Food and feed trade has greatly impacted global land and nitrogen use efficiencies over 1961-2017

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Abstract

International trade of agricultural products has complicated and far-reaching impacts on land and nitrogen use efficiencies. We analyzed the productivity of cropland and livestock and associated use of feed and fertilizer efficiency for over 240 countries, and estimated countries' cumulative contributions to imports and exports of 190 agricultural products for the 1961-2017 period. Crop trade has increased global land and partial fertilizer nitrogen productivities in terms of protein production, which equaled savings of 2270 M ha cropland and 480 Tg synthetic fertilizer nitrogen over the analyzed period. However, crop trade decreased global cropland productivity when productivity is expressed on an energy (per calorie) basis. Agricultural trade has generally moved towards optimality, i.e. has increased global land and N use efficiencies during 1961-2017, but remains at a relatively low level. Overall, mixed impacts of trade on resource use indicate the need for re-thinking trade patterns and improving their optimality.

Introduction

Concerns are increasing about the need to provide enough nutritious food for a growing global population within environmental limits [1]. International trade in food and feed has significant contributions to local food security and has rapidly increased during recent decades [2]. However, trade of food and feed also has complex impacts on water use [3], biodiversity [4], air quality [5], land use [6-7] and climate change [8-9]. Currently, many African countries rely on food imports to fill the gap between increasing food demand and lagging domestic food production [10]. Some medium and high income countries also require food imports; for example, the United Kingdom imports almost 50% of its food supply and increasingly rely on vegetable imports from climate-vulnerable countries [8-9], while China is the largest importer of soybean to support its domestic livestock industry and vegetable oil demand [11-12].

There is debate about hidden resource depletion and environmental impacts associated with food and feed trade across country borders. Groundwater depletion by products used for export was reported to be equivalent to 11% of total global groundwater depletion in 2011 [3]. Around 15-25% of global ammonia emissions associated with food production originated from internationally traded food products [13-14], and the proportion of reactive nitrogen (N) losses embedded in the trade of feed and livestock products is high [15]. However, these studies mainly focused on the impacts of trade on exporting countries, with little emphasis on the distributions of production efficiencies of exporting vs. importing countries. Some studies have considered productivity differences between exporting and importing countries, but found contradictory results of the impact of trade on land use efficiency [16-18]. Two studies used multi-regional input-output data to investigate how global trade of all commodities contributed to the externalization of some environmental impacts [19-20].

Global land and N use efficiencies are important elements for achieving the United Nations Sustainable Development Goals [21], but the information about the impacts of food and feed trade on global land and N use efficiencies is still limited. There is also little information available about the optimality of trade, specifically improving global land and N use efficiencies, i.e., whether high efficiency countries export to low efficiency countries, and its variability in terms of land and N use efficiencies at the global level. Here, we aim to develop and use a systematic method to quantify the impacts of food and feed trade on global land and N use efficiencies, and to determine the non-monetary optimality of trade and their changes at the global level over the time period for which FAOSTAT data is available (1961-2017) [12].

Global land and N use efficiencies were defined in terms of productivities. Four main productivity parameters were selected to assess the impacts of trade on global land and fertilizer N use efficiencies: (i) cropland productivity, (ii) partial fertilizer N productivity in crop production, (iii) livestock productivity, and (iv) partial feed N productivity in livestock production (see Methods and Table 1). These parameters have been used to develop productivity distribution curves, separately for importing and exporting countries, and indicators that describe essential features of these curves: the Concentration of Production in High Efficiency countries (CPHE), a dimensionless indicator describing the inequality in a given group of countries (high when productivity and production are both high in very few countries); and the Concentration Weighted Production Efficiency (CWPE), representing the CPHE adjusted productivity for a given group of countries.

Results

A new analytical framework

Cumulative productivity distribution curve. The cumulative productivity distribution curve for all countries in the world was developed to quantify the concentration of agricultural production in high productivity countries. The idea of this curve is derived from the Lorenz Curve and the Gini coefficient [22-23], which have been widely used to quantify the degree of inequality in the distributions of income and natural resources. We built the curve by plotting each country on the X-axis in ascending order of commodity productivity (Fig. 1a), while the contribution of each country to the total global production of a commodity was plotted on the Y-axis (%). The cumulative productivity distribution curve of a commodity divides the graph into two parts, namely: area A (dark green) lying between the Y-axis, 100% contribution line and the cumulative productivity distribution curve; and area B (light blue) lying between the X-axis, the maximum productivity line (Max X) and the cumulative productivity distribution curve (Fig. 1a).

Evaluation of trade functionality and optimality. We used two complementary indicators for assessing the impacts of international trade on cropland and livestock productivities and partial fertilizer N and feed N productivities, which stems from the cumulative productivity distribution curve developed in this study: CPHE and CWPE. CPHE is area A divided by areas A+B in Fig. 1a; CPHE may range from 0 to 1. A relatively high value indicates concentration of production in few high-efficiency countries (Fig. 1a). The indicator CWPE is CPHE multiplied by areas A+B (Max X in Fig. 1a); CWPE may range from minimum to maximum productivity in few extreme situations but different with average productivity (Fig. 1a).

Based on differences in CPHE and CWPE of net importing and net exporting countries (Fig. 1b), we developed a scheme for trade functionality and trade optimality. Trade was considered functional when CPHE of exporting countries ($CPHE_{ex}$) > 0.50 and CPHE of importing countries ($CPHE_{im}$) < 0.50. Trade was considered near-optimal when $CWPE_{ex} / CWPE_{im} \geqslant 1.0$ (Fig. 2). Hence, trade of a commodity was considered functional when more than 50% of that commodity is exported by relatively high-efficiency countries, and more than 50% of that commodity is imported by relatively low-productivity countries. Trade of a commodity is considered near-optimal when exporting countries have higher CWPE than importing countries; this reflects that goods are transferred from areas of high to areas of low productivity. Conversely, trade was considered less optimal when

$CWPE_{ex} < CWPE_{im}$; and trade was considered less functional when $CPHE_{ex} < 0.50$ and $CPHE_{im} > 0.50$ (Supplementary Table 1). There are eight possible combinations of $CPHE_{ex}$, $CPHE_{im}$, $CWPE_{ex}$ and $CWPE_{im}$, as presented in Fig. 2 and Supplementary Fig. 1. These eight combinations were categorized into two groups: an 'optimal' group (Level I to IV) (Fig. 2a), and a 'non-optimal' group (Level V to VIII) (Fig. 2b). Hence, trade optimality increases when the ratio of $CWPE_{ex} / CWPE_{im}$ increases, and trade functionality increases when the ratio of $CPHE_{ex} / CPHE_{im}$ increases (Fig. 2a, b).

Potential saving or wastage of resources through trade. The framework allows the effects of trade on a potential saving or wastage of resources (i.e., cropland, livestock unit, fertilizer N, feed N) to be estimated at global scale, that is, based on the average productivity and total calorie or protein trade between exporting and importing countries, relative to a status without trade. Such a comparison implicitly assumes that sufficient cropland (and other resources, such as labor, water and nutrients) would exist in importing countries (in the hypothetical situation without trade), and that the fraction of imported commodities would be produced additionally at the same productivity level as that of the existing domestic production. However, many importing countries face great shortage of cropland (and possibly other resources), which is a key driver for import of food and feed, such as in the case of China, Japan and the Netherlands [24-25]. Hence, possible savings or wastage of resources may be lower than the potential values estimated here.

Impacts of trade on resources during 1961-2017

Global cropland productivity. The impact of international trade of food and feed on cropland productivity was estimated from the total trade in crop products, and the difference between the $CWPE_{ex}$ and $CWPE_{im}$ for these products. Mean CWPE of crop production was 10.5 M kcal ha^{-1} in net exporting countries and 11.2 M kcal ha^{-1} in net importing countries during the past 57 years (Fig. 3a). This suggests that crop products were exported from relatively low to relatively high productivity countries in terms of crop energy production, which implies a potential decrease of global cropland use efficiency. The associated cumulative potential wastage of cropland due to international trade was 870 Mha when adding up areas each year over the period 1961-2017 (Fig. 4).

The potential wastage of cropland was on average 15 M ha of harvested area per year between 1961 and 2017. For comparison, the total area of cropland was 1500 M ha in 2017 [12], hence the potential cropland wastage was in the order of one percent of the global cropland area. The gap between $CWPE_{ex}$ and $CWPE_{im}$ has been reduced from -3.80 M kcal ha^{-1} in 1960s to -0.16 M kcal ha^{-1} in 2010s, indicating that the potential negative effect of trading crop products on global cropland productivity has decreased over time (Supplementary Table 2), an effect that was not fully compensated by the stark increase in trade volumes. Overall, potential wastage of cropland decreased, from 36 M ha harvested area each year in the 1960s to 4.9 M ha harvested area each year in the 2000s (Fig. 5b).

In contrast, the $CWPE_{ex}$ was 36% larger than $CWPE_{im}$ when cropland productivity was expressed in terms of crop protein production (Fig. 3b). This indicates a potential increase in global cropland use efficiency through trade, as traded crop products were transferred from high productivity to low productivity countries. The cumulative potential saving of cropland through trade was about 2270 Mha of harvested area between 1961 and 2017 (Fig. 4). This equals to a potential saving of on average 40 Mha of harvested area per year, which is equivalent to about 2.7% of the global cropland area in 2017. The average potential saving of cropland increased from near 0 in 1960s to 84 Mha per year in the 2010s (note there were only 7 years in 2010s), which reflects an increasing gap between $CWPE_{ex}$ and $CWPE_{im}$ for crop protein productivity between 1960s and 2010s (Fig. 5c, d). The average annual potential saving of cropland in the 2010s was 5.6% of the global cropland area [12].

