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Spatial mismatch and inequality between ecological pressure and economic benefits embodied in agricultural trade

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ABSTRACT

Agricultural trade can balance regional supply and demand but also induces spatial transfers of ecological pressure. However, few studies have combined the spatial transfers of ecological pressures with economic benefits to explore spatial mismatch and inequality. Understanding this relationship can reveal underlying reasons for the dilemma between economic development and ecological conservation. This study uses China as an example, combines the Lund-Potsdam-Jena Dynamic Global Vegetation Model with an environmentally extended multiregional input-output model to track spatial flows of Human Appropriation of Net Primary Productivity (HANPP) across provinces and establishes an Ecological Pressure Inequality index to quantify inequality by comparing them with value-added flows in time and space. The results show that northeast China bored net HANPP from central and western region, but it still need transferred 17.36 million yuan to those regions in 2012, in contrast, central China bore only 16.59% of the net HANPP yet still receiving 45.02% of the net value-added, revealing a significant spatial mismatch. After 2015, despite the increase in net HANPP transferred from western region to the northeast region, the net value added transferred to the northeast has been declining. At the provincial level, Anhui, Hunan, and Sichuan provinces transitioned toward dual-benefit positions, gaining economic advantages while offloading ecological pressure, whereas Jilin remained in a loss–loss state, suffering both ecological and economic deficits. Distant trade contributes more significantly to ecological inequality than adjacent trade. Stratified analysis reveals that variations in transportation accessibility, fiscal priority, and mechanization jointly characterize the structural heterogeneity of the mismatch across provinces. The study also emphasizes that distant trade cross-regional governance requires attention in ecological compensation. The methodology and insights offer valuable guidance for addressing similar sustainability challenges in other countries experiencing rapid economic development and regional disparities.

1. Introduction

Since the industrial revolution, the Earth's system has entered the Anthropocene epoch, where human activities have been the predominant driver of global environmental changes (Reader et al., 2022; Steffen et al., 2011). This leaves developed regions facing a dual challenge: declining agricultural production capacity because of the occupation of agricultural land and ecological resources by urban expansion (Wang et al., 2012), and rising demand for agricultural products driven by population influx (Liang et al., 2021). Inter-regional agricultural trade can effectively mitigate human-land conflict caused by tight land resources. As consumption regions obtain agricultural goods and services from beyond their borders, production regions must bear the additional ecological resource pressures caused by others' demands through agricultural trade (Du et al., 2024). Consequently, ecological resource burdens are transferred along the supply chain from consumption to production, further intensifying cross-regional imbalances and unequal ecological pressure (Lyu et al., 2024).

A promising approach to measure human dominance over landscapes and pressure on ecosystems is the concept of "Human Appropriation of Net Primary Production (HANPP)" (Casas-Ledón et al., 2023; Haberl et al., 2007). Net primary production (NPP) refers to the biomass produced by plants through photosynthesis and is the most fundamental and indispensable resource in the ecosystem (Wackernagel et al., 2021).

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Human land-use activities such as agriculture, forestry, and grazing inevitably interfere with and utilize part of the NPP (Lyu et al., 2024). Based on this, the HANPP quantifies the portion of NPP appropriated by humans for economic purposes and is considered a suitable metric for assessing human-induced ecological resource pressure.

The assessment of HANPP is receiving increasing scholarly attention (Haberl et al., 2014; Wang et al., 2024b). Existing HANPP measures typically adopt either production-based or consumption-based HANPP (Erb et al., 2009; Haberl et al., 2014). The production-based HANPP assesses the appropriation of ecological resources within the territory of a region (Krausmann et al., 2013). Haberl et al. (2007) found that the territorial HANPP in Southeast Asia was more than three times higher than that in north America. However, part of the territorial HANPP stems from the consumption of other regions through trade, meaning that these figures do not fully reflect the spatial transfers driven by cross-regional trade (Weinzettel et al., 2019). The consumption-based HANPP can trace the HANPP embodied in goods consumed within a region, thus capturing the ecological impact of human consumption (Roux et al., 2022). This reflects a spatial disconnection between production and consumption (Wiedmann and Lenzen, 2018). For example, production-based agricultural HANPP is concentrated in major producers such as Brazil, China, and the U.S., whereas large economies tend to show the highest consumption-based HANPP (Liang et al., 2023). Therefore, countries with relatively low domestic production can still appropriate extensive ecological resources globally owing to high consumption demand. Many studies have revealed the HANPP flows embedded in agricultural trade at the national level by comparing production-and consumption-based HANPP (Erb et al., 2009; Liang et al., 2023; Wang et al., 2024a). However, research on the intra-national spatial transfers of HANPP remains scarce despite similar phenomena occurring within countries.

Moreover, existing research has rarely analyzed the spatial transfers of HANPP alongside another critical factor in trade: economic gain (value-added). Trade is profit-driven. Inter-regional exchanges not only cause HANPP flows but also generate economic benefits (Zhang et al., 2023). Many less-developed regions seeking economic growth and poverty alleviation intensively export primary ecological resources (e.g., raw grains, forestry products, fisheries, and livestock) to earn income (Pan et al., 2022). Because of their limited technological capacity and underdeveloped industrial structures, these areas rely on exporting minimally processed agricultural goods, which yield low value-added and poor economic returns. Consequently, ecological pressure intensifies while local economies remain stagnant (Pan et al., 2022; Qi et al., 2024). Developed regions import "low value-added, high ecological pressure" products from less-developed areas, and export "high value-added but low ecological resource pressure" products in return. This leads to an imbalance between the spatial transfer of ecological pressure and economic benefits, thereby exacerbating inter-regional ecological inequality (Su and Ang, 2014; Zhang et al., 2023). Such inequality manifests not only as a spatial disconnect between ecological pressure and economic benefits but also in the uneven distribution of environmental costs across regions (Zhang et al., 2018a).

According to the above analyses, although the HANPP embodied in agricultural consumption has attracted increasing attention, three critical research gaps remain. First, as the largest administrative unit for regional governance, provinces play a central role in formulating land use, ecological compensation, and development strategies. Thus, understanding intra-national HANPP flow is essential for designing equitable and effective sustainability policies. However, most existing studies focus on international trade, with limited attention paid to HANPP transfers within national borders. Second, current research often treats HANPP as an isolated ecological indicator (Liang et al., 2023; Wang et al., 2024a), overlooking its relationship with value-added flows. This lack of integration hinders a comprehensive understanding of the ecological–economic tradeoffs and spatial inequalities embodied in agricultural trade. Third, trade flows connect regions that are distant from the geographic boundaries (Liu, 2023; Xu et al., 2020). Compared with adjacent trade, distant trade often obscures ecological impacts and may be neglected by policymakers (Jia et al., 2024; Xiao et al., 2024). However, no study has systematically compared HANPP flows and ecological inequality between adjacent and distant trade relationships, leaving it unclear whether the spatial effects of trade vary with regional contiguity.

Over the past four decades, China has experienced unprecedented urbanization. To ensure food security and protect farmland, the government established seven major agricultural production zones under major function-oriented zones and implemented policies, such as the occupation-compensation balance for cultivated land. These measures have concentrated agricultural land in remote and less-developed regions, increasing reliance of developed areas on external ecological resources. Meanwhile, extensive cross-regional transportation networks have facilitated the efficient flow of agricultural products, further intensifying intra-national ecological resource transfer. As a result, ecological resources from remote rural areas are continuously funneled toward urban centers. Research has shown that although China has achieved ecological resource self-sufficiency, significant regional disparities remain (Du et al., 2021) because of its vast territory, diverse resource endowments, and pronounced economic heterogeneity across provinces (Wei et al., 2020; Zhang et al., 2023). As one of the most populous countries and the world's second-largest economy, China provides a representative case for exploring the spatial transfers of HANPP within national borders as well as the domestic ecological inequality embodied in agricultural trade.

To address the research gap summarized above, we used China as a case study and applied the HANPP indicator to represent ecological pressures. We first used a dynamic global vegetation model (LPJ-DGVM) and multisource data to calculate production-based HANPP. Based on this, we integrated production-based HANPP into an environmentally extended multiregional input–output (MRIO) model to calculate the consumption-based HANPP in 2012, 2015, and 2017. We then traced the spatial transfer and temporal trends in the net HANPP and value-added flows embodied in agricultural trade. Finally, we extended the widely used Pollution Terms of Trade (PTT) framework (Antweiler, 1996), by replacing "pollution" with HANPP and then applied a symmetric and bounded standardization to improve the stability and comparability of the index without introducing distortion. Since differences in ecological inequality between adjacent and distant trade relationships remain unclear, we further classified agricultural trade into adjacent trade (Trade among provinces sharing a border) and distant trade (Trade among provinces hat do not share a common boundary) based on topological contiguity and compares their respective impacts on ecological pressure transfers and inequality (Anderson, 2003). The findings of this study, which highlight regional disparities, can support decision-makers in seeking region-specific strategies to alleviate ecological resource pressures and promote balanced economic development.

2. Method

2.1. Methodology framework

A flowchart of the study methodology is shown in Fig. 1. We adopted the HANPP indicator to represent ecological pressure. In the first step, we employed the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) to simulate potential NPP (NPP_{pot}), and used remote sensing land-use data and socioeconomic statistics to derive the actual NPP (NPP_{act}) and human-harvested NPP ($HANPP_{harv}$). These three components were used to calculate the production-based HANPP. By integrating HANPP with input–output data, we applied an environmentally extended multiregional input–output (EE-MRIO) model to estimate the consumption-based HANPP embodied in interprovincial agricultural trade. In the second step, the provinces are divided into four

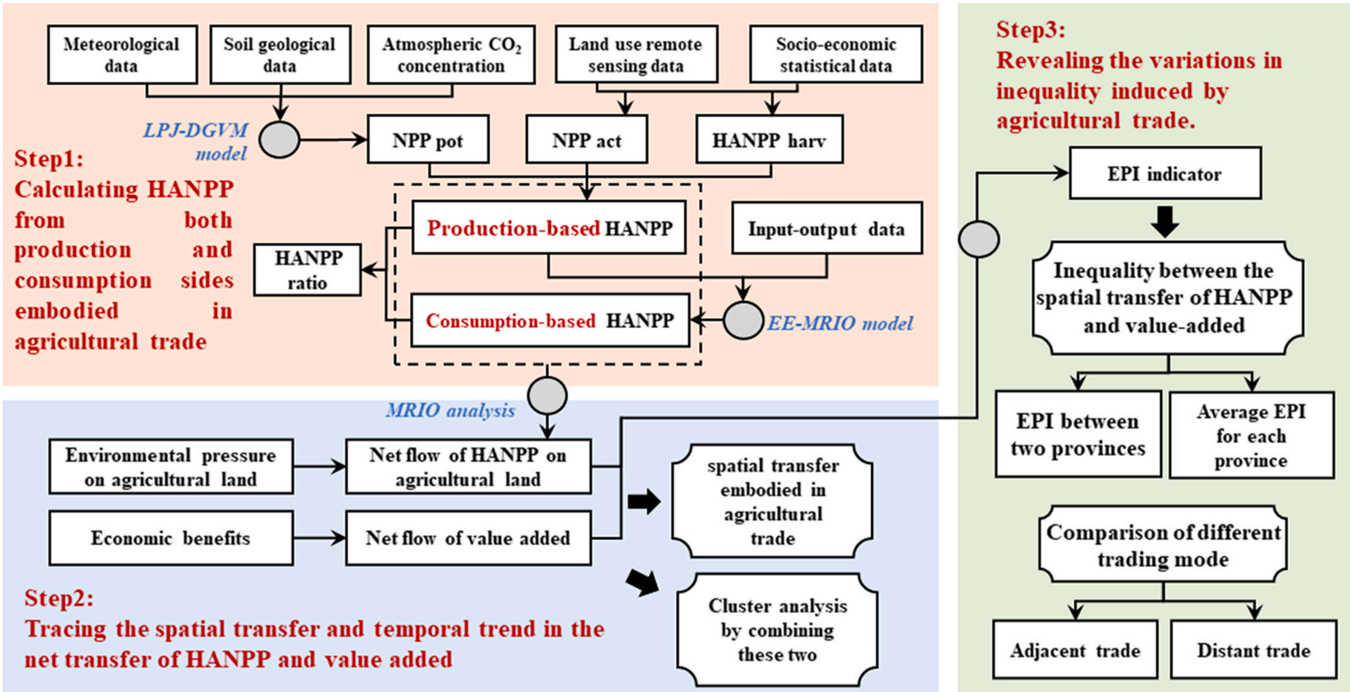

Fig. 1. Methodology framework.

