_j=1 while r_i is calculated to satisfy the row constraint, namely

$$r_i^n = \frac{E_i}{\sum_i f_{i,j}}. \tag{12}$$

At step n=2, $r_i = r_i^{n-1}$ and s_j is equal to

$$s_j^n = \frac{I_j}{\sum_j r_i^{n-1} \cdot f_{i,j}}. \tag{13}$$

Once the full iteration is completed, it is possible to determine the final row (R_i) and column (S_j) coefficients, namely

$$R_i = \prod_n r_i^n \quad \text{and} \quad S_j = \prod_n s_j^n \tag{14}$$

Hence, the generic bilateral trade flow reads

$$f'_{i,j} = R_i \cdot f_{i,j} \cdot S_j. \tag{15}$$

The bilateral trade flows projected at the national scale are finally aggregated at the regional level in order to provide a more robust picture of the future trade network. Aggregations are made in order to get estimates of the import and export flows of each region. We also aggregate the flows moving within the same region in order to compare intra- and inter-regional flows. We consider nine different regions (Table 7 in the SI material): Northern America (NAm), Latin America and Caribbean (LAC), Europe (E), Middle East and Northern Africa (MENA), Africa (Af), Eastern Europe and Central Asia (EECA), South Asia (SA), east Asia and Pacific Islands (EAP), Oceania (O).

1.5. Trade model validation

The trade model proposed in this Section is validated with past trade data available from [41] over the period 1986-2016. Validation is provided both at country and regional scale for each study products. Details about validation can be found in Section 3 of the SI material. Figures 1,2 in the SI provide the performances of the trade model through network sketches (i.e., rice and maize network in 2016) and by means of scatter plots between real and predicted values. At the country scale, we find an average coefficient of determination (R^2) of 0.60, while at the regional scale R^2 is always larger than 0.80. These outcomes hold true over the entire period 1986-2016 and confirm a good agreement between predicted and real trade flows data. Moreover, the RAS algorithm (Section 1.3.3) used to estimate bilateral trade flows does not requires *a-priori* calibration of the model parameters, but it only needs gross national exports and imports, and the network topology. Overall at an aggregated scale, our trade scenarios are in line with those elaborated by [4, 49, 50, 51].

2. Results

The model's outcomes are commodity-specific projections of demand, supply, and trade in metric tonne. For the sake of clarity, we show results aggregated over commodities by means of food calories equivalent and virtual water content [52], despite other measures (e.g., proteins, dollars, CO_2) can be similarly used. All the variations shown are referred to year 2016, unless otherwise specified. Commodity-specific and country-level results can be found in the SI material.

2.1. Future scenarios of global agricultural demand

As a global trend, future demand of agricultural products, expressed as food calorie equivalent, will increase between 10% (SD scenario) and 50% (EO scenario) by 2050 (see Figure 1A), while it will slow down after 2050, mostly following decreasing population (Figure 1B). In the *Economic Optimism* scenario, demand will increase due to a global transition toward meat-intensive diets (+43% meat consumption at the global scale, Figure 1C). This will increase by 90% the demand of crops for livestock, which will further enlarge the amount of human-edible calories that do not directly end-up in the food system [53]. The largest increases in meat consumption are projected to happen in Sub-Saharan Africa (+400%), as also shown by [54], due to the increase of both per-capita consumption (+200%, Table 5), thanks to larger per-capita income [55], and population (+130%, SSP5). The per-capita consumption of meat will increase also in South Asia and in Middle East and Northern Africa, but at slower rates. However, in these regions total meat consumption will increase only by 150% due to a slower population growth. As an opposite trend, North

America, Europe, and Oceania show a stagnant or decreasing trend of the per-capita consumption of cattle and pig meat in accordance with past years [41], despite a persisting increase of meat consumption in North America due to a 50% population growth (EO scenario). Under the *Sustainable Development* scenario meat consumption will reduce by 18% worldwide, hence requiring half the feed required under the EO scenario. Indeed, under the SD scenario more plant-based products will directly serve as food (Figure 1C). The largest reduction of meat consumption will happen across the Western economies and in the Eastern Asian region, which will potentially follow a Green Road aiming at reducing the impacts on natural resources. However, this will not diminish the feed demand of Europe and North America due to their important role as meat producers and exporters in the global market.

