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RESEARCH ARTICLE

# A Dual-Scale Zoning Strategy for Water–Energy–Food Supply and Demand Ecosystem Services

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The water–energy–food (WEF) nexus is essential for balancing resource use, yet most assessments overlook mismatches between administrative boundaries and ecological processes. This study developed a dual-scale framework for 105 counties and 89 sub-watersheds in Anhui Province, China, to quantify WEF supply–demand relationships and guide spatial governance. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, supply–demand index (SDI), 4-quadrant model, and entropy-weighted TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) model were applied to assess water yield, carbon storage, and food production supply–demand relationships. Additionally, a 4-step methodology was developed to delineate management zones. The results showed the following: (a) From 2000 to 2020, water supply increased by about 92% while demand rose by 97%. Food supply grew by 63%, whereas demand declined by 37%. Energy supply remained nearly stable, but demand surged by more than 340%. Both county and sub-watershed scales captured these overall patterns, while the sub-watershed perspective revealed sharper local fluctuations. Cross-service interactions were observed with trade-offs between W–F and E–F and synergies between W–E supply, reflecting the complex ecological coupling within the WEF nexus. (b) Supply–demand matching indicated that water and energy were deficit-dominated and food was surplus-oriented. The food SDI improved more markedly at the sub-watershed scale (0.04 to 0.50) than at the county scale (0.01 to 0.37), showing stronger local recovery and more evident clusters of mismatches. (c) The study area was divided into 3 resource partitioning zones, 4 matching typologies, and 4 priority strategies, and merged into 9 integrated governance zones. This research can give complementary insights from dual scales enabling targeted strategies for integrated WEF management in ecosystems.



## Introduction

Ecosystems provide various ecosystem services (ESs) essential for human well-being. Water, energy, and food (WEF) constitute the core resources supporting human survival and socioeconomic progress [1]. The interdependence of WEF resources has become increasingly apparent in the face of global change, and understanding their interactions within an integrated WEF nexus framework is a critical step toward achieving sustainable development [2]. The concept was formally highlighted at the 2011 Bonn Conference in Germany, where it was promoted as a holistic approach to resource management. It emphasized that securing one resource in isolation can undermine others if interlinkages are ignored. In recent decades, global population growth, economic expansion, climate variability, and rapid land-use change have accelerated the demand for WEF resources, placing mounting pressure on their supply [3,4]. These trends have contributed to biodiversity loss, resource scarcity, and socioeconomic challenges, underscoring the urgency for coordinated resource governance [5–8]. Consequently, developing integrative frameworks that simultaneously account for the supply and demand of WEF resources has become imperative for achieving both ecological sustainability and human well-being.

The WEF nexus is characterized by strong synergies and potential trade-offs. Overlooking these relationships can lead to unintended consequences [9]. For instance, in arid and semi-arid regions, excessive groundwater extraction for agricultural irrigation can temporarily increase food production but may deplete water sources [10] and ultimately threaten the sustainability of agriculture [11]. Additionally, fossil fuel-based energy generation requires substantial water and land resources, which can constrain agricultural production and compromise water availability [12]. Conversely, certain interventions such as protecting forested watersheds can simultaneously enhance water yield, improve carbon sequestration, and sustain agricultural productivity. Therefore, assessing WEF supply and demand from an ES perspective can offer a scientific foundation for integrated ecosystem governance and policy-making.

Another crucial challenge in WEF studies is the role of spatial scale [13]. ES supply capacity and demand intensity often exhibit marked spatial heterogeneity, and patterns at one scale may be different with another. Administrative-level assessments correspond to administrative boundaries, where policies, infrastructure investment, and industrial structure shape resource flows [14]. For example, large-scale investments in high-standard farmland can increase water use, potentially intensifying competition between agricultural, domestic, and industrial sectors [15]. Ecological-level assessments, by contrast, align with hydrological boundaries, capturing ecological processes such as runoff generation, groundwater recharge, and upstream–downstream interactions that cross administrative borders [16–18]. Changes in land use and consumption in upstream areas can amplify resource shortages downstream, highlighting the need for governance strategies that integrate both administrative and ecological perspectives [19].

In recent years, WEF-related ESs have been measured using multisource data integration, ecological modeling, valuation methods, and land-use analysis [13,20,21]. Studies have employed diverse analytical approaches, such as supply–demand ratios, coordination indices, and spatial clustering to reveal spatial and temporal patterns [22,23]. However, gaps still remain: (a) many studies examine WEF resources separately, without integrating them into a single coordinated assessment framework; (b) few studies have systematically compared results across different spatial scales; and (c) strategies for reconciling administrative and ecological zoning in resource governance remain underdeveloped. Bridging these gaps is essential for revealing both the direct impacts of policy interventions and the influence of natural processes on supply–demand dynamics. In light of these challenges, the key research question of this research is how can an integrated dual-scale assessment of WEF-related ESs reveal supply–demand mismatches and guide the formulation of targeted governance strategies that balance resource security with ecosystem sustainability? The main objectives of this research are to (a) quantify the spatiotemporal distribution and interrelationships of WEF-related ESs in Anhui Province from 2000 to 2020; (b) compare WEF supply–demand patterns and matching mechanisms at the county and sub-watershed scales to reveal scale effects; and (c) develop a zoning-based management framework and propose differentiated governance strategies for sustainable regional WEF management.