Global livestock productivity. International trade of livestock products was from high-efficiency countries to low-productivity countries, since the $CWPE_{ex}$ was higher than $CWPE_{im}$, in terms of both energy and protein production between 1961 and 2017 (Fig. 6a, b). As a result, trade has led to a potential saving of 170 to 80 M livestock standard unit (LSU) during 1961-2017 when productivity was expressed in terms of energy and protein, respectively (Fig. 4). Again, this potential saving implicitly assumes that there are no biophysical or policy limitations in importing countries to produce enough livestock products for domestic consumption. The potential saving of the total number of livestock units in 57 years, through trade of livestock products, was equivalent to 20-50% of the average total number of livestock units in the world in a year [12, 26]. The leading high-efficiency livestock exporting countries (responsible for around 80% of total livestock protein export) were the Netherlands, New Zealand and Germany. These countries had an average annual livestock productivity of >40 kg protein LSU^{-1}, and contributed most to the potential saving of livestock units in the past 57 years (Fig. 6b). The potential saving has increased in the 2010s to around 17 M LSU (Fig. 5j, l), which was equivalent to 4.2% of global LSU in the 2010s [26].

Partial fertilizer N and feed N productivities.

Trade of crop products were sourced from countries with high partial fertilizer N productivity and were imported by countries with relatively low partial fertilizer N productivity, because $CWPE_{ex}$ was 180-250% larger than $CWPE_{im}$ between 1961 and 2017, for partial fertilizer N productivity when expressed in calorie or protein production (Fig. 3c, d). As a result, trade has led to a cumulative potential saving of 360 Tg synthetic fertilizer N when expressed in crop calorie production, and of 480 Tg synthetic fertilizer N when expressed in crop protein production (Fig. 4). Global synthetic fertilizer N consumption has rapidly increased during this period, from 11 Tg in 1961 to 109 Tg N in 2017 [12]; international trade has potentially saved 5.8 to 7.7% of the annual global synthetic fertilizer N consumption between 1961 and 2017. Around half of the potential saving of synthetic fertilizer N occurred in the last two decades (Fig. 5f, h), although the difference between $CWPE_{ex}$ and $CWPE_{im}$ has decreased between 1960s and 2010s (Fig. 5e, g). The potential global synthetic fertilizer N saving was 12 to 18 Tg per year between 2011 and 2017, depending on calorie or protein based estimates, which was 11 to 16% of the global annual consumption in 2017 [12]. However, our partial fertilizer N productivity indicator did not account for N inputs via manure nor biological N_2 fixation, which have increased during the last few decades [9]. Hence, impact of trade on global N use efficiency is likely to have been overestimated in this study.

Trade has had contradictory impacts on global partial feed N productivity in livestock production (Fig. 6c, d). A negative impact of trade on protein-based partial feed N productivity was noted, which was related in part to the finding that some large importing countries were efficient in converting feed N into animal protein. For example, leading importing countries, such as Japan, South Korea and Israel, had a relatively high partial feed N productivity of 1.0-2.0 kg protein (kg feed N)$^{-1}$ (Fig. 6c, d), and these countries contributed as much as 70% to the total imports. Higher partial feed N productivity in Japan, South Korea and Israel may partly be due to a higher proportion of poultry animals to total livestock production, and to a higher livestock productivity and management [12, 15]. Exporting countries with relatively low partial feed N productivity of >0.5 kg protein (kg feed N)$^{-1}$ were responsible for as much 50% of the total exports during the past 57 years (Fig. 6d). The negative gap between exporting and importing countries in livestock partial feed N productivity has decreased in recent decades both in terms of livestock calorie and protein production (Fig. 5n, p).

Ultimate fate of traded N in importing countries

There is little information available about the ultimate fate of N embedded in traded crop and livestock products. Here, we separated traded agricultural products into those used for human food and animal feed, to estimate the distribution of traded N between utilization and losses to environment (Supplementary Fig. 2). Our results indicate that much of the traded N ended up in the environment, and little was recycled in the crop production system. Globally, around 3.7 Tg N was embedded in the trade of human food in 2017 and this 3.7 Tg N was likely also excreted by humans, as retention in human bodies is negligibly small. We estimated that about 40% (1.4 Tg N) of human excreted N was converted into N_2, in part following sewage treatment [13-14]. The latter occurred mainly in economically developed regions, e.g. Japan, South Korea, America and European Union due to environmental regulations related to sewage collection and treatment (Supplementary Fig. 3). We estimated that of all feed N traded (10 Tg) in 2017, a total of about 2.5 Tg N was retained in milk, meat and egg, about 3.1 Tg N was recovered as manure used to fertilize cropland and the remaining 4.4 Tg N was lost to the environment. China was a main leakage point of globally traded feed N, due to its large soybean import and poor manure management [27-28]. Overall, more than 40% of total traded food and feed N (14 Tg N) was not recycled and ended up in the environment (Supplementary Fig. 3). This lost N likely contributed 5 to 10% to the exceedance of the ‘safe operating space’ for biogeochemical N flows (about 60 Tg N) [29]. These estimates indirectly indicate that trade of animal products rather than feed may improve the global N use efficiency at food system level, as some of the leading feed importing countries currently have lower livestock N use efficiency and manure recycling rate than the leading livestock exporting countries [30].

Optimality and functionality of traded products

We evaluated the international trade of crop products as non-optimal and low-functional (Level VI) in terms of cropland calorie productivity during the period 1961 to 2017, as the ratio of $CWPE_{ex}$ / $CWPE_{im}$ was < 1.0, and the $CPHE_{ex}$ was < 0.50 and $CPHE_{im}$ was < 0.50 (Fig. 7a). When expressed in terms of protein productivity, trade of crop products was evaluated at near optimal level (Level I) (Fig. 7b). Trade optimality was relatively high but trade functionality was relatively low from the point of view of partial fertilizer N productivity (Fig. 7a, b). Trade of livestock products was evaluated as optimal and functional (Level II) in terms of calorie and protein based livestock productivity (Fig. 7a, b). Trade of livestock products was optimal and functional (Level I) when expressed in terms of calorie-based partial feed N productivity, but it was non-optimal and low-functional (Level VI) in terms of protein-based partial feed N productivity (Fig. 7b).

Changes over time The $\mathrm{CPHE}_{\mathrm{ex}}$ of cropland calorie productivity has decreased from 0.50 in 1960s to 0.36 in 2010s (Supplementary Fig. 4, upper panel). This is a result of decreasing contributions of high-efficiency exporting countries to the total export of crop calories. However, the negative effect of trading crop products on global cropland productivity has decreased over time due to the faster increase of productivity in the net exporting country group compared to the net importing countries (Supplementary Fig. 4, upper panel); the negative gap between $\mathrm{CWPE}_{\mathrm{ex}}$ and $\mathrm{CWPE}_{\mathrm{im}}$ diminished (Fig. 5a). Hence, trade optimality improved slowly from Level VII in 1960s to Level VI in 2010s in terms of crop calorie productivity (Fig. 7c).

International trade of crop products has had a positive effect on global cropland productivity over the last six decades (except in the 1960s), when cropland productivity was expressed in terms of protein production per hectare (Fig. 5c). There were also steady increases in trade functionality of crop products (Fig. 7e), which is partly related to the massive expansion of soybean production in Brazil, United States and Argentina for export to China and the European Union over the last 2-3 decades, but which was partially at the cost of precious tropical forests and related biodiversity [31-32].

Mean CWPE values of exporting and importing countries for partial fertilizer N productivity have decreased over time (Fig. 7d), which was related to the rapidly increasing use of synthetic N fertilizer in the past six decades, especially in emerging economies, such as China [12, 33]. Differences between $\mathrm{CWPE}_{\mathrm{ex}}$ and $\mathrm{CWPE}_{\mathrm{im}}$ for partial fertilizer N productivity were positive, and were relatively high in the 1960s but greatly decreased thereafter (Fig. 5e, g). However, there were no changes in trade functionality level in terms of partial fertilizer N productivity; trade functionality was at the bottom-left of quadrant III, when expressed in terms of either calorie or protein production (Fig. 7d, f).

International trade in livestock products has contributed to an increase in global livestock productivity, both in terms of livestock calorie and protein production, during the last four decades (from 1980s to 2010s) (Fig. 5i, k). Some countries with high livestock productivity are main importers of crop products and main exporters of livestock products; these countries import calorie and protein-rich feed to produce and export milk, meat and egg (e.g., the Denmark, Germany, Netherlands and Spain). There were no large changes in trade functionality during the last four decades, both in terms of calorie and protein based livestock productivity (Supplementary Fig. 5). However, trade optimality and functionality varied in the past 6 decades, and the trend was different when the partial feed N productivity was expressed in terms of calorie and protein productivity (Fig. 5m, o; Supplementary Fig. 5-6).

Trade optimality of different products. International trade of six selected main traded crop products (maize, wheat, rice, barley, soybean and potato) was optimal in terms of crop calorie and protein productivity between 1961 and 2017 (Supplementary Fig. 7).