The divergence between EO and SD scenarios increases when we look at the daily per-capita values of production (or demand): 4500 kcal/day/cap (by 2050) produced in the EO scenario *versus* 3000 kcal/day/cap produced in the SD scenario. This gives a coarse insight of the future per-capita demand of arable land and water resources. Such difference broadly represents the daily amount of human-edible calories that we may save with a transition toward less meat-intensive diets. Saving this amount of calories has profound implications for the environment, because it would reduce the amount of water and land used, the quantity of GHG emissions, and the loss of biodiversity. It is worth noticing that these per-capita production (demand) values are different from the usual recommended calories intake because they refer to the gross demand of food, feed, and other uses. Interestingly, under the *Regional Competition* scenario agriculture will need to feed 50% more people than under the EO scenario, but the demand will be 20% lower than that of the EO scenario (Figure 1A). Indeed, in RC scenario meat consumption will increase only by 11%, which will cause a 12% increase of crops for livestock. Finally, global demand in the *Baseline* scenario will vary similarly to that projected in the RC scenario, but it will remain stable after 2050 due to population slow down.

2.2. Future scenarios of global agricultural trade

According to our projections, the international agricultural trade will keep increasing in the upcoming decades, but at different rates depending on the national market openness (Table 1) and on the national production surplus (see Figures S5-S13 for country-level details). Figure 1A shows the modelled past agricultural trade (i.e., red dashed line) along 1986-2016 (Section 1 in the SI) which exhibits a very good accordance with the real data (i.e., black line), and the future projections. In the EO scenario, trade will increase by 178% by 2050 with respect to current levels (Figure 1A); the most traded crop will be maize, mostly due to the increased feed demand for meat production. Also the trade of barley and soybean will significantly increase under the EO scenario to sustain the livestock market. In the other scenarios, trade will increase slower, between 74% (RC scenario) and 83% (SD scenario) by 2050 with respect to year 2016. Interestingly, trade forecasts for the RC scenario are always below those from the other scenarios, except when approaching year 2080. Indeed, in the RC scenario the assumption of a restricted market (Table 1) will imply for countries to primarily satisfy their domestic demand and to start exporting only surplus production. Under the RC scenario, wheat will be the most traded crop to fulfil displaced food demands. Rice and wheat demand will be almost the same by 2050 ($2{\cdot}10^{15}$kcal), but rice will be traded three times less than wheat. In the EO and SD scenarios, agricultural trade will acquire much importance compared to production: i.e., nearly 50% of the production will be traded in the global market by 2050, with consequent issues for the transportation management and routes planning, trade agreements, and externalization of the impacts arisen by faraway consumption patterns. Conversely, in the RC and RE scenarios the trade magnitude will remain stable around 35% of that of production, hence similar to current levels.

2.3. *Future geography of agricultural trade: dynamics and implications at the regional scale*

All the considered scenarios agree in showing an increase of the trade flow intensity, even if at different rates (Figure 1A). The Economic Optimism scenario shows the largest increase with international trade reaching $7{\cdot}10^{15}$kcal, i.e., 2850 kcal/cap/day, in 2050, while the other scenarios predict a future flow around $4\text{-}5{\cdot}10^{15}$kcal, i.e., 1240-1640 kcal/cap/day. In the following we aggregate the country scale scenarios of future trade at the regional scale (see Table 7 in the SI) to focus on the key spatial heterogeneity and fragmentation of the future agricultural market.

2.3.1. *Eastern economies*

Goods produced in **Eastern Europe and Central Asia** (EECA, Figure 3A) will dominate the future agricultural market (export share of 30% in all scenarios by 2050) mostly at the expense of North America and Latin America and Caribbean, whose exports will significantly reduce (Figure 2). By 2050 the largest flows will be directed toward Europe (wheat and soybean mostly, Figure S4A), Middle East and Northern Africa (wheat and barley mostly), and Eastern Asia and Pacific Islands (wheat and soybean mostly). This will happen thanks to a surplus of crop production (Figures S5-S11) that will be attainable through yield boosting that could be achieved through technological investments. At the same time, population growth in this region will slow down, hence limiting the domestic demand for agricultural goods. Indeed, EECA will become a net exporter of food equivalent calories under all scenarios (Figure S14) and in 2080 it will be the least populated region, except under the Regional Competition scenario. Interestingly, while under the BL scenario EECA will export predominantly wheat, under the EO scenario (Figure S4B) EECA will export a great amount of soybean, especially toward Europe.

