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The land use, trade, and global food security impacts of an agroecological transition in the EU

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The need for an agroecological transition is regularly advocated by many actors and policymakers on the European scene, but many questions arise regarding the potential consequences that this transition may have on the rest of the world. Using a world biomass balance model, in this paper we show that a deep agroecological transition in the EU, if accompanied by a shift of EU food regimes towards more plant-based diets, is not detrimental to global food security. Without increasing its cropland areas, the EU can maintain the same level of exported calories as in a business-as-usual scenario while reducing its import needs. This result holds true also in an alternative scenario in which the other world regions adopt agroecological production methods and healthier diets. In contrast, an agricultural transition taking place in the EU without a change of EU food regimes, would drastically increase EU food dependence on global markets and contribute to the expansion of agricultural land in the rest of the world.

KEYWORDS

agroecology, agricultural transition, DIETS, modelling, organic agriculture, TYFA

1. Introduction

In the last years, several biophysical scenarios at the European or world scale designed sustainable transitions for the European and the world agriculture (Erb et al., 2016; Muller et al., 2017; Karlsson et al., 2018; Poux and Aubert, 2018; Willett et al., 2019; Mora et al., 2020; Billen et al., 2021). Among these scenarios, the one examined by Poux and Aubert, named TYFA, aims at reconciling a logic based on greenhouse gas (GHG) emission reduction with a logic of biodiversity conservation in the European agro-systems. This scenario models a deep agroecological transition in the European Union (EU) by 2050. It involves a phase-out of synthetic fertilisers, pesticides and antibiotics on the supply side, and a shift towards more plant-based food regimes with a reduction of food waste on the demand side. In a future context where world food demand is expected to rise sharply as a result of the joint effects of dietary transition and demographic growth in emerging and developing countries (FAO, 2018), the TYFA scenario attracted some criticisms because it did not consider international trade between the EU and the rest of the world nor the eventual transition of agri-food systems that non-EU countries could experience as well.

Scenarios promoting an agroecological transition, as the TYFA one, are often criticised pointing out the fact that the changes involved could undermine current EU agricultural production levels and lead to increased global food insecurity, with potential negative effects for importing countries (Zahrnt, 2011; Baquedano et al., 2022; Leroy et al., 2022). In the last years, following the announcement of the European Green Deal (European Commission, 2020), several analyses evaluated the potential consequences of the Farm to Fork and Biodiversity Strategies, and more generally of a large-scale agricultural transition in the EU. Some studies focused on biophysical aspects and evaluated the impacts of inputs use reduction on EU agricultural output, and the role of plant breeding in offsetting the drop of production (Noleppa and Cartsburg, 2021). Others gave particular attention to impacts on trade, commodities' prices, and producers' income (Beckman et al., 2020; Barreiro-Hurle et al., 2021; Bremmer et al., 2021; Henning and Witzke, 2021). The common feature of these studies is that they only focused on supply-side measures.

The first objective of this paper is to show that a deep agroecological transition taking place in Europe would not deteriorate the European agricultural trade balance and lower the EU contribution to global food security if this agroecological transition involves a shift in food regimes and in food waste jointly with the change of agricultural production methods. As shown in Röös et al. (2022) and in Rieger et al. (2023), introducing a change in food regimes can help the EU agricultural production system to lower its environmental footprint and meet EU policy targets. In contrast, considering exclusively one side of the EU agroecological transition *de facto* narrows this transition to only its potential negative effects on the EU agricultural production and trade balance and on global food security. Indeed, in such a case, the potential compensatory effects that a shift in diets and a reduction in food waste would generate in terms of lowering EU domestic needs are not taken into account. The second objective of this paper is to test if this result remains valid regardless of the future pathway retained by food systems in the rest of the world. More specifically we show how the impacts of the agroecological transition in Europe change when food systems in the other regions of the world remain on business-as-usual trends or initiate an agroecological transition together with the EU. We add to the literature in several ways. Differently from previous exercises, in this paper we simultaneously consider the change in food regimes, the trade flows between the EU and the other world regions as well as the trajectories that the other countries could take in parallel to the EU food system transformations. We also focus our analysis on global food security, and we use caloric trade balances as main indicator to estimate the level of food dependence in each world region.

In the following sections, we assess the impacts of three variants of the TYFA scenario. The first one is the original version, which includes a change in production systems and in food regimes in the EU. The second one is a truncated version of TYFA in which the change in diets does not take place and the EU population continues to adopt high caloric diets rich in animal and ultra-processed (NOVA classification, Monteiro et al., 2019) food products. Since a shift of food demand is identified as a key social factor to foster changes in food supply, this truncated version of TYFA has less internal consistency than the first variant. It is nevertheless discussed as it allows a sensitivity analysis to show the importance of involving food demand in agroecological transition. The third variant associates TYFA with an alternative future scenario for food systems in the rest of the world. It allows to test how the results of the TYFA scenario may change when an agroecological transition, involving changing production methods and a shift towards healthier diets, also takes place in the rest of the world.

2. Methods

2.1. The GlobAgri-Agt model

The world biomass balance model GlobAgri-Agt (Mora et al., 2020) is used to carry out simulations of contrasting scenarios of future world food systems by 2050. Based on FAOSTAT Commodity Balances (FAOSTAT Statistics Database, 2016), GlobAgri-Agt integrates 38 agri-food products and encompass 13 world regions, one of them being the European Union. The model is calibrated to the 2007–2009 average year (called "2010") and has a 40-year simulation time horizon. As other biomass balance models, for each agri-food product and each region, GlobAgri-Agt includes a resource-utilisation balance equation where domestic resources (production plus imports minus exports) equal domestic uses (food consumption, feed, seed and other uses, loss and waste, and stock change). Imports and exports are determined, respectively, as a fixed share of total domestic use and as a fixed share of the world market. A world equilibrium equation ensures that for each product the sum of world imports equals the sum of world exports. Finally, a constraint on maximum cultivable land for each region limits the potential expansion of cropland areas. In GlobAgri-Agt, population, diets, as well as some parameters such as crop yields, cropping intensities and animal efficiencies are fixed by the modeller as part of the simulated scenario, while production, land-use change, and trade are the outcomes of the model. Following changes in the use of agri-food products in one or several regions, GlobAgri-Agt works to balance resources and measures the impact of these changes in terms of production, land use and trade for every world region. The model works without a price adjustment mechanism. If one region exceeds its maximum cultivable area, GlobAgri-Agt finds a new equilibrium first evenly decreasing the level of its exports, and then if this is not sufficient, by increasing the level of its imports (see Supplementary material, for more information about the GlobAgri-Agt model). Using a world biomass balance model implies that only the biophysical impacts of scenarios will be assessed since economic variables such as input and output prices, income and welfare changes are not considered.