Trade of maize and soybean had a relatively high optimality level, which is reflected by the larger diameter of the red circles in Supplementary Fig. 7. However, trade functionality varied among these six crop products, with maize, soybean and barley in quadrant I (Supplementary Fig. 7). Additional information about different crop and livestock products can be found in Supplementary Table 3.

Discussion

Trade allows an exchange of reciprocal productivity advantages between different regions, communities or cultures, when there are no trade restrictions or cultural barriers. Hence, food and feed trade was expected to contribute to improved global land and N use efficiencies. Our study identified contradictory results, however, when comparing cropland and livestock productivities and partial fertilizer N and feed N productivities on the basis of calorie vs. protein production. This may indicate that protein productivity more strongly influences the establishment of trade flows than the calorie content of the products. This may require a re-thinking of the main functions of agricultural trade, especially as the current UN Sustainable Development Goal on "Zero Hunger" mainly addresses the daily dietary energy supply [21].

Implications of trade for cropland productivity

The estimated average annual potential saving of cropland through international trade of food and feed in 2010s was comparable with estimates of previous studies, when expressed in terms of crop protein production [17-18]. However, trade of crop products contributed to a potential wastage of global cropland when productivity was expressed in terms of calorie production (Fig. 5a). This was related to the import of crop products by some leading high-efficiency importing countries, such as the Netherlands and Japan, with an average crop calorie productivity >16 M kcal ha^{-1} (Fig. 3a); it reflects a relative scarcity of cropland. The cropland area also declined in these countries because of competition from infrastructure and nature conservation (Supplementary Fig. 8a-c). Conversely, export-oriented production in Brazil, Malaysia and Indonesia was associated with cropland expansion and deforestation [32, 34] (Supplementary Fig. 8d-f). Expanding high-efficiency cropland at the expense of natural land in some areas may contribute to saving cropland at the global level when a large expansion of low-productive cropland in other areas can be minimized. However, this may conflict with the concept of land sharing to protect biodiversity and reduce greenhouse gas (GHG) emissions, i.e., expanding soybean production in Brazil may increase global protein productivity, but at the cost of biodiversity losses [35].

The idea of trade optimality is that production occurs in areas with the best possible output - resource input ratio, and that products are transferred (traded) from these high-efficiency areas to areas with lower output - resource input ratio. High-productivity importing countries with little land could expand their domestic crop production in high-tech and high productive greenhouses [36], which would decrease $CWPE_{im}$ value and hence increase the $CWPE_{ex}/CWPE_{im}$ ratio. Increase of the trade optimality level could also be achieved by increasing $CWPE_{ex}$, via transfer of knowledge and technology. This is important for exporting countries with low productivity, such as Kazakhstan, Russia, Zambia and Uruguay (Fig. 3), as it may increase crop calorie productivity and subsequent export without expanding cropland [37]. Increasing productivity in high-productivity countries faces the challenge of reaching potential yield limits, for example wheat yields in some European countries have reached biophysical limits [38].

The potential saving of livestock units as a result of international trade of livestock products will likely have contributed to a reduction of several million tons of N losses and greenhouse gas emissions into the atmosphere, as the livestock sector has likely contributed to the emission of 7.1 billion ton CO_{2eq} and 119 M ton of ammonia annually during last decade [15, 39]. The subsequent effects of trade on the potential saving of livestock units in terms of potential saving of feed use and cropland area have not been assessed in this study, but may be large [40]. However, these effects are difficult to quantify, because part of the feed consumed in a country may have been imported from other countries, and there are large differences in feed composition and feed conversion ratio between animal categories and between countries [11, 41-42].

Implications of trade on partial fertilizer N productivity

The positive impact of the trade of food and feed on partial fertilizer N productivity at global level through time is in part related to the inefficient fertilizer use at the beginning of the study period for some of the world's major crop exporters. It is also related to the increasing proportion of export coming from countries with high partial fertilizer N productivity (e.g., in Africa and South America) (e.g., in Africa and South America) [43]. The high partial fertilizer N productivity in African countries results from soil N mining, which is not sustainable for any country in the longer term [43-44]. The high partial fertilizer N productivity in American countries was likely related to the relative large N input via biological N fixation in soybean production, which we did not account for.

Partial fertilizer N productivity may also increase through better utilization of N from animal manure and household wastes, and an equivalent decrease in synthetic fertilizer use [44]. We estimated that 1.4 Tg N contained in traded food was converted into N_2 following treatment in sewage treatment plants, the residue of which can potentially be recycled into agricultural production systems. Around 4.4 Tg N in traded animal feed N was lost from animal houses and manure storages. For example, only around 1/3 of China's livestock manure N was effectively applied to cropland; the remainder was either emitted to air or discharged to watercourse and landfills [45]. Technological development and investments in low-emission animal housing and manure storages, and in low-emission manure transport and application facilities would help to reuse a greater proportion of the N embedded in traded feed products [46]. The total synthetic fertilizer N use in China could be reduced from around 30 Tg in 2012 to 5.0 Tg if these technologies and advances in crop and livestock production were have been fully implemented. This would contribute greatly to the global attempt to keep N use within the planetary boundaries [47].

Trade optimality level and implications

The trade optimality and functionality as defined in this study do not consider wider ecosystem impacts. However, it is well-known that some leading exporting countries have increased the export of crop and livestock products in part through land expansion and deforestation [31-32]. For example, soybean export from Latin America is associated with deforestation and biodiversity loss [31, 48]. Palm oil export from some south-east Asian countries is associated with deforestation, peatland degradation and biodiversity loss [34]. Similarly, some leading livestock exporting countries, such as the Netherlands, Denmark and Germany suffer from N pollution and biodiversity loss caused by NH_3 emissions from livestock production, especially in livestock-dense regions [49]. Hence, though trade of crop and livestock products may be evaluated as optimal and functional in terms of land and N use efficiencies, it may be non-optimal and low-functional when evaluated in terms of GHG emissions, biodiversity conservation and environmental pollutions. The new analytical framework with the cumulative productivity distribution curve developed in this study allows such indirect impacts to be included, but it will require additional indicators for quantitative assessments, such as land use change, GHG emissions, N losses and biodiversity losses. Further, the trade of crop products (e.g., sugar cane, corn, soybean) used for biofuel, and products used for pharmaceuticals and industry may also be evaluated using this framework.

Overall, our framework allows uniform assessments for importing and exporting countries to be made, using multiple indicators, and may help to set priorities for specific countries and specific products. In addition, the framework developed here is simple, transparent and may be easily extended. It provides a functional tool and various useful indicators for researchers and policy makers. More applications of the cumulative production curve approach can be envisaged, including in industry and ecology.

Methods

Cumulative productivity distribution curve

The cumulative productivity distribution curve was developed to quantify the relative concentration of production in high-efficiency countries, and to evaluate trade optimality and functionality. The idea of this curve originates from the Lorenz Curve, but is applied in a different way. We plotted each country in the world on the X-axis in ascending order of productivity (for one product or for a combination of products). This is different from Lorenz Curve, as our aim is to quantify the relative concentration of production of a certain product (or combination of products) in high-efficiency countries. The contribution of each country to the total global production of a commodity was plotted on the Y-axis (%). Then the cumulative productivity distribution curve was estimated.

Definition and estimation of CPHE. The relative concentration of production in high-efficiency countries (CPHE) was defined by area A over areas A + B in Fig 1a, i.e. CPHE = A / (A+B). A hypothetical value of CPHE = 1.0 indicates that the most productive country in the world contributes 100% to the global production. A CPHE = 0.50 indicates that productivity was equally distributed over low and high productivity countries.

The cumulative productivity distribution curves were approximated by Piecewise-Defined continuous and non-negative functions $f(x)$, that is, $f(x) = \begin{cases} f_1(x), a \le x \le a_1 \\ f_2(x), a_1 \le x \le a_2 \\ \vdots \\ f_n(x), a_{n-1} \le x \le b \end{cases}$, where $[a, b] = [a, a_1] \cup [a_1, a_2] \cup \cdots \cup [a_{n-1}, b],$ and the functions $f_i(x), i = 1,2,\cdots, n,$ can be either a polynomial function or a Logarithmic function. Based on the simulation curve, we calculated the area following the definite integral method [36-37]. The interval on the X-axis between the minimum productivity and maximum productivity was denoted as $[a,b]$. The area below the graph of f over $[a,b]$ was denoted as *B*. Then the area *B* is given exactly by the sum of the definite integrals of f_i over the corresponding subintervals, that is, $B = \int_a^{a_1} f_1(x)dx + \int_{a_1}^{a_2} f_2(x)dx + \cdots + \int_{a_{n-1}}^{b} f_n(x)dx.$

It is straightforward to check that the area of $A + B$ is a rectangle with length $x_{\max} - x_{\min}$ and width $y_{\max} - y_{\min}$, where x is the productivity and y is the cumulative production. Therefore, the area A is the difference between the area $A+B$ and the area B. Areas A and B are sensitive for extreme low and high productivity values; hence very low and very high productivity countries with a low contribution (< 1.0%) to the total production or trade were excluded. These extreme values may relate to statistical errors or to highly unique conditions. The impacts of the maximum productivity on CPHE are illustrated in Supplementary Fig 1. We have also tested the sensitive of potential resources saving to the selection of maximum productivity, when set at 98.5%, 99.0% and 99.5% contribution to the total production, and show that a 99.0% contribution presented the best value [50-51].

