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Original Research

Global mismatch between ecosystem service supply and demand driven by climate change and human activity

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A B S T R A C T

Assessing the balance between ecosystem service supply and demand (ESSD) relationship and identifying its driving factors is essential for addressing ecosystem degradation. While previous local-scale studies have highlighted climate change and human activities as critical influences, their roles at a global scale remain poorly understood. Here, we analyze the global dynamics of supply–demand relationships for four key ecosystem services—food production, carbon sequestration, soil conservation, and water yield—over the period 2000–2020. We find that ESSD relationships generally exhibit spatially high supply-low demand and quantitatively surplus characteristics. Climate change and human activity influence ESSD relationships in dual-directional pathways. Specifically, they positively affect food production and soil conservation in 80.69% and 72.50% of global regions respectively; while negatively influencing carbon sequestration and water yield in 76.74% and 62.44% of global regions respectively. Human activity primarily shapes the ESSD relationships for food production and carbon sequestration, with mean contribution rates of 66.54% and 60.80% respectively; whereas climate change exerts greater control over soil conservation and water yield, with mean contribution rates of 54.62% and 55.41% respectively. Our findings clarify the direction (positive or negative), mode (individual or combined), contribution rates, and geographic distribution of these impacts. This research closes a critical gap in understanding global ESSD relationships and provides essential insights to inform sustainable ecosystem management from local to global scales.

1. Introduction

Ecosystem services (ESs), which refer to the benefits humans obtain directly or indirectly from ecosystem structures, functions, and processes [1], have become a key enabler in achieving sustainable development goals [2,3]. ES supply and demand represent a complete process connecting natural ecosystems to human social systems [4]. Supply reflects the intrinsic capacity and potential of ecosystems to provide specific goods and services [5], while demand captures the actual or perceived needs of human societies [6]. Due to heterogeneity in ecosystem characteristics, regional ES supply often fails to meet demand, resulting in spatiotemporal mismatches between ES supply and demand [7]. Understanding these ES supply–demand (ESSD) relationships and their driving mechanisms is critical for achieving sustainable ecosystem management.

Assessing ESSD relationships typically involves spatial mapping of both supply and demand to identify areas of imbalance or mismatch [8,9]. As research perspectives have expanded, the theoretical understanding of ESSD relationships has deepened, leading to analytical framework refinement. Research scopes have gradually diversified, covering both administrative [10] and natural units [11]. With a growing focus on regional collaboration and governance, researchers have increasingly adopted trans-administrative boundary concepts, focusing on spatial entities such as urban agglomerations [12] and metropolitan areas [13]. Temporally, research has evolved from static snapshots (e.g., a single year [14]) to dynamic assessments, including interdecadal

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[15] and seasonal variations [16]. However, studies using continuous time series remain scarce. Existing dynamic research indicates that ESSD relationships vary linearly or non-linearly over time and are sometimes reversible under specific conditions [17], highlighting the need for continuous time-series analyses to identify critical transition points. Spatially, research has expanded from local to broader scales. While small and medium scale are often prioritized due to the strong connection between ecosystems and human activity [18], ESSD relationships vary significantly by scale and location [19]. Larger-scale studies can offer broader insights into ES balance [18], prompting some researchers to explore ESSD relationships at national [20] and intercontinental [21] scales. At the global scale, although research on ESs has been extensive [22], ESSD relationships have only recently received attention and are often analyzed using county-level units [23]. However, previous work has emphasized the critical role of pixel-scale analysis in advancing ESSD research [5,24]. Pixels, as the basic spatial unit of an image, offer greater precision in capturing and describing spatial patterns and changes in ESSD [25]. Analyzing global ESSD dynamics over a long time series at the pixel scale can thus provide a scientific basis for sustainable ecosystem management and policy formulation.

Identifying the driving mechanisms underlying ESSD relationships can further support accurate and regionally tailored ecosystem management policies. Both physical and anthropogenic factors influence ESSD relationships directly or indirectly [15,26]. Some studies suggest that natural factors have a greater influence on ESSD equilibrium, while human activities have a greater impact on ESSD mismatches [14,27]. In the existing studies, climate change and human activities characterized by land use are regarded as the two major driving forces of the relationship between ESSD, with an evident interaction between them. For example, Fang et al. [28] found that rainfall and land use jointly shaped water yield ESSD in the Central Plains urban agglomeration, while Lv et al. [13] reported that the forest cover and ground temperature interact to influence carbon sequestration ESSD in the Nanjing Metropolitan Area. Nonetheless, significant uncertainty about the impact of specific drivers remains due to differences in ES types, driver characteristics, and assessment methodologies [29]. Multiscale analyses indicate that ESSD relationships and their drivers are both scale-dependent and spatially heterogeneous [12]. One study incorporating both pixel- and county-level analyses found that as the scale increases, certain features of ESSD mismatches may disappear, while the influence of some drivers becomes more pronounced [30]. The lack of information resulting from gaps between global and local studies and policy can limit the scalability of actions and strategies [31]. Most existing work has focused on the local scale, but as climate change and human activity continue to degrade ecosystem functions globally [32], understanding how these drivers influence global ESSD relationships and where spatial gaps exist—remains an urgent research need.

Given growing concerns around food security, climate warming, soil degradation, and water scarcity, this study selects four key ESs—food production, carbon sequestration, soil conservation, and water yield (a detailed rationale for ESs selection is provided in Supplementary Material Text S1), to reveal changes in the spatial and quantitative matching relationships of ESSDs and to quantify the impacts of climate change and human activities on the ESSD relationships, based on the realization of a continuous time-series of supply and demand from 2000 to 2020. The findings can support decision-making for sustainable global ecosystem management.

2. Material and methods

2.1. Data sources and pre-processing

The data sources used in this study are listed in Table S1 (Supplementary Material). Land use and land cover data were reclassified into six categories based on existing studies [33]: cropland, forest, grassland, built-up land, bare land, and water bodies. Annual normalized difference vegetation index (NDVI) data were derived using the maximum value composite method. Soil data included seven depth layers, and this study primarily focused on the topsoil layer (0–20 cm). Annual temperature values were obtained by averaging monthly data, and annual precipitation was calculated through monthly aggregation.

Food production and supply data covers the years 1961–2013 and 2010–present, data for 2010–2020 in this paper are taken from the latter segment. Food items were categorized into cropland, forest, and grassland, aligned with agriculture, forestry, and livestock industries (Supplementary Material Table S2). Fisheries were excluded, as the food production supply was spatialized using NDVI. Since global freshwater withdrawal data were unavailable before 2014, we supplemented the missing data for 2000–2013 based on a United Nations report [34] which stated that global water use has increased by roughly 1% per year over the last 40 years. All datasets were resampled to 1 × 1 km using ArcGIS to ensure consistent spatial resolution.

2.2. Assessment of ecosystem services supply and demand

2.2.1. Calculation of ecosystem services supply and demand

Food production supply is estimated through the linear relationship between the yield of different land use categories and NDVI [35]. Carbon sequestration supply was calculated based on the principle of photosynthesis [36]. Soil conservation supply, defined as the difference between theoretical and actual erosion, was estimated using the revised universal soil loss equation [37]. Water yield supply was derived from the water balance equation [38] and converted to volume based on raster area [39].

Soil conservation demand was represented by actual soil erosion [40,41], while the demand for food production [42], carbon sequestration [14], and water yield [43] were estimated based on population density. Per capita food demand was calculated by taking the total domestic food supply as the total demand [44], and per capita water yield demand was calculated using total freshwater withdrawals. More information on calculation principles and formulas is presented in Table 1, with additional details in Supplementary Material Text S2 and Table S3.

2.2.2. Trend analysis of ecosystem services supply and demand

Temporal trends in ESSD were analyzed using a univariate linear regression method [45]. Spatial trends were assessed using the Theil–Sen median method, with statistical significance tested via the Mann–Kendall approach [33]. Calculation formulas are provided in Supplementary Materials Text S3 and Table S4.