Together with EECA, also the **Eastern Asia and Pacific Islands** (EAP, Figure 3A) will become important exporters of calories (15% export share in 2050, Figure 2), with flows mostly originating from China, as found by [51], whose production of wheat and maize, and also of pig meat, chicken meat, and cattle meat will exceed the national demand (Figures S6, S9, S11-S13). Specifically, under the Baseline scenario the largest flows will be directed toward North America (Figure 3B), particularly in the form of maize and South Asia and Africa in the form of rice (Figure S4A). Despite increasing its export, EAP will remain an important importer of soybean from **Latin America and Caribbean** (LAC), wheat from EECA, and rice from South Asia. Only in 2080 it will be a net exporter in all scenarios (Figure S14).

Overall, all scenarios agree in forecasting a translation of the trade pole toward the Eastern economies, at the expense of the Atlantic pole.

2.3.2. Western economies

According to our scenarios, **Europe** will predominantly import from the EECA, while North America from Latin America and Eastern Asia (Figure 3). Europe will be also in the future e net importer of calories (Figure 20 in the SI) under all scenarios. Under the Baseline scenario it will probably reduce its export toward the MENA region that will import more calories from EECA. Under the EO scenario, **North America** will exhibit the largest degree of dependency from foreign commodities (Figure S14) due to population growth (+50% in 2050 with respect to 2016) and lower land productivity especially for maize, wheat, and soybean possibly due to climate change [56]. Under three out of four scenarios, North America will reduce its export share from 30% in 2016 to 7-12% in 2050, as previously suggested by [51]; only in the Regional Competition scenario it will remain a key exporter in the global market (15% export share, Figure S15H), thanks to the lower demand which still guarantees production surplus. This framework will call for significant adaptation and technological advances for North America to merely maintain its current productivity [56]. However, while diminishing the export of crops, North America will continue to export large amounts of chicken meat (mostly coming from the United States) toward Africa and the Middle East and Northern Africa region and pig meat (mostly coming from Canada) toward EAP and LAC. Such exports will further rise the domestic demand for plant-based feed.

2.3.3. *Southern economies*

Under three out of four scenarios, **Africa** will increase the imports of calories from other regions due to the lack of self-sufficiency in the domestic production of most commodities. However, under the Economic Optimism scenario there will be only a slight increase of import, while the export will importantly increase (Figure 2) thanks to the production enhancement attainable through economic investments and to the more liberalized market (Table 1) that will allow this region to increase its role in the global market. In the EO scenario (Figure S15 panels F,G), the export flows from Africa will reach $7{\cdot}10^{14}$kcal by 2050 and most of them will be directed toward North America in the form of maize. Indeed, rainfed maize in Africa currently has the greatest yield potential and the largest yield gap [54]. Hence, especially under the EO scenario Africa may close the maize yield gap in many countries (Figure S6A, e.g., Kenya, Tanzania, Mozambique, Zimbabwe, South Africa) by enhancing the inputs to soil and the mechanization level and expanding areas under irrigation. Indeed, in the EO scenario Africa may exceptionally reach the export share of Europe (Figure 2). Particularly, it seems likely that South Africa will increase its export of all the analysed commodities with the exception of rice and sorghum (Figures S5-S13), as found by [50]. As shown by [54], the path to self-sufficiency will require yield gap closure, increasing cropping intensity and expansion of irrigated production through adequate policies that ensure intensification without within the environmental limits.

The overall picture seems to pose EAP and EECA at the guide of the future trade network. The progressive transition of the trade center from the West to the East will determine a new configuration of the network. The intensification of the Oriental pole will be possible through a great increase of crop and meat production (also found by [20]), which will allow these regions to have surplus production, and become net exporters toward most regions, notwithstanding the increasing population. Overall, some regions, which used to exchange almost the same amount of calories in the past (e.g., Figure 24 in the SI, EAP to Af or EAP to E), will become net exporters toward the regions they used to have a balanced relation with. In other cases, the largest preferential flow will maintain the same direction (e.g., Figure 26 in the SI, LAC to MENA) or will be reversed (e.g., Figure 28 in the SI, NAm to LAC). The "Easternization" of the agricultural market has been also predicted in other studies, either specific on agricultural trade [4, 49] or pertaining to the gross trade dynamics [57, 58]. In the following, we will show how the Easternization of the global market will imply an Easternization of the impacts on water resources induced by the agricultural practises for the export.