Definition and estimation of CWPE. The concentration weighted productivity (CWPE) represents a CPHE corrected productivity of a given product. It was calculated as follows:

$$\text{CWPE} = \text{CPHE} * \text{Area}_{\text{rectangle}} \qquad (1)$$

Where, CWPE is the concentration weighted production efficiency, the unit depends on the unit of productivity in X-axis; $\text{Area}_{\text{rectangle}}$ represented the area of the rectangle (areas A+B), of which the length is from 0 to maximum productivity in the X-axis and the height is from 0 to 100% contribution line in the Y-axis (Fig. 1a). Hence, $\text{Area}_{\text{rectangle}}$ is equal to maximum productivity multiplied by 100%, and basically equal to maximum productivity. CWPE is positively correlated to average productivity. In few extreme situations CWPE may equal to average productivity of given products across the world. For example, CWPE may equal to the maximum productivity when

CPHE = 1.0, since only the highest productivity country produce all the products.

Relationship between CPHE and CWPE. CPHE and CWPE are interrelated because they both share the same cumulative distribution curve; a high CPHE usually means a high CWPE, and vice versa. Relationships between CPHE and CWPE vary when the maximum productivity (or partial fertilizer or feed productivity) varies, as follows from Supplementary Fig. 9.

Trade optimality and functionality. We applied the concepts of CPHE and CWPE to importing and exporting countries, to estimate the functionality and optimality of the international trade of food and feed commodities at global level (Fig. 2). The indicator was estimated for both importing and exporting countries. International trade was considered 'functional' when CPHE of exporting countries ($CPHE_{ex}$) was larger than that of importing countries ($CPHE_{im}$) and also larger than 0.50, and trade was deemed as optimal when $CWPE_{ex}$ / $CWPE_{im}$ is larger than 1.0 (Fig. 2, Supplementary Fig. 1).

Agricultural production and trade data

We used data from the FAOSTAT statistical database to analyze crop and animal productivity distributions and trade efficiency distributions in the world. In total, 164 crop products, 26 animal products from 6 main animal categories from >200 countries were selected for this study (Supplementary Table 4). Cropland productivity was expressed in terms of calorie (kcal) or kg protein production per unit of harvest area (ha). Livestock productivity was expressed in calorie (kcal) or kg protein production per livestock unit (LSU). Partial fertilizer N productivity in crop production was expressed in kcal or kg protein per kg fertilizer N input. Partial feed N productivity in livestock animal production was expressed in kcal or kg protein per kg of feed protein N intake (Table 1).

Productivity indicators

Global land and N use efficiencies were defined in terms of productivities. Four main productivity parameters were selected to assess the impacts of trade on global land and fertilizer N use efficiencies. (i) Land use efficiency was expressed in terms of 'cropland productivity', i.e., the summed annual calorie (or protein) harvest of all crops in a country divided by the total harvested area of cropland in that country [52]. (ii) Partial fertilizer N productivity in crop production was defined as annual total crop yield, in terms of energy (or protein) per kg of mineral fertilizer N applied in a country (Table 1). Hence, only the new N input via synthetic fertilizer was considered in the estimation of partial fertilizer N productivity, which gives an upper estimate as it neglects the N inputs via biological N_2 fixation and via recycling of manure, crop residues and net soil organic matter mineralization. (iii) Livestock productivity was defined as annual total livestock production, in terms of energy (or protein) per livestock unit (LSU) in a country. (iv) Partial feed N productivity in livestock production was defined as total livestock production, in terms of calorie (or protein) per kg of feed N used in a country (Table 1). Hence, cropland and livestock productivities and partial fertilizer N and feed N productivities were evaluated both in terms of energy (calories) and protein, because of their important but different roles in food security, trade and environmental impacts.

Crop productivity. A weighted mean productivity of crop products per country was used in this study.

$$Cropland\ productivity = \frac{\sum Calorie\ or\ Protein_{crop\ product\ i}}{\sum Harvested\ area_{product\ i}} \tag{2}$$

Where, *Cropland productivity* (Table 1) was the average calorie production per ha (or average protein production per ha) of all crops within a country, expressed in kcal ha^{-1}, or kg protein ha^{-1}; $\sum Calorie\ or\ Protein_{product\ i}$ was the sum of calorie or protein production of the harvested crop products per country per year, expressed in kcal or kg protein; $\sum Harvested\ area_{\ product\ i}$ was the sum of the harvested area of the crop species in a country in a year, expressed in ha. In addition, the productivity of single crops was also calculated based on its harvested areas, production quantities, and calorie and protein contents.

Livestock productivity. For livestock products, we calculated the average productivity per livestock unit (LSU), using the total production quantities, animal numbers, and the calorie and protein contents of animal products. The livestock number was transferred to standard livestock units (LSU), following the coefficients used by Liu et al., 2017 [24].

$$Livestock\ productvity = \frac{\sum Calorie\ or\ Protein_{livestock\ product\ i}}{\sum Livestock\ unit_{product\ i}} \tag{3}$$

Where, *Livestock productivity* was the average calorie or protein production per livestock unit in a country, expressed in kcal LSU^{-1} or protein LSU^{-1}; $\sum$*Calorie or Protein* $_{livestock\ product\ i}$ was the sum of the calorie or protein produced by all livestock categories in a country, expressed in kcal or kg protein per year; $\sum$*Livestock unit product i was* the sum of animal numbers, expressed in LSU. Here, 6 livestock categories (pigs, layer hens, broilers, beef cattle, dairy cattle, sheep and goat) were considered; they accounted for 99% of total animal products trade in 2017 (Supplementary Table 4). The calorie and protein contents and protein/N transfer index for each crop product and livestock product were derived from literature [38-41].

Partial fertilizer nitrogen productivity. The average calorie or protein production per unit of fertilizer N input was used to quantify the partial fertilizer N productivity in crop production. The partial fertilizer N productivity only considered the inputs from mineral N fertilizer, and not the inputs from for example biological N_2 fixation, atmospheric N deposition, or recycled N from animal manures, crop residues and composts, or the net mineralization of soil organic matter.

$$PFP_{crop} = \frac{\sum Calorie\ or\ Protein_{crop\ product\ i}}{Fertilizer\ N} \tag{4}$$

Where, the PFP_{Crop} is the partial factor productivity of applied fertilizer N, or the average crop calorie or protein production per kg fertilizer N in a country, expressed in kcal (kg N)$^{-1}$ or kg protein (kg N)$^{-1}$; *Fertilizer N* was the total fertilizer N input in crop production, expressed in kg N. Fertilizer N inputs were derived from the Inputs Module of FAOSTAT database (Supplementary Table 5), and were corrected for the amount of fertilizer N used on grassland, following Lassaletta et al (2014) [39]. We made correction for the estimated fertilizer N use in the Netherlands and New Zealand, because of the large share of fertilizer N use for managed grass production. However, estimated fertilizer N use in cropland is relatively uncertain for some countries. It should be note that the partial fertilizer N productivity is an upper estimate of the actual fertilizer N use efficiency; partial fertilizer N productivity was used here mainly to show the applicability of our method and the relative differences between importing and exporting countries.

Partial feed nitrogen productivity. The partial feed nitrogen productivity in livestock production was estimated based on mass balance method as follows:

$$PFP_{Livestock} = \frac{\sum Carolie\ or\ Protein_{\ livestock\ product\ i}}{\sum N_{Product\ i} + \sum N_{\ Manure\ excretions\ i}} \qquad (5)$$

Where, the $PFP_{Livestock}$ is partial factor productivity of feed N, or the average animal-source calorie or protein produced per kg feed N in the livestock production sector in a country, expressed in kcal kg N^{-1} or kg protein kg N^{-1}; $\sum N$ *product i* is the sum of N in the livestock products for the 6 livestock categories selected, expressed in kg N. Information about products of different livestock categories were derived from Livestock Yield database from FAOSTAT (Supplementary Table 5); $\sum N$ *Manure* *excretions i* was the sum of manure N excreted by 6 livestock categories, expressed in kg N. Information about manure N excretions of different livestock categories was derived directly from the FAOSTAT database using the category of Agri-Environmental Indicators (Supplementary Table 5).

Annual import and export of agricultural products. Since some countries import/re-export certain products, such as soybeans and bananas, we used net food import and net export per food category from the FAOSTAT database (Supplementary Table 5), combined with data on protein content and protein/N conversion factors, to calculate the annual N import and export for each food category in countries, and the share of each country/regions to the global total import and export. Hence there is no need to quantify the import and re-export issue, or the different final use of a product, because we are using the net trade and convert all products to calorie or protein content. We used the recently updated (February 2020) trade data from Commodity Balance Module of FAOSTAT (Supplementary Table 5).

Effects of trade on land and resources use

The effects of trade on global cropland productivity were estimated from the differences in the CWPE of exporting countries and importing countries. Potential saving of cropland through international trade was defined as:

$$Land_{saving\ or\ wastage} = \sum \frac{Crop_{import\ i}}{Productivity_{import\ i}} - \sum \frac{Crop_{export\ i}}{Productivity_{export\ i}} \qquad (6)$$

where $\text{Land}_{\text{saving or wastage}}$ was the potential saving or wastage of cropland through the trade in crop products, in ha; $\text{Crop}_{\text{import i}}$ and $\text{Crop}_{\text{export i}}$ was net import or export of crop products in certain net import or export country, respectively, expressed in kcal, or kg protein; $\text{Productivity}_{\text{import i}}$ and $\text{Productivity}_{\text{export i}}$ was the national crop productivity of certain net import or export country, respectively, expressed in kcal, or kg protein. The evaluation of the impacts of trade of food and feed on the saving or wastage of livestock number, fertilizer N and feed N followed the same calculation method as presented above cropland saving or wastage.