2.3. Assessment of ecosystem service supply–demand relationships

2.3.1. Spatial matching

The four-quadrant model was originally developed as a combination of qualitative and quantitative analyses to evaluate property market dynamics and long-term equilibrium development [46]. As interdisciplinary research has advanced, the model has been widely adopted for spatial assessments of ESSD matching [47,48]. The model uses a two-dimensional coordinate system, plotting ES

Table 1
Methodology for measuring supply and demand for ecosystem services.

Ecosystem services	Supply/demand	Formula	Variable description
Food production	Supply	$FPs_i = \frac{NDVI_i}{NDVI_{sum}} \times G_{sum}$	FPs_i is the food production supply of grid i; $NDVI_i$ is the NDVI value of grid i, $NDVI_{sum}$ is the sum of the NDVI of a certain land use type; G_{sum} is the total food production of a certain land use type.
	Demand	$FPd_i = D_{pcf} \times POP_i$	FPd_i is the food production demand of grid i; D_{pcf} is the per capita food demand; and POP_i is the population size of grid i.
Carbon sequestration	Supply	$CSs_i = W_{CO_2} \times Area_i$ $W_{CO_2} = NPP \times 2.2 \times 1.63$	CSs_i is the carbon sequestration supply of grid i; W_{CO_2} denotes the CO_2 fixation per unit area; $Area_i$ is the area of grid i; NPP denotes the NPP value of vegetation per unit area.
	Demand	$CSd_i = D_{pcce} \times POP_i$	CSd_i is the carbon sequestration demand of grid i; D_{pcce} is the per capita carbon emission.
Soil conservation	Supply	$SC = RKLS - USLE$ $RKLS = R \times K \times L \times S$ $USLE = R \times K \times L \times S \times C \times P$	SC is the soil conservation supply, $RKLS$ is the potential soil erosion, and $USLE$ is the actual soil erosion. R is the rainfall erosivity factor; K is the soil erodibility factor; L is the slope length factor; S is the slope gradient factor; C is the crop/vegetation cover and management factor; and P is the soil and water conservation measures factor.
	Demand	$USLE = R \times K \times L \times S \times C \times P$	The variables in the formula are defined as above.
Water yield	Supply	$Y_i = \left(1 - \frac{AET_i}{P_i}\right) \times P_i$	Y_i is the annual water yield of grid i (mm); AET_i is the annual actual evapotranspiration of grid i (mm); and P_i is the annual precipitation of grid i (mm).
	Demand	$WYd_i = D_{pcw} \times POP_i$	Where WYd_i is the water yield demand of grid i; D_{pcw} is the per capita water demand.

supply on the horizontal (x) axis and ES demand on the vertical (y) axis, resulting in four ESSD matching categories. Prior to the analysis, ESSD data are normalized using the z-score method to account for positive and negative attributes [49]. The resulting matches typically fall into one of four categories: high supply—high demand (L—L), high supply—low demand (H—L), low supply—low demand (L—L), and low supply—high demand (L—H) (Supplementary Material Table S5).

2.3.2. Quantitative matching

The supply-demand ratio model is among the most commonly used approaches for evaluating the quantitative relationship between actual ES supply and human demand [50]. This approach quantifies a supply and demand matching index to indicate whether ESs are in a surplus or deficit at a regional scale. The model is defined as follows:

$$ESSDR_i = \frac{S_i - D_i}{(S_{\max} + D_{\max}) \div 2} \begin{cases} < 0, \text{Deficit} \\ = 0, \text{Balance} \\ > 0, \text{Surplus} \end{cases} \quad (1)$$

where $ESSDR_i$ is the supply—demand ratio for grid cell i, S_i and D_i are the supply and demand values for ES in grid i, respectively, and $S_{\max}$ and $D_{\max}$ represent the maximum observed supply and demand values for the ES, respectively.

2.4. Quantifying the impacts of climate change and human activities on ecosystem service supply and demand

Changes in ESs are driven by complex factors, especially at the global scale, where regional heterogeneity is amplified. In this paper, we assume that the ESSD relationships are driven only by climate change and human activities. Temperature and precipitation are selected as fundamental indicators of climate change, as they directly reflect climatic variability at multiple scales. Other climate-related indicators, such as evapotranspiration and drought indices, are largely derived from these variables and influenced by environmental conditions. Previous studies have also commonly used temperature and precipitation as proxies for climate change [51–53], supporting their use here.

2.4.1. Correlation analysis

Correlation analysis is widely employed across disciplines to evaluate the relationship between two variables [54,55]. Among available techniques, Spearman correlation analysis [56] does not require a priori parameters and is more robust than other methods [57]. In this study, we used this method to assess the relationship between climate variables (temperature and precipitation) and the ESSD ratio. A positive correlation coefficient (>0) indicates a positive association, a coefficient of 0 indicates no correlation, and a negative coefficient (<0) indicates a negative association. Statistical significance was tested at the 0.05 level.

2.4.2. Multiple regression residual analysis

Multiple regression residual analysis is a widely recognized method for isolating the individual contributions of climate change and human activities, particularly in studies on vegetation dynamics [58,59]. Its use has expanded to other variables, such as ES values [60] and ecosystem health [61]. Here, this method was employed to examine the impact of climate change and human activities on ESSD relationships. A regression model was constructed using the ESSD ratio as the dependent variable and climate variables (temperature and precipitation) as independent variables. Assuming that other undetermined factors have negligible influence, the residuals between the observed and predicted ESSD values can be attributed to human activities. The model is written as follows:

$$ESSDR_{\mathrm{CC},i} = a_i \times T_i + b_i \times P_i + C_i \tag{2}$$

$$ESSDR_{\mathrm{HA},i} = ESSDR_{\mathrm{OR},i} - ESm_{\mathrm{CC},i} \tag{3}$$

where $ESSDR_{\mathrm{CC},i}$ is the predicted ESSD ratio based on climate change for grid i; T_i and P_i are the temperature and precipitation of grid i; a_i, b_i, and C_i are the regression coefficients and intercepts; $ESSDR_{\mathrm{HA},i}$ is the residual of the ESSD ratio of raster i, representing the impact of human activities impact on the ESSD relationship; and $ESSDR_{\mathrm{OR},i}$ is the original ESSD ratio of grid i.

Additionally, the Theil–Sen median method was used to calculate the slopes of each time series (original, climate-based prediction, and residual). These slopes were then used to classify the type and strength of contributions from climate change and human activities to ESSD relationships (Supplementary Material Table S6).

3. Results

3.1. Spatiotemporal changes in global ecosystem services supply and demand

From 2000 to 2020, the supply of food production, carbon sequestration, and soil conservation generally increased (Fig. 1a–c, e), while water yield decreased (Fig. 1g). Demand increased for food production, carbon sequestration, and water yield (Fig. 1b–d, h) but declined for soil conservation (Fig. 1f). Over the period from 2000 to 2020, the changes in the supply and demand for food production and carbon sequestration (Fig. 1a–d) and the demand for water yield (Fig. 1h), remained relatively stable. However, the increase in food production supply and demand, as well as carbon sequestration demand, showed slower or lower growth in 2009 and 2020 compared to other phases. The supply and demand for soil conservation and the supply of water yield exhibited notable fluctuations (Fig. 1e–g). Both the supply of soil conservation and water yield reached their lowest values in 2015.