2.4. The role of trade globalization on water resources

International agricultural trade shapes distant inter-dependencies among countries, not only in economic terms, but also under environmental perspectives. Recent studies have shown how agricultural trade drives an outsourcing of environmental impacts pertaining to biodiversity losses [8, 9], depletion and pollution of freshwater resources [6, 59], eutrophication of river bodies [5], and tropical deforestation [49]. However, trade can also encourage production where it is most efficient, hence minimizing the use of natural resources required by agriculture [60]. It has been shown that food trade help saving water on a global scale and that savings have increased since the Eighties thanks to production shifts in regions where less water is required per unit product [61, 59]. While the role of other environmental issues, such as land use change and GHGs emissions, has been analysed by recent studies (e.g., [4]), the impacts of the future trade network on water resources has been poorly investigated.

In this Section, we show how the future agricultural market will shape a regional inter-dependencies over water resources under the Regional Competition scenario -where trade will increase only favoured by the export of surplus production- and under the Economic Optimism scenario -where the mutual effect of production surplus and market liberalization will increase trade flow.

We measure the market-induced impact on water resources by means of the Virtual Water indicator [52], which is widely used in the literature to quantify the water hidden behind each commercial flow that leaves the country where water has been used during the production process and reaches the country-of-consumption [62]. Accordingly, we transform the projected trade flows into virtual water flows (see [63]) and we infer how much water will be used to sustain the agricultural trade by 2050. In doing this transformation we account for the fact that the water amount used to produce each product will change in the future according to the crop yield: namely, the larger is the yield, the smaller is the unit water use [63]. We find that, as a consequence of the increased market liberalization (i.e., EO), by 2050 countries will enlarge their impact on foreign water resources with respect to current levels by three times. Indeed, the virtual water trade will reach 2200 km^3/year by 2050 (260 m^3/cap/yr on average), meaning that a giant volume of water will be locally exploited to sustain the global demand. In particular, around 120 km^3/year will be displaced from surface and ground water bodies (i.e., blue water) due to irrigation, hence increasing the probability of water stress. The largest virtual water exporters will be Latin America and Caribbean and Eastern Europe and Central Asia, while North America and Africa will increasingly rely on foreign water resources despite Africa increasing its export share of virtual water by 7% (Figure 4B).

Under the Regional Competition scenario (Figure 4C), countries will enlarge their impact on external water resources (around 1500 km^3/year of virtual water, 150 m^3/cap/yr), but to a lower extent than under the EO scenario. North America will be a key exporter of virtual water, especially toward Africa and Latin America. Europe will diminish its reliance on foreign water resources and will keep its export share as small as 10%, while South Asia will increase its water-dependence from Eastern Europe and Central Asia and Eastern Asia. The EAP region will have an important role in shaping the future water-based inter-dependency both as an exporter and as an importer. However, its export share of virtual water (13% in EO and 17% in RC, Figure 4C) will be lower than its real export share of commodities (17% in EO and 20% in RC, Figures

21 F,H in the SI). Differently, North America will have a larger export share in terms of virtual water than of traded commodities. Indeed, North America will export a significant amount of animal-based products, which are much more water-intensive than other products.

Overall, both scenarios point out an important increase in the heterogeneity of the cross-regional water dependency, which unavoidably challenges the resilience and vulnerability of the whole system. Despite a general increase of the traded water (+120% under the EO and +45% under the RC with respect to year 2016), we find that trade enhances efficiencies that in turn are fundamental for sustainability. Indeed, in all scenarios trade may generate water savings around 350-570 km^3/yr (40-60 m^3/cap/yr), which otherwise would be required if countries domestically produced what they consume. Trade generates global water saving when the commercial relation is directed from a more efficient (i.e., less water use per unit product) to a less efficient country. This provides a first insight about the possible water savings generated by international trade; however, further analyses should be done to account for local water availability, and thus for possible water stress, land expansion and land-use change.

Finally, the total water use for agricultural production will remain similar to that of year 2016 under the EO scenario, while it will decrease by 15-20% under the other scenarios. Indeed, under the EO scenario cultivated lands will call for both yield-based intensification and land expansion to meet the global demand of crops. The combined effects of intensification, which decreases the water used per tonne of crop produced, and expansion, which requires additional water, will result in a water consumption similar to the 2016 levels. Conversely, under the other scenarios future demand could be met by the only effect of land intensification, coupled sometimes with land reduction (e.g., for sorghum, barley, and wheat), hence fostering water savings in producing countries.