major regions (the regions corresponding to each province are listed in Table S7). MRIO analysis was used to trace inter-provincial and regional flows of both HANPP and value-added and to calculate their net flows, capturing the spatial transfer and temporal dynamics of ecological pressure and economic benefit. Based on these two indicators, we conducted a cluster analysis to categorize provinces with similar trade patterns. In the third step, we constructed an EPI indicator based on the HANPP and value-added flows to quantify bilateral inequality between provinces as well as the overall inequality within each province. Finally, we distinguish between adjacent and distant trade modes, and compare their contributions to ecological inequality.

2.2. Calculating HANPP

HANPP quantifies the reduction of potential ecosystem productivity due to human activities. It is conceptually defined as the difference between the potential NPP under natural vegetation (NPP_{pot}) and the NPP remaining in ecosystems under current land use. Meanwhile, HANPP can be decomposed into two additive components: the biomass directly appropriated by humans through harvest ($HANPP_{harv}$) and the productivity reduction caused by land use/cover change ($HANPP_{lucc}$), where $HANPP_{harv}$ is calculated as the difference between (NPP_{pot}) and actual NPP (NPP_{act}) (Haberl et al., 2007, 2014). This can be represented by the following equation:

$$\mathrm{HANPP} = HANPP_{harv} + HANPP_{lucc} \quad (1)$$

$$HANPP_{lucc} = NPP_{pot} – NPP_{act} \quad (2)$$

NPP_{pot} was simulated using the Lund–Potsdam–Jena Dynamic Global Vegetation Model (LPJ-DGVM) (Sitch et al., 2003), which dynamically couples carbon and water cycles and has been widely validated in previous ecological studies. The specific method is described in Supplementary 1.1.

The calculations of $HANPP_{harv}$ and NPP_{act} were divided into four categories: cropland, forest, grassland, and settlements. For croplands, $HANPP_{harv}$ include both the primary crop yield and crop residues. Used and unused aboveground harvest residues were deduced from yield data using harvest factors (Krausmann et al., 2013). NPP_{act} equal the sum of $HANPP_{harv}$ and pre-harvest losses because of herbivory and weeds (Krausmann et al., 2013). For forests, $HANPP_{harv}$ include industrial wood, bamboo, and fuelwood extraction, as well as timber harvested for domestic use. Based on Krausmann et al. (2013), NPP_{act} was assumed to be similar to NPP_{pot}, meaning minimal productivity loss due to land use. $HANPP_{harv}$ of grassland was calculated as the difference between the total calculated feed requirement of roughage consuming livestock and the total feed available from commercial feed and crop residues used as feed. NPP_{act} of grassland were categorized as natural or artificial, and each was calculated differently (Haberl et al., 2007). For settlement and infrastructure areas, $HANPP_{harv}$ represents vegetation removed or managed due to human occupation (e.g., mowing, maintenance) (Krausmann et al., 2013).

Supplementary 1.2 and 1.3 explain the detailed methodology for calculating NPP_{pot}, $HANPP_{harv}$, and NPP_{act}. The HANPP calculated here is the production-based HANPP referred to below.

2.3. MRIO analysis

An environmentally extended MRIO model was used to estimate provincial and regional HANPP and value-added transfers embodied in trade within China from 2012 to 2017. MRIO is suited to tracing direct and indirect flows across regions within a unified accounting framework. This model has been extensively developed to investigate environmental pollution and resource depletion associated with trade, including air pollution (Chen et al., 2018a, 2018b; Zhang et al., 2018b), carbon emissions (Chen et al., 2017; Dong et al., 2022; Meng et al., 2018), water consumption (Liu et al., 2019; Zhang and Anadon, 2014), land use (Chen et al., 2018a, 2018b; Yu et al., 2013), energy use (Lee et al., 2021).

The original MRIO dataset combines agriculture, forestry, animal husbandry, and fisheries into a single sector due to the data structure provided by the national input–output compilation. And the HANPP used in this study only reflects the ecological resources provided by terrestrial ecosystems. To ensure consistency between the MRIO table and the HANPP, we have revised the MRIO dataset to exclude the fishery component from the aggregated “agriculture” sector, following a widely applied method supported by Wenz et al. (2015). Specifically, for each province and year, we calculated the share of fishery gross output in the total gross output of farming, forestry, livestock, and fisheries, and then proportionally adjusted the corresponding intermediate and final demand matrices in the MRIO model using a gross output weighted proportional scaling method (Du et al., 2025).

The fundamental linear equation can be represented as:

$$X = (I - A)^{-1}F^j = LF^j \quad (4)$$

Here, $X = \left(x_k^i\right)$ is a vector of the total output of sector k in region i; $F^j = (f_k^{ij})$ is region j's final demand for goods of sector k from region i; A is a technical coefficient matrix with elements $\left(a_{ks}^{ij}\right)$ which is derived from $a_{ks}^{ij} = z_{ks}^{ij}/x_k^i$, where z_{ks}^{ij} represents the intersector monetary flows from sector k in region i to sector s in region j; $L = (I - A)^{-1} = \left(l_{ks}^{ij}\right)$ is the Leontief inverse matrix that captures both direct and indirect inputs required to satisfy one unit of final demand in monetary values; and I is the identity matrix.

The consumption-based HANPP and economic benefits embodied in agricultural trade can be calculated by combining the monetary MRIO table with information on the use of the HANPP and value-added. The complete details and formula for calculating consumption-based HANPP are provided in Supplementary 1.4.

2.4. Ecological Pressure Inequality (EPI) index

We developed an EPI indicator based on the concept of the Pollution Terms of Trade (PTT). The PTT proposed by Antweiler (1996) measure the environmental gains or losses that a country obtains through international trade. Simply, it is the ratio between the pollution content per dollar of exports and that per dollar of imports. When imported goods contain higher pollution intensity than exported goods, a country gain environmentally. This PTT index since been widely applied and modified to reflect trade imbalances and long-term ecological inequalities. For example, Wang et al. (2020) used sulfur dioxide emissions as a proxy for pollution to assess environmental inequality in China's trade, and Zhang et al. (2023) replaced pollution with carbon emission to construct the Emission Terms of Trade for CO_2. We adapted this approach to focus on ecological pressure rather than pollution. Following this approach, we replace pollution with HANPP to couple ecological pressure with economic benefits in interprovincial trade.

First, we calculate the inequality between the two provinces in bilateral trade:

$$R_{ij} = \frac{CHANPP^{ij}/CV^{ij}}{CHANPP^{ji}/CV^{ji}} \quad (5)$$

Since $R_{ij} = 1/R_{ji}$, this formulation faces two issues: (1) the values are not symmetric between trading pairs, making bilateral comparisons and aggregation difficult, and (2) the ratio can vary over several orders of magnitude, causing instability and overemphasis on extreme cases.

To resolve this, we standardized the ratio using a symmetric, bounded transformation:

$$EPI_{ij} = \frac{R_{ij} - 1}{R_{ij} + 1} \quad (6)$$

The EPI value ranges from −1 to 1, where negative values indicate that province i gains higher economic returns relative to its ecological pressure (trade advantage), and positive values indicate that province i bears higher ecological pressure relative to its economic gains (trade disadvantage). Values near zero represent balanced ecological–economic exchanges, while larger absolute values reflect stronger inequality between trading partners. Sensitivity analysis of the EPI metric can be found in Supplementary 2.

Based on this, we calculate the average EPI for each province across all trading partners:

$$EPI_i = \frac{1}{n}\sum_{j=1}^{n} EPI_{ij}\ (i \neq j) \quad (7)$$

We further classified provincial trading partners into adjacent and distant groups based on topological contiguity. Specifically, we define adjacent trade as trade flows between provinces that share a common administrative boundary, and distant trade as flows between provinces that do not share a common boundary. This adjacency-based definition emphasizes topological rather than metric proximity and is widely adopted in spatial econometric and interregional trade studies (Anderson, 2003; Xu et al., 2020). For each province, we then calculated the average EPI values separately for its adjacent and distant trading partners to compare the ecological–economic relationships. The classification of adjacent and distant partners is provided in Supplementary Table S8.

2.5. Stratified analysis

To further explore the potential socioeconomic and technological factors affecting the mismatch between ecological pressure and economic benefits, we conducted a stratified analysis of the EPI. This method compares the distributional differences of EPI under varying socioeconomic conditions to reveal structural characteristics. Four representative indicators were selected to capture variations in agricultural prices, transportation accessibility, fiscal priorities, and mechanization levels: (1) Agricultural value-added deflator, calculated as the ratio of agricultural value added at current prices to that at constant prices multiplied by 100, which reflects changes in the agricultural output price level relative to the base year; (2) Transportation accessibility, measured by highway density, defined as the ratio of total highway length to the provincial area; (3) Agricultural fiscal priority, defined as the proportion of budgetary expenditure on agriculture, forestry, and water affairs to total general public budget expenditure, reflecting the internal fiscal emphasis on the agricultural sector; and (4) Mechanization level, proxied by total agricultural machinery power per unit of arable land, representing the intensity of agricultural technological equipment across provinces. Unlike the other indicators, agricultural value-added deflator is inherently time-dependent. The deflator reflects the relative change in agricultural prices against a moving base year and is affected by nationwide inflation, input costs, and grain procurement policies. To isolate spatial differences in price structures from overall temporal fluctuations. The stratified analysis was conducted separately for 2012, 2015, and 2017, thereby capturing EPI responses under different price contexts. For each indicator, provinces were divided into three groups (low, middle, and high) based on the tertile distribution of the indicator values. The distributions of EPI across the three strata were then compared to evaluate whether EPI differed significantly under different socioeconomic conditions. Statistical significance was assessed using the Kruskal–Wallis H test, followed by pairwise Wilcoxon rank-sum tests to identify differences between groups.