2.2. TYFA assumptions

The rationale and the technical parameters of the TYFA scenario are fully described in Poux and Aubert (2018) and Poux and Aubert (2022). In these papers, the authors show that the adoption of TYFA in the EU would lead to healthier diets reducing the risk of food-related diseases, a higher preservation of natural capital and biodiversity, lower GHG emissions and higher adaptation capacities of the agricultural sector to mitigate the effect of climate change. Similar to other agroecological scenarios, the main priorities envisioned by TYFA regard the closing of the nitrogen cycle, the extensification of crop and livestock production, the development of semi-natural vegetation, the limitation of non-food to food competition for the use of land, and the adoption of more sustainable diets. The assumptions related to each priority are summarised in Table 1.

The construction of the TYFA food regime as a EU average is based on the European Food Safety Authority references (EFSA, 2017), regarding macronutrients intake (carbohydrates and sugars, fibres, proteins, lipids, and fatty acids), supplemented with the French

TABLE 1 The main assumptions of the TYFA scenario.

Priorities in the TYFA scenario	Main assumptions
Closing of nitrogen cycle	• Phase-out of soybean imports
	• Reintroduction of legumes into crop rotations, including in cover-crops
	• High N fixation in extensive (not fertilised) permanent grasslands
	• Despecialisation of livestock and cropland areas
Extensification of production	• Removal of synthetic fertilizers and pesticides as farming inputs
	• Extension of semi natural vegetation and redeployment of natural/ permanent grasslands
Limitation of competition for land use	• Phase-out of biofuel and biogas
More sustainable diets	• Shift to healthier food regimes (lower energy and meat consumption, increased shares of fruits, vegetables, pulses, and coarse cereals)
	• Reduction of food waste by 10%

Agency for Food, Environmental and Occupational Health and Safety (ANSES, 2016) and World Health Organization recommendations, regarding the health risks and benefits related to the consumption of certain product groups. This food regime slightly decreases the current caloric intake at around 2,400 kcal/person/day and involves a strong reduction in animal proteins (−50%) and in the sugar content of the diet (−72%) (Poux and Aubert, 2018). As the TYFA scenario involves the preservation of extensive grasslands to favour a high level of agrobiodiversity and to provide fundamental ecosystem services (Dainese et al., 2019; Schils et al., 2022), the share of ruminant meat only slightly decreases. As the overall intake of meat halves, this results in a significant decrease in the share of poultry and pig meat, which nevertheless remain the most consumed types of meat in TYFA. In addition, the TYFA diet is rich in legumes because they are nutritionally sound, and they contribute to nitrogen provision in agricultural soils. Because of new technologies available in 2050 and a better management of losses at the production and consumption level, TYFA scenario envisages a 10% food waste improvement.

TYFA extensification of cropping systems relies on abandoning synthetic pesticides and fertilisers. The choice to abandon pesticides is connected to the improvement of health conditions for agricultural workers (INSERM, 2021), the decrease of the risk related to the presence of traces of pesticides in food, the protection of biodiversity (IPBES, 2016) and the decline of the emergence of crop resistances to new molecules (Hawkins et al., 2019). As far as synthetic fertilisers are concerned, their elimination contributes to lowering the risk of eutrophication, alteration of soil life, water contamination and fungal diseases and weed development in fields (Billen et al., 2011; Sutton et al., 2011). Furthermore, reducing fertilisation in cropping systems is a key element in climate change mitigation since nitrogen application to arable soils is one of the main factors contributing to agricultural sector GHG emissions. In such a perspective, the impact of organic fertilisers on GHG emissions in temperate areas is 2.6 times less important than that of synthetic fertilisers (IPCC, 2019). TYFA scenario also aims to phase-out soybean imports and reintroduce legumes such as peas, alfalfa, and fava beans into crop rotations. Despite, the big challenges that EU farmers will need to face to unlock a sector which is currently locked-in (Magrini et al., 2016), Guilpart et al. (2022) show that the agricultural area currently harvested is much lower than the area suitable for soybean cultivation and that the agroclimatic conditions would make possible to reach European self-sufficiency on soya in 2050. However, the reintroduction of legumes into crop rotations is not exempt from possible side effects. Legume production may lead to an increased reliance on pesticides when compared to cereals. Using more pesticides is clearly against the logic of the TYFA scenario. This means that a combination of genetic, agronomic, technological, and organizational innovations is needed to improve varieties, methods of plant protection and acquire better references on crop successions (Meynard et al., 2018).

Since TYFA cropping systems phase-out pesticides and synthetic fertilisers, they can easily be compared to current organic agricultural systems. For this reason, TYFA crop yields assumptions in 2050 (Table 2) were based on Eurostat data and current knowledge regarding the yield gaps between conventional and organic systems (de Ponti et al., 2012; Seufert et al., 2012; Guyomard, 2013; Ponisio et al., 2015). Following Ponisio et al. (2015) and Guyomard (2013), the reduction of 2010 yields in TYFA is in the order of −25% for cereals, between −20% and −45% for oilseeds and protein crops, −5% to −20% for fruits and vegetables and −10% to −15% for fodder and grass (Poux and Aubert, 2018).

TYFA assumes no further impact on crop yields due to climate change. The assumption is that the effect of water stress in Southern Europe is compensated by CO_2 fertilisation and projected rain regimes in Northern Europe, resulting in a balanced climate impact at the EU level. This modelling choice is consistent with the results of Makowski et al. (2020) for their scenario based on higher temperatures (+4°C), combined with a higher CO_2 concentration (+100 ppm) and the implementation of adaptation measures (−1.42 to +1.24% effect on C3 crop yields depending if a −10% rainfall decrease is considered or not).