3. Limitations and uncertainties

This study provides estimates of future demand, supply, and bilateral trade flows under variegate scenarios for 6 key primary crops (together with their derived products) and 3 key animal products. Our results contribute to the Agricultural Model Intercomparison and Improvement Project (AgMIP, `https://agmip.org`) aiming at improving agricultural models to evaluate alternative climate and policy futures.

The integrated approach used here to estimate future bilateral flows on the basis of exogenous agricultural demand and supply is inherently associated with different sources of uncertainties due to input data and modelling assumptions. Here we analyse the main sources of uncertainty that can impact our scenarios. The uncertainty associated with future population reflects the uncertainty about future fertility and mortality rates, and education trends [29]. SSPs population scenarios come out without probabilistic projections; however, we give a measure of the uncertainty that is usually associated with population scenarios by taking advantage of the probabilistic projections provided by the UN [64], although their model does not take into account education trends as SSPs' models do. According to these estimates, world population will reach 9.7 billion by 2050 with a standard deviation in the range between 0.17 and 0.25 billion people (nearly 2% of the projected population). The future diet composition we adopted in this study is based on the work by Erb *et al.*, which provides a "western high meat" scenario and a "less meat" scenario [30]. These scenarios are constructed under different assumptions pertaining, e.g., to GPD variations, and are only available at the regional scale for products categories. Hence, some uncertainty occurs when we associate these scenarios to specific countries because this removes the diet heterogeneity within each region. Nevertheless, our estimate of future demand is in accordance with the previous estimates by [11, 10, 4]. Uncertainties pertaining to production scenarios rise due to the assumption of constant cultivated areas in the future, namely equal to the 2016 levels. According to our scenarios, in fact, production will increase only driven by yields enhancement. However, when we compare the global supply with the global demand for each product, we find that for some commodities (e.g., maize and soybean) yield boosts will not be sufficient to satisfy future demand. Accordingly, we adjust the national cultivated areas with a global factor in order to meet the demand. Our conservative assumption of initially constant area coupled with the uniform adjusting factor may hide new land clearing that some countries might adopt to satisfy future agricultural demand while limiting, e.g., fertilizers use and genetically modified plants. Another source of uncertainty pertaining to production scenarios is the assumption of constant portion of area equipped for irrigation with respect to the total area. However, spatially-explicit and crop-specific information on future irrigated area scenarios are not available in the literature.

Providing the above mentioned sources of uncertainty in the demand and supply, which are inputs to our trade model, we test the robustness of our results through a sensitivity analysis (see Section 2.6 in the SI) that shows how uncertainties in the estimates of country demand and supply propagate and impact bilateral trade estimates. We find that the commodity-specific error applied to these input variables do attenuate when we aggregate trade flows across products. Indeed, the resulting coefficient of variations (CV) are in the range of 0.03-0.04 for all scenarios, thus much smaller than the CV equal to 0.1 characteristic of the perturbation we have applied.

4. Conclusion

Agriculture accounts for 70% of the global freshwater use [65], 22% of the global anthropogenic GHG emissions [66], and 11% of world's land surface [67]. Increasing demand for agricultural goods [10, 11] driven by population growth and diet shifts toward meat-intensive products will add further pressure on natural resources, with important implications for the whole Earth system. With food production causing major global environmental risks, the EAT-LANCET report [68] has stated that sustainable food production should use no additional land, safeguard existing biodiversity, reduce consumptive water use and manage water responsibly, while limiting GHGs emissions.

In this context we have elaborated and analysed possible future scenarios of demand, supply, and trade of agricultural goods by 2020, 2050, and 2080 with the introduction and validation of a new approach. The biggest novelties of our study rely in the trade model. As an advancement from current literature, we have included: (i) commodity-specific and bilateral trade flows prediction at the country scale, (ii) dynamic structure of the network topology where partnerships can change in time, (iii) global and country-scale balance constraints between demand, supply, import, and export, and (iv) identification of those countries that are at the same time importer and exporter of a particular commodity (e.g., wheat).

According to our forecasts, global agricultural demand is expected to increase by 10-50% over the period 2016-2050 and according to two out of four scenarios nearly half of the demand will be met by the international trade. Indeed we forecast an increase of the global trade flow with changes between 74% (i.e., Regional Competition scenario) and 178% (i.e., Economic Optimism scenario) by 2050 depending on the market openness and national production surplus. Based on these factors, the future trade network architecture will be very different from the current one. Indeed, all scenarios agree in showing a transition of the trade pole from the Western toward the Eastern economies.