## Materials and Methods

### Study area

Anhui Province was selected as the study area due to its representative geographic and hydrological characteristics. It lies at the intersection of the Yangtze and Huai River Basins and contains important water resources with superior geographical location and water resources conditions (Fig. 1). The province enjoys a favorable geographical position and abundant water resources, covering about 139,000 km$^2$ and home to more than 60 million residents. Anhui Province experiences a warm temperate monsoon climate, with average annual temperatures between 14 and 17 °C and precipitation ranging from 800 to 1,800 mm. The average altitude is 119.3 m, along with diverse topography, consisting of mountains, hills, and plains. The central and northern plains are densely populated and agriculture is the dominant economic activity.

In this study, 89 sub-watersheds were divided based on the digital elevation model (DEM). Administratively, Anhui Province consists of 105 counties. Based on these sub-watershed and county divisions, this study conducted a dual-scale assessment and comparative analysis of WEF supply–demand dynamics.

### Data sources

We used multisource datasets covering the years 2000, 2010, and 2020. Land-use types included cropland, shrubland, forest, grassland, impervious surfaces, barren land, and water bodies. Detailed data sources are listed in Table 1. All spatial layers were standardized to the WGS_1984_UTM_Zone_50N projection and uniformly resampled to 30 m resolution.

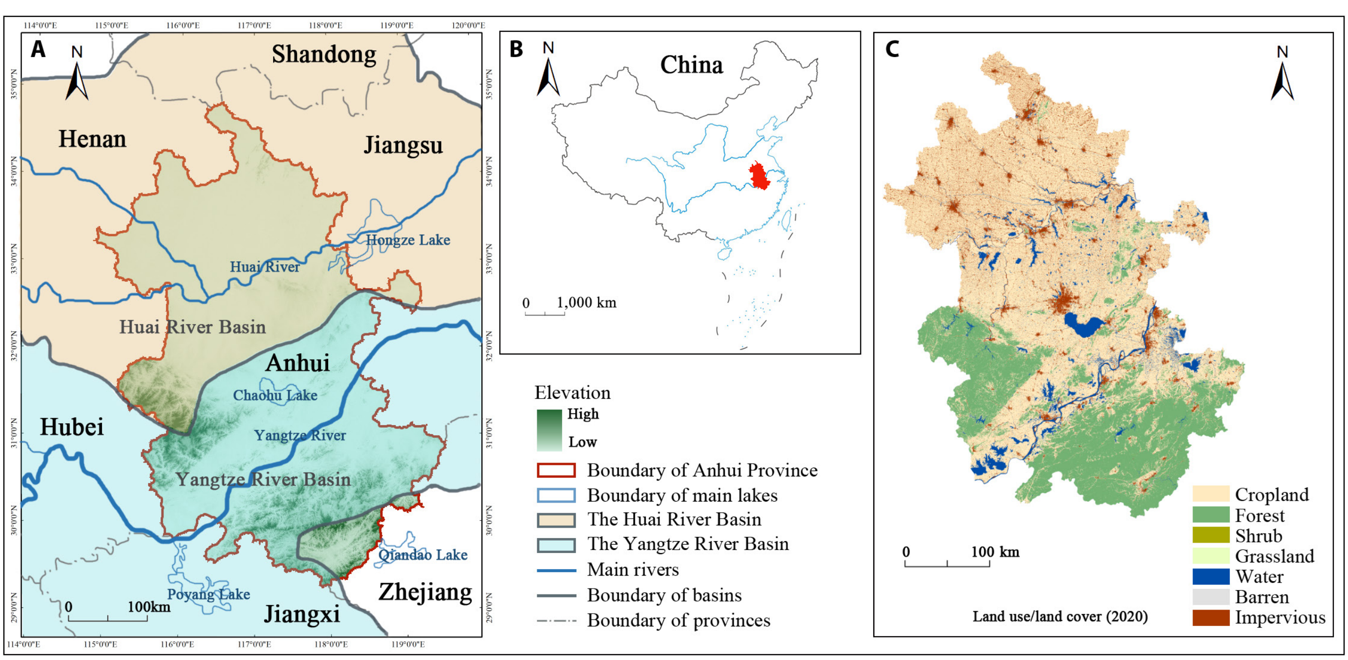


**Fig. 1.** Study area overview. (A) Geographical location of Anhui Province, including major river basins and administrative boundaries. (B) Position of Anhui Province in China. (C) Land use/land cover (LULC) of Anhui Province in 2020.

**Table 1.** Major data sources

| Data | Type | Data source | Spatial resolution |
|---|---|---|---|
| LULC | Raster | The 30-m annual land cover datasets and its dynamics in China from 1990 to 2021 [49] | 30 m |
| Precipitation | Raster | National Earth System Science Data Center, National Science and Technology Infrastructure of China (http://www.geodata.cn) | 1 km |
| Evapotranspiration | Raster | National Earth System Science Data Center, National Science and Technology Infrastructure of China (http://www.geodata.cn) | 1 km |
| Root depth, soil texture, and soil type | Raster | National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn) | 30 arc-second |
| DEM | Raster | National Earth System Science Data Center, National Science and Technology Infrastructure of China (http://www.geodata.cn) | 30 m |
| NDVI | Raster | http://www.resdc.cn | 1 km |
| Population density | Statistical data | Anhui Provincial Bureau of Statistics 2000–2020 (tjj.ah.gov.cn) | County |
| Carbon density | Spreadsheet | China terrestrial ecosystem carbon density dataset [33] | – |
| Standard coal consumption | Statistical data | Anhui Provincial Bureau of Statistics 2000–2020 (tjj.ah.gov.cn) | County |
| Food production | Statistical data | Anhui Provincial Bureau of Statistics 2000–2020 (tjj.ah.gov.cn) | County |
| Food consumption | Statistical data | Anhui Provincial Bureau of Statistics 2000–2020 (tjj.ah.gov.cn) | County |
| Water consumption | Statistical data | Anhui Provincial Bureau of Statistics 2000–2020 (tjj.ah.gov.cn) | County |