An aspect which is only considered from a qualitative point of view in the TYFA scenario is the reduction of fossil fuels for agricultural production. Low inputs production methods are often criticised since they need a higher number of mechanised operations in the field to replace synthetic inputs such as pesticides (for example, soil tilling or mechanical weeding). Emissions related to energy consumption represent today around 7% of farm gate GHG emissions for the EU agricultural sector (FAOSTAT Statistics Database, 2016) and need to be reduced. This reduction can be obtained by switching to decarbonised sources of energy for tractors such as electricity from renewable sources or green hydrogen. Another option is limiting the share of heated greenhouses and relocate the production of fruits and vegetables to the areas having the most suitable soil and climate conditions. A condition for this shift will be the flexibility of EU consumers to purchase food products, which respect seasonality and the local availabilities.

TYFA livestock systems are characterized by a feed ration based on a limited use of concentrates and a higher amount of grass. Such

TABLE 2 Yield change for the main crops in the simulated scenarios.

	EU		Rest of the world (average)		
	2010	2050	2010	2050	
Crop yields (t/ha)	Initial (GlobAgri-Agt Initial situation)	TYFA-EU, TYFA-EU-Supply, TOGETHER	Initial (GlobAgri-Agt Initial situation)	TYFA-EU, TYFA-EU-Supply	TOGETHER
Crop yields not including climate change impacts					
Maize	6.7	5.4	5.2	8.7	5.8
Wheat	5.3	4.2	2.5	4.0	2.7
Rice	6.6	5.1	4.2	4.5	4.3
Other cereals	4.0	2.6	1.6	2.4	3.3
Soybean	2.6	2.3	2.5	3.2	2.4
Pulses	2.4	1.6	0.9	1.3	1.9
Sugar plants	67.1	54.4	68.6	91.6	73.5
Fruits and vegetables	14.8	11.9	14.3	19.6	24.8
Roots and tubers	29.2	26.3	13.0	16.1	14.6
Crop yields including climate change impacts					
Maize	6.7	5.4	5.2	8.0	5.8
Wheat	5.3	4.2	2.5	3.5	2.7
Rice	6.6	5.1	4.2	4.0	4.3
Other cereals	4.0	2.6	1.6	2.1	3.3
Soybean	2.6	2.3	2.5	2.6	2.4
Pulses	2.4	1.6	0.9	1.1	1.9
Sugar plants	67.1	54.4	68.6	103.8	73.5
Fruits and vegetables	14.8	11.9	14.3	17.4	24.8
Roots and tubers	29.2	26.3	13.0	15.3	14.6

feed ration contributes to reduce the competition between feed and food on cropland areas, increase the EU autonomy towards soybean imports (limiting possible future disruption of feed value chains, as the one experienced during the Ukrainian conflict, and imported deforestation), preserve grasslands, and produce omega-3 rich products with acknowledged nutritional benefits (Daley et al., 2010). Criteria such as the animal capacity to eat alternative source of fodder and the hardiness are privileged in ruminant selected species rather than physical productivity. The core of European livestock systems remains dairy production. Two dairy production systems coexist in TYFA and are configured based on Réseaux d'élevage et al. (2005), Coquil et al. (2014) and Barataud et al. (2015). The first one is a grass-fed system spread in medium- and high-altitude regions in which most of the fodder comes from permanent grasslands (5,000 kg milk/year). The second is a mixed system developed in wet plains, in which permanent grasslands are combined with temporary grasslands, cereals and legumes (5,700 kg milk/ year). Both systems involve the reintroduction of rustic varieties, a longer lifespan in animals (11 years for grass-fed, 9 years for mixed), the first freshening raised to 3 years and a lower replacement rate, which leads to a higher share of meat coming from heifers not intended for replacement which are slaughtered. Beef and sheep livestock systems follow the same logic as TYFA dairy systems with an extensified meat production and a feed ration, which is mainly grass-based (Chambres d'agriculture et al., 2014; Tchakérian and Bataille, 2014). The technical configuration of TYFA monogastric systems is based on the organic monogastric systems in Brittany (a region located in North-West France, which concentrates the largest share of French monogastric production) with specific feed rations for each stage of the production cycle (Bouvarel et al., 2013; Jurjanz and Roinsard, 2014; Bordeaux, 2015; Calvar, 2015).

2.3. Simulated scenarios

In addition to the reference scenario, we simulate three scenarios: TYFA-EU, TYFA-EU-Supply, and TOGETHER. We chose as our reference scenario the Metropolization_Ultrap scenario from the Agrimonde-Terra foresight (Le Mouël et al., 2018; Mora et al., 2020). In the reference scenario, both the EU and the rest of the world keep the on-going trends based on conventional intensification of agricultural production and the most recent nutritional transition in food consumption. In TYFA-EU, the EU fully adopts TYFA assumptions. In contrast, in TYFA-EU-Supply, we assume that despite the adoption of TYFA production systems, the EU consumers are not ready to change their energy-rich diets based on a high share of animal proteins, sugar and vegetable oils contained in ultra-processed food products. In TYFA-EU and TYFA-EU-Supply, the rest of the world remains on the pathway of the reference scenario. In the TOGETHER scenario, we test an agroecological transition involving agroecological production methods with a shift towards healthier food diets also taking place in the rest of the world. In TOGETHER, assumptions for the rest of the world are an adaptation of those of the Healthy_AE scenario from Agrimonde-Terra.

The assumptions of the Metropolization_Ultrap and Healthy_AE scenarios borrowed from the Agrimonde-Terra foresight are fully described in Le Mouël et al. (2018). A detailed description is also provided in the Supplementary material. Main assumptions may be summarized as follows.

In Metropolization_Ultrap, every world region keeps the on-going trends based on conventional intensification of agricultural production. Technological solutions and intensification of chemical inputs allow to reduce the yield gap between current and potential yields (−50% on average). Because of induced technical change, this reduction is stronger for the crops which are the most grown in the scenario, such as primary cereals (maize, rice, and wheat), oilseeds and sugar crops, and lower for the other crops. In this scenario, the climate change affects the evolution of crop yields limiting the yield gap reduction for most of the crops and world regions (Table 2). Livestock systems also increase their efficiencies for both the ruminant and monogastric sectors. On the food consumption side, the past and current observed trends continue, which means an increased oils and sugar consumption in developed countries, increased caloric intake and share of poultry meat in emerging countries, and increased caloric and animal products intake in developing countries.