2.6. Data source

The driving data of the LPJ-DGVM included meteorological variables (temperature, precipitation, cloud cover, and wet days), soil texture, and CO_2 concentrations. Table S1 lists all the input datasets and their sources. We used socioeconomic statistics from the China Statistical Yearbook, China Animal Husbandry Yearbook, and China Forestry Statistical Yearbook to calculate the $HANPP_{harv}$ and NPP_{act} across Chinese provinces. For the grassland NPP_{act}, the spatial distribution of natural and artificial grasslands was identified using an annual 30-m global grassland map (Parente et al., 2024). To estimate $HANPP_{harv}$ in settlement and infrastructure areas, we used built-up land data from the Global Artificial Impervious Area product developed by Tsinghua University from

Landsat images and auxiliary datasets (Gong et al., 2020). In this dataset, built-up areas represent the spatial extent of settlement and infrastructure areas in each province.

The 2012, 2015, and 2017 China MRIO tables were obtained from the CEADS database (Zheng et al., 2021). The database consists of 42 industrial sectors and 31 provinces in China, in which final consumption is divided into five parts: rural resident consumption, urban resident consumption, governmental consumption, capital formation, and inventory increase. All data required for stratified analysis can be found in the China Statistical Yearbook.

3. Results

3.1. Comparison of production-based and consumption-based HANPP embodied in agricultural trade

Consumption- and production-based HANPP exhibited distinct spatial heterogeneity across China (Fig. 2). By 2017, most central and eastern provinces had achieved that the consumption-based HANPP exceeded the production-based HANPP in 2017, indicating these regions relied heavily on external ecological resources. In contrast, most northeastern and western provinces exhibited the consumption-based HANPP was lower than the production-based HANPP, demonstrating these areas were net ecological providers. Affluent and developed regions were typically consumption-dominant, whereas less-developed regions are production-dominant.

Regional differences emerged clearly in temporal trends. Most central provinces experienced continuous increases in consumption-based HANPP, while Many eastern provinces showed declining trends. In the central region, Henan, Hunan, Jiangxi and Shanxi provinces transitioned from production dominance to consumption dominance between 2012 and 2017, reflecting increased local biomass demand driven by urbanization and dietary changes, while local production lagged due to land constraints or stagnating yields. As the two most developed cities in China, Shanghai and Beijing, both recorded the highest HANPP ratios during this period but showed different trajectories. Shanghai had the highest consumption-based HANPP in 2012 (HANPP ratio = 0.91) but declined continuously over the following five years. Beijing's consumption-based HANPP initially decreased but rebounded to surpass Shanghai in 2017, reaching the highest ratio in China (0.81).

The average self-supply rate (i.e., the portion that is produced for self-consumption divided by the total consumption-based HANPP) across provinces continued to decline, reaching 53.68% in 2017. This indicates growing dependence on external sources for agricultural and ecological needs and rising regional specialization through trade. Self-supply rates in major eastern coastal regions remained consistently low. Over a five-year average, only 7.08% and 6.69% of the biomass consumed in Shanghai and Beijing, respectively, were sourced from local production, while the remainder was imported from other regions. In contrast, agricultural provinces such as Heilongjiang and Inner Mongolia had the highest production-based HANPP but consumed only 38.42% and 45.89% locally, respectively, indicating that a significant share of ecological pressure on agricultural land in these areas stemmed from external consumption via trade.

3.2. Spatial transfer of HANPP and value-added embodied in agricultural trade for regions and provinces

The spatial transfers of HANPP and value added revealed a clear mismatch between ecological pressure and economic benefits across China's regions (Fig. 3a–f). From 2012 to 2017, the central region imported decreasing HANPP to the eastern regions, while simultaneously exporting increasing HANPP from the western and northeastern region. And, the net HANPP outflow from the central region tend to flow into

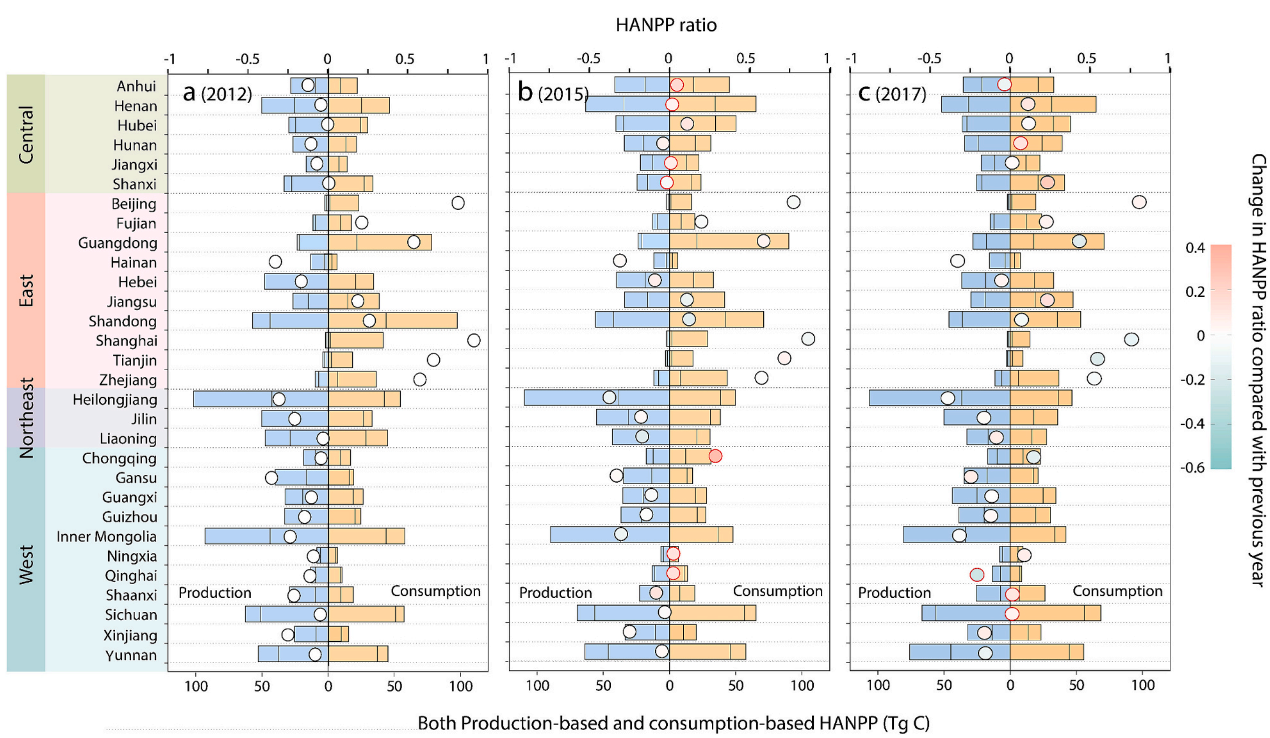

Fig. 2. Comparison of production-based and consumption-based HANPP for each province during 2012–2017. The blue bars on the left and the orange bars on the right represent production-based HANPP and consumption-based HANPP, respectively. The internal line within each bar indicates the portion that is produced for self-consumption. The circles reflect the comparison between consumption-based HANPP and production-based HANPP in each province, i.e., the HANPP ratio. A red circle border denotes a shift in position (from left to right or right to left) compared to the previous year. The circle's fill color indicates changes in the HANPP ratio, with red signifying an increase and green signifying a decrease relative to the previous year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

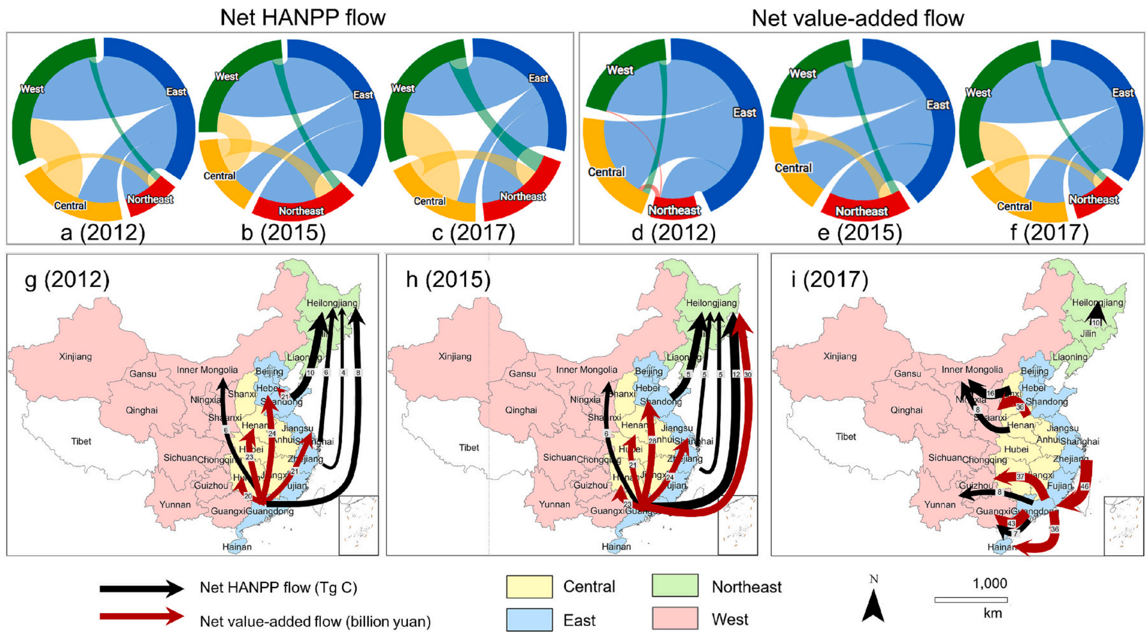

Fig. 3. Changes in the net flow of HANPP and value-added for regions and provinces. Fig. a-c, Net HANPP flows between regions in (a) 2012, (b) 2015, (c) 2017. Fig. d-f, Net value-added flows between regions in (d) 2012, (e) 2015, (f) 2017; Fig. g-i, Top 5 pairs for net HANPP flows and net value-added flows between provinces in (g) 2012, (h) 2015, (i) 2017.

the western region. In 2012, compared to the west and northeast, the central region bore the least HANPP(16.59%), yet received 45.02% of the net value-added from the other three regions, as the largest beneficiary with 312.32 million yuan in net economic gains. After 2015, the central region began transferring net value-added to both the northeastern and western regions. By 2017, a new imbalance emerged: the net HANPP transferred from the central region to the western was 2 times that transferred to the northeastern region, whereas the net value-added flow to the west was 4 times that transferred to the northeast. From 2012 to 2017, the central region bears an average annual net HANNPP of 12.84%, and receives only 29.94% of the net value added.

The eastern region was the largest net HANPP exporter and the largest net value-added transfer to the other three regions. However, both net HANPP and value-added outflows decreased gradually over time (HANPP: 191.54 TgC in 2012, 166.56 TgC in 2015, 128.42 TgC in 2017; Value-added: 650.94 million yuan in 2012, 524.85 million yuan in 2015, 414.07 million yuan in 2017). After 2015, eastern regions tend to transfer more net value added to western regions. There is also a phenomenon of spatial mismatch here: on average, the eastern region transfer of net HANPP to the central regions amounts to half of that to the northeastern region, whereas the net value added directed to the central region is 1.6 times that directed to the northeastern region.