Spatially, the supply and demand for the four ESs followed four distinct trends: slight decrease, no change, slight increase, and significant increase. Regions with no change were primarily located in deserts, tundra, and other areas with extensive unused land and limited vegetation growth (Supplementary Material Fig. S1). Among the changing regions, the food production supply increased significantly by nearly 97%, with only a slight decrease of 0.65% in built-up areas (Supplementary Material Fig. S1a). Approximately 35.04% of regions showed an increasing trend in food production demand, with 23.18% exhibiting a significant increase, concentrated in densely populated areas such as Asia and East Africa. In contrast, 28.94% of the regions showed a slight decrease, primarily in central and northern sub-Saharan Africa, eastern South America, and Europe (Supplementary Material Fig. S1b). Nearly 70% of regions showed an increase in carbon sequestration supply, while 27.66% decreased, with more pronounced decreases in the Southern Hemisphere (Supplementary Material Fig. S1c). The area with decreasing demand for carbon sequestration (37.04%) was larger than the area with increasing demand (24.74%). However, the temporal changes analysis indicates that demand is generally increasing, with high demand for carbon sequestration more concentrated in localized areas, especially in areas with high population density (Supplementary Material Fig. S1d). The supply of soil conservation has been trending upward in more than half of the regions but with significant increases in less than 10%, concentrated in countries such as the United States, Canada, China, India, and Russia. Meanwhile, 38.61% of the regions showed a slight

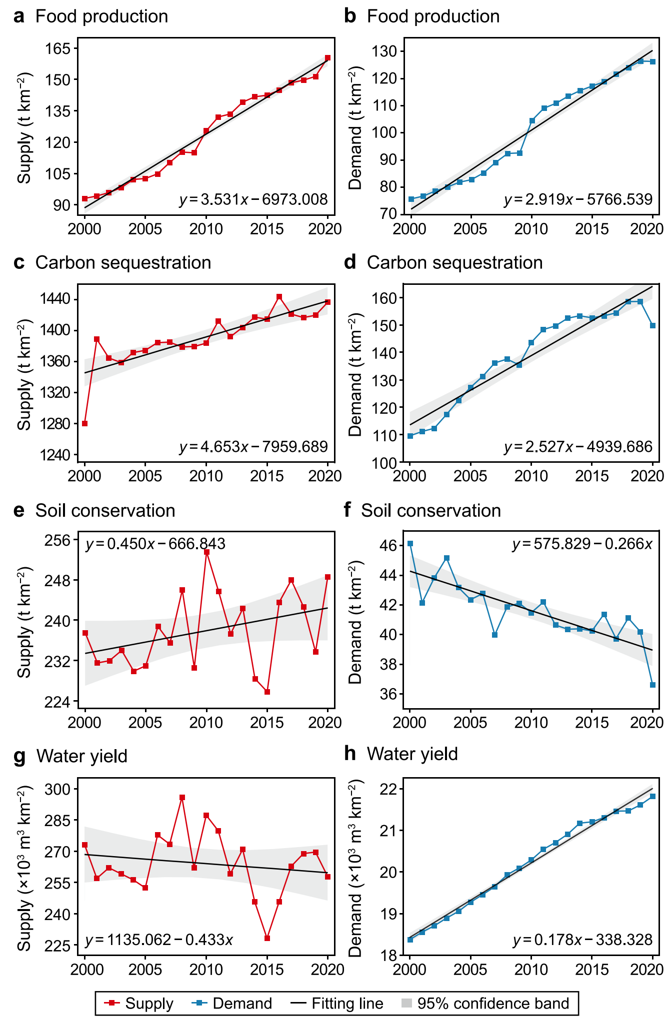


Fig. 1. Temporal changes in global ecosystem services supply and demand: **a**–**b**, food production supply (**a**) and demand (**b**); **c**–**d**, carbon sequestration supply (**c**) and demand (**d**); **e**–**f**, soil conservation supply (**e**) and demand (**f**); **g**–**h**, water yield supply (**g**) and demand (**h**).

decrease, primarily in Australia, South America, West Asia, Southeast Asia, sub-Saharan Africa, and Southeast Asia (Supplementary Material Fig. S1e). The area shares with increasing (39.45%) and decreasing (36.73%) trends in soil conservation demand were roughly equal. The regions with increasing demand were concentrated in western North America, northern Africa, and northwestern Asia, while decreasing demand was clustered in Eastern Europe and the southern parts of South America, Africa, and Oceania (Supplementary Material Fig. S1f). The proportions of regions with increasing (50.02%) and decreasing (48.3%) trends in the water yield supply were nearly equal, with notable spatial differentiation (Supplementary Material Fig. S1g). The demand for water yield showed a slight decrease in 51.77% of regions, while 14.22% of regions exhibited increasing trends, concentrated in India and sub-Saharan Africa (Supplementary Material Fig. S1g).

At the national level, China, Russia, and Canada recorded the most significant net increases in food production, carbon sequestration, and soil conservation supply, respectively. In contrast, Brazil led the global net decrease in water yield supply, accounting for 86.14%. Meanwhile, India led the increase in net demand for food production, carbon sequestration, and water yield, while

China was the main contributor to the net decrease in soil conservation demand. Changes in total quantity do not necessarily reflect changes in unit area. For example, China, which has the largest total food production supply, has a much lower unit area supply than countries like India, Ukraine, and Thailand (Supplementary Materials Table S7–S10).

3.2. Global dynamics of ecosystem services supply–demand relationships

3.2.1. Spatial matching dynamics

The spatial matching relationships of the four key ESSD globally are predominantly characterized by L–L, with an area share of more than 50% (Fig. 2). The area shares of supply–demand spatial matching for food production and carbon sequestration were in the order of L–L > H–L > H–H > L–H, while for soil conservation and water yield, the order was L–L > H–L > L–H > H–H. Notably, H–L, rather than L–H mismatches, dominated the spatial mismatch type across all four ESSD. The mismatch between supply and demand for carbon sequestration was the most pronounced, with nearly 40% of the area exhibiting H–L, followed by water yield, with over 23% of the area in H–L. For food production, carbon sequestration, and water yield, H–L mismatches were typically concentrated in areas with widespread cropland, forest, or grasslands and well-developed water systems but relatively low population densities (e.g., Europe). L–H mismatches were more concentrated in densely populated areas, especially in Asia, sub-Saharan West and East Africa, and some built-up areas. Soil conservation H–L mismatches were most pronounced in regions with extensive forest coverage, such as the eastern United States, the east and west sides of Canada, and southern China. L–H mismatches were mainly found in areas with large ice sheets and deserts, such as the western United States, northwestern China, and northeastern Russia. Comparing 2000 and 2020, food production, carbon sequestration, and soil conservation all showed increases in L–L and H–L mismatches, while L–H and H–H mismatches decreased. In contrast, water yield increased the area share of all types except L–H, which decreased.

3.2.2. Quantity matching dynamics

The supply–demand ratios of the four key ESs were positive, meaning supply exceeded demand, and all were in surplus during the study period. Changes in the different ESs varied. Comparing the base period with the end period, the supply–demand ratios for food production and soil conservation increased by 38.38% and 6.51%, respectively (Fig. 3a–c), while those for carbon sequestration and water yield decreased by 7.79% and 9.58%, respectively (Fig. 3b–d). The surplus status of food production and soil conservation is improving, while that of carbon sequestration and water yield is worsening. Additionally, the supply–demand ratios of the four key ESs all showed clear phase changes. Among them, the changes in the supply–demand ratios for food production, carbon sequestration, and water yield were similar, with an increasing trend from 2000 to 2009 and a decreasing trend from 2009 to 2020, with a relatively flat change from 2012 to 2019 (Fig. 3a, b, d).

The area shares of balanced food production and surplus regions increased by 6.15% and 21.4%, respectively. In contrast, the area shares of deficit regions decreased by 27.54%, mainly in southern North America, South America, Africa, and Eastern Europe. This indicates an improvement in the global food production deficit over the study period (Fig. 4a and b). For carbon sequestration, the area shares of balance and surplus regions rose by 4.24% and 0.34%, respectively, while deficit regions declined by 4.57%, suggesting a global improvement—particularly in northern Africa, Central Asia, and South Asia (Fig. 4c and d).

Soil conservation showed a mixed spatial distribution of deficits and surpluses. The area shares of balanced regions remained largely unchanged. Deficit regions, mainly in Asian countries (excluding Southeast and South Asia), northern and southern Africa, southern South America, and both southern and northern North America decreased by 2.1%, while surplus regions increased by the same margin (Fig. 4e and f).

Most regions had a surplus in water yield, but the overall area share decreased by 1.46% over the study period. Balanced regions—mainly Algeria, Libya, and Egypt—decreased by 0.25%, while deficit regions, particularly in the United States and Central Asia, increased by 1.72% (Fig. 4g and h).

By mapping transitions between the surplus and deficit ESs over the study period (Supplementary Material Fig. S2), we found that in 2020, the four key ESs largely maintained their previous status—balanced, surplus, or deficit—across most regions, with area shares of 68.65%, 92.29%, 96.65%, and 87.16%, respectively. Thus, ES transitions occurred mostly in localized areas.