The increase of trade will drive increasingly displaced environmental impacts, which will be caused in many cases by consumption patterns based on long-range imports. As shown in this study, the role of diet composition and the shifts toward meat-intensive regime under the Economic Optimism scenario will have profound implication for water resources: i.e., 2200 km^3 of water will be virtually traded in a year compared to the 1500 km^3 that may be traded under the Regional Competition scenario. At the same time, under the EO scenario land cultivated with maize, soybean, and barley may increase by 150% on average due to larger feed demand, hence going in the direction which is opposite to that suggested by the LANCET report. Conversely, under the Sustainable

Development scenario land can stay constant or even decrease (except for rice) in time thanks to a decreased meat consumption in the Western economies and a moderate increase in the Eastern and Southern economies.

Results suggest that a major objective for future negotiations should be to account for the environmental externalities pertaining to both land use (deforestation), GHGs emissions and water resources depletion and impose the related costs on the produced goods. More collaboration is needed in order to reduce situations where countries gain from trade but damaging the environment at the same time. The study by [4] shows that regions which gain from increased trade are able to pay a sufficient portion of their benefits to account for related environmental damages like deforestation and GHG emissions.

5. Data availability

The data that support the findings of this study are available from the corresponding author upon request.

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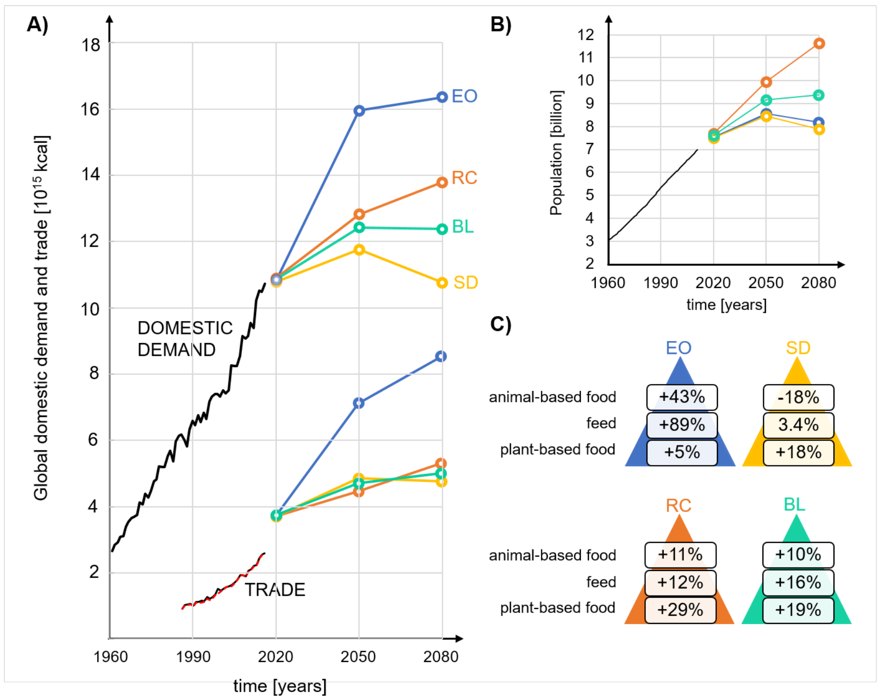

Figure 1: Past trends and future scenarios of global plant-and animal- based domestic supply and international trade flow expressed in food calorie supply (A); past trend and future scenarios of global population (B); variations of the global animal-based food supply, feed supply, and plant-based food supply in 2050 with respect to 2016 under the four scenarios (C). The red line in panel A shows the trade model outcomes for historical trade.