In Healthy_AE, agricultural production systems in the rest of the world evolve towards agroecology. We assume two different pathways of yield evolution. Differently from Le Mouël et al. (2018), developed regions such as North America, the European countries not taking part in the EU, or Oceania experience the same magnitude of crop yields reduction as the EU with the TYFA scenario. In contrast, in the same way as in Le Mouël et al. (2018), emerging and developing regions reduce their yield gap: −30% on average. Since these regions have a lower level of intensification of agricultural production systems than developed countries, we assume that the negative impact on yields of less intensive practices is limited and may be compensated by other positive impacts on yields such as those related to reduced loss on the production side resulting from continued technical change in harvesting and stocking equipment, transport infrastructure and logistics. In these regions, due to induced technical change, the higher demand of coarse cereals, pulses, fruits and vegetables and roots and tubers in Healthy_AE leads to greater than average yield gap reduction for these crops and lower than average yield gap reduction for other crops (including primary cereals and sugar crops). In this scenario, because of a collective effort on emission reduction, the objective of stabilisation of global warming is reached. For this reason, no impact of climate change on crop yields is assumed. Livestock systems are more extensive in Healthy_AE with a higher share of pastoral systems for ruminants and lower efficiencies for monogastric animals when compared to Metropolization_Ultrap. On the consumption side, the population adopts healthier food diets (maximum and minimum thresholds regarding the caloric intake, animal products, oils, sugars, fruits and vegetables and coarse cereals, for developed, emerging, and developing countries).

3. Results

3.1. TYFA-EU

In the TYFA-EU scenario, the agricultural land use in the EU remains at the same level as in the reference scenario (Metropolization_Ultrap) with almost no variations both for cropland (+0.3%) and pastureland (+0.2%) (Figure 1) (see Supplementary material for more information regarding the simulation results). This means that the effects of healthier and more sustainable diets completely offset the impact of TYFA assumptions regarding the reduction of agricultural productivity in the EU. The land constraint is respected, and no trade adjustment is needed to keep the agricultural areas inside the EU physical limits. When we take a deeper look at EU cropland, we observe a despecialisation of EU agricultural systems with crops that are currently marginal in EU agricultural systems taking a larger share of land use (Table 3). For pulses and soybeans in particular, the area expansion is particularly high and is a consequence of shifting EU consumer preferences on one hand (substitution of vegetable proteins to animal products) and of changing livestock feed rations on the other. For soybeans, the main reason explaining the rise of this crop production area is the phase-out of soybeans imports and the ban of synthetic fertilisers in the EU as prescribed by TYFA assumptions (Table 1). In terms of agricultural production, the lower productivity levels imposed by the agroecological transition drive down the volumes of EU vegetal (−35%) and animal (−48%) production (in calories) (Figure 2). For this reason, the EU reduces its share in world production and passes from 7% to 5% for vegetal products and from 12% to 7% for animal products. Despite this drop in domestic production, the EU can get its agricultural trade balance improved. While there is little change in exported quantities for vegetal and animal products with respect to the reference scenario (−5% and −1%, respectively), imported quantities substantially diminish because of lower domestic food consumption and the phase-out of soya import leading to a reduction by −58% for vegetal products imports and by −78% for animal products (in calories) (Figure 3). Therefore, the EU passes from being a net importer of calories to a position of net exporter of calories (net imports equal imports minus exports, when the balance is positive the country is a net importer while when it is negative the country is a net exporter). In terms of net import dependence (ratio between the net imports and total domestic use), the EU switches from a level of 5% in the reference scenario to −12% in TYFA-EU (Figure 4).

The other world regions (rest of the world) are only slightly influenced by the transformations of EU agri-food systems. The rest of the world land use remains at almost the same level as in the reference scenario (−2% for cropland and +0.3% for pastureland) showing the rather limited role that EU has in shaping the future world pathways. The same reasoning applies to the rest of the world production, which is only slightly impacted by EU changes: −2% for vegetal products and −1% for animal products. The production reduction in the rest of the world results from the decline of EU imports. For this reason, in TYFA-EU, the rest of the world reduces its exports (−7% compared to the reference scenario), while its imports remain unchanged. The exports of American and South-East Asian regions are the most sensitive to the EU agroecological transition. Since these regions are the main world exporters of soybeans and other oilseed products, they are the first world regions impacted in terms of net exports (−12%) mainly because of EU increased domestic production of protein crops.

3.2. TYFA-EU-Supply

In the TYFA-EU-Supply sensitivity test scenario, the assumption of unchanged food regimes makes the EU agricultural production no

FIGURE 1
Land use in 2010 (initial) and 2050 for the simulated scenarios (million hectares).

TABLE 3 Relative change in land use between TYFA-EU and the reference scenario for the main cultivated crop categories in the EU.

Crop category	% Change
Fruits and vegetables	21
Grass	0
Maize, rice, and wheat	−11
Oilcrops	−53
Other cereals	4
Other forages	−3
Pulses	596
Soybeans	1,856
Sugar plants	−30

longer sufficient to cover EU food needs without expanding the initial level of EU cropland. Since this is not possible because we assume that the EU has already reached its maximum cultivable area in the initial situation, GlobAgri-Agt solving rules force the EU to decrease its exports and then to increase its imports, resulting in an increased EU import dependence. In terms of land use, while the EU cropland is unchanged, the pastureland increases with respect to the reference scenario (+28%). Indeed, as forages are not exchanged on the world market, the EU must produce its own domestic needs of forages, which are used to feed extensively the remaining domestic livestock (grass-like forage +44%, other forages +45%). In the meantime, the area employed to grow almost all the other crops decline, except for soybean production (+38%). Like in the TYFA-EU scenario, TYFA lower productivity levels affect the total output of EU agricultural production, which is lower in TYFA-EU-Supply than in the reference scenario. However, as the cropland is constrained while the pastureland is let to adjust freely in the model and the EU maintains food regimes, which are rich in meat and dairy products, the EU agricultural systems specialise relatively more in livestock production in TYFA-EU-Supply than in the TYFA-EU. The TYFA-EU-Supply vegetal production is lower than the TYFA-EU's vegetal production (−18%), while for animal production the situation is reversed (+50%). In the TYFA-EU-Supply scenario, the EU develops a large-scale soybean domestic production and becomes the fourth soybean-producing region in the world (16.5 million tons). Therefore, the EU can reach self-sufficiency for vegetable proteins, remove its dependence to protein imports and close its domestic nitrogen cycle, while maintaining diets rich in animal products. However, for balancing uses and resources the EU needs to increase the amount of imported calories with respect to TYFA-EU (+241%). Hence, the EU becomes a net importer of commodities such as dairy products, cereals, and pork meat for which it was previously a net exporter. The EU also develops a serious level of net import dependence (36%) reaching a similar dependence level as the one experienced today by North Africa and Near and Middle East (Le Mouël and Schmitt, 2018).