Food production showed a notable shift from deficit to surplus (22.76%, of the area), mainly in southern North America, both sides of northern South America, sub-Saharan Africa, Northern Europe, and East and South Asia (Supplementary Material Fig. S2a). Carbon sequestration mainly transitioned from deficit to balance (4.59%), notably in sub-Saharan Africa, West Asia, and Central Asia (Supplementary Material Fig. S2b). Soil conservation shifted from deficit to surplus in 2.73% of the area, with a relatively scattered distribution (Supplementary Material Fig. S2c). In contrast, water yield predominantly changed from surplus to deficit (6.75%), particularly in Eastern Europe, Central Asia, and North America (Supplementary Material Fig. S2d).

In most countries, the four ESs remained in surplus with little change, especially carbon sequestration. Food production shifted from deficit to surplus in Germany, Italy, Switzerland, Suriname, and French Guiana, while it changed from surplus to deficit in Niger, Benin, Togo, Cameroon, Uganda, Kenya, and Malawi. Soil conservation improved in Mongolia. Water yield shifted from surplus to deficit in Saudi Arabia and Western Sahara. Conversely, it changed from deficit to surplus in Hungary, Romania, Serbia, Moldova, Bulgaria, Greece, and Eritrea (Supplementary Materials Fig. S3–S6).

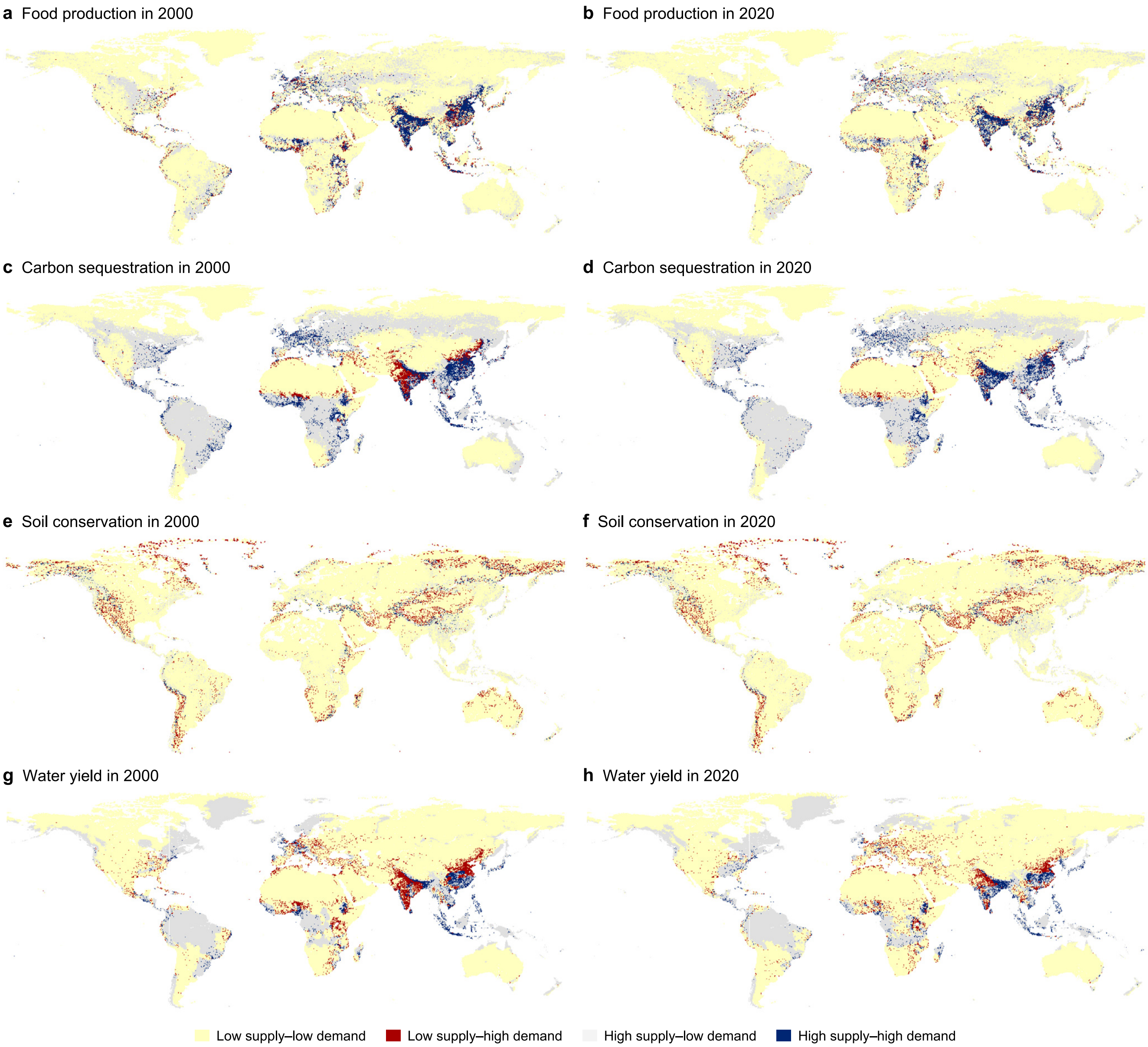
3.3. Impacts of climate change and human activities on the global ecosystem services supply–demand relationship

3.3.1. Correlation between climate change and ecosystem services supply–demand relationships

The correlations between climate change factors and the four key ESSD relationships had positive and negative attributes, varying by region. Precipitation was positively correlated with all four ESSD relationships in over 50% of regions, although the strength of this association varied. It showed a strong positive correlation with water yield (92.04% of regions) but a much weaker one with food production (7.66%).

For temperature, except for 69.74% of the regions positively correlated with the food production ESSD relationship, the correlation with the other three ESSD relationships was mainly negative, with an area share ranging from 57.54% to 76.78%. Carbon sequestration showed the strongest negative correlation and is significant in 24.22% of regions.

Regionally, the same climate variable affected different ESSD relationships in different ways. For example, in sub-Saharan Central Africa, precipitation showed a significant negative correlation with food production but a significant positive correlation with carbon sequestration (Fig. 5a–c). Significant differences exist in the correlation of different climate factors with the same ESSD



Types	Food production		Carbon sequestration		Soil conservation		Water yield	
	2000	2020	2000	2020	2000	2020	2000	2020
Low supply–low demand	73.35	74.05	53.73	54.64	85.63	85.87	67.71	68.36
Low supply–high demand	3.11	2.72	2.55	1.59	5.22	4.92	5.67	4.34
High supply–low demand	17.62	18.24	37.85	38.31	7.59	7.97	23.26	23.91
High supply–high demand	5.92	4.99	5.87	5.45	1.56	1.24	3.35	3.40

Area share of different match types (%)

Fig. 2. Spatial matching of global ecosystem service supply–demand: **a**–**b**, food production in 2000 (**a**) and 2020 (**b**); **c**–**d**, carbon sequestration in 2000 (**c**) and 2020 (**d**); **e**–**f**, soil conservation in 2000 (**e**) and 2020 (**f**); **g**–**h**, water yield in 2000 (**g**) and 2020 (**h**). The table presents the area share of each matching type (the ratio of the number of a specific type of grid to the total number of all types of grids).

relationship in the same region. For example, in Australia, precipitation was predominantly positively correlated with carbon sequestration and water yield (Fig. 5c–g), while temperature negatively correlated with both (Fig. 5d–h). These contrasting patterns were also observed for soil conservation (Fig. 5e and f).