## Methodology for quantifying supply and demand of WEF-related ESs

In this study, we selected 3 ESs within the WEF nexus: water yield service (W), carbon storage service (E), and food production service (F). These ESs were chosen because they directly correspond to the provisioning and regulating ESs most relevant to regional sustainable development and can be quantitatively assessed using widely validated models and statistical datasets. Previous research commonly quantified WEF supply and demand using water yield and actual water consumption for W, grain production and food consumption for F, and carbon storage alongside carbon emissions for E [24,25].

1. W supply: The annual water yield was quantified using the Annual Water Yield module of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, which is grounded in the water balance principle [26,27]. This module estimates annual runoff as the difference between precipitation and actual evapotranspiration, thereby reflecting the capacity of ecosystems to generate renewable water resources. Water yield directly captures the hydrological processes that sustain ESs and agricultural productivity, and the InVEST model allows water yield to be mapped at fine spatial resolution based on land use, soil, and climatic conditions, making it possible to assess spatial heterogeneity across counties and sub-watersheds. The calculation method is as follows, with detailed parameters provided in the Supplementary Materials.

$$S_{wi} = \left(1 - \frac{\mathrm{AET}_i}{P_i}\right) \times P_i \tag{1}$$

where $S_{wi}$ indicates the amount of water generated annually (mm). This value is computed using the recorded precipitation $P_i$ (mm) and the corresponding actual annual evapotranspiration $\mathrm{AET}_i$ (mm).

2. W demand: In this study, water use was estimated as the aggregate demand from multiple anthropogenic activities, including agricultural irrigation, industrial production, urban public services, household consumption, and ecological maintenance. In practice, this was operationalized by multiplying population density by per-capita water consumption. This method integrates demographic distribution with average consumption intensity, capturing the spatial variability of human water demand. Although it simplifies sectoral differences, it provides a robust and widely applicable proxy that aligns with available statistical data [25]. The formula is as follows:

$$D_{wi} = \rho_i \times W_i \tag{2}$$

where $D_{wi}$ represents annual water demand ($m^3/hm^2$). This value is obtained by multiplying the local population density (persons/$hm^2$) with the corresponding per-capita water consumption $W_i$ ($m^3$/person).

3. E supply: The selection of indicators for representing energy (E) in the WEF nexus needs to balance ecological measurability, policy relevance, and data availability. Directly mapping energy supply (e.g., hydropower, thermal generation, or electricity distribution) at fine ecological scales is extremely difficult due to the lack of consistent, spatially explicit data, as well as the dynamic and infrastructure-dependent nature of energy systems. By contrast, ecosystem carbon storage provides an ecologically meaningful and biophysically consistent proxy for the supply dimension of energy.

Specifically, the InVEST Carbon Storage module quantifies aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter [28]. Carbon storage represents the capacity of ecosystems to offset fossil-fuel emissions through sequestration, thereby connecting energy use with climate regulation. Besides, the InVEST model allows carbon storage to be mapped across LULC types, aligning energy supply with water and food services in the nexus framework. The formula is as follows:

$$S_{ci} = C_{\text{above}} + C_{\text{below}} + C_{\text{soil}} + C_{\text{dead}} \quad (3)$$

where $S_{ci}$ indicates the total carbon storage (t/hm$^2$), which is the sum of aboveground biomass carbon stock ($C_{\text{above}}$), belowground biomass carbon stock ($C_{\text{below}}$), soil organic carbon stock ($C_{\text{soil}}$), and dead organic matter carbon stock ($C_{\text{dead}}$). The carbon density used in the InVEST model for each LULC is provided in the Supplementary Materials.

4. E demand: Household energy use in Anhui Province is still dominated by coal consumption, which constitutes the largest single source of direct carbon emissions. Using per-capita coal consumption as a proxy for energy demand captures the pressure that human populations exert on the environment through energy use. The indicator integrates population density with average carbon intensity of household energy, thus reflecting spatial heterogeneity in demand. Although coal does not cover all forms of energy use, it is the most representative and statistically reliable energy source over long time periods in the study region, and its carbon-based accounting is consistent with the carbon storage measure of supply [25]. The formula is as follows:

$$D_{ci} = \rho_i \times C_i \times C_t \quad (4)$$

where $D_{ci}$ represents the carbon demand (t/hm$^2$), which is obtained by multiplying the population density $\rho_i$ (persons/hm$^2$) with the per-capita carbon consumption $C_i$ (t standard coal/person), and $C_t$ is the carbon emission conversion factor for coal consumption with the value of 0.67.