The rest of the world is impacted by the TYFA-EU-Supply scenario. Since the EU renounces to export in the world markets and increases substantially its imports, the rest of the world agricultural land use grows to cover for the EU lost export market share and increased imports (cropland +5%, pastureland +2%). For this reason, if compared to TYFA-EU, in TYFA-EU-Supply, the rest of the world production raises both for vegetal (+5%) and animal products (+3%). In terms of trade, since in TYFA-EU and TYFA-EU-Supply the rest of the world regions share the same food regimes, their imports remain constant. At reverse, the rest of the world exports grow for vegetal (+23%) and animal (+30%) products to offset EU declined export share and to provide food commodities such as fruits and vegetables, grains, oils, and sugar for the EU growing import demand. Rest of Asia, Former Soviet Union, Oceania, and Canada/USA are the regions which have a comparative advantage on these products, and, for this reason, they increase the most their net exports (+445%, +46%, +41%, +20%, respectively).

3.3. TOGETHER

In the TOGETHER sensitivity test scenario, the world population adopts healthier food regimes based on food diversity. The adoption of these diets reduces the global food demand and contracts the world market. For this reason, EU exports decline in volume relatively to TYFA-EU (−3% for vegetal products and −22% for animal products). The EU also experiences a change in terms of the types of products, which are traded. While in TYFA-EU the EU exported large quantities of wheat, sugar, dairy products, pork, and poultry meat, in TOGETHER it exports more coarse cereals, pulses, fruits and vegetables. Since the EU maintains the same food regime and the same agricultural systems as in TYFA-EU, the impact on land use (cropland −1%, pastureland −2%) and production (−6% for vegetal products

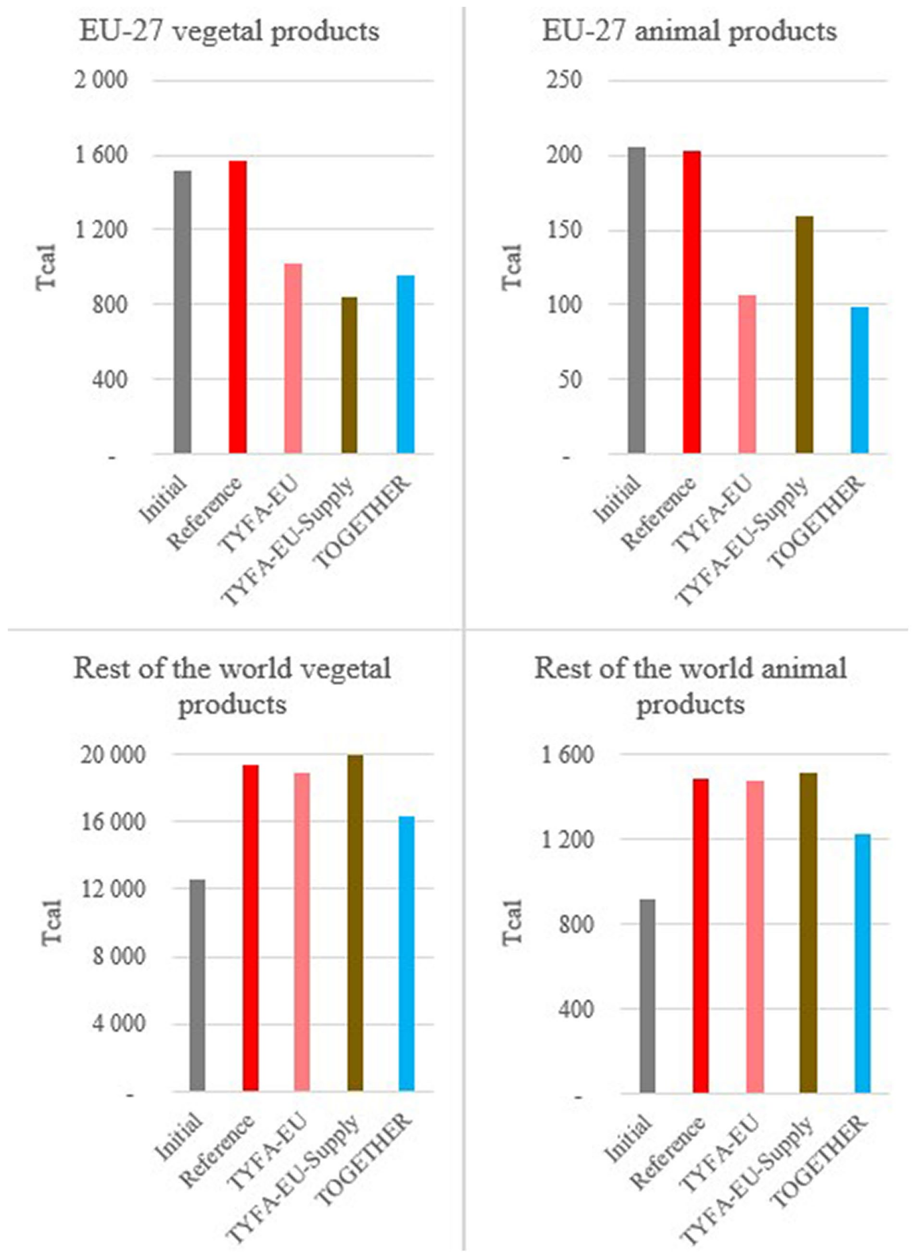

FIGURE 2
Production of calories in 2010 (initial) and in 2050 for the simulated scenarios (Tera calories).

and −7% for animal products) is only determined by the contraction of EU exports. Despite a reduction in the total amount of exported calories and a lower area of agricultural land, in TOGETHER the EU enlarges its export shares for vegetal and animal products in the world market passing from 8% in TYFA-EU to 10% in TOGETHER.