The northeastern region bore increasing ecological pressures transferred from the other three regions, totaling 66.65 TgC in 2012, 89.05 TgC in 2015, and 78.21 TgC in 2017. In 2012, although the northeast bored 8.53 TgC net HANPP from central and western region, but it still need transferred 17.36 million yuan to those regions. In 2015 and 2017, despite the increase in net HANPP transferred from west to the northeast (rising from 10.44 TgC in 2015 to 17.33 TgC in 2017), the net value added transferred to the northeast has been declining. From 2012 to 2017, the northeastern region bears an average annual net HANNPP of 36.90%, yet receives only 23.93% of the net value added.

The western region bored net HANPP from the central and eastern regions, and transferred net HANPP to northeast. It has received the most net HANPP over the past five years, and its share of net value added rose substantially from 38.12% in 2012 to 60.21% in 2017, making it the largest recipient of net economic gains after 2015. From 2012 to 2017, the western region bears an average annual net HANNPP of 50.26%, and receives 46.12% of the net value added.

Analysis of the top five provincial pairs for net HANPP and value-added flows revealed changing patterns over time (Fig. 3g–i). In 2012 and 2015, the largest net HANPP flows occurred from the eastern coastal provinces to Inner Mongolia and Heilongjiang. By 2017, the largest net HANPP flow shifted from Jilin Province to Heilongjiang, indicating a more dispersed pattern of HANPP transfers nationwide. Guangdong consistently had the largest net economic outflow of value-added flows. In 2012 and 2015, it primarily transferred value-added to the eastern and central provinces; however, by 2017, the main recipients had shifted to closer provinces in the western region.

Provincial classification based on net HANPP and value-added flows revealed four distinct groups with evolving patterns (Fig. 4). Group I (blue) includes many provinces in the central, northeastern, and western regions, characterized by net imports of both HANPP and value-added, indicating these provinces bear ecological pressure while gaining economic benefits. Many provinces were located in Group I from 2012 to 2017; however, the number gradually decreased over time. Group III (yellow) consists mainly of developed eastern provinces, such as Guangdong, Beijing, Shanghai, and Zhejiang, and is defined by net exports of both HANPP and value-added, suggesting they outsource ecological pressure by compensating for other regions economically. Group III expanded over time, with new members emerging from the central and western regions.

Groups I and III represent relatively balanced situations in which regions either bear ecological pressure while receiving economic gains or transfer ecological pressure while losing economic benefits. However, this balance was disrupted in some provinces. Provinces such as Anhui, Sichuan, and Hunan moved from Group I to Group IV, becoming dual winners by gaining value added while exporting ecological pressure. In contrast, Jilin fell into Group II (lost-lose), with negative net flows of both HANPP and value-added.

Some provinces moved toward more balanced positions. Inner Mongolia shifted from a lost–lost position to Group I after 2015 as its trade benefits improved. Similarly, Jiangsu moved from Group IV to Group II in 2015, becoming a province with net ecological gains but economic losses.

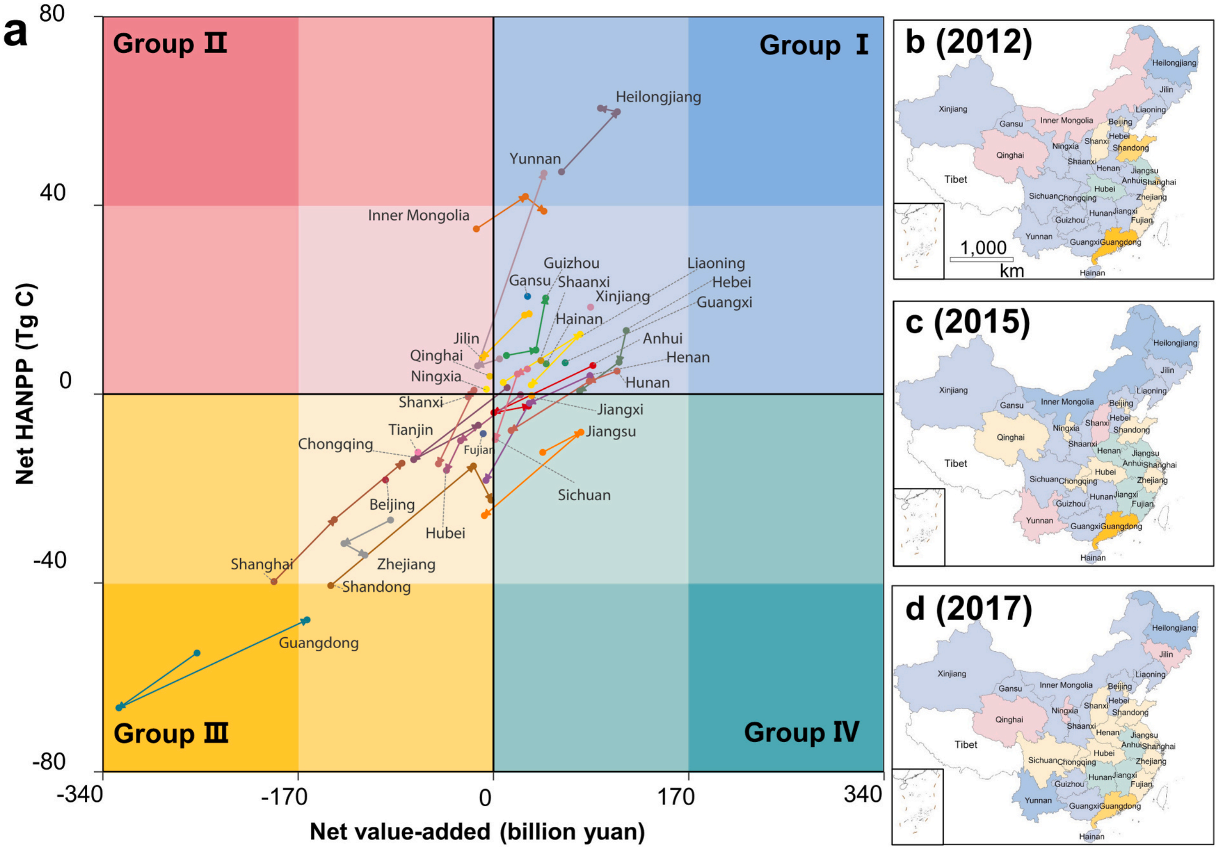

Fig. 4. Classification of 30 provinces according to net flows of HANPP and value- added embodied in agricultural trade from 2012 to 2017. Fig. a, The temporal change of the groups. The horizontal axis represented the net value-added, and the vertical axis referred to net HANPP. A positive net flow value-added indicates that it bears ecological pressure from, or receives economic benefit from other provinces, while a negative net flow value-added indicates that the province transfers ecological pressure or pays economic benefits to other provinces. The three connected points of the same color connected by arrows represent each province's values in 2012, 2015, and 2017, with the direction of the arrows indicating the progression to the next year. If a province's values remained similar across all three years, only a single point is shown on the graph to represent the average value over the three years. Fig. b-d, Spatial distribution of the groups in (b) 2012, (c)2015 and (d) 2017. The colors of the groups in Fig. a represent the legends in Fig. b c d.

3.3. Quantification of inequality in agricultural trade based on EPI indicator

The EPI analysis revealed that the number and intensity of unequal trade relationships increased substantially by 2017 (Fig. 5). The most extreme bilateral inequality occurred between Guangdong and Qinghai in 2017, with an EPI value of 0.96 for Qinghai relative to Guangdong and − 0.96 in reverse. This represents the most severe bilateral inequality, indicating that to obtain the same amount of added value as Guangdong, Qinghai had to bear 52 times more ecological pressure.

In addition, we calculate the average EPI value for each province based on bilateral agricultural trade with all other provinces. This value reflects the ratio between the HANPP per unit of value-added exports and HANPP per unit of value-added imports, offering a comprehensive measure of each province's trade position relative to that of the remaining provinces. As shown in Fig. 5d, most central and eastern provinces, with the exception of Shanxi, Shanghai, and Tianjin, were in an advantageous position from 2012 to 2017, with average EPI values below 0. This indicates that they receive more value-added per unit of HANPP than they give, meaning that their economic compensation is insufficient to offset the ecological pressure that has shifted to other regions. Among them, Zhejiang, Fujian, and Guangdong provinces had the lowest EPI values, indicating the highest levels of ecological inequity in their favor. In contrast, most provinces in the northeastern and western regions (excluding Liaoning, Chongqing, Guangxi, Shaanxi, and Sichuan) were disadvantaged, with average EPI values above zero, indicating that they bear more HANPP per unit of value added received than they export. Gansu, Inner Mongolia, and Qinghai had the highest EPI values, suggesting that they were the most disadvantaged in terms of their ecology and economics.

By combining the EPI and HANPP ratios, we assigned four distinct labels to the 30 provinces (Fig. S1). Most affluent provinces fell into Group II: HANPP exporters with a trade advantage, meaning that they shifted ecological pressure while remaining net beneficiaries. The farther a province is from the origin, the more pronounced this pattern becomes, as in Zhejiang and Guangdong provinces. Many less-developed provinces with abundant ecological resources, such as Guizhou, Jilin, and Inner Mongolia, fall into Group IV, indicating that they supply ecological pressure while remaining at a disadvantage in trade. Several central provinces are located in Group III, representing HANPP importers with a trade advantage; that is, they bear HANPP transferred from other regions while remaining in a relatively advantaged position. Notably, a shift was observed from Group III to Group II between 2012 and 2017. Provinces such as Hunan, Jiangxi, Henan, Anhui, and Sichuan transitioned from net HANPP importers to net exporters while still maintaining an advantageous trade position.