5. F supply: In this study, Normalized Difference Vegetation Index (NDVI) was used as a proxy for vegetation biomass to estimate food supply. NDVI is strongly and positively correlated with crop yield, as vegetation greenness reflects photosynthetic activity and biomass accumulation [29]. By distributing total grain yield across grid cells according to the relative NDVI of cultivated land, the method enables a spatially explicit allocation of agricultural production. This approach accounts for heterogeneity in land productivity, providing a more ecologically realistic distribution of food supply than using uniform averages. Moreover, NDVI-based estimation allows long-term and large-scale analysis, as satellite data are consistently available and comparable across time and space [30]. The formula is as follows:

$$S_{fi} = \left( \frac{\text{NDVI}_i}{\text{NDVI}_{\text{sum}}} \right) \times G_{sum} \quad (5)$$

where $S_{fi}$ represents the annual food production (t/hm$^2$), $\text{NDVI}_i$ is the NDVI value at raster $i$, $\text{NDVI}_{\text{sum}}$ is the sum of NDVI values for all cultivated land, and $G_{\text{sum}}$ is the total annual grain production (t).

6. F demand: Food consumption is inherently linked to human population distribution. Therefore, food demand was estimated by multiplying population density by per-capita food demand. This method integrates demographic factors with consumption intensity, producing a spatially explicit pattern of demand across the study area. It also captures urban–rural contrasts, since high-density urban areas typically exert greater pressure on food supply chains. F demand is calculated based on per-capita food consumption and population density [25].

$$D_{fi} = \rho_i \times F_i \quad (6)$$

where $D_{fi}$ is the food demand at raster $i$ (t/hm$^2$), $\rho_i$ is the population density at raster $i$ (persons/hm$^2$), and $F_i$ is the per-capita food demand at raster $i$ (t/person).

## Assessment of ESs supply–demand matching

### *Correlation among ESs*

We applied the Pearson correlation coefficient to analyze the interrelationships among ESs [31]. By calculating the correlation coefficients between each pair of ESs indicators, the study revealed their relationships at different spatial scales. The formulas are presented in the Supplementary Materials.

### *Spatiotemporal of supply–demand matching mode*

This study employed the supply–demand index (SDI) to assess the balance between ESs supply and demand [24]. The SDI quantifies the degree of matching between supply and demand, reflecting the adequacy of ESs allocation and their capacity to support regional sustainability. The formulas are in the Supplementary Materials.

### *ESs supply–demand mode based on the 4-quadrant model*

This study adopted the 4-quadrant method by standardizing ES supply and demand data and projecting them onto a 2-dimensional coordinate system. The standardized supply values are assigned to the $X$-axis and demand values are assigned to the $Y$-axis, resulting in a 2D scatter plot. The supply–demand relationships are classified into 4 quadrants: high supply–high demand, high supply–low demand, low supply–high demand, and low supply–low demand [32]. The formulas are in the Supplementary Materials.

### *Overall WEF performance*

The entropy-weighted Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method combines entropy-based weighting with the technique for order preference by similarity to the ideal solution approach, providing a multicriteria decision-making framework based on proximity to an ideal solution. In this study, the entropy-weighted TOPSIS model is applied to comprehensively evaluate the overall performance of the WEF supply–demand balance. Integrating WEF supply–demand relationships into a comprehensive score objectively reflects the comparative importance of various indicators. The score represents the proximity of the supply–demand balance to the ideal solution. A score close to 1 indicates a better overall condition of WEF supply–demand balance while a score close to 0 indicates a poorer overall condition of the WEF supply–demand balance. The supply–demand difference is min–max normalized to eliminate the influence of different unit. Details are in the Supplementary Materials.

### WEF supply–demand zoning framework

To establish a comprehensive WEF management framework, we integrated supply–demand matching, spatial pattern analysis, and coordination assessment to adopt a 4-step approach: resource partitioning, matching typology, priority strategy, and integrated governance to delineate management regions (Fig. 2). In step 1, we identified 3 primary ES supply zones based on the spatial distribution of W, E and F SDI values: W supply zone (areas with relatively high W supply), E supply zone (areas with higher E supply), and F supply zone (areas with high F supply). In step 2, within each ES supply zone, the 4-quadrant model was applied to further categorize supply–demand relationships into 4 subcategories: core zone (high supply–high demand), surplus zone (high supply–low demand), pressure zone (low supply–high demand), and deficit zone (low supply–low demand). In step 3, to enhance the zoning system, entropy-weighted TOPSIS scores were incorporated to rank the regions into 4 levels: priority zone, growth zone, improvement zone, and concern zone. In step 4, the results of step 2 were overlaid with the TOPSIS-based management zones (step 3) to generate a comprehensive WEF management zoning system. Zoning criteria were therefore defined by combining resource abundance identified by SDI values of WEF, supply–demand relationship type determined via the 4-quadrant classification, coordination level ranked through entropy-weighted TOPSIS scoring, and spatial governance scale integrating county-scale and sub-watershed boundaries to ensure both administrative operability and ecological relevance. This integrated framework provided a scientific basis for sustainable resource governance, ensuring a balanced and strategic management approach for WEF resources.