3.3.2. *Impacts types of climate change and human activities on ecosystem services supply-demand relationships*

Overall (considering both individual and combined impacts), climate change and human activities had mostly positive effects on the ESSD relationships of food production and soil conservation, leading to surpluses in 80.69% and 72.5% of regions, respectively. In

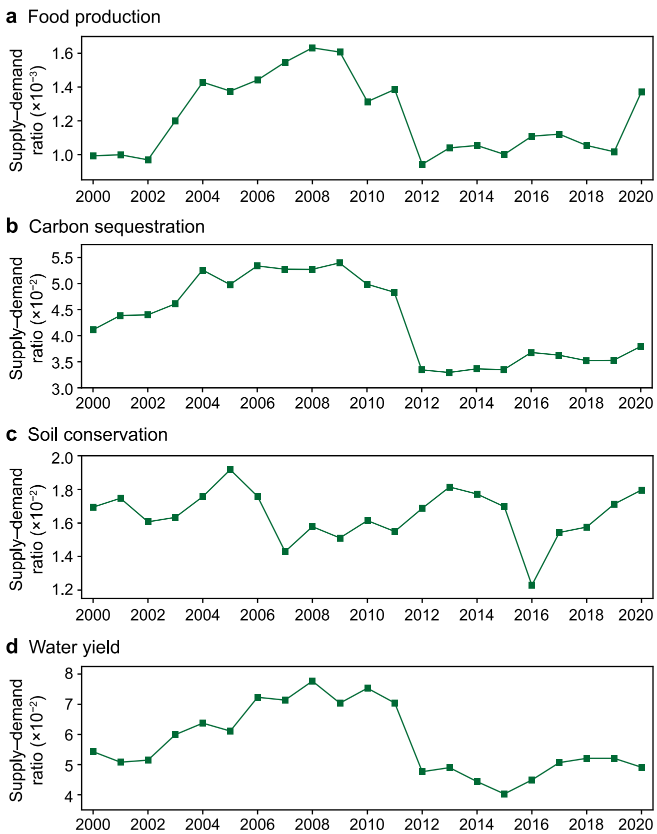


Fig. 3. Interannual global ecosystem services supply–demand ratio changes from 2000 to 2020: **a**, food production; **b**, carbon sequestration; **c**, soil conservation; **d**, water yield.

contrast, they negatively affected carbon sequestration and water yield, resulting in deficits in 76.74% and 62.44% of regions, respectively (Fig. 6).

ESSD relationships of food production, carbon sequestration, and soil conservation were more influenced by combined effects than climate change or human activity alone. Specifically, combined positive impacts on food production and soil conservation were observed in 67.48% and 60.78% of regions, respectively. Combined negative impacts on carbon sequestration were observed in 60.53% of regions.

For the ESSD relationship of water yield, combined and individual positive impacts were similar (18.73% and 18.83% of regions, respectively), but climate change alone contributed more to negative impacts (42.85% of regions) than combined effects (11.55% of regions). When considering positive and negative individual impacts, human activities had a broader impact on the ESSD relationship of food production than climate change. The reverse was true for the ESSD relationship of soil conservation and water yield, where climate change has a greater impact. For the ESSD relationship of carbon sequestration, human activities had a broader negative impact, while climate change had slightly greater positive effects.

Spatially, ESSD relationships in the same region could be similarly or differently affected by climate change and human activities. For instance, in Greenland and North Saharan Africa, the ESSD relationships of food production and carbon sequestration were positively affected by both factors (Fig. 6a and b). Conversely, the ESSD relationship of water yield in the same regions was more negatively impacted individually and combined (Fig. 6d).

3.3.3. Contribution of climate change and human activities to the ecosystem services supply-demand relationships

On average, human activities contributed more to ESSD relationships of food production (66.54%) and carbon sequestration (60.8%) than climate change (36.54% and 40.07%, respectively). In contrast, climate change contributed more to soil conservation (54.62%) and water yield (55.41%) than human activities (39.93% and 44.88%, respectively).

The spatial patterns support this: regions with high anthropogenic contributions (>80%) to ESSD relationships of food production and carbon sequestration accounted for 34.1% and 27.58% of the total area, respectively—5.83 and 3.03 times higher than areas with high climate change contributions. In contrast, regions where human activities heavily influenced ESSD relationships of soil conservation and water yield were limited to 9.35% and 15.67% of the area, respectively, amounting to just 45.32% and 68.1% of the areas dominated by climate contributions.

Spatially, human and climate contributions to the ESSD relationships of food production, carbon sequestration, and soil conservation often showed complementary patterns, with areas with low climate change contributions tending to be areas of high human activity and vice versa. For example, in Canada, the United States, southern Russia, and southern China, the contribution of climate change to ESSD relationships of food production and carbon sequestration was low, while human impacts were high. In contrast, the Amazon basin and sub-Saharan Central Africa showed high climate contributions and low human impact (Fig. 7a–d). This complementary pattern was less pronounced for water yield.

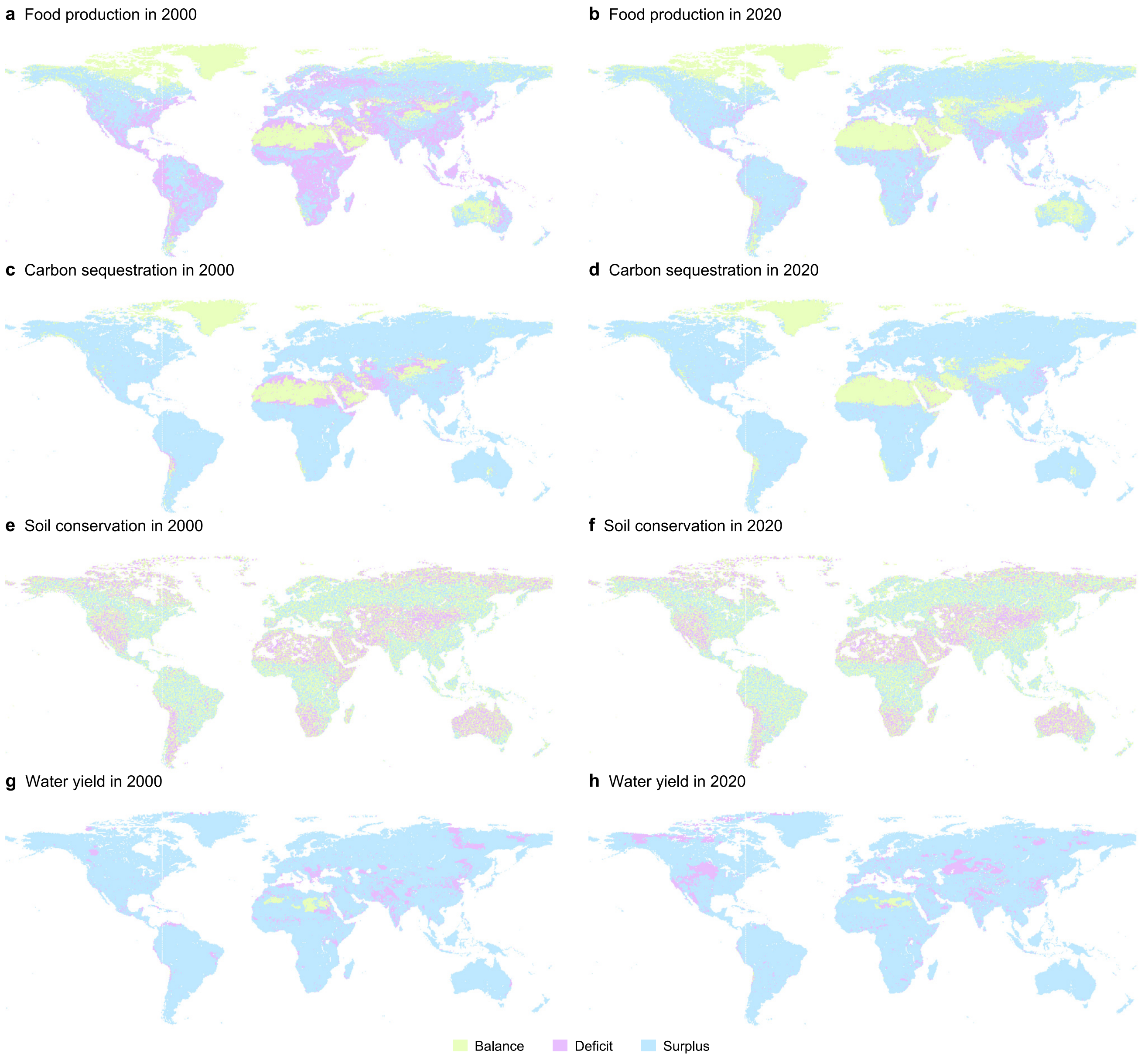
These trends held at both the pixel and national levels. Human activities influence food production and carbon sequestration (Fig. S7a and b), and the countries with the highest contribution rates are the Vatican and Uruguay, respectively (Table S11). In contrast, soil conservation and water yield were more strongly affected by climate change (Fig. S7c and d), with Palau and French Southern Territories exhibiting the highest contribution rates, respectively (Table S12).