Data availability

All data needed to evaluate the conclusions of this study are available in the paper itself and/or the Supplementary Information file.

Code availability

The custom code and algorithm used for this study is available in the Method and Supplementary file.

References

1. Erb, K.H., et al. Exploring the bio-physical option space for feeding the world without deforestation. Nat Commun. 7, 1–11. (2016).
2. Falkendal, T., et al. Grain export restrictions during COVID-19 risk food insecurity in many low-and middle-income countries. Nat Food, 2(1), 11-14. (2021).
3. Dalin, C., et al. Groundwater depletion embedded in international food trade. Nature, 543(7647), 700-704 (2017).
4. Lenzen, M., et al. International trade drives biodiversity threats in developing nations. Nature, 486(7401), 109-112 (2012).
5. Zhang, Q., et al. Transboundary health impacts of transported global air pollution and international trade. Nature, 543(7647), 705-709 (2017).
6. Yu, Y., et al. Tele-connecting local consumption to global land use. Global Environ Chang, 23(5), 1178-1186 (2013).
7. Kastner, T., et al. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. Environ Res Lett, 9(3), 034015 (2014).
8. Scheelbeek, P. F., et al. (2020). United Kingdom's fruit and vegetable supply is increasingly dependent on imports from climate-vulnerable producing countries. Nat Food, 1(11), 705-712.
9. de Ruiter, H., et al. Global cropland and greenhouse gas impacts of UK food supply are increasingly located overseas. J R Soc Interface, 13(114), 20151001 (2016).
10. Rakotoaroa, M., et al. Why has Africa become a net food importer. FAO (2011).
11. Bai, Z.H., et al. China's livestock transition: driving forces, impacts and consequences. Sci Adv, 4(7), eaar8534 (2018).
12. FAO STAT 2020. http://faostat.fao.org/. Accessed July in 2020.
13. Galloway, J.N. and Leach, A.M. Sustainability: Your feet's too big. Nat Geosci, 9(2), 97-98 (2016).
14. Oita, A., et al. Substantial nitrogen pollution embedded in international trade. Nat Geosci, 9(2), 111-115 (2016).
15. Uwizeye, A., et al. Nitrogen emissions along global livestock supply chains. Nat Food, 1(7), 437-446. (2020).
16. Fader, M., et al. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol Earth Syst Sc, 15(5), 1641 (2011).
17. Fader, M., et al. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. Environ Res Lett, 8(1), 014046 (2013).
18. Kastner, T., et al. Cropland area embodied in international trade: Contradictory results from different approaches. Ecol Econ, 104, 140-144 (2014).
19. Wood R, et al. Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. J Ind Ecol 22 (3):553-564 (2018).
20. de Boer BF, et al. Modeling reductions in the environmental footprints embodied in European Union's imports through source shifting. Ecolog Econ 164:106300

(2019).

21. Sachs, J., et al. The Sustainable Development Goals and COVID-19. Sustainable Development Report 2020. Cambridge: Cambridge University Press (2020).
22. Piketty, T., & Saez, E. Income inequality in the United States, 1913–1998. The Quarterly Journal of Economics, 118(1), 1-41 (2003).
23. Atkinson, A. B. On the measurement of inequality. Journal of Economic Theory, 2(3), 244-263 (1970).
24. Hayami, Y., & Yamada, S. The agricultural development of Japan: a century's perspective. University of Tokyo Press. (1991).
25. Liu, F. Chinese cropland losses due to urban expansion in the past four decades. Sci Total Environ, 650(1), 847-857.
26. Liu, Q., et al. Global animal production and nitrogen and phosphorus flows. Soil Res, 55.6: 451-462 (2017).
27. Bai, Z., et al. Nitrogen, phosphorus, and potassium flows through the manure management chain in China. Environ Sci Techn, 50(24), 13409-13418 (2016).
28. Sun, J., et al. Importing food damages domestic environment: Evidence from global soybean trade. P Natl Acad Sci USA, 115.21, 5415-5419 (2018).
29. Steffen, W., et al. Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223) - 1259855 (2015).
30. Bai, Z., et al. A food system revolution for China in the post-pandemic world. Resources, Environment and Sustainability, 100013 (2020).
31. Bowman, M. S., et al. Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production. Land Use Policy, 29(3), 558-568 (2012).
32. Elizabeth, B., et al. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ Res Lett, 5, 024002 (2010).
33. Vitousek, P.M., et al. Nutrient imbalances in agricultural development. Science, 324(5934): 1519-1520 (2009).
34. Koh, L.P., & Wilcove, D.S. Cashing in palm oil for conservation. Nature, 448, pages993–994 (2007).
35. Kremen, C. Reframing the land‐sparing/land‐sharing debate for biodiversity conservation. Annals of the New York Academy of Sciences, 1355 (2015) 52–76 (2015).
36. Statistics Netherlands (CBS). Upscaling of greenhouse vegetable production. https://www.cbs.nl/en-gb/news/2018/16/upscaling-of-greenhouse-vegetable-production. Accessed in July 2020.
37. Sanchez, P. A. En route to plentiful food production in Africa. Nature Plants, 1(1), 1-2 (2015).
38. Mueller, N. D., et al. Closing yield gaps through nutrient and water management. Nature, 490(7419), 254-257 (2012).
39. Sutton, M.A., et al. Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative (2013).

40. Mottet, A., et al. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Glob Food Secur, 14, 1-8. (2017).

41. Eshel, G., et al. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. P Natl Acad Sci USA, 111(33):11996-12001 (2014).

42. Gerber, P.J., et al. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome (2013).

43. Zhang, X., et al. Managing nitrogen for sustainable development. Nature, 528(7580), 51-59 (2015).

44. Lassaletta, L., et al. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ Res Lett, 9(10), 105011 (2014).

45. Bai, Z. H., et al. Changes in pig production in China and their effects on nitrogen and phosphorus use and losses. Environ Sci Techn, 48(21), 12742-12749 (2014).

46. Lassaletta, L., et al. Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. Biogeochemistry, 118(1-3), 225-241 (2014).

47. Jin, X., et al. Spatial Planning Needed to Drastically Reduce Nitrogen and Phosphorus Surpluses in China's Agriculture. Environ Sci Technol, 54(19), 11894-11904 (2020).

48. Soterroni, A.C., et al. Expanding the Soy Moratorium to Brazil's Cerrado. Sci Adv, 5(7), eaav7336 (2019).

49. Jongbloed. A.W., et al. Environmental and legislative aspects of pig production in The Netherlands, France and Denmark. Livestock Production Science, 58 (3): 243-249 (1999).

50. Litchfield, J. A. Inequality: Methods and tools. World Bank, 4 (1999).

51. Cobham, A., & Sumner, A. Is it all about the tails? The Palma measure of income inequality. Center for Global Development Working Paper, (343) (2013).

52. Renard, D., & Tilman, D. National food production stabilized by crop diversity. Nature, 571, 257 (2019).

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (31572210, 31272247), Program of International S&T Cooperation (2015DFG91990), President's International Fellowship Initiative (PIFI) of CAS (2016DE008, 2016VBA073 and 2019VCA0017), the Youth Innovation Promotion Association, CAS (2019101) and Distinguished Young Scientists Project of Natural Science Foundation of Hebei (D2017503023). The input of PS contributes to the

N-Circle China-UK Virtual Joint Centre on Nitrogen, funded by the Newton Fund *via* UK BBSRC/NERC (grant BB/N013484/1). Zhaohai Bai also thanks Francesco N. Tubiello from FAOSTAT help to interpret the data and results, FAOSTAT for providing different functional data which used in this study, and Yanan Cui, Juan Liu, Shijie Xu, Yungang Wang, Mengyu Guo, Shanli Zhao and Yajing Cao for helping collect the data at early stage.

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Contributions

Z.B., W.M., L.M., and O.O. designed research; Z.B., H.Z., X.L., P.W., N.Z., L.L., S.G., X.F., and W.W. performed research and analyzed data; and Z.B., W.M., L.M., O.O., G.V., P.S., M.L., and C.H. wrote the paper. All authors contributed to analysis of the results. All authors read and commented on various drafts of the paper.

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Ethics declaration - Competing interests

The authors declare that they have no competing interests.

Supplementary information

Supplementary Figs. 1-10 and Tables 1-6;

Extended Figs. 1-4.

Source data 1-8.

Table 1. Indicators used to assess the impacts of trade on global resource use efficiencies. The four indicators refer to cropland productivity, livestock productivity, partial fertilizer N productivity and partial feed N productivity - in terms of both calorie and protein production.