The rest of the world is deeply impacted by the TOGETHER scenario. When compared to TYFA-EU, the healthier food diets of developed and emerging countries lead to a reduction of world food production for vegetal (−14%) and animal products (−17%). This reduction is particularly strong in oilseed exporting regions (countries in South and North America and South-East Asia), which see their shares in world production reduced. In contrast, in developing countries in Sub-Saharan Africa and India, where adopting healthier diets implies consuming more calories, the production levels are similar as in TYFA-EU and substantially greater than in the initial situation. Because of lower yields and lower livestock production efficiencies with respect to TYFA-EU, the rest of the world increases relatively more its agricultural land use (+15%). The situation is very different for grassland (+24%) and cropland (−2%). The grassland expansion takes place especially in developing regions (Sub-Saharan Africa and India) where adopting healthier diets implies a higher consumption of animal proteins, partly obtained from grass-fed livestock. In reverse, the reduction of cropland takes place especially in oilseed exporting regions since the world demand of these products declines. The reduction of around a fourth of the rest of the world exports and imports of vegetal and animal proteins when compared

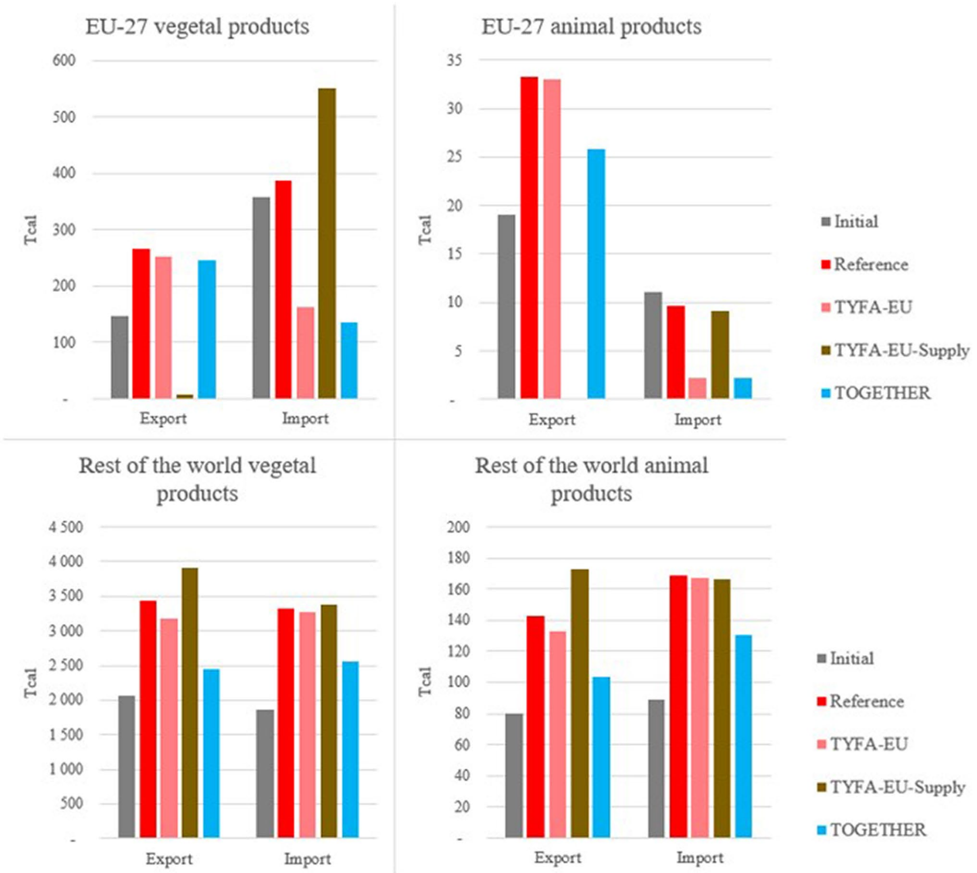

FIGURE 3
Exports and imports of calories in 2010 (initial) and in 2050 for the simulated scenarios (Tera calories).

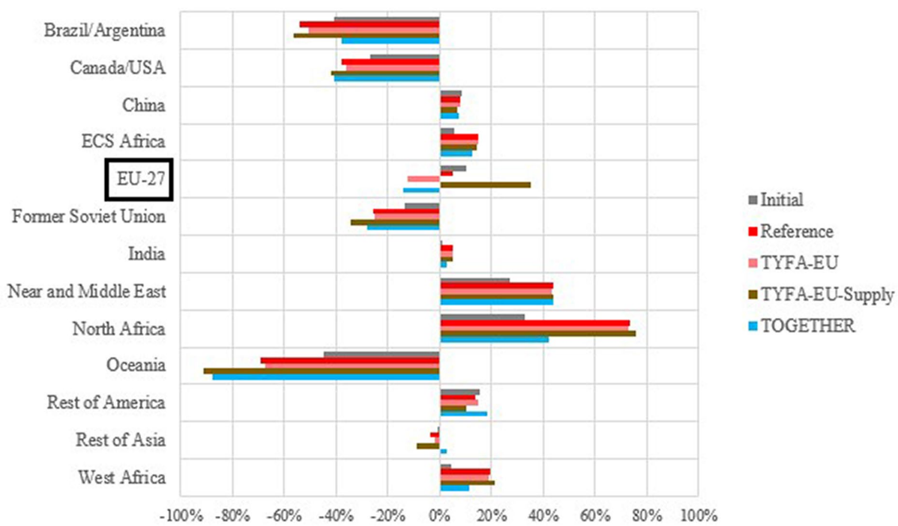

FIGURE 4
Net import dependence in 2010 (initial) and in 2050 for the simulated scenarios for each world region (%).

to TYFA-EU implies a reconfiguration of the world market. Similarly to what happens in the EU, the rest of the world increases its exports of fruits and vegetables, coarse grains and pulses, while the trade of all the other products is reduced. Differently from oilseed exporting countries in South America and South-East Asia whose export shares decline, regions such as the Former Soviet Union and Oceania improve their trade balance mostly because of their comparative advantage in cereals production.

4. Discussion

4.1. The EU contribution to world food security

Our results show that from a biophysical point of view, an agroecological transition in the EU involving the adoption of healthy food regimes by EU consumers allows the EU to maintain unchanged its level of exports when compared to a business-as-usual scenario in 2050 without needing more agricultural lands. While the EU is initially a net importer of calories because of a high amount of vegetable protein imports used for animal feeding, results under the TYFA-EU scenario demonstrate that a full agroecological transition can allow the EU to increase its contribution to global food security becoming a net exporter of calories (Figure 5). Indeed, in this scenario, the level of EU exports is considerably higher than in the initial situation, in a future marked by a substantial growth of world food demand. However, as also mentioned in Tibi et al. (2020), the share of EU exports remains incomparable with the one of the main exporting regions such as Canada/United States, Brazil/Argentina, Former Soviet Union, and Oceania, which would be considerably higher than the one of EU in 2050.