## Results

### Spatiotemporal characteristics of WEF supply–demand

From 2000 to 2020, high spatial heterogeneity in WEF supply and demand was observed at both county and sub-watershed scales in Anhui Province (Fig. 3). At the county scale, W supply demonstrated a rising pattern, with hotspots mainly distributed in the southwestern region, exceeding 13,000 $m^3/hm^2$ in 2020, representing an overall increase of about 92%. In contrast, W demand intensified in the central region, peaking at over 20,000 $m^3/hm^2$, which corresponded to a growth of nearly 97%. The supply of E in the province remained relatively stable, which decreased 2%, with higher values in the western and southern regions than in other areas, while E demand showed



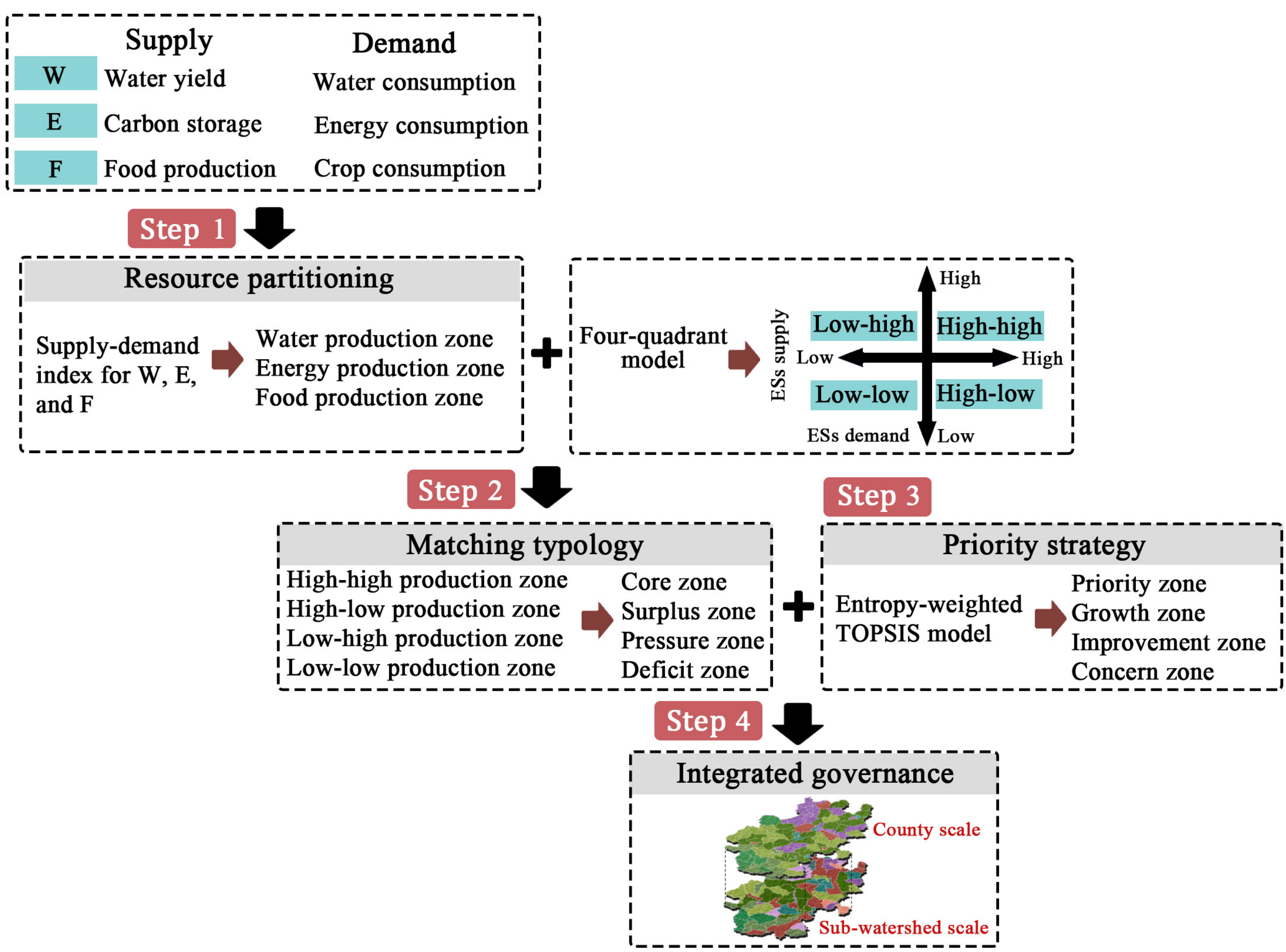


**Fig. 2.** The 4-step approach for WEF management under the dual-scale framework.

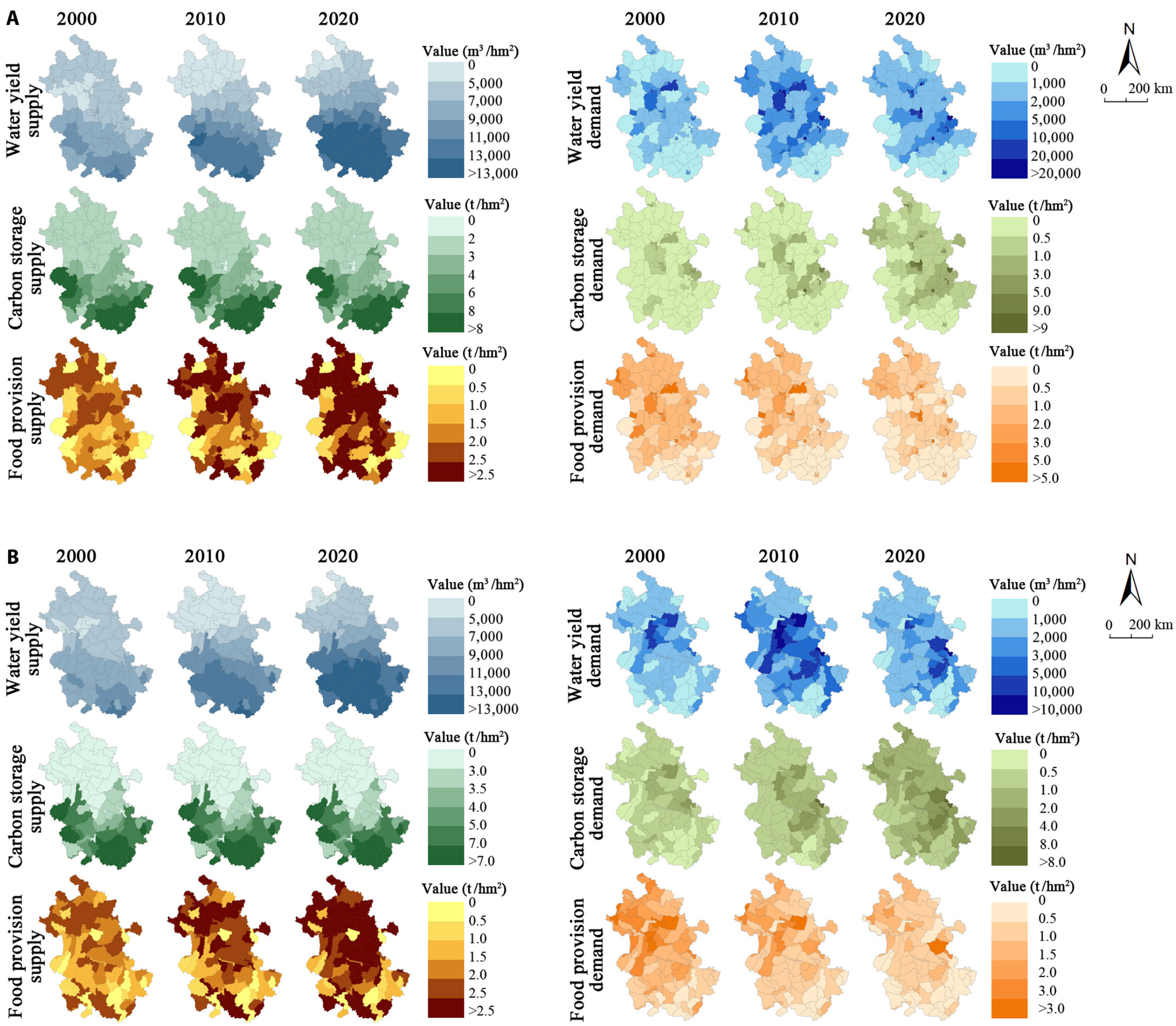


**Fig. 3.** Supply and demand patterns of WEF for the years 2000, 2010, and 2020, illustrated at (A) the county scale and (B) the sub-watershed scale.



a sharp upward trend, rising by more than 340%, with values in the eastern region exceeding 9 t/hm$^2$ in 2020. The supply of F had increased about 63% over the last 2 decades, mainly concentrated in the central and northern regions, while the demand for F had shown a decline of around 37%.

At the sub-watershed scale, similar spatial differentiation was observed, but the spatial gradients were clearer. W supply increased from west to east, while W demand was concentrated in the central and eastern regions. On average, sub-watershed W supply and demand values were about 10% to 15% lower than county-scale averages, reflecting the localized hydrological constraints. E supply remained relatively stable, whereas E demand experienced notable growth, which was over 340%, with the central and eastern regions showing sharper increases than county-scale estimates. F supply showed an upward trend of around 