3.4. Differences in ecological inequality between adjacent and distant trade

Comparison of adjacent and distant trade scenarios revealed significant differences in ecological inequality patterns (Fig. 6). At the regional level, the EPI values for adjacent trade were generally closer to zero than those for distant trade, indicating that trade with adjacent

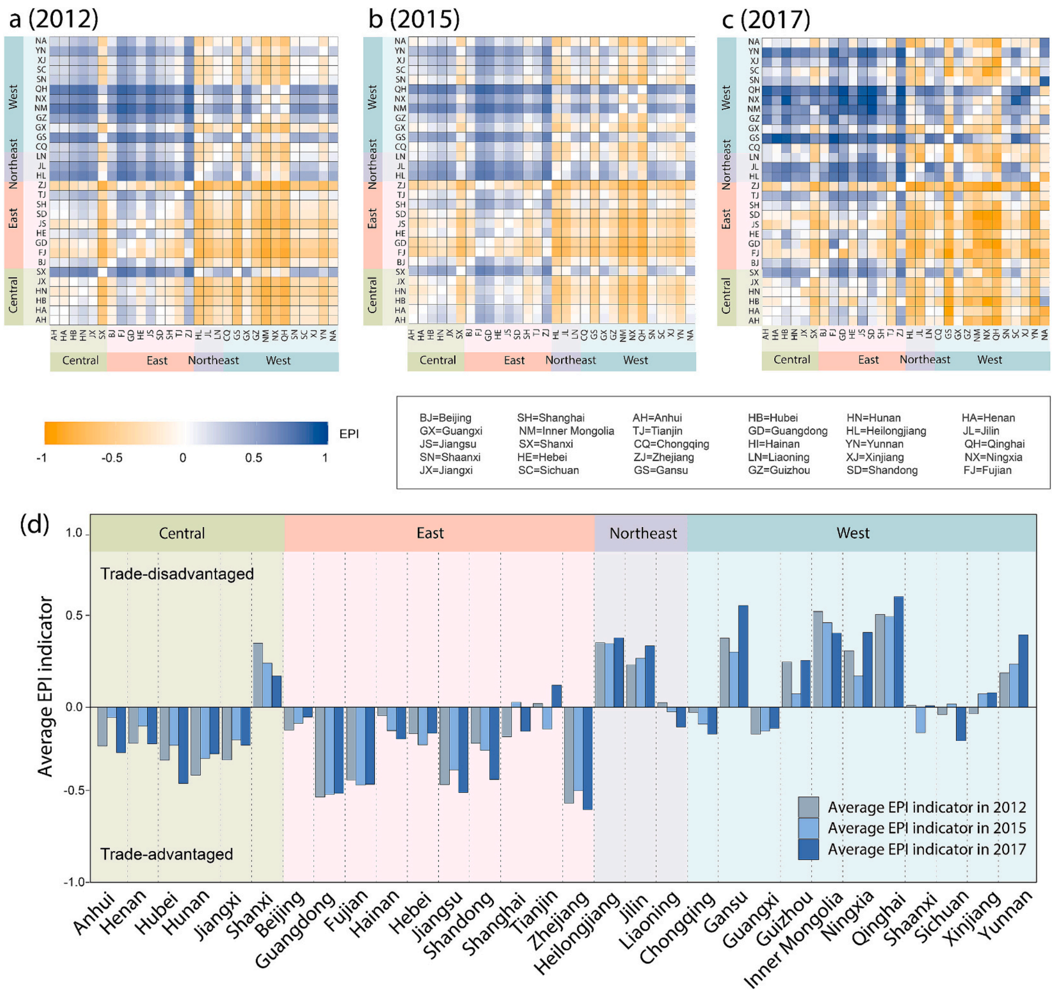

Fig. 5. Inequality embodied in agricultural trade based on EPI indicator from 2012 to 2017. Fig. a-c, EPI value between two provinces in (a) 2012, (b) 2015, and (c) 2017. The vertical axis shows the EPI index of the focal province relative to other provinces, and the horizontal axis shows the EPI index of other provinces relative to the focal province. Fig. d, The average EPI for each province from 2012 to 2017. A value of EPI less than 0 indicates that the province or regions is in an advantageous position when trading with other provinces or regions, while a value of EPI greater than 0 indicates the opposite.

provinces tends to be more equitable than trade with distant provinces (Fig. 6b). The central region was disadvantaged in adjacent trade but becomes advantaged in distant trade. In contrast, the northeast region was advantaged in adjacent trade but shifted to a disadvantaged position under distant trade. The eastern region remains consistently advantaged, whereas the western region is persistently disadvantaged in both trade scenarios. At the province level, distinct patterns emerged between adjacent and distant trade relationships. Anhui, Jiangxi, and Hainan were disadvantaged when trading with adjacent provinces but shifted to advantaged positions under distant trade. Conversely, Xinjiang and Liaoning were advantaged under adjacent trade but became disadvantaged under distant trade from 2012 to 2017 (Fig. 6a).

4. Discussion

4.1. Stratified analysis on the drivers of the ecological - economic mismatch

To design targeted intervention measures for improving the balance between ecological pressure and economic benefits, we selected four indicators, namely the agricultural value-added deflator, transportation accessibility, agricultural fiscal priority, and mechanization level, to stratify the EPI, comparing its variations across different socioeconomic levels in terms of agricultural prices, transportation costs, fiscal priorities, and technological levels. The stratified analysis aims to identify potential underlying factors that may explain the heterogeneity of ecological–economic relationships among provinces.

Across 2012, 2015, and 2017, pairwise comparisons among the low, middle, and high groups based on the agricultural value-added deflator are not significant (Fig. 7a), indicating that provincial differences in price levels were not systematically associated with the EPI during the study period. China's grain price support policies have played an important role in stabilizing domestic grain markets since 2004, with the variance of grain prices declining from 1.7% to 0.98% (Lyu and Li, 2019). These national price-support arrangements effectively stabilized domestic prices while simultaneously suppressing interprovincial price transmission (Huang and Yang, 2017). Consequently, under such a stable pricing regime, variations in agricultural price levels did not constitute a dominant source of spatial heterogeneity in the EPI.

The stratified analysis based on provincial transportation accessibility reveals a clear and significant gradient in the ecological–economic trade mismatch (Fig. 7b). Provinces with lower transportation density exhibit significantly higher EPI values than those with medium or high densities, while the difference between the latter two groups is not significant. This indicates that regions with poorer transportation accessibility tend to experience stronger mismatches, bearing greater ecological pressure relative to economic returns. Limited connectivity constrains the ability of resource-producing provinces to integrate into

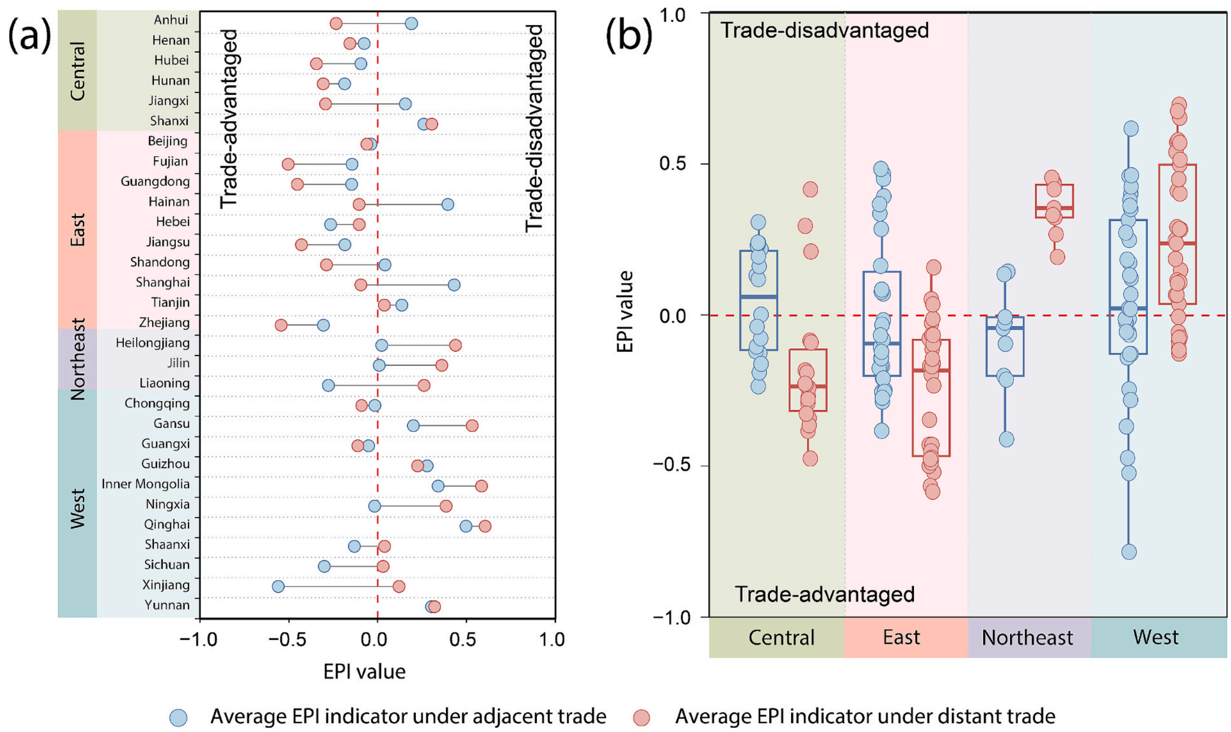

Fig. 6. Comparison of EPI value under adjacent trade and distant trade for (a) each province and (b) each region. A value of EPI less than 0 indicates that the province or regions is in an advantageous position when trading with other provinces or regions, while a value of *epi* greater than 0 indicates the opposite.

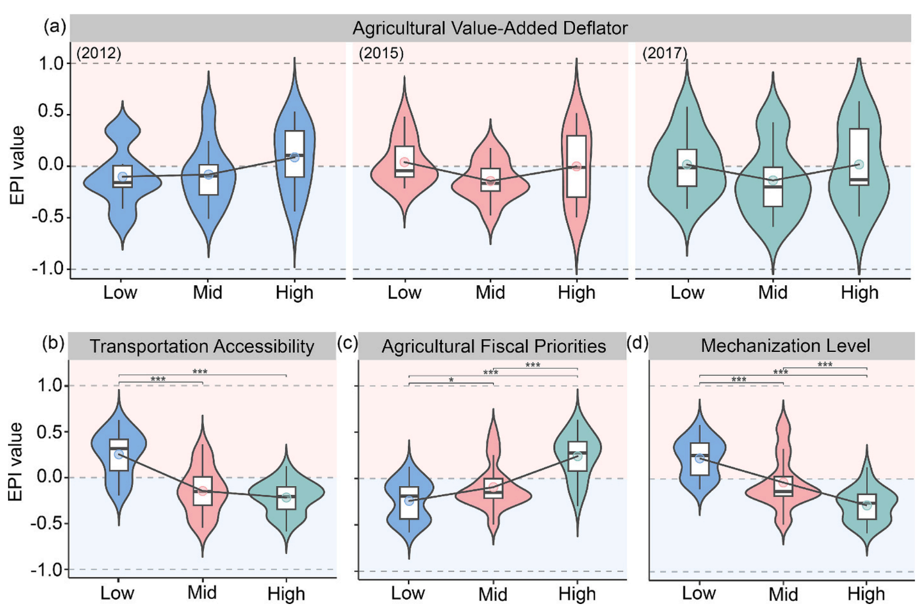

Fig. 7. Comparison of EPI values across different (a) agricultural value-added deflator, (b) transportation accessibility, (c) agricultural fiscal priorities, and (d) mechanization level. * indicates the significance of pairwise comparisons (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$), and no labeling means no significant difference between the two groups.

broader value chains and capture value-added benefits, as high transportation costs hinder the outward flow of agricultural and ecological goods and restrict access to downstream markets (Egger et al., 2023). Consequently, ecological pressure remains localized in low access areas, whereas the corresponding economic benefits are realized mainly in well-connected consumption centers. This finding aligns with recent evidence that improved transport networks improve urban-rural income gap (Lu et al., 2022), boost regional productivity and reduce spatial disparities (Banerjee et al., 2020), and deepen national market integration (Egger et al., 2023). As transportation density increases, the EPI approaches zero, suggesting that better connectivity promotes a more balanced relationship between ecological pressure and economic benefit. However, the insignificant difference between the medium and high groups suggests a potential threshold effect, where additional infrastructure brings diminishing returns once basic connectivity is achieved. Therefore, policy efforts should prioritize transportation investment in under-connected, ecologically burdened provinces.