In a context already marked by a risk of stagnation of crop yields (Brisson et al., 2010; Ray Deepak et al., 2012; Wiesmeier et al., 2015) and increased variability, and where plant breeding research is unlikely to compensate alone the lower agricultural productivity (Noleppa and Cartsburg, 2021), the results provided in this paper also prove that changing the current human diets is a compulsory aspect for the EU agroecological transition. TYFA-EU-Supply scenario shows that without such changes on the demand side, the EU would drastically increase its food dependence on global markets, which in turn contributes to the expansion of agricultural land in the rest of the world. The alternative to high food import dependence may be the extension of agricultural areas in the EU. Nevertheless, this also appears as a drastic solution as EU agricultural areas would need to grow by around 40% compared to the current situation, triggering negative effects on forest and grassland preservation.

In the TYFA-EU-Supply scenario, EU food import dependence increases, which limits the extension of EU agricultural areas and the induced threat to environment in the EU. However, this threat is exported to the rest of the world. Indeed, since the EU renounces to export on the world markets and increases substantially its imports, the rest of the world production grows, and the world agricultural land use raises relatively to the business-as-usual scenario. In a global context marked by conventional intensification of cropping and livestock systems, this would increase the pressure of agriculture on natural resources.

Finally, the TOGETHER scenario teaches us that the EU contribution to world food security remains unchanged in a scenario also involving healthier food regimes and deep transformations of agricultural practices towards more sustainability in the rest of the world. In this context, the EU adapts to the new world food demand changing the composition of its exported basket. The results demonstrate that this has no significant impact on the aggregate EU land use or trade balance. As also described in Mora et al. (2020), the main effects of this scenario take place in the rest of the world. One key result is the expanding grassland area in Sub-Saharan Africa where healthier diets mean an increase in the intake of animal proteins. Since deforestation is clearly against the pathway of TOGETHER, this means that further developments in efficiencies in livestock and agricultural production systems are likely needed in this region to preserve world forest areas.

4.2. Comparison with previous studies

In the last few years various studies analysed the potential impacts of transformative changes of European food systems. Beckman et al. (2020) and Barreiro-Hurle et al. (2021) using, respectively, a general and a partial equilibrium model of world agriculture, both simulated the impacts of the Farm to Fork and Biodiversity Strategies of the EU (F2F). Similarly to TYFA-EU-Supply, their simulated scenarios only consider the supply side targets of the EU Strategies, leaving unchanged the consumption patterns in the EU. The results of the TYFA-EU-Supply scenario confirm their findings: both scenarios find a potential drop of EU agricultural production, a decrease in EU export shares, and a rise of EU food import dependence, with induced higher agricultural prices and a potential threat to global food security. Since the tested assumptions in TYFA are more ambitious than the F2F targets (for example the phase-out of pesticides and synthetic fertilisers, while in the F2F the development of organic farming is limited at only 25% of EU agricultural land areas and the targets for pesticides and fertilisers use reduction are fixed at, respectively, −50% and −20% of current levels), the consequences of TYFA-EU-Supply are even more disruptive for the EU than the ones simulated in these two assessments. In Beckman et al. (2020) the production reduction is estimated at around −12% and between −15% and −5% in Barreiro-Hurle et al. (2021).

When we consider the TYFA-EU scenario, despite the drop of agricultural production, the shift in EU food regimes and the reduction of food wastes make the transition of EU farming systems not challenging for world food availability. Similarly, the compensating effect of decreased domestic demand in the TYFA-EU scenario prevents the transition of EU farming systems resulting in increased leakage effects in other countries (like in Henning and Witzke, 2021, where their sensitivity analysis shows the key role of the EU domestic demand for meat products). These results are aligned with the findings of Röös et al. (2022), Billen et al. (2021), and Tibi et al. (2020). Röös et al. (2022) demonstrate that the spread of local-agroecological food systems, involving lower-intensity cropping and livestock methods in half of EU cropland, the reduction of food waste, and the adoption of EAT-Lancet diets (Willett et al., 2019) by the EU consumers, allows the EU to spare more than half of its agricultural lands. The results of the scenario tested in Billen et al. (2021) indicate that from a biophysical perspective, Europe can relieve some pressure exerted by its current agricultural systems in the rest of the world if an agroecological transformation towards organic agriculture also involves a dietary change toward less animal products. In their scenario, the authors localise domestically the production of all oilseeds, fruits, and vegetables consumed by the European population,

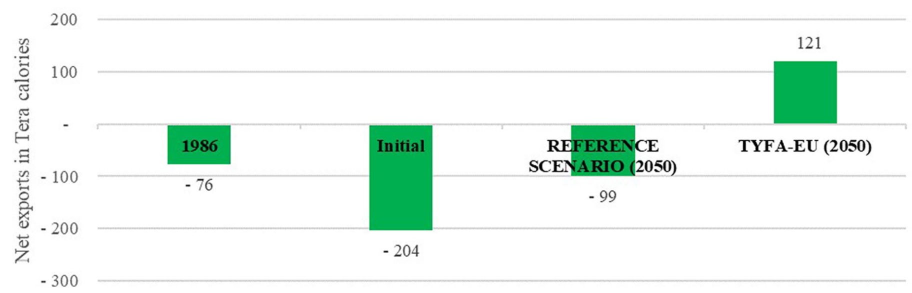

FIGURE 5
EU net exports in 1986, 2010 and 2050 under the reference and TYFA-EU scenarios. Treatment from FAOSTAT and GlobAgri-Agt model.

and obtain a positive Nitrogen net exports balance for cereals and animal products. In Tibi et al. (2020), despite more optimistic projected yield assumptions and lower changes in EU food regimes, the results show that in 2050 the EU could use part of its land surplus to increase the domestic production of protein crops and/or extensify its agricultural production systems, without reducing the amount of exported calories in the world market.