55% increase in the central and northern areas, while F demand exhibited a continuous decline over the past 2 decades. Overall, the average values of WEF supply and demand at the sub-watershed scale were consistently 5% to 20% lower than those at the county scale, reflecting the finer spatial resolution and the influence of natural hydrological boundaries that tend to capture more localized constraints.

## WEF supply–demand data rationality

By integrating statistical data and models to quantify the supply and demand of the 3 ESs, this method guaranteed data accessibility while aligning with the specific features of the region, providing a feasible technical pathway for further supply–demand balance analysis. For W supply, the InVEST model estimated the annual water yield for the years 2000, 2010, and 2020, with provincial average values of 4,800.06, 7,335.70, and 9,199.60 m$^3$/hm$^2$, respectively (Table S3). A comparison with data from the Anhui Provincial Water Resources Department's Water Resources Bulletin revealed official statistics of 64.421, 93.905, and 128.041 billion m$^3$ for the respective years. After unit standardization, the relative errors were 3.99%, 9.01%, and 6.24%, all values fell within a

10% margin, demonstrating that the simulation results closely matched the official statistics and were highly reliable. For E supply, we employed the InVEST carbon storage module combined with carbon density database for regions with similar latitudes and longitudes [33] to estimate carbon storage. The results showed a spatiotemporal pattern similar to Wu [34] who used the net primary productivity method for E estimations, further validating the rationality of results in this study. To validate F supply estimation, NDVI-based calculations were compared with actual agricultural yield data from the Anhui Statistical Yearbook. The error was consistently below 10%, which could confirm that the methodology used in this study was reliable.