Indicators	Unit	Interpretation	Equations	Data source
Cropland productivity - calorie	kcal $ha^{-1}yr^{-1}$	Cropland productivity, expressed as (i) crop calorie produced per ha per yr, and (ii) crop protein produced per ha per year	Equation ［2］	Extended data 1
Cropland productivity - protein	kg protein ha^{-1} yr^{-1}		Equation ［2］	Extended data 2
Partial fertilizer N productivity - calorie	kcal (kg fertilizer N)$^{-1}$ yr^{-1}	Partial fertilizer nitrogen productivity in crop production, defined in terms of (i) crop calorie produced per kg fertilizer N applied per yr, (ii) crop protein produced per kg fertilizer N applied per yr. Note: N input to crop production via manure N, deposition and biological N fixation was not considered.	Equation ［4］	Extended data 3
Partial fertilizer N productivity - protein	kg protein (kg fertilizer N)$^{-1}$ yr^{-1}		Equation ［4］	Extended data 4
Livestock productivity - calorie	kcal LSU^{-1} yr^{-1}	Livestock productivity, defined in terms of livestock production, and expressed as (i) animal-source calorie produced per livestock unit per yr, and (ii) animal source protein produced per livestock unit per yr.	Equation ［3］	Extended data 5
Livestock productivity - protein	kg protein LSU^{-1} yr^{-1}		Equation ［3］	Extended data 6
Partial feed N productivity - calorie	kcal (kg feed N)$^{-1}$ yr^{-1}	Partial feed nitrogen productivity of livestock production, expressed in terms of (i) animal source calorie produced per kg of feed protein N, and (ii) animal source protein per kg of feed protein N consumed per yr.	Equation ［5］	Extended data 7
Partial feed N productivity - protein	kg protein (kg feed N)$^{-1}$ yr^{-1}		Equation ［5］	Extended data 8

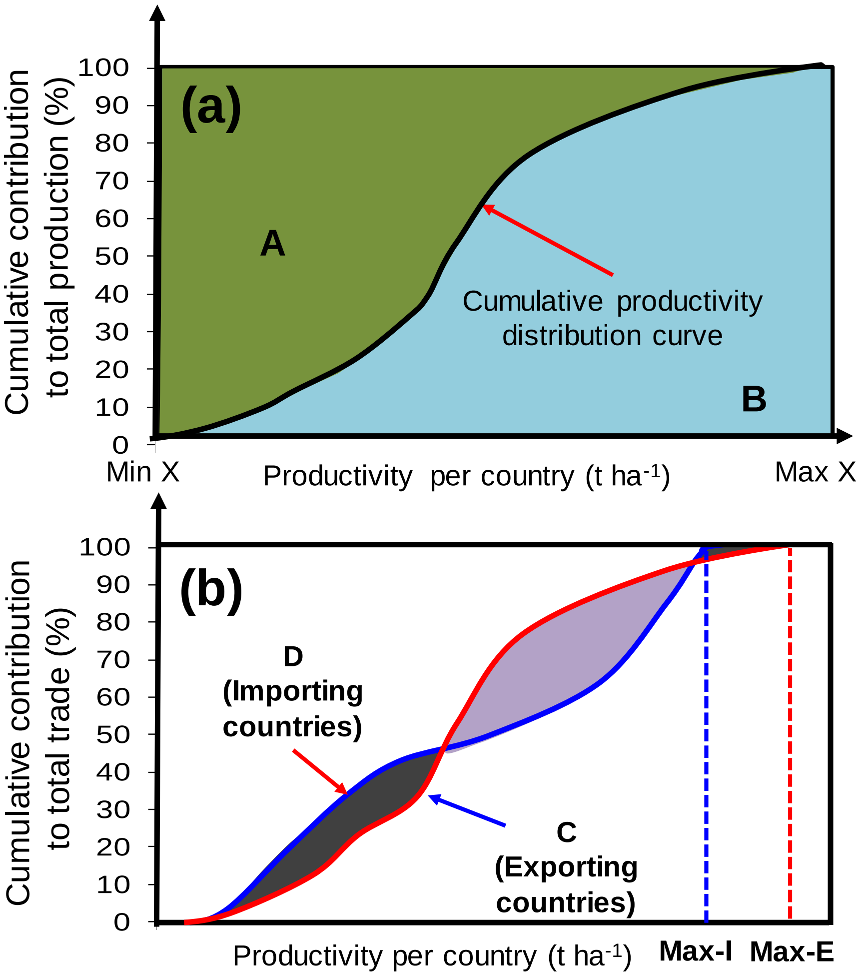

Fig 1. Productivity distribution curves. Panel (a) illustrates the concept of relative concentration of high-productivity countries in the world (CPHE = A / (A+B)), and panel (b) illustrates the concept of CPHE applied to exporting and importing countries separately so as to evaluate global trade functionality and optimality (see Fig 2). Countries were plotted on the x-axis in ascending order of productivity. Max-I is the max productivity for importing countries; Max-E is the max productivity for exporting countries.

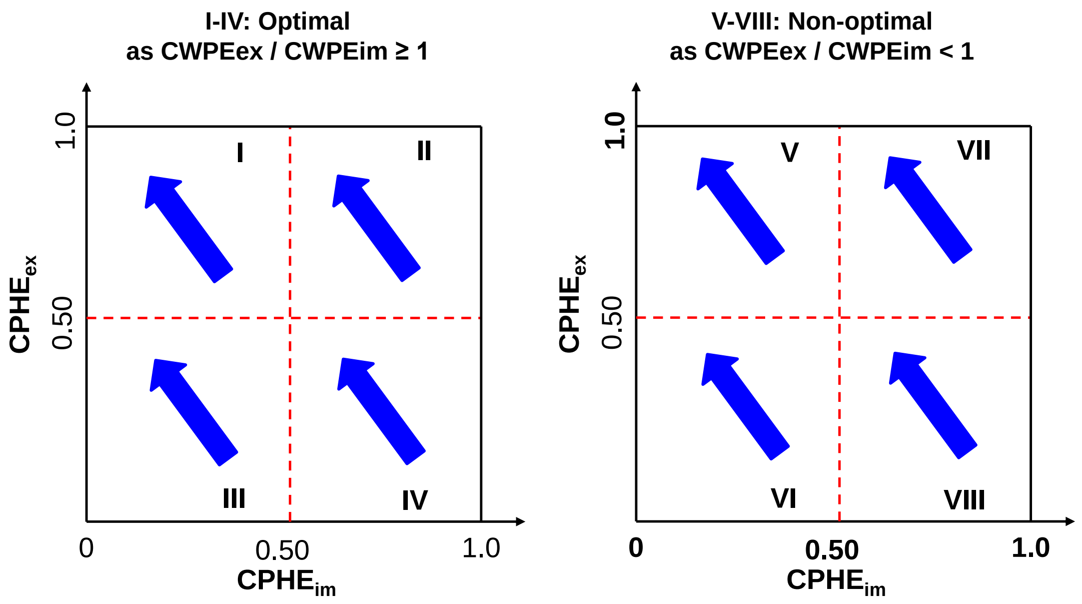

Fig 2. Illustrations of the concept of trade functionality and optimality, as determined by the CPHE and CWPE of exporting and importing countries. Trade is defined functional when $\mathrm{CPHE_{ex}} > 0.5$ and $\mathrm{CPHE_{im}} < 0.5$; it increases as the ratio of $\mathrm{CPHE_{ex}} / \mathrm{CPHE_{im}}$ increases. An optimal trade ($\mathrm{CWPEex} / \mathrm{CWPEim} \geqslant 1.0$) combined with a high trade functionality ($\mathrm{CPHE_{ex}} / \mathrm{CPHE_{im}} \geqslant 1.0$) is associated with potential improved resource use efficiency at global level (see Supplementary Table 1 for further details). The optimality level of trade decreased in the order of I > II > III > IV > V > VI > VII > VII. Arrow represents the direction of increasing trade functionality in each quadrant. CPHE is the relative concentration of production in high-productivity countries applied to importing and exporting countries ($\mathrm{CPHE_{im}}$ and $\mathrm{CPHE_{ex}}$; dimensionless). CWPE is the weighted production efficacy, applied to importing and exporting countries ($\mathrm{CWPE_{im}}$ and $\mathrm{CWPE_{ex}}$; the unit of CWPE depends on the unit of X axis; see Fig 1).