4.3. Policies to support EU agroecological transition

A multitude of studies show that changing food regimes based on sugar, fats, animal, and ultra-processed food products currently observed in developed and emerging countries, including the EU, is important from an environmental or public health perspective (see for example Tilman and Clark, 2014; Aleksandrowicz et al., 2016; Ridoutt et al., 2017; Springmann et al., 2018; Willett et al., 2019; Seconda et al., 2021). In this paper, we show that changing such food regimes in the EU is also key for maintaining the EU position in the world market in the context of EU agroecological transition. For this reason, policies aiming to change food diets appear as a precondition for EU agroecological transition. These policies can be divided in two groups. In the first group, we can find policies aiming to inform the consumer regarding the positive aspects of a healthy food diet. Examples of these policies are the launch of public education campaigns, the food labelling, the advertising regulation and the reinforcement of origin indications. The implementation of these policies may be relatively straightforward and do not require deep legislative changes. However, to be effective they need to be well financed and targeted possibly through participative activities (ex. nutrition education for pupils at school since the young age, cooking workshops in specific neighbourhoods etc.) (George et al., 2016). Similar to the policies of the first group is the creation of "nudges" which aim to softly change the food choice architecture using indirect conditioning or social norms to push the consumer towards a healthier food behaviour (Leonard et al., 2008; Wahlen et al., 2012; Ensaff, 2021).The second group of food policies embraces measures such as subsidies or taxes on food products (ex. taxes on unhealthy products, subsidies on healthy products, food stamps, VAT rate differentiation), the regulation of food canteens in schools and in workplaces. This last group of policies may certainly have a greater impact than policies in the first group. However, they are the ones, which risk causing the highest degree of public opposition because of their potential impacts on the cost of food and the perceived limitation of freedom of choice that some of these policies may impose.

When economic factors are considered, a scenario such as TYFA-EU appears riskier for the EU than a scenario like TOGETHER and would probably need a stronger policy support. In TYFA-EU, since EU food commodities are produced using agroecological techniques, they may result as more costly than the ones produced in the other world regions where farmers continue to use conventional agricultural methods. Consequently, EU farmers may implement a deep change in the structure of their agricultural production systems in order to respect environmental constraints and the planetary boundaries, but without having the certainty to be able to sell their high environmental value products in the world markets since they may be perceived as too expensive by other countries' consumers. Simultaneously, cheaper imports coming from geographic areas where growers have lower environmental and GHG emissions standards could overwhelm the EU domestic market. For this reason, in a current situation which is already marked by the decline of EU market shares (Schiavo et al., 2021), the maintenance of EU competitiveness appears as a prerequisite for the development EU agroecological transition. Several policies may be envisaged to reach this objective. In the first place, economic incentives aiming to boost the varietal research in diversification crops (ex. coarse cereals, legumes) can be mentioned. Results in this fields would make available for growers a wider range of varieties, which better resist to plant pests and diseases. Secondly, EU countries may adopt large-scale public investments to increase the potential of their circular economies. For example, additional sources of fertilizers coming from currently unexploited organic resources [for example home-sorted and market bio-waste, green waste and human excreta not already composted as advocated in Launay et al. (2021) and Billen et al. (2021)] could boost agroecological crop yields. Third, national and regional governments could also favour investments aimed at building new facilities to massify the national processing of diversification crops, achieve economies of scale and reduce transport costs (Schiavo and Aubert, 2020). Smaller and more versatile new storage facilities adapted to pulses, soybeans, and coarse cereals as well as new sorting equipment to favour the crop associations are example of tangible investments that policymakers may promote to support the transition (Magrini et al., 2016). Finally, a period of temporary increase of taxes and tariffs seems necessary at least for the sector of protein crops. This market intervention could take the form of a tariff for specific food products coming from countries not complying with EU environmental standards or be inserted in a broader environmentally friendly scheme as the European Parliament and the Council carbon adjustment mechanism proposition (European Parliament and the Council, 2021). In both cases, these measures risk being considered not compatible with WTO rules (Bellora and Fontagné, 2022). However, this intervention would help EU farmers which are often subjected to more rigid environmental regulations than farmers producing in other parts of the world, but without being protected by trade measures. This period could be used by growers and processors to test innovations and develop new farming techniques to be competitive in the world markets even in absence of trade protection.

Supporting an ambitious agroecological transition such as the one simulated in our scenarios would also demand strong adjustments in the structure of the Common Agricultural Policy. In the short term, increasing the environmental criteria for having access to the Basic Payment Scheme could be a first signal sent to farmers to start considering a possible change towards more sustainability of their crop and livestock systems. In the medium term, more direct measures aiming to remunerate the ecosystem services may be necessary. Because of the specific ecological interest of protein crops, particularly legumes, the increasing of first pillar coupled aids can also be considered as well as the development of agri-environment-climate measures remunerating higher legumes shares in crop rotations. Increasing the budget of the eco-scheme jointly with the implementation of more environmentally ambitious rules regulating its access could encourage more farmers to implement the agroecological transition. Finally, the maintenance of grassland areas could be fostered through coupled aids directed to not fertilised pastures or through more indirect measures such as a carbon farming scheme remunerating carbon sequestration in soils (Bamière et al., 2023) or the restriction of livestock aids to pasture-based systems.

5. Conclusion

This study analysed the implications of a full-scale agroecological transition in the EU for the rest of world by 2050, and how the assumptions regarding the EU food regimes could impact the results. Due to the modelling tool used, we only assessed the consequences of this transition on the biomass balances of food products. Further work is needed to provide a broader impact assessment of the EU agroecological transition on economic indicators such as commodity prices, income, welfare changes, inside and outside the EU.

Despite these limits, our results reveal that an agroecological EU involving a shift towards more plant-based diets does not contribute to expanding agricultural lands, both inside and outside EU. Furthermore, such a transition would help the EU to contribute more importantly to global food security (at least from a biophysical point of view) by improving the EU trade balance in calories compared to the business-as-usual scenario. This finding remains consistent in an alternative scenario in which the rest of the world also adopts an agroecological pathway and healthier food diets. However, we also show that an agroecological transition taking place in the EU without corresponding changes in diets would lead the EU to drastically increase its food dependence on world markets and to contribute to the expansion of agricultural land in the other world regions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MS, CLM, XP, and P-MA: conceptualization, methodology, and writing—review. MS and CLM: model development and writing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1189952/full#supplementary-material

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