For agricultural fiscal priorities, stratified results showed that EPI increases with higher fiscal priority, with pairwise differences being significant (Fig. 7c), suggesting that provinces allocating a larger budget share to agriculture-related functions tend to be those where ecological pressure outweighs economic returns. This may be because regions with heavier ecological burdens or weaker value-added performance allocate a higher internal share to agriculture, forest, water resources, and related management. Such expenditures often emphasize farmland and irrigation infrastructure, conservation programs, and ecological management, which may not translate into short term value-added gains. Xiao et al. (2025) take transfer payment policy for China's national key ecological functional zones as an example, and find that there is heterogeneity and diminishing marginal incentives, suggesting that we need to emphasize the system design and absorptive capacity, rather than only pursuing intensity. Therefore, future fiscal reforms should shift from expansionary spending toward a strategy emphasizing sustainable transformation and value retention, with priority given to supporting green innovation, ecological compensation mechanisms, and industrial chain upgrading in resource-based regions, so that the inter-provincial EPI gap that can be narrowed.

The stratified analysis based on the agricultural mechanization level reveals a significant downward trend in EPI across mechanization strata (Fig. 7d), indicating that increasing mechanization is consistently associated with a reduction in the ecological–economic trade mismatch. It suggests that provinces with more advanced mechanization tend to achieve more efficient agricultural production systems that better integrate ecological resource use with economic performance (Peng et al., 2022). Recent empirical research supports this conclusion. Studies have demonstrated that higher mechanization rates substantially improve agricultural productivity and resource-use efficiency (Zheng et al., 2021). Furthermore, cross-provincial analyses reveal that agricultural mechanization contributes to green total factor productivity and promotes sustainable intensification by reducing unit environmental pressure while maintaining output growth (Lu et al., 2024). From a policy perspective, the findings highlight that technological upgrading through mechanization is an effective approach to mitigate the ecological–economic mismatch.

4.2. Applicability of the tele-coupling framework

We observe that for most provinces, the Top 3 outbound HANPP destinations are non-adjacent provinces (Table S9). This indicates that ecological pressure is more strongly connected to distant partners than to nearby ones. Such a pattern is not fully consistent with Tobler's First Law of Geography, which states that "everything is related to everything else, but near things are more related than distant things (Tobler, 1970)." The observed pattern suggests that the spatial organization of ecological pressure flows cannot be explained solely by geographic proximity. Spatial interactions in agricultural trade are increasingly shaped by market forces, institutional arrangements, transportation infrastructure, and policy incentives rather than geographic proximity alone. As described in the tele-coupling framework (Liu, 2017), flows such as information, material, and energy flows can replace physical proximity to connect two or more systems (Liu, 2023). The emergence of a tele-coupling framework signals that geographic constraints on resource flows have weakened or even reversed (Manning et al., 2023). This is particularly relevant for understanding how China's extensive transportation networks and policy interventions have facilitated distant agricultural trade flows.

Beyond the significantly higher HANPP in distant trade, we also found that ecological–economic inequality is more pronounced in distant trade relationships than in adjacent ones (Fig. 6b). In other words, distant interactions tend to generate stronger or more disruptive transboundary effects than nearby interactions. Similar results have been reported in other studies. For example, Jia et al. (2024) showed that geographically distant countries experienced greater disruptions in food production and trade during the Russia–Ukraine war. Xiao et al. (2024) found that synergistic effects transmitted through trade were 14.94% stronger between non-adjacent countries than between neighboring ones.

There are two key reasons that can explain why distant trade relationships exhibit higher ecological–economic inequality. First, the similarity in agricultural structures among adjacent provinces reduces the comparative advantages of adjacent trade (Xu et al., 2020), encouraging ecological pressures to shift toward more distant provinces with different production systems and resource endowments. This spatial specialization partly explains why distant trade bears greater ecological costs. Second, tele-coupled relationships often involve remote agricultural regions (e.g., Guizhou, Gansu, Qinghai, and Heilongjiang) that rely on low-value-added primary production and face institutional and infrastructure constraints. In contrast, peri-coupling relationships benefit from stronger coordination, information flow, and feedback mechanisms, enabling consumption regions to better recognize ecological costs and negotiate compensatory responses.

In summary, our study found that both the spatial transfer of the HANPP and the inequality between the HANPP and value-added flows were more pronounced in distant trade than in adjacent trade. Moreover, the ecological pressure embodied in distant trade is often less visible and difficult to trace. Therefore, greater attention must be paid to addressing inequalities associated with distant agricultural trade.

4.3. Policy implication for ecological compensation

Our results show pronounced ecological–economic inequalities in interprovincial agricultural trade, with stronger effects in distant trade. These patterns call for a evidence-based compensation framework that reflects spatial disparities in trade linkages, informed by HANPP flows and EPI metrics.

First, the HANPP indicator should be integrated with regional ecological resource endowments to identify vulnerable areas facing high ecological pressure from agricultural production (Wang et al., 2024c). These regions, often face ecosystem-carrying capacity challenges and are prone to irreversible risks such as land degradation and biodiversity loss (Godfray et al., 2018; Liang et al., 2023). Therefore, restricted production zones should be designated to prevent ecological imbalance from overexploitation. Meanwhile, economic compensation should be provided at the national level through fiscal transfer payments, green development funds, and so on, to balance ecological conservation with development opportunities (Zhou et al., 2022).

In addition, build an ecological pressure tracking platform to link production with consumption regions and enhance the visibility of ecological costs in distant trade. Based on inter-provincial agricultural trade data and spatial HANPP flows, the platform can visualize embedded ecological costs, support bilateral compensation and ecological investment, and disclose information through footprint maps, product labeling, and public accounts. Integrate the EPI to monitor bilateral and provincial inequalities and to guide compensation and restoration consistent with the beneficiary-pays principle (Ding et al., 2022; Du et al., 2023).

Furthermore, embed EPI index and mapped HANPP flows into regional development planning and national ecological governance frameworks. Incorporate these indicators into inter-provincial collaboration, rural revitalization, and agricultural modernization strategies so that provinces with high EPI values receive priority in restoration, industrial adjustment, and funding, while beneficiary provinces co-finance restoration in source regions. These steps translate empirical evidence into actionable policy tools for mitigating spatial inequality.

4.4. Implications and limitations

This study considers China as a representative case. The interprovincial focus is essential for two reasons. First, the COVID-19 pandemic exposed the instability of the international trading system and its risks to regional resource security (Barlow et al., 2021; Nguyễn and Phan, 2025).taxi In response, China proposed a dual-circulation development pattern in which the domestic economic cycle plays the leading role while the international cycle serves as its extension and supplement. This shift implies that interregional flows within China are poised to supersede international trade as the key driver of sustainable development (Zhuang et al., 2023). Second, the principal policy instruments such as ecological compensation, cropland protection and offsets, fiscal transfers, and industrial support are designed and implemented largely at the provincial level. Aligning measurement with the governance scale is therefore necessary to inform who compensates whom and by how much. Against this backdrop, analyzing China's interprovincial ecological resource flows provides timely and policy-relevant evidence for regional coordination under the domestic-circulation framework.

From our study, we found that distant trade has a greater ecological and economic impact than adjacent trade. This pattern of spatial transfer. Although demonstrated in China, this pattern is not unique. It also occurs in other developed and developing countries (Fang et al., 2021), experiencing rapid urbanization and regional disparities. For example, in the United States, the average indirect land use of urban residents is approximately 23 times greater than their direct land use, indicating a substantial displacement of land use beyond urban areas (Zeng and Ramaswami, 2020). Similar cross-boundary displacement can also be observed at the national scale globally (Kirchner and Schmid, 2013; Wang et al., 2024d). Over 70% of the HANPP embodied in agricultural production in Latvia, Canada, and Ireland has been linked to exports to other EU countries such as Germany, Italy, and France (Liang et al., 2023). Therefore, the methodology and policies proposed in this study are broadly applicable to other cross-regional production-consumption systems, both within China and other countries.

Nonetheless, this study has several limitations. First, although we used the most up-to-date and detailed available MRIO tables, they still lack the capacity to fully reflect China's rapidly evolving economy and ecological governance. Because of data constraints, our latest year was 2017. However, in 2018, the Chinese government implemented a revised cropland protection policy that allowed cross-provincial cropland displacement, replacing previous within-province restrictions. This reform is expected to accelerate the spatial displacement of grain production (Yang et al., 2020) and may further intensify the ecological pressure transfers driven by interprovincial trade (Ke et al., 2020). Therefore, our results may not fully reflect the most recent trends, and should be interpreted with this temporal lag in mind. Second, China's MRIO tables aggregate farming, forestry, livestock, and fisheries into a single “agricultural” sector. This limits our ability to differentiate ecological pressures from distinct production activities, such as cropping, grazing, and deforestation. This limits a more nuanced analysis and sector-specific policy recommendations. Third, China, as a net importer of ecological resources, imported approximately 53.59 TgC of HANPP from abroad in 2017 (Du et al., 2025). As a major participant in global agricultural trade, China's ecological pressures are inevitably influenced by international trade (Sun et al., 2018). For example, the substitution effect can reduce domestic ecological pressures by replacing domestic agricultural production with imports. While, the complementarity effect operates through the import of intermediate products that stimulate the expansion of downstream industries, thereby influencing both ecological pressures and economic returns across provinces. Consequently, international agricultural trade can reshape the redistribution of HANPP and value added among Chinese provinces through these substitution and complementarity effects. Future research should further expand the analytical boundary by integrating China's subnational MRIO framework with global MRIO and HANPP satellite accounts, in order to comprehensively assess ecological–economic inequalities at both domestic and international scales under multi-scale tele-coupling processes. Finally, our distinction between adjacent and distant regions is based on administrative boundary contiguity rather than explicit distance thresholds. While this topology-based classification is consistent with the meta-coupling framework and appropriate for our research focus, it is important to acknowledge that the notions of neighboring and distant are context dependent, and there is no universally recognised distance metric that unequivocally separates them (Liu, 2017). For studies that aim to investigate mechanisms more closely related to physical distance (e.g., transport costs or distance-decay effects), it would be valuable to identify distant regions using alternative distance thresholds and to compare how the estimated impacts of transboundary interactions vary across these thresholds. Future work could therefore complement our contiguity-based approach by incorporating distance-threshold and continuous-distance analyses to provide a more refined understanding of spatial interaction patterns.