Based on these findings, the WEF supply–demand evolution in Anhui Province from 2000 to 2020 exhibited distinct trends. W supply and demand both increased, driven by improvements in water infrastructure, stable to above-average precipitation, and increased forests cover [35]. F supply continuously increased mainly due to advancements in agricultural technology and improved irrigation efficiency. Meanwhile, F demand declined, which could be attributed to dietary diversification and a slowing population growth rate. E supply declined, primarily due to rapid urbanization, leading to the alteration of forest and grassland areas, as well as soil degradation, reducing carbon sequestration capacity per unit area [36]. In contrast, industrialization and transportation expansion highly increased energy consumption, causing E demand to rise continuously [37]. These trends were consistent with the economic, social, and ecological transformations that Anhui Province had undergone over the past 2 decades. They further supported the reliability of the data selection and model applications used in this study.

## Correlation between WEF supply–demand

At county and sub-watershed scales, the correlation between WEF supply–demand exhibited both consistency and scale dependence (Fig. 4). At the county scale, W–E supply showed a positive correlation, while F supply exhibited a weak negative correlation with both W and E, indicating resource allocation competition. In terms of demand, the strongest positive correlation was observed between W–E demand, followed by W–F and E–F, which suggested that there was a certain degree of synergy among the three.

At the sub-watershed scale, W–E supply maintained a strong positive correlation, but the negative correlations between F–W supply and E–F supply were more pronounced. Compared to the county scale, the correlation of demand at the sub-watershed scale was reduced but still significantly related. Among demand relationships, W–E demand exhibited the strongest positive correlation, followed by W–F and E–F. Notably, cross-scale comparison revealed that supply trade-offs were more intense at the sub-watershed scale, while demand synergies were stronger at the county scale, indicating that different spatial frameworks may shape how W, E, and F relationships are perceived.

Overall, the results revealed evident cross-service interactions among WEF supply. In particular, significant trade-offs were found between W–F and E–F, while W–E supply exhibited synergies in certain regions. Regarding demand, all ES pairs were positively correlated with the strongest synergy between W–E demand. These results indicated that resource supply and demand were interconnected across sectors and spatial frameworks, suggesting that cross-service interactions play a vital role in shaping regional resource dynamics.



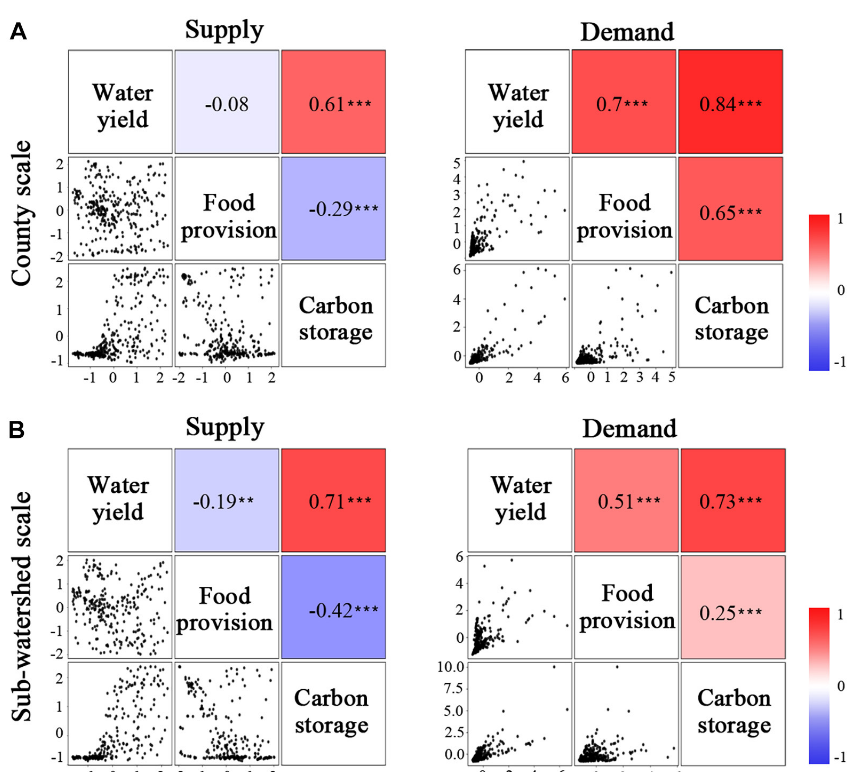


**Fig. 4.** Correlation between WEF supply–demand at (A) the county scale and (B) the sub-watershed scale.

## Spatiotemporal characteristics of WEF SDI

At the county scale, from 2000 to 2020, W SDI showed positive values in the western and southern regions, which indicated sufficient W supply (Fig. 5). In contrast, some central and eastern counties had negative values, suggesting W supply deficits. However, these deficit areas gradually decreased over time. This trend aligns with the quantitative SDI values in Table S4, where W SDI decreased from 0.59 in 2000 to 0.31 in 2010, then rebounded to 0.54 in 2020, reflecting fluctuations but overall improvement in water supply–demand balance at the county scale. The E SDI remained relatively stable across the province. However, some eastern counties began showing negative SDI values from 2010 and the deficits further expanded by 2020. This indicated that E demand growth exceeded supply in these areas. This is supported by the E SDI values (Table S4), which decreased consistently from 0.77 in 2000 to 0.43 in 2020 at the county scale, reflecting a declining energy supply relative to demand. The F SDI revealed marked supply–demand imbalances in the central and northern counties, where demand consistently exceeded supply over time. In contrast, the eastern and southern regions maintained positive SDI values, reflecting a relative balance of F supply–demand relationship. Correspondingly, the F SDI increased steadily from a low 0.01 in 2000 to 0.37 in 2020 at the county scale, suggesting gradual improvements in food supply relative to demand over time.