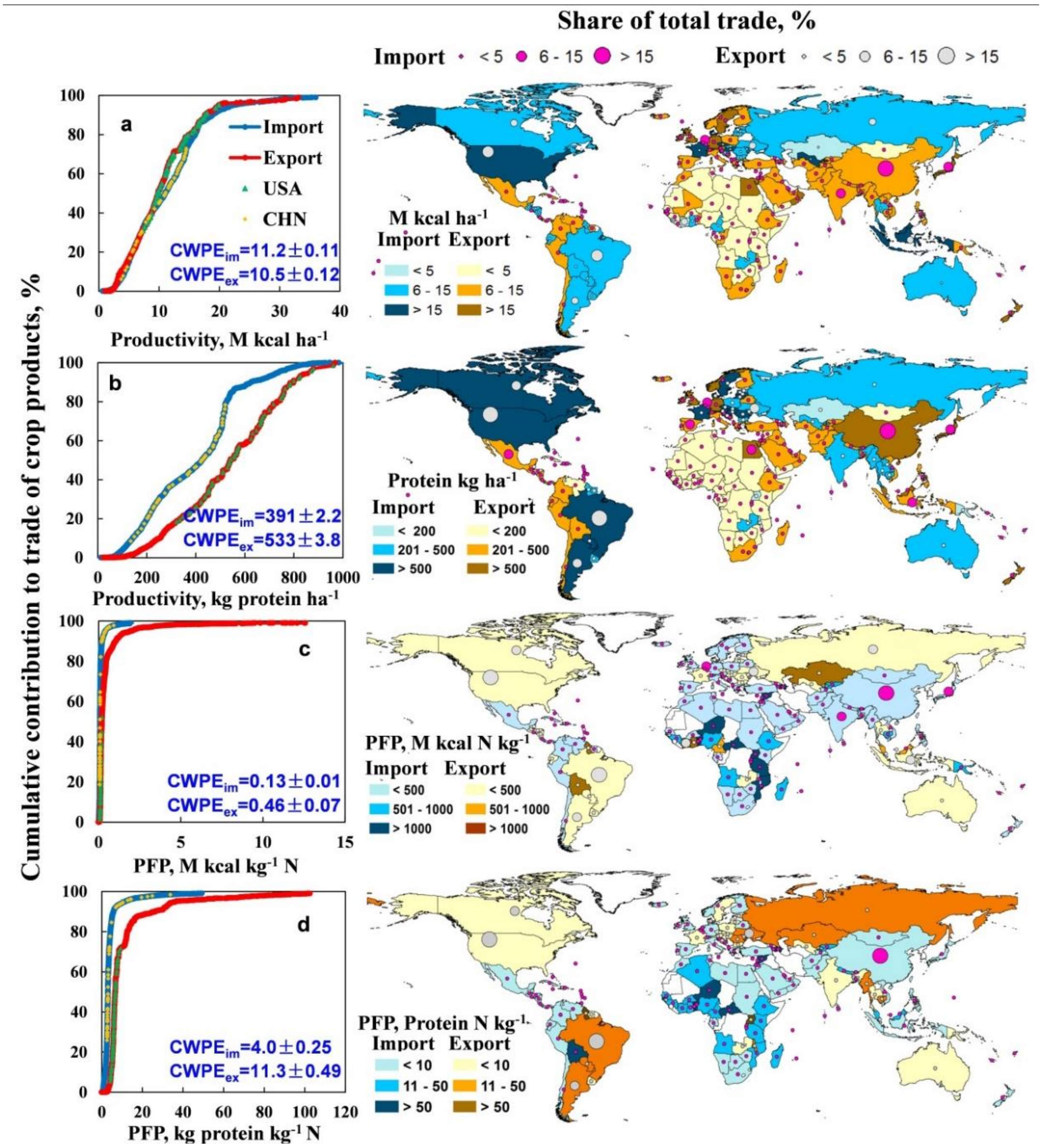

Fig 3. Cumulative productivity-trade distribution curves. Panels (a,b) refer to exporting and importing countries for crop productivity and panels (c,d) refer to partial fertilizer productivity (PFP) of N in terms of calorie and protein production from 1961 to 2017 (left), and productivity and contributions of each country to total trade in 2017 (right). Colors in the maps represent the level of productivity of exporting and importing countries; the size of the circle of each country represents the contribution to total export or import. CWPE$_{im}$ or CWPE$_{ex}$ are the concentration weighted average productivity (CWPE) of importing or exporting countries, respectively. The error bars related to the selection of the max productivity at 98.5%, 99.0% and 99.5%contributions to the total traded products.

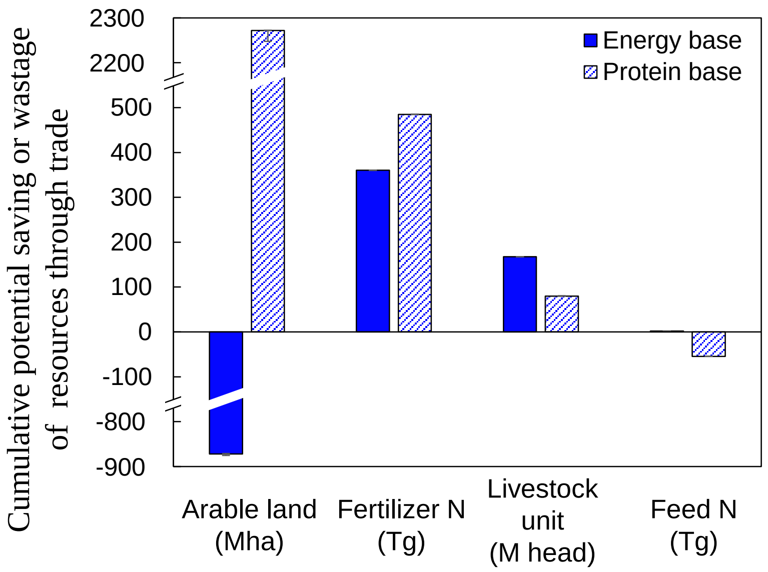

Fig 4. Cumulative potential saving. Positive values correspond to savings and negative values correspond to wasting of arable land (Mha), synthetic fertilizer N (Tg), livestock units (M head), and feed N (Tg), as a result of trade of crop land livestock products between exporting and importing countries with productivity differences during the period 1961 to 2017.

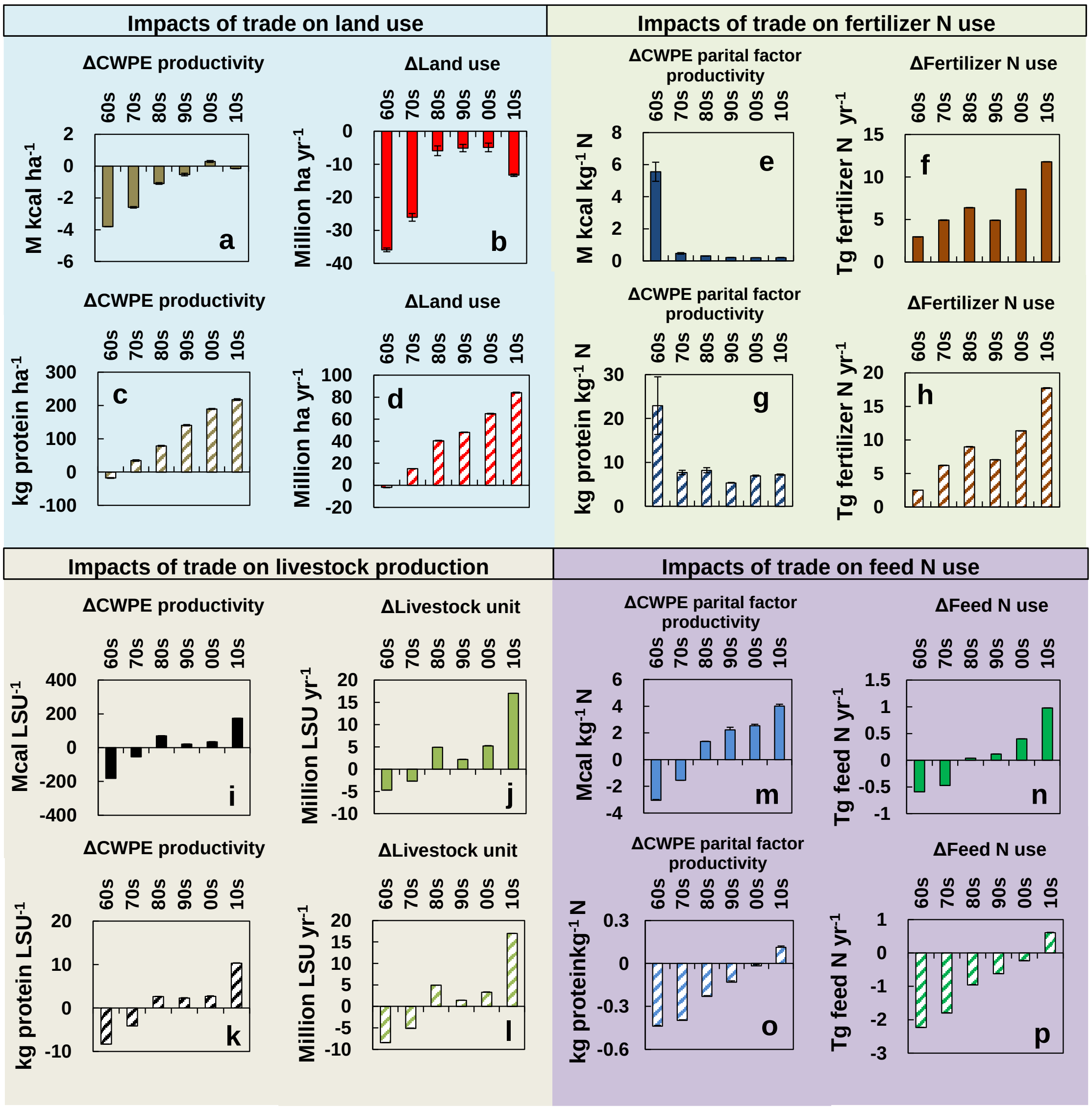

Fig 5. Changes per decade in the impacts of trade. Panels show impacts on crop productivity (a, c) potential land saving (b, d), partial fertilizer nitrogen (N) productivity of crop production (e, g), potential synthetic fertilizer N saving (f, h), livestock productivity (i, k), potential livestock units saving, partial feed N productivity of livestock production (m, o), and potential feed N saving (n, p). Δmeans the differences between exporting and importing countries. $CWPE_{im}$ and $CWPE_{ex}$ were the weighted production efficiency for importing and exporting countries, respectively. 2010s including data of 2011-2017. The error bars related to the selection of the max productivity at 98.5%, 99.0% and 99.5% of total traded products. Solid filled column were energy-based results, while diagonal line filled column were protein-based results.