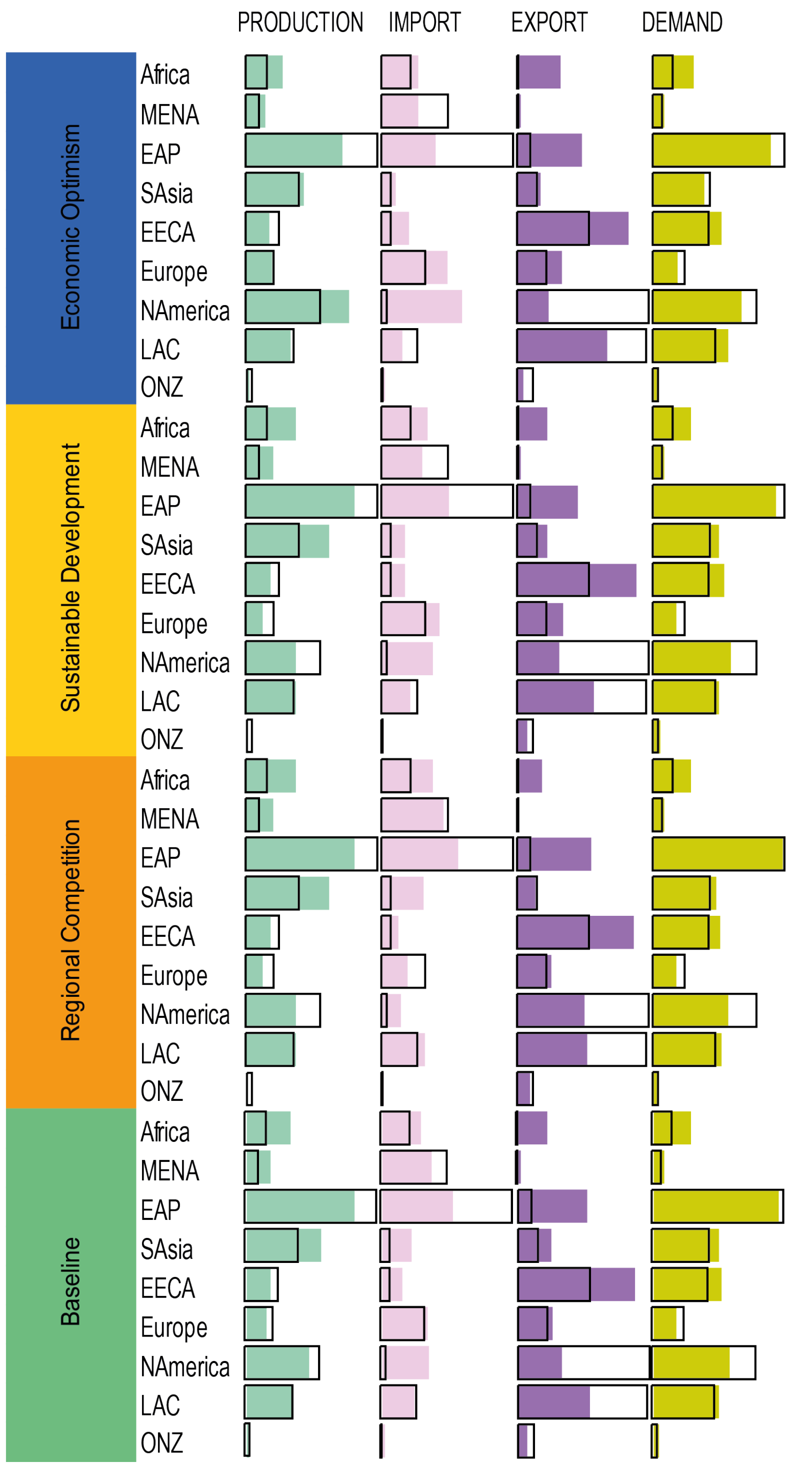

Figure 2: Regional shares of global production, import, export, and demand (sum of human food, feed for livestock, and other uses) under the Economic Optimism, Sustainable Development, Regional Competition, Baseline scenarios in 2050. Empty boxes represent the regional share of each region in 2016. See Figure 3A for the regions' acronyms.