4. Discussion

4.1. Accuracy and uncertainty in ecosystem services supply and demand assessments

The accuracy of research results is fundamental to ensuring the validity of conclusions and the reliability of subsequent decision-making. This paper aligns with existing research findings in reflecting the overall trends in ESSD (particularly supply). For instance, Pereira et al. [62] identified an upward trend in global food production. Multiple studies have shown increased global terrestrial carbon sinks [63,64]. Borrelli et al. [65] reported a general increase in global potential soil erosion. Gao and Jin [66] observed a decreasing trend in water yield.

Nevertheless, the results still carry a degree of uncertainty. On one hand, due to the differences in statistical standards, the basic data from various sources can lead to deviations in research outcomes. For example, evapotranspiration data, critical for calculating water yield, have shown significant variation across different data products [67]. Additionally, this study relies primarily on food balance sheet data from Food and Agriculture Organization Statistics to estimate food production. However, compared with other sources (e.g., national census portals), this dataset is considered less accurate in terms of classifying and tracking spatial changes in crop areas and yields across different agroecological zones [68]. This may explain the observed shift from the food deficit in sub-Saharan Africa and the persistent deficit in eastern China. Evidence also suggests that sub-Saharan Africa can achieve food self-sufficiency



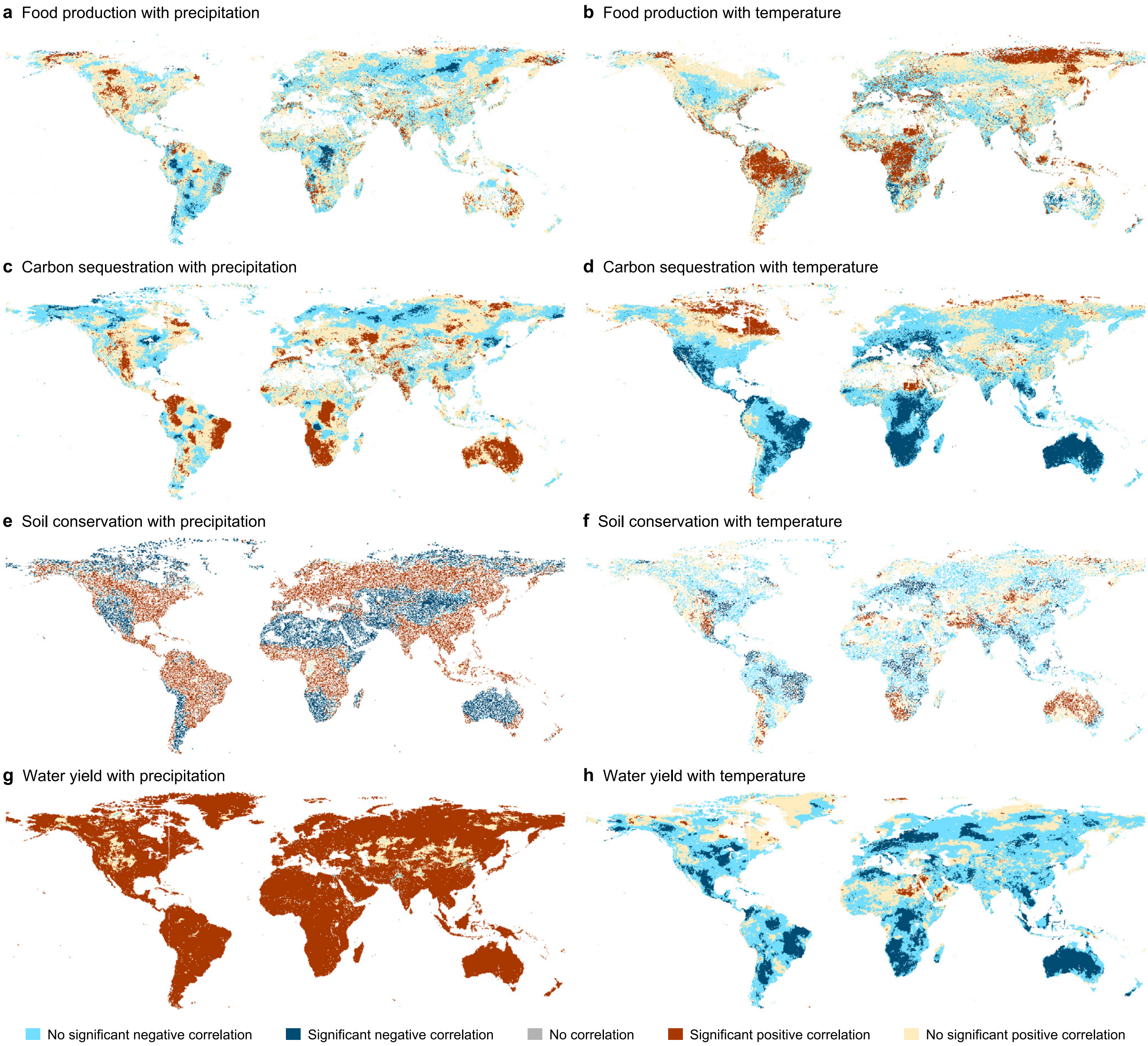
Types	Area share of different types (%)							
	Food production		Carbon sequestration		Soil conservation		Water yield	
	2000	2020	2000	2020	2000	2020	2000	2020
Balance	17.47	23.62	11.02	15.26	48.76	48.76	1.23	0.98
Deficit	38.76	11.22	7.33	2.76	23.26	21.16	7.61	9.33
Surplus	43.76	65.16	81.65	81.99	27.98	30.08	91.16	89.70

Fig. 4. Global distribution of surpluses and deficits in ecosystem services: **a**–**b**, food production in 2000 (**a**) and 2020 (**b**); **c**–**d**, carbon sequestration in 2000 (**c**) and 2020 (**d**); **e**–**f**, soil conservation in 2000 (**e**) and 2020 (**f**); **g**–**h**, water yield in 2000 (**g**) and 2020 (**h**). The table presents the area share of each type (the ratio of the number of a specific type of grids to the total number of all types of grids).

[69], while the food deficit in eastern China may be linked to high population density and intensive economic activity. Moreover, this study's assessment of ESSD is primarily based on traditional empirical models. Differences in model parameters, structures, and transmission mechanisms can also introduce uncertainties. Previous studies on soil erosion [65] and carbon sequestration [70] have demonstrated that employing different methods may yield assessment results that differ by more than an order of magnitude.

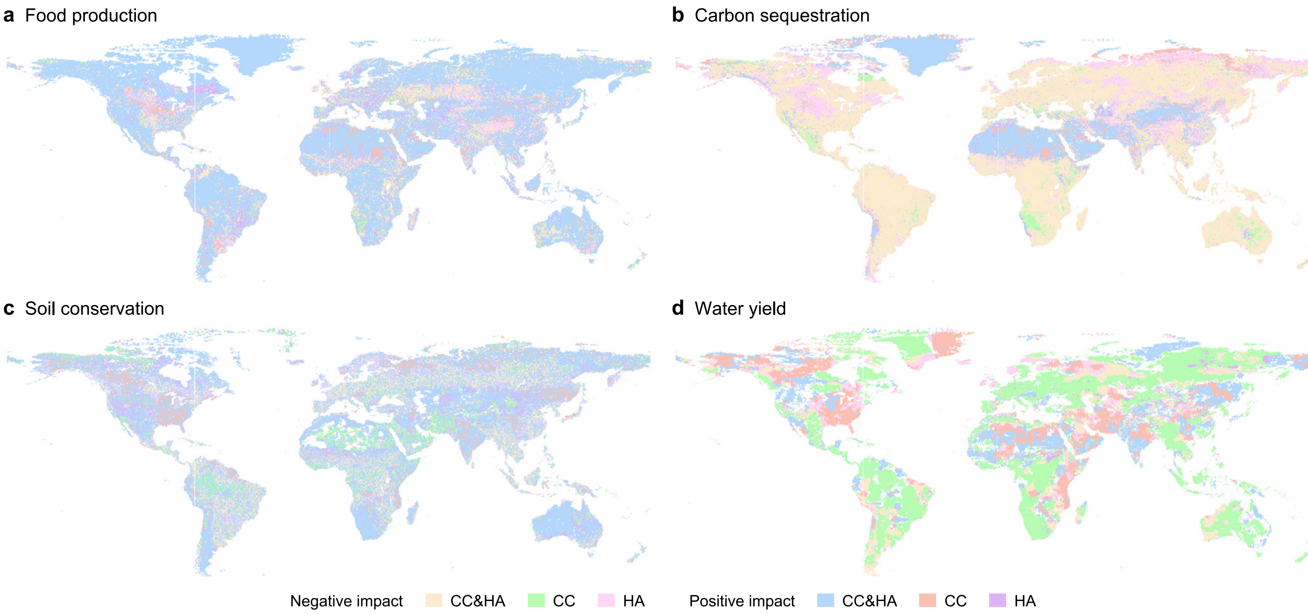
4.2. The impact of sudden and extreme events on global ecosystem services supply and demand