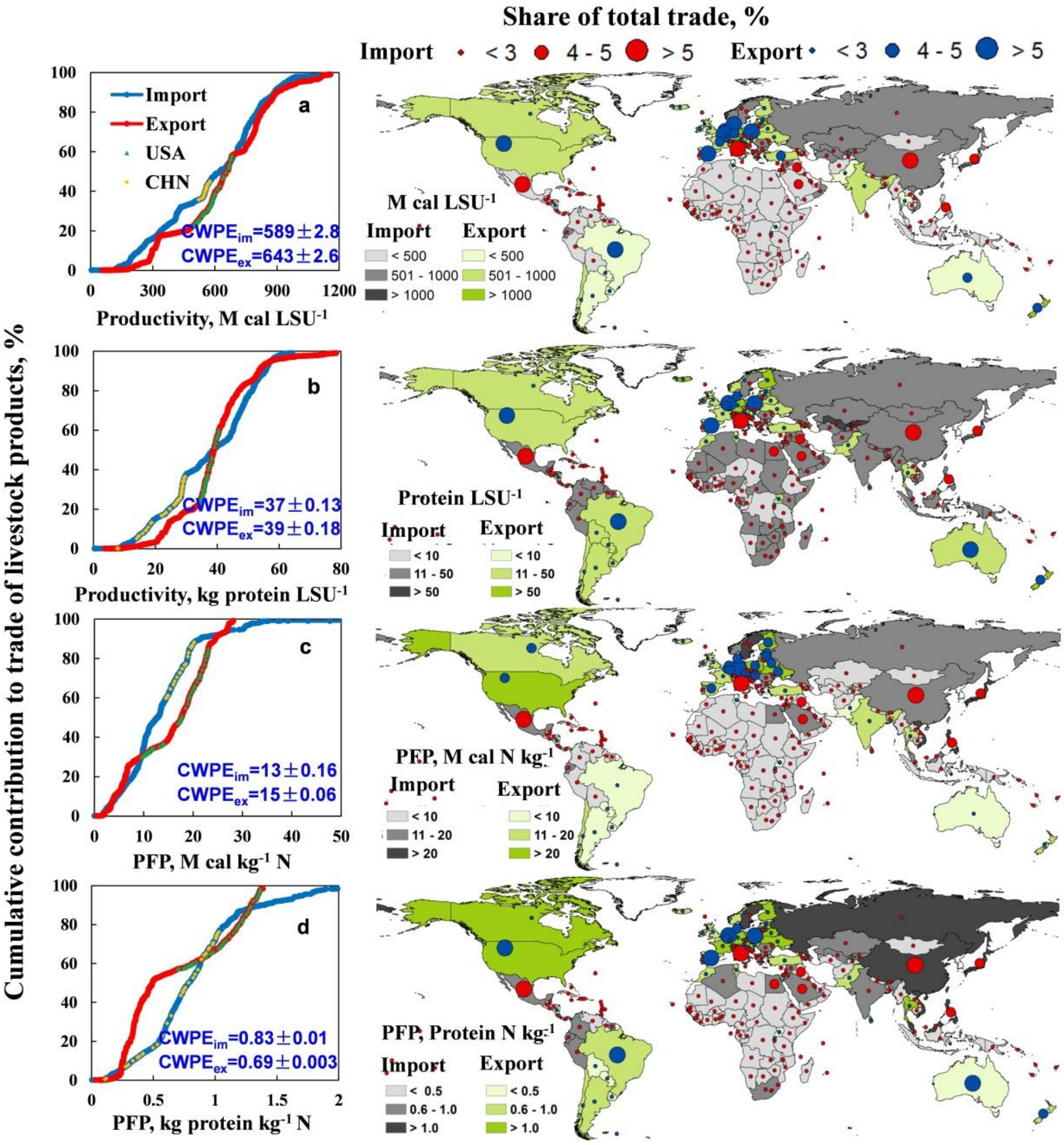

Fig 6. Cumulative productivity-trade distribution curves of exporting and importing countries. Panels correspond to livestock energy and protein production per livestock unit (a, b) and per feed nitrogen (N) input (c, d) from 1961 to 2017 (left panel), and productivity and contributions of each country to total trade in 2017 (right panel). Color in the maps represents the level of productivity or efficiency of exporting and importing countries; the size of the circle of each country represents the contribution to total export or import. CWPE$_{im}$ or CWPE$_{ex}$ are the concentration weighted average productivity/efficiency (CWPE) of importing or exporting countries, respectively. The error bars related to the selection of the max productivity at 98.5%, 99.0% and 99.5%contributions to the total traded products.

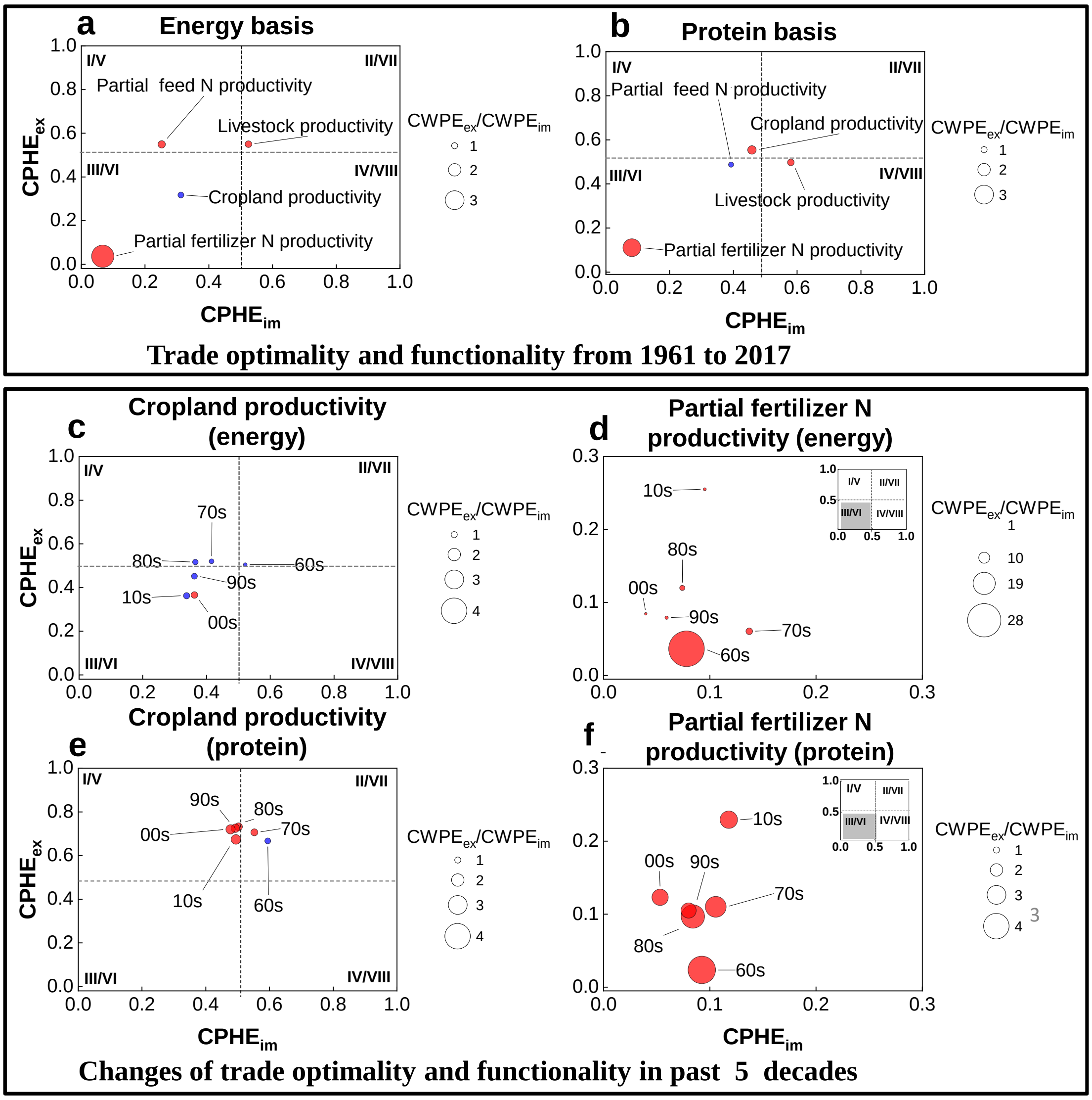

Fig 7. Trade optimality and functionality levels. Optimality and functionality of crop and livestock products from 1961 to 2017 in show in terms productivity using a calorie basis (a) or an protein basis (b), and in different decades in terms of calorie basis (c, d) and protein basis (e, f) of crop and livestock production. The size of the circles represents the differences of the concentration weighted production efficiency (CWPE) between exporting and importing countries, i.e., CWPE$_{ex}$-CWPE$_{im}$. The red solid dots represent positive trade optimality (levels I to IV; i.e., CWPE$_{ex}$ / CWPE$_{im}$ $\geq$ 1.0), and blue solid dots represent the negative trade optimality (levels V to VIII; i.e., CWPE$_{ex}$ / CWPE$_{im}$ < 1.0.