5. Conclusions

This study presents a comprehensive assessment of the inequality of ecological pressures and economic benefits embedded in interprovincial agricultural trade in China by integrating the HANPP and MRIO models. We reveal that although the northeastern region bore the largest ecological pressure, the western region received greater economic benefits, leading to a spatial mismatch in the regional transfers of ecological pressure and economic benefits. The northeastern China bored 8.53 TgC net HANPP from central and western region, but it still need transferred 17.36 million yuan to those regions in 2012, in contrast, central China bore only 16.59% of the net HANPP yet still receiving 45.02% of the net value-added, revealing a significant spatial mismatch. After 2015, despite the increase in net HANPP transferred from western region to the northeast, the net value added transferred to the northeast has been declining. At the provincial level, heterogeneous trajectories were observed: provinces such as Anhui, Hunan, and Sichuan transitioned toward a dual-benefit position, gaining economic advantages while offloading ecological pressure, whereas Jilin remained trapped in a lose-lose state, suffering both ecological and economic deficits. Some provinces, such as Inner Mongolia and Jiangsu, moved toward a more balanced trade status, reflecting improvements in ecological-economic equity over time. Trade inequalities intensified in both frequency and severity, with most central and eastern provinces consistently advantaged and many western and northeastern provinces disadvantaged. The most extreme case observed between Qinghai and Guangdong demonstrates that to obtain the same value-added, Qinghai must bear 52 times more ecological pressure than Guangdong. According to the EPI value, most central and eastern provinces remained in advantaged positions under agricultural trade, whereas many northeastern and western provinces remained in disadvantaged positions. For both the spatial transfer of the HANPP and the inequality between the HANPP and value-added flows, trade with distant provinces tended to be more significant than trade with adjacent provinces. Stratified analysis revealed structural heterogeneity. Provinces with better transportation accessibility and higher mechanization levels tended to show a more balanced ecological–economic relationship, whereas those with higher agricultural fiscal priority often faced persistent mismatches, as a larger share of their budgets was directed to farmland and ecological management with limited short-term economic returns. We also recommend identifying ecologically vulnerable regions for targeted protection and compensation, establishing a national ecological pressure network platform to visualize interprovincial HANPP flows, and integrating EPI into compensation frameworks. These measures would enhance transparency and enable the fair distribution of both ecological costs and economic benefits, especially under distant trade relationships. The methodology and insights from this study offer valuable guidance for addressing similar sustainability challenges in other countries experiencing rapid economic development and regional disparities.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2026.108379.

Data availability

Data will be made available on request.

References

Anderson, E.W., 2003. International Boundaries: A Geopolitical Atlas. Psychology Press.
Antweiler, W., 1996. The pollution terms of trade. Econ. Syst. Res. 8, 361–366. https://doi.org/10.1080/09535319600000027.
Banerjee, A., Duflo, E., Qian, N., 2020. On the road: access to transportation infrastructure and economic growth in China. J. Dev. Econ. 145, 102442. https://doi.org/10.1016/j.jdeveco.2020.102442.
Barlow, P., van Schalkwyk, M.C., McKee, M., Labonté, R., Stuckler, D., 2021. COVID-19 and the collapse of global trade: building an effective public health response. Lancet Planet. Health 5, e102–e107. https://doi.org/10.1016/S2542-5196(20)30291-6.
Casas-Ledón, Y., Andrade, C., Salazar, C., Martínez-Martínez, Y., Aguayo, M., 2023. Understanding the dynamics of human appropriation on ecosystems via an exergy-based net primary productivity indicator: a case study in south-central Chile. Ecol. Econ. 210, 107862. https://doi.org/10.1016/j.ecolecon.2023.107862.
Chen, W., Wu, S., Lei, Y., Li, S., 2017. Interprovincial transfer of embodied energy between the Jing-Jin-Ji area and other provinces in China: a quantification using interprovincial input-output model. Sci. Total Environ. 584–585, 990–1003. https://doi.org/10.1016/j.scitotenv.2017.01.152.
Chen, B., Han, M.Y., Peng, K., Zhou, S.L., Shao, L., Wu, X.F., Wei, W.D., Liu, S.Y., Li, Z., Li, J.S., Chen, G.Q., 2018a. Global land-water nexus: agricultural land and freshwater use embodied in worldwide supply chains. Sci. Total Environ. 613–614, 931–943. https://doi.org/10.1016/j.scitotenv.2017.09.138.
Chen, L., Meng, J., Liang, S., Zhang, H., Zhang, W., Liu, M., Tong, Y., Wang, H., Wang, W., Wang, X., Shu, J., 2018b. Trade-induced atmospheric mercury deposition over China and implications for demand-side controls. Environ. Sci. Technol. 52, 2036–2045. https://doi.org/10.1021/acs.est.7b04607.
Ding, W., Jimoh, S.O., Hou, X., Shu, X., Dong, H., Bolormaa, D., Wang, D., 2022. Grassland ecological subsidy policy and livestock reduction behavior: a case study of herdsmen in northern China. Rangel. Ecol. Manage. 81, 78–85. https://doi.org/10.1016/j.rama.2022.01.002.
Dong, B., Xu, Y., Li, Q., 2022. Carbon transfer under China's inter-provincial trade: evaluation and driving factors. Sustainable Prod. Consumption 32, 378–392. https://doi.org/10.1016/j.spc.2022.04.031.
Du, W., Yan, H., Feng, Z., Yang, Y., Liu, F., 2021. The supply-consumption relationship of ecological resources under ecological civilization construction in China. Resour. Conserv. Recycl. 172, 105679. https://doi.org/10.1016/j.resconrec.2021.105679.
Du, H., Zhao, L., Zhang, P., Li, J., Yu, S., 2023. Ecological compensation in the Beijing-Tianjin-Hebei region based on ecosystem services flow. J. Environ. Manage. 331, 117230. https://doi.org/10.1016/j.jenvman.2023.117230.
Du, W., Yan, H., Feng, Z., Liu, G., Li, K., Peng, L., Xiang, X., Yang, Y., 2024. Zoning for the sustainable development mode of global social-ecological systems: from the supply-production-demand perspective. Resour. Conserv. Recycl. 203, 107447. https://doi.org/10.1016/j.resconrec.2024.107447.
Du, W., Xiang, X., Zhang, C., Yan, H., Niu, Z., 2025. Exploring the spatio-temporal patterns and driving forces of ecological resource flows in China for post-epidemic sustainable development. Resour. Environ. Sustain. 21, 100237. https://doi.org/10.1016/j.resenv.2025.100237.
Egger, P.H., Loumeau, G., Loumeau, N., 2023. China's dazzling transport-infrastructure growth: measurement and effects. J. Int. Econ. 142, 103734. https://doi.org/10.1016/j.jinteco.2023.103734.
Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009. Embodied HANPP: mapping the spatial disconnect between global biomass production and consumption. In: Ecological Economics, Special Section: Analyzing the global Human Appropriation of Net Primary Production - Processes, Trajectories, Implications, 69, pp. 328–334. https://doi.org/10.1016/j.ecolecon.2009.06.025.
Fang, K., Wang, S., He, J., Song, J., Fang, C., Jia, X., 2021. Mapping the environmental footprints of nations partnering the belt and road initiative. Resour. Conserv. Recycl. 164, 105068.
Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. Science 361, eaam5324. https://doi.org/10.1126/science.aam5324.
Gong, P., Li, X., Wang, J., Bai, Y., Cheng, B., Hu, T., Liu, X., Xu, B., Yang, J., Zhang, W., Zhou, Y., 2020. Annual maps of global artificial impervious area (GAIA) between 1985 and 2018. Remote Sens. Environ. 236, 111510. https://doi.org/10.1016/j.rse.2019.111510.
Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc. Natl. Acad. Sci. 104, 12942–12947. https://doi.org/10.1073/pnas.0704243104.
Haberl, H., Erb, K.-H., Krausmann, F., 2014. Human appropriation of net primary production: patterns, trends, and planetary boundaries. Annu. Rev. Env. Resour. 39, 363–391. https://doi.org/10.1146/annurev-environ-121912-094620.
Huang, J., Yang, G., 2017. Understanding recent challenges and new food policy in China. Glob. Food Sec. 12, 119–126. https://doi.org/10.1016/j.gfs.2016.10.002.
Jia, N., Xia, Z., Li, Yinshuai, Yu, X., Wu, X., Li, Yingjie, Su, R., Wang, M., Chen, R., Liu, J., 2024. The Russia-Ukraine war reduced food production and exports with a disparate geographical impact worldwide. Commun. Earth Environ. 5, 1–17. https://doi.org/10.1038/s43247-024-01915-5.
Ke, X., Qiushi, Zhou, Chengchao, Zuo, Lanping, Tang, Turner, A., 2020. Spatial impact of cropland supplement policy on regional ecosystem services under urban expansion circumstance: a case study of Hubei Province, China. J. Land Use Sci. 15, 673–689. https://doi.org/10.1080/1747423X.2020.1817166.
Kirchner, M., Schmid, E., 2013. Integrated regional impact assessment of agricultural trade and domestic environmental policies. Land Use Policy 35, 359–378. https://doi.org/10.1016/j.landusepol.2013.06.008.
Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci. 110, 10324–10329. https://doi.org/10.1073/pnas.1211349110.
Lee, L.-C., Wang, Y., Zuo, J., 2021. The nexus of water-energy-food in China's tourism industry. Resour. Conserv. Recycl. 164, 105157. https://doi.org/10.1016/j.resconrec.2020.105157.
Liang, L., Chen, M., Luo, X., Xian, Y., 2021. Changes pattern in the population and economic gravity centers since the reform and opening up in China: the widening gaps between the South and North. J. Clean. Prod. 310, 127379. https://doi.org/10.1016/j.jclepro.2021.127379.
Liang, J., Wang, S., Liu, K., Wang, J., Zhou, J., Liu, X., Feng, K., Fang, C., 2023. Agricultural HANPP embodied in consumption: tracing pressure on ecosystems based on an MRIO analysis. Environ. Sci. Technol. 57, 13838–13850. https://doi.org/10.1021/acs.est.3c04225.
Liu, J., 2017. Integration across a metacoupled world. Ecol. Soc. 22.
Liu, J., 2023. Leveraging the metacoupling framework for sustainability science and global sustainable development. Natl. Sci. Rev. https://doi.org/10.1093/nsr/nwad090.
Liu, X., Du, H., Zhang, Z., Crittenden, J.C., Lahr, M.L., Moreno-Cruz, J., Guan, D., Mi, Z., Zuo, J., 2019. Can virtual water trade save water resources? Water Res. 163, 114848. https://doi.org/10.1016/j.watres.2019.07.015.
Lu, H., Zhao, P., Hu, H., Zeng, L., Wu, K.S., Lv, D., 2022. Transport infrastructure and urban-rural income disparity: a municipal-level analysis in China. J. Transp. Geogr. 99, 103292. https://doi.org/10.1016/j.jtrangeo.2022.103292.
Lu, F., Meng, J., Cheng, B., 2024. How does improving agricultural mechanization affect the green development of agriculture? Evidence from China. J. Clean. Prod. 472, 143298. https://doi.org/10.1016/j.jclepro.2024.143298.
Lyu, J., Li, X., 2019. Effectiveness and sustainability of grain price support policies in China. Sustainability 11, 2478. https://doi.org/10.3390/su11092478.
Lyu, F., Wu, J., Yu, Z., Di, H.J., Pan, Y., 2024. Mapping ecological resource use and supply-consumption difference in China from 2000 to 2020. Resour. Conserv. Recycl. 211, 107879. https://doi.org/10.1016/j.resconrec.2024.107879.
Manning, N., Li, Y., Liu, J., 2023. Broader applicability of the metacoupling framework than Tobler's first law of geography for global sustainability: a systematic review. Geogr. Sustainability 4, 6–18. https://doi.org/10.1016/j.geosus.2022.11.003.
Meng, J., Mi, Z., Guan, D., Li, J., Tao, S., Li, Y., Feng, K., Liu, J., Liu, Z., Wang, X., Zhang, Q., Davis, S.J., 2018. The rise of South–South trade and its effect on global CO2 emissions. Nat. Commun. 9, 1871. https://doi.org/10.1038/s41467-018-04337-y.
Nguyễn, H.V., Phan, T.T., 2025. Impact of economic growth, international trade, and FDI on sustainable development in developing countries: impact of economic growth, international trade and FDI. Environ. Dev. Sustain. 27, 4017. https://doi.org/10.1007/s10668-023-04060-9.
Pan, Y., Zhu, J., Zhang, Y., Li, Z., Wu, J., 2022. Poverty eradication and ecological resource security in development of the Tibetan plateau. Resour. Conserv. Recycl. 186, 106552. https://doi.org/10.1016/j.resconrec.2022.106552.
Parente, L., Sloat, L., Mesquita, V., Consoli, D., Stanimirova, R., Hengl, T., Bonannella, C., Teles, N., Wheeler, I., Hunter, M., Ehrmann, S., Ferreira, L., Mattos, A.P., Oliveira, B., Meyer, C., Şahin, M., Witjes, M., Fritz, S., Malek, Z., Stolle, F., 2024. Annual 30-m maps of global grassland class and extent (2000−2022) based on spatiotemporal