At the sub-watershed scale, the overall trend was similar to that at the county scale. W and F deficits were prominent in central sub-watersheds, which indicated severe supply shortages. The W SDI values were slightly higher than at the county scale, ranging from 0.64 in 2000 to 0.66 in 2020, showing relatively better water supply conditions locally. F SDI also increased more markedly at this scale, from 0.04 in 2000 to 0.50 in 2020, supporting the observed trends of improving food supply–demand balance. The E SDI remained relatively stable, but eastern sub-watersheds started experiencing E deficits after 2010, which intensified further by 2020. This highlighted the growing pressure on E supply in the eastern and central regions. These findings revealed high spatial disparities in the WEF supply–demand balance across Anhui Province during the past 2 decades. The supply and demand mismatches in central and eastern regions were particularly severe. It is necessary to take out targeted management strategies to alleviate resource pressures.

## Spatial matching patterns of WEF supply–demand

We utilized the 4-quadrant approach to reveal spatial coordination patterns between WEF supply and demand (Fig. 6). At the county scale, areas with high supply–high demand for water were concentrated in the central and eastern regions, accounting for 11.4% of the area, where dense populations and vigorous economic activities drove substantial demand. High supply–low demand dominated in the western and southern regions, covering 40.9%, while low supply–high demand appeared in the central part with 14.28%, leaving 32.47% as low supply–low demand. For energy, only 0.95% of the area fell into the high supply–high demand category, while more than half of the counties, 52.38%, were characterized by low supply–low demand. The remaining areas were distributed between high supply–low demand at 26.67% and low supply–high demand at 20%, highlighting energy stress in fast-growing regions. Food supply patterns were different: high supply–high demand was more common, covering 16.19% mainly in the western mountainous regions, while high supply–low demand dominated in the northern agricultural counties with 43.84%. The rest was divided between low supply–high demand at 13.3% and low supply–low demand at 26.67%.

At the sub-watershed scale, spatial mismatches became more pronounced. For W, high supply–high demand accounted for 12.36%, high supply–low demand for 38.2%, low supply–high demand for 14.6%, and low supply–low demand for 34.84%. For E, high supply–high demand covered 4.76%, high supply–low demand covered 25.84%, low supply–high demand covered 28.09%, and low supply–low demand covered 41.34%. F exhibited the highest proportion of high supply–high demand zones,

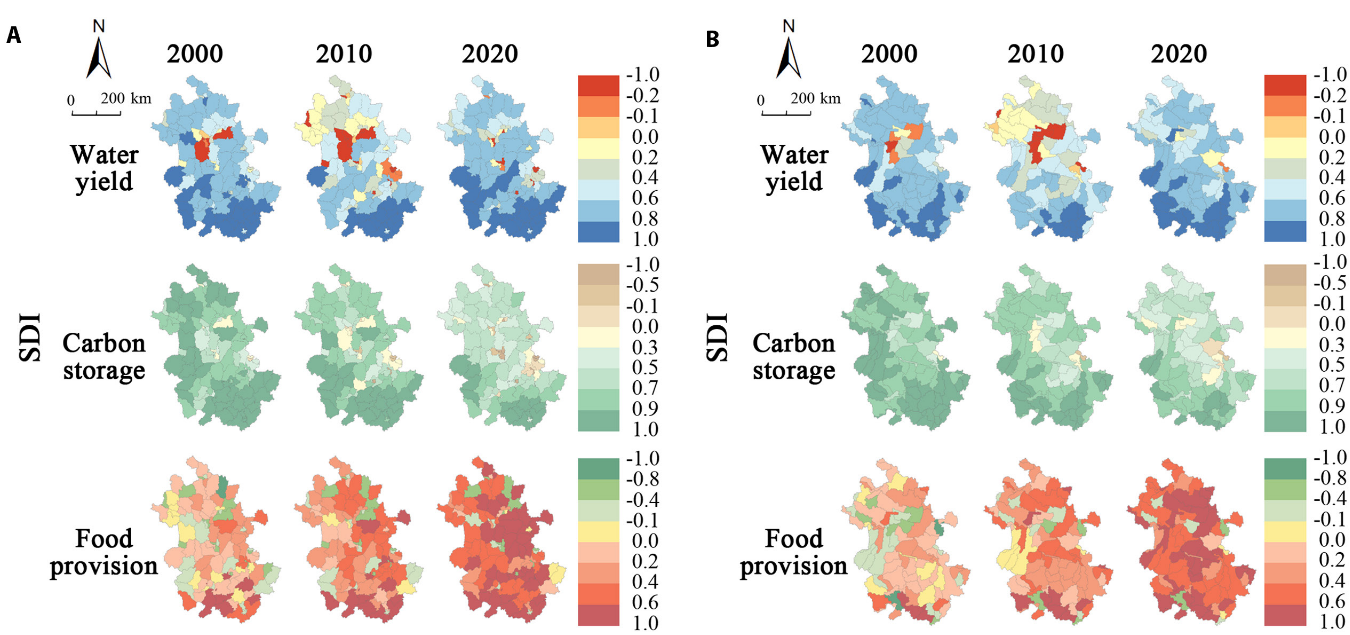


**Fig. 5.** SDI of W, E, and F across 2000, 2010, and 2020 at (A) the county scale and (B) the sub-watershed scale.