Sudden and extreme events can exacerbate the complexity and risk uncertainty of socio-ecological systems, thereby altering ESSD. We observed that food production supply and demand, as well as carbon sequestration demand, grew more slowly—or even declined—during the periods 2008–2009 and 2019–2000. These trends



Area share of different correlations (%)						
Ecosystem services	Climate factor	No significant negative correlation	Significant negative correlation	No correlation	Significant positive correlation	No significant positive correlation
Food production	Precipitation	37.18	3.92	0.24	7.66	51.00
	Temperature	26.56	3.51	0.19	19.56	50.18
Carbon sequestration	Precipitation	29.88	2.71	0.20	18.18	49.03
	Temperature	46.48	24.22	0.18	4.22	24.90
Soil conservation	Precipitation	4.37	38.18	0.01	52.60	4.84
	Temperature	42.96	14.58	0.11	10.84	31.51
Water yield	Precipitation	0.48	0.01	0.00	92.04	7.45
	Temperature	54.61	22.17	0.14	1.25	21.84

Fig. 5. Spatial patterns in the correlation between climate factors and ecosystem services supply–demand relationships: **a**–**b**, food production with precipitation (**a**) and temperature (**b**); **c**–**d**, carbon sequestration with precipitation (**c**) and temperature (**d**); **e**–**f**, soil conservation with precipitation (**e**) and temperature (**f**); **g**–**h**, water yield with precipitation (**g**) and temperature (**h**). The table presents the area share of each correlation type (the ratio of the number of a specific type of grids to the total number of all types of grids).



Area share of different impact types (%)

Ecosystem services	Negative impact			Positive impact		
	CC&HA	CC	HA	CC&HA	CC	HA
Food production	11.72	2.63	4.96	67.48	5.37	7.84
Carbon sequestration	60.53	4.03	12.19	16.09	4.10	3.07
Soil conservation	14.31	7.81	5.38	60.78	6.53	5.19
Water yield	11.55	42.85	8.04	18.73	16.40	2.43

Fig. 6. Distribution of the impact types of climate change and human activities on the ecosystem services supply–demand relationships: **a**, food production; **b**, carbon sequestration; **c**, soil conservation; **d**, water yield. The table presents the area share of each impact type (the ratio of the number of a specific type of grids to the total number of all types of grids). CC: the individual impact of climate change; HA: the individual impact of human activities. CC&HA: the combined impact of climate change and human activities.

are likely linked to the 2008 global financial crisis and the COVID-19 pandemic in 2020.

Regarding food production, supply chain disruptions caused by such emergencies [71] limited food production, supply, and consumption capacity. For instance, the COVID-19 pandemic resulted in the loss of more than one-third of the annual food supply for low-income countries in Asia and Africa [72]. Additionally, the proportion unable to afford half the cost of a healthy diet increased by 7% [73]. Extreme events can also affect food prices, thereby influencing supply and demand. Food and Agriculture Organization data show that the food price index declined and rebounded between 2008 and 2010. As the global economy gradually recovered, resurgent food demand pushed prices higher, which stimulated food production.

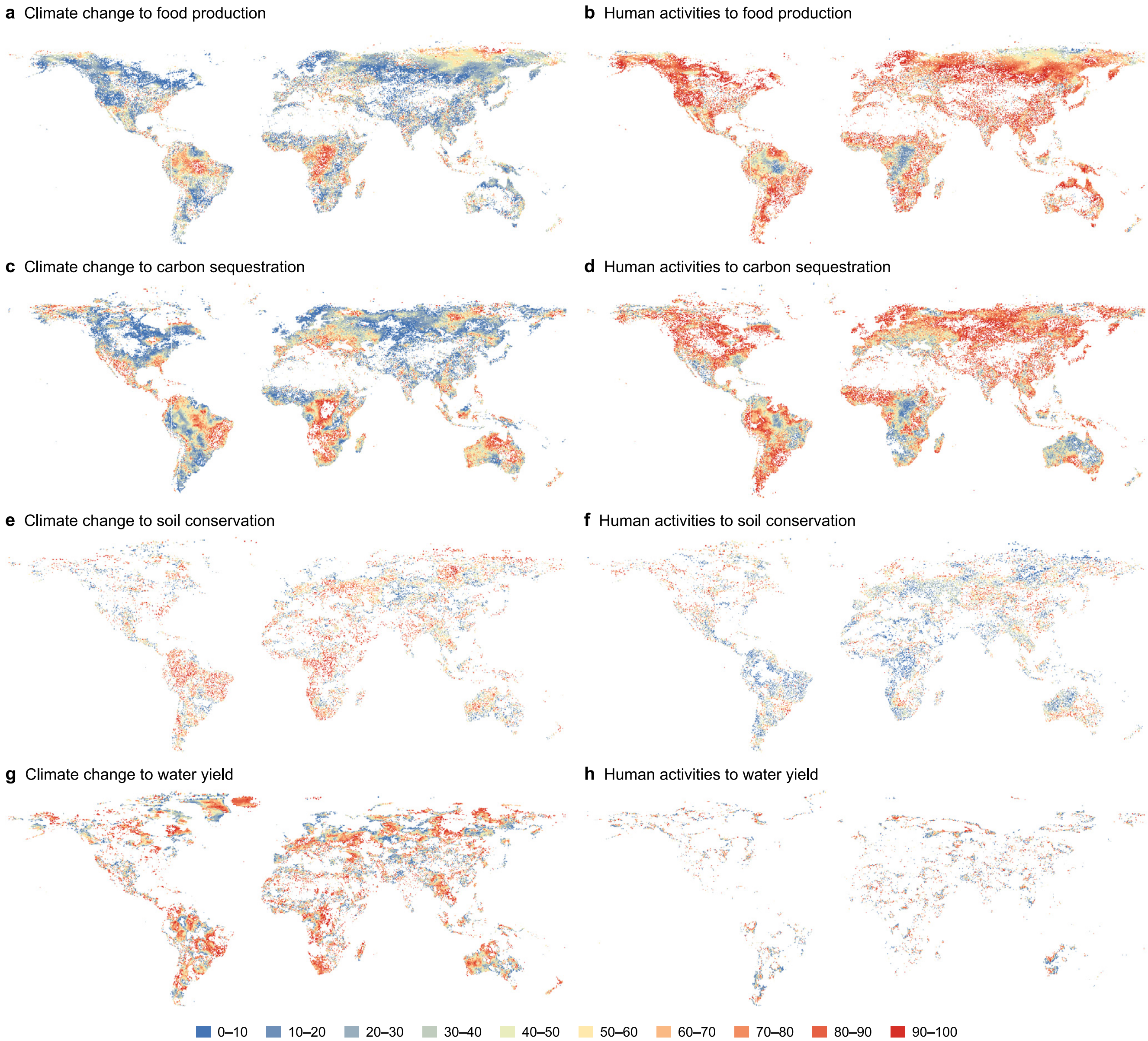
Regarding carbon sequestration, economic crises can cause stagnation or contraction in global industrial activity, reducing energy consumption. Simultaneously, sequestration measures, such as travel and consumption restrictions, lower carbon emissions and, consequently, the demand for carbon sequestration [74].