Machine Learning. Sci. Data 11, 1303. https://doi.org/10.1038/s41597-024-04139-6.
Peng, J., Zhao, Z., Liu, D., 2022. Impact of agricultural mechanization on agricultural production, income, and mechanism: evidence from Hubei Province, China. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.838686.
Qi, X., Xu, H., Teng, R., Chen, T., Wang, X., 2024. Ecological restoration largely alleviates livestock grazing pressure in a montane grassland. J. Clean. Prod. 467, 143044. https://doi.org/10.1016/j.jclepro.2024.143044.
Reader, M.O., Eppinga, M.B., de Boer, H.J., Damm, A., Petchey, O.L., Santos, M.J., 2022. The relationship between ecosystem services and human modification displays decoupling across global delta systems. Commun. Earth Environ. 3, 1–13. https://doi.org/10.1038/s43247-022-00431-8.
Roux, N., Kaufmann, L., Bhan, M., Le Noe, J., Matej, S., Laroche, P., Kastner, T., Bondeau, A., Haberl, H., Erb, K., 2022. Embodied HANPP of feed and animal products: tracing pressure on ecosystems along trilateral livestock supply chains 1986–2013. Sci. Total Environ. 851, 158198. https://doi.org/10.1016/j.scitotenv.2022.158198.
Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob. Chang. Biol. 9, 161–185. https://doi.org/10.1046/j.1365-2486.2003.00569.x.
Steffen, W., Grinevald, J., Crutzen, P., McNeill, J., 2011. The Anthropocene: conceptual and historical perspectives. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 369, 842–867. https://doi.org/10.1098/rsta.2010.0327.
Su, B., Ang, B.W., 2014. Input–output analysis of CO2 emissions embodied in trade: a multi-region model for China. Appl. Energy 114, 377–384. https://doi.org/10.1016/j.apenergy.2013.09.036.
Sun, J., Mooney, H., Wu, W., Tang, H., Tong, Y., Xu, Z., Huang, B., Cheng, Y., Yang, X., Wei, D., Zhang, F., Liu, J., 2018. Importing food damages domestic environment: evidence from global soybean trade. Proc. Natl. Acad. Sci. 115, 5415–5419. https://doi.org/10.1073/pnas.1718153115.
Tobler, W.R., 1970. A computer movie simulating urban growth in the detroit region. Econ. Geogr 46, 234. https://doi.org/10.2307/143141.
Wackernagel, M., Hanscom, L., Jayasinghe, P., Lin, D., Murthy, A., Neill, E., Raven, P., 2021. The importance of resource security for poverty eradication. Nat. Sustain. 4, 731–738. https://doi.org/10.1038/s41893-021-00708-4.
Wang, L., Li, C., Ying, Q., Cheng, X., Wang, X., Li, X., Hu, L., Liang, L., Yu, L., Huang, H., Gong, P., 2012. China's urban expansion from 1990 to 2010 determined with satellite remote sensing. Chin. Sci. Bull. 57, 2802–2812. https://doi.org/10.1007/s11434-012-5235-7.
Wang, F., Li, Y., Zhang, W., He, P., Jiang, L., Cai, B., Zhang, J., Zhang, P., Pan, H., Jiang, H., 2020. China's trade-off between economic benefits and sulfur dioxide emissions in changing global trade. Earth's Future 8, e2019EF001354. https://doi.org/10.1029/2019EF001354.
Wang, S., Chen, X., Xie, R., Liu, K., Wang, J., Liu, X., Hubacek, K., Wu, C., Feng, K., Yan, Y., Liu, Z., Sun, L., Fang, C., 2024a. Demand-side insights for steering human appropriation of net primary productivity within planetary boundaries. One Earth 7, 650–662. https://doi.org/10.1016/j.oneear.2024.02.010.
Wang, S., Fang, C., Chen, X., Liang, J., Liu, K., Feng, K., Hubacek, K., Wang, J., 2024b. China's ecological footprint via biomass import and consumption is increasing. Commun. Earth Environ. 5, 1–12. https://doi.org/10.1038/s43247-024-01399-3.
Wang, S., Liang, J., Chen, X., Fang, C., Liu, K., Wang, J., Feng, K., Liu, Z., Hubacek, K., Liu, X., 2024c. The impact of international trade on environmental vulnerability. Sci. Bull. 69, 426–430. https://doi.org/10.1016/j.scib.2023.12.029.
Wang, S., Wang, J., Fang, C., Chen, X., Liang, J., Liu, Y., Gao, S., Hubacek, K., Liu, X., Zhou, C., Shan, Y., Feng, K., Liu, Z., Hong, C., Davis, S.J., 2024d. International trade reshapes the decoupling of emissions from economic growth. Environ. Sci. Technol. 58, 14662–14674. https://doi.org/10.1021/acs.est.4c03995.
Wei, W., Hao, S., Yao, M., Chen, W., Wang, S., Wang, Z., Wang, Y., Zhang, P., 2020. Unbalanced economic benefits and the electricity-related carbon emissions embodied in China's interprovincial trade. J. Environ. Manage. 263, 110390. https://doi.org/10.1016/j.jenvman.2020.110390.
Weinzettel, J., Vačkářů, D., Medková, H., 2019. Potential net primary production footprint of agriculture: a global trade analysis. J. Ind. Ecol. 23, 1133–1142. https://doi.org/10.1111/jiec.12850.
Wenz, L., Willner, S.N., Radebach, A., Bierkandt, R., Steckel, J.C., Levermann, A., 2015. Regional and sectoral disaggregation of multi-regional input–output tables – a flexible algorithm. Econ. Syst. Res. 27, 194–212. https://doi.org/10.1080/09535314.2014.987731.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11, 314–321. https://doi.org/10.1038/s41561-018-0113-9.
Xiao, H., Bao, S., Ren, J., Xu, Z., Xue, S., Liu, J., 2024. Global transboundary synergies and trade-offs among Sustainable Development Goals from an integrated sustainability perspective. Nat. Commun. 15, 500. https://doi.org/10.1038/s41467-023-44679-w.
Xiao, Y., Shimada, K., Shao, S., Liu, L., Pan, S., Xiao, W., 2025. The diminishing incentive of ecological fiscal transfer on local government environmental expenditure — evidence from National Key Ecological Function Zone in China. Ecol. Econ. 235, 108634. https://doi.org/10.1016/j.ecolecon.2025.108634.
Xu, Z., Li, Yingjie, Chau, S.N., Dietz, T., Li, C., Wan, L., Zhang, J., Zhang, L., Li, Yunkai, Chung, M.G., Liu, J., 2020. Impacts of international trade on global sustainable development. Nat. Sustain. 3, 964–971. https://doi.org/10.1038/s41893-020-0572-z.
Yang, B., Ke, X., van Vliet, J., Yu, Q., Zhou, T., Verburg, P.H., 2020. Impact of cropland displacement on the potential crop production in China: a multi-scale analysis. Reg. Environ. Chang. 20, 97. https://doi.org/10.1007/s10113-020-01690-x.
Yu, Y., Feng, K., Hubacek, K., 2013. Tele-connecting local consumption to global land use. Glob. Environ. Chang. 23, 1178–1186. https://doi.org/10.1016/j.gloenvcha.2013.04.006.
Zeng, L., Ramaswami, A., 2020. Impact of locational choices and consumer behaviors on personal land footprints: an exploration across the urban-rural continuum in USA. Environ. Sci. Technol. 54. https://doi.org/10.1021/acs.est.9b06024, 30911-3102.
Zhang, C., Anadon, L.D., 2014. A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. Ecol. Econ. 100, 159–172. https://doi.org/10.1016/j.ecolecon.2014.02.006.
Zhang, W., Liu, Y., Feng, K., Hubacek, K., Wang, J., Liu, M., Jiang, L., Jiang, H., Liu, N., Zhang, P., Zhou, Y., Bi, J., 2018a. Revealing environmental inequality hidden in China's inter-regional trade. Environ. Sci. Technol. 52, 7171–7181. https://doi.org/10.1021/acs.est.8b00009.
Zhang, W., Wang, F., Hubacek, K., Liu, Y., Wang, J., Feng, K., Jiang, L., Jiang, H., Zhang, B., Bi, J., 2018b. Unequal exchange of air pollution and economic benefits embodied in China's exports. Environ. Sci. Technol. 52, 3888–3898. https://doi.org/10.1021/acs.est.7b05651.
Zhang, H., Zhang, W., Lu, Y., Wang, Y., Shan, Y., Ping, L., Li, H., Lee, L.-C., Wang, T., Liang, C., Jiang, H., Cao, D., 2023. Worsening carbon inequality embodied in trade within China. Environ. Sci. Technol. 57, 863–873. https://doi.org/10.1021/acs.est.2c05990.
Zheng, H., Bai, Y., Wei, W., Meng, J., Zhang, Z., Song, M., Guan, D., 2021. Chinese provincial multi-regional input-output database for 2012, 2015, and 2017. Sci. Data 8, 244. https://doi.org/10.1038/s41597-021-01023-5.
Zhou, Z., Sun, X., Zhang, X., Wang, Y., 2022. Inter-regional ecological compensation in the Yellow River Basin based on the value of ecosystem services. J. Environ. Manage. 322, 116073. https://doi.org/10.1016/j.jenvman.2022.116073.
Zhuang, M., Gao, Z., Geng, Y., Zhang, C., Xiao, S., 2023. Exergy analysis of natural resources embodied in China's interregional trade and its implication for regional imbalance. Environ. Sci. Pollut. Res. 30, 90814–90829. https://doi.org/10.1007/s11356-023-28025-7.