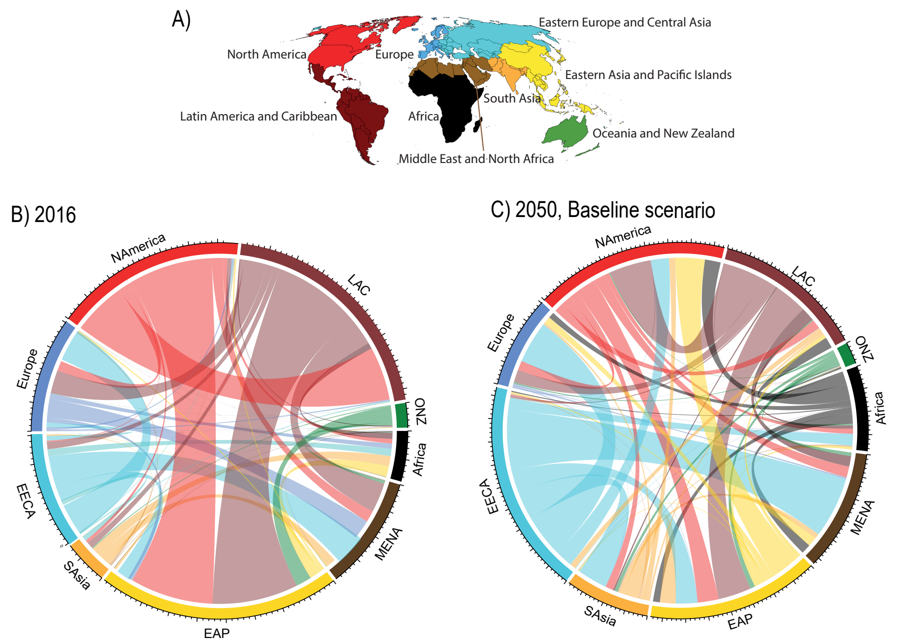

Figure 3: The inter-regional trade network of plant-based and animal-based products among the study regions (A) in 2016 (B) and in 2050 under the Baseline scenario (C). Each region is identified by a color; links' color correspond to the exporting regions and their size is proportional to the traded amount of calories. The circles in panels B and C are split into 9 arcs according to the portion of calories that is imported and exported by each region. The regional map provides a key to the colors and the acronyms of the regions' names.

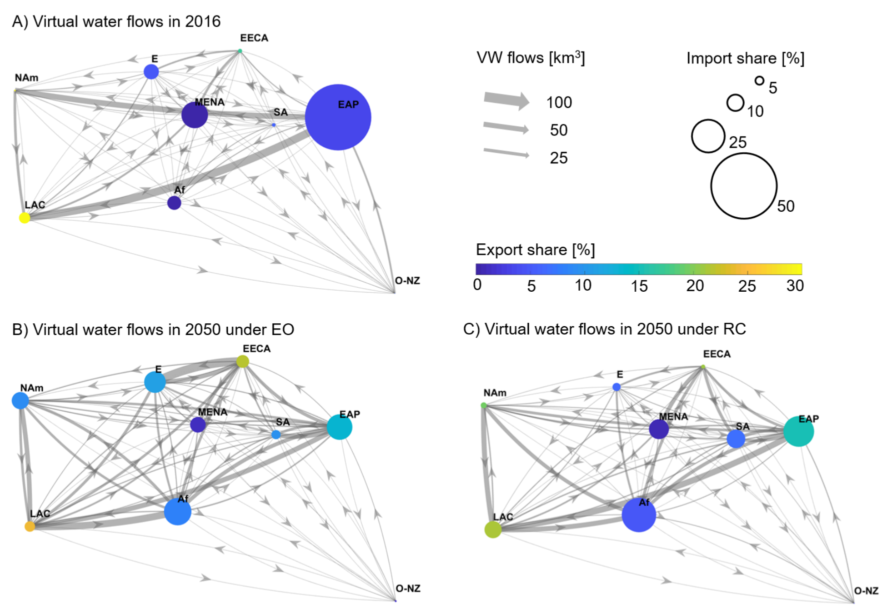

Figure 4: Baseline and future bilateral virtual water flows at the regional scale. Bilateral VW flows in year 2016 (A); scenarios of bilateral VW flows in 2050 under the Economic Optimism (B), and the Regional Competition (C) scenarios. Each region is identified by a circle whose color expresses its export share of virtual water in the global market while the size represents the import share. Link's thickness is proportional to the amount of water that is used in the country-of-origin along the production process and that is virtually exported toward the country-of destination.

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Nomenclature

c	country
cr	crop
$D_{p,c}$	agricultural domestic demand of product p in country c
$d_{p,c}$	per-capita agricultural domestic demand of product p in country c
$E_{p,c}$	export of product p from country c
$f_{c,p}^{glob}$	country-level and commodity-based level of market openness
$fe_{c,cr,m}$	per-capita feed demand of product p in country c going to animal m
$fo_{p,c}$	per-capita food demand of product p in country c
$I_{p,c}$	import of product p from country c
l^{2016}	fraction of domestic demand going to food, feed, and other uses
m	animal product
p	product
$P_{p,c}$	agricultural production of product p in country c
PP_c	country population
r	row factor for the RAS algorithm
$rate_{c,m}^{2050,2080}$	rate of animal production variation calculated with respect to year 2016
s	column factor for the RAS algorithm

A adjacency matrix of the bilateral trade flow

F bilateral trade network