Furthermore, we found that soil conservation and water yield supply reached their lowest levels in 2015, likely due to climate extremes. According to the *Global State of the Climate Statement Report 2015* published by the World Meteorological Organization, that year saw the highest global average near-surface temperature on record. The associated droughts and wildfires severely damaged vegetation, reducing soil and water conservation capacity. High temperatures also increased evapotranspiration and reduced surface runoff.

4.3. Mismatch in ecosystem services supply–demand: the roles of climate change and human activities

Understanding ESSD mismatches helps decision-makers identify major supply areas and service gaps, providing a basis for ecosystem compensation mechanisms. In this study, H–L mismatches in food production, carbon sequestration, and water yield commonly occurred in regions with extensive cropland, forest, or grasslands and well-developed water systems but with relatively low population densities. In contrast, L–H mismatches were found in densely populated built-up areas. Higher population densities usually correspond to more intensive socio-economic activities, resulting in greater food consumption, water use, and carbon emissions—thus, higher demand for these ESs. Urban expansion often encroaches on cropland, forests, grasslands, and even watersheds, reducing the ecosystem's capacity to supply food, sequester carbon, and yield water. An example is carbon sequestration in India. Since 2000, rapid population growth and economic development have fueled energy demand, leading to substantial carbon emissions from coal-based energy use. Consequently, India has consistently shown high demand for carbon sequestration. Early environmental protection measures may have lagged, with deforestation and land use changes limiting supply. However, after joining the United Nations Climate Action initiative, India strengthened ecological protection, and vegetation recovered, improving the carbon sequestration supply.

Regions with H–L mismatches in soil conservation typically feature widespread forest cover, which enhances soil and water retention. L–H mismatches are generally found in areas dominated



		Area share of different contribution rate (%)									
Ecosystem services	Drivers	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Food production	CC	13.55	15.40	16.53	15.16	12.07	9.57	7.01	4.88	3.55	2.30
	HA	1.72	2.90	4.12	5.92	8.64	11.20	14.33	17.08	17.69	16.40
Carbon sequestration	CC	12.84	13.03	12.79	12.66	12.45	11.21	9.05	6.88	5.21	3.88
	HA	2.72	4.35	6.63	8.90	10.86	12.24	13.16	13.55	13.89	13.69
Soil conservation	CC	5.89	6.95	8.23	9.70	11.22	12.27	12.69	12.43	11.48	9.15
	HA	12.89	13.73	14.38	14.15	11.79	9.58	7.79	6.34	5.12	4.23
Water yield	CC	6.17	7.21	8.25	9.27	10.33	11.24	12.01	12.50	12.00	11.01
	HA	13.13	12.35	11.56	10.71	9.92	9.37	8.89	8.41	8.05	7.62

Fig. 7. Distribution of the contribution of climate change and human activities to the ecosystem services supply–demand relationships: **a**–**b**, contribution of climate change (**a**) and human activities (**b**) to food production; **c**–**d**, contribution of climate change (**c**) and human activities (**d**) to carbon sequestration; **e**–**f**, contribution of climate change (**e**) and human activities (**f**) to soil conservation; **g**–**h**, contribution of climate change (**g**) and human activities (**h**) to water yield. The table presents the area share of each contribution rate (the ratio of the number of a specific type of grids to the total number of all types of grids). CC: climate change; HA: human activities.

by ice sheets or deserts, where sparse vegetation and vulnerability to freeze–thaw cycles and wind erosion limit soil conservation capacity.

This study finds that climate change and human activities can positively and negatively affect the four ESSD relationships. Clarifying these dual impacts is essential for more effective policy formulation. For example, in areas where food production supply–demand is positively correlated with precipitation—typically forest, grassland, or bare land—greater rainfall improves soil fertility and quality, supports vegetation growth, and increases yields of livestock and forest products. On bare land, precipitation helps mitigate water shortages. Conversely, in forested areas where food production supply–demand is negatively correlated with precipitation, excessive rainfall can oversaturate the soil, reduce oxygen content, and cause soil erosion, thereby degrading soil structure and fertility, ultimately reducing crop productivity.

Regions where the food production supply–demand relationship is positively correlated with temperature are mainly forested or grassland areas with temperate continental, tropical rainforest, or tropical savanna climates. Higher temperatures in these areas stimulate microbial activity, accelerate nutrient cycling, promote vegetation growth, and extend growing seasons, thereby boosting food supply [75]. In turn, regions such as the central United States, eastern Brazil, Namibia, and parts of Australia experience negative correlations between temperature and food production. Heat stress, reduced photosynthesis, accelerated water evaporation, and soil degradation contribute to diminished productivity and supply deficits.

Human activities, including over-farming, unstable land management, and unchecked development, disrupt soil structure and reduce soil conservation capacity, further impacting crop yields [76]. Sustainable agricultural practices, such as organic farming and agroecosystem management, can improve soil health, enhance crop yields [77], and mitigate environmental degradation.

4.4. Limitations

Regulating ESSD relationships is crucial for optimizing the allocation of ecosystem resources and achieving sustainable development goals. To address limitations in previous studies, this research clarified the spatial and temporal dynamics of global ESSD, evaluated the spatial and quantitative matching relationships, identified the geographic distribution of the impacts of climate change and human activities on ESSD, and quantified their respective contributions. These findings offer valuable reference information for policymaking to mitigate global ecosystem degradation.

However, the complexity of ecosystems necessitates the inclusion of more comprehensive indicators to support effective ecosystem management decisions. First, the spatial mapping of food production, carbon sequestration, and water yield demand in this study was based on population density. Although this method is widely adopted in current research, it does not fully reflect the multifaceted nature of human demand for ESs. Second, this study used multiple regression residual analysis to distinguish the contributions of climate change and human activities to ESSD relationships. While this method is effective, it overlooks other drivers, such as geological activities and ecological succession. Moreover, the analysis treated human activities as a single aggregated factor, although these activities are highly diverse. Different types of human interventions may have markedly different effects on ESSD relationships. Accordingly, future research should consider incorporating a broader range of indicators and differentiating among types of human activities to improve the granularity and accuracy of assessments. This would offer more nuanced and actionable insights to support sustainable ecosystem management.

5. Conclusions

This study assessed global ESSD dynamics by analyzing spatial and quantitative matching relationships for four key ESs—food production, carbon sequestration, soil retention, and water yield—from 2000 to 2020. It also evaluated the influence of climate change and human activities on these relationships.

Overall, ESSD levels increased during the study period, except for a decline in soil conservation demand and water yield supply. Spatially, all four ESSDs primarily exhibited L–L matching and H–L mismatch patterns. The quantity-matching relationships showed distinct phase changes but indicated a general trend toward surplus. Climate change and human activities contributed to surpluses in the ESSD relationships for food production and soil conservation while leading to deficits in carbon sequestration and water yield in over half of the world's regions. In the cases of food production and carbon sequestration, human activities contributed more than climate change; for soil conservation and water yield, climate change played a more significant role. This research enhances our understanding of global ESSD trends and relationships over time and underscores the importance of accounting for both climate change and human activity in ecosystem management decisions aimed at sustainability.

CRediT authorship contribution statement

Shiqi Tian: Writing - Review & Editing, Writing - Original Draft, Visualization, Validation, Software, Methodology, Investigation, Formal Analysis, Data Curation, Conceptualization. **Wei Wu:** Writing - Review & Editing, Supervision, Resources, Project Administration, Methodology, Funding Acquisition, Formal Analysis, Conceptualization, Data Curation. **Shaofeng Chen:** Writing - Review & Editing, Funding Acquisition, Formal Analysis, Conceptualization, Data Curation. **Zhe Li:** Writing – Review & Editing, Software, Methodology, Data Curation, Formal Analysis, Validation. **Kai Li:** Writing - Review & Editing, Data Curation, Formal Analysis, Investigation, Methodology.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2025.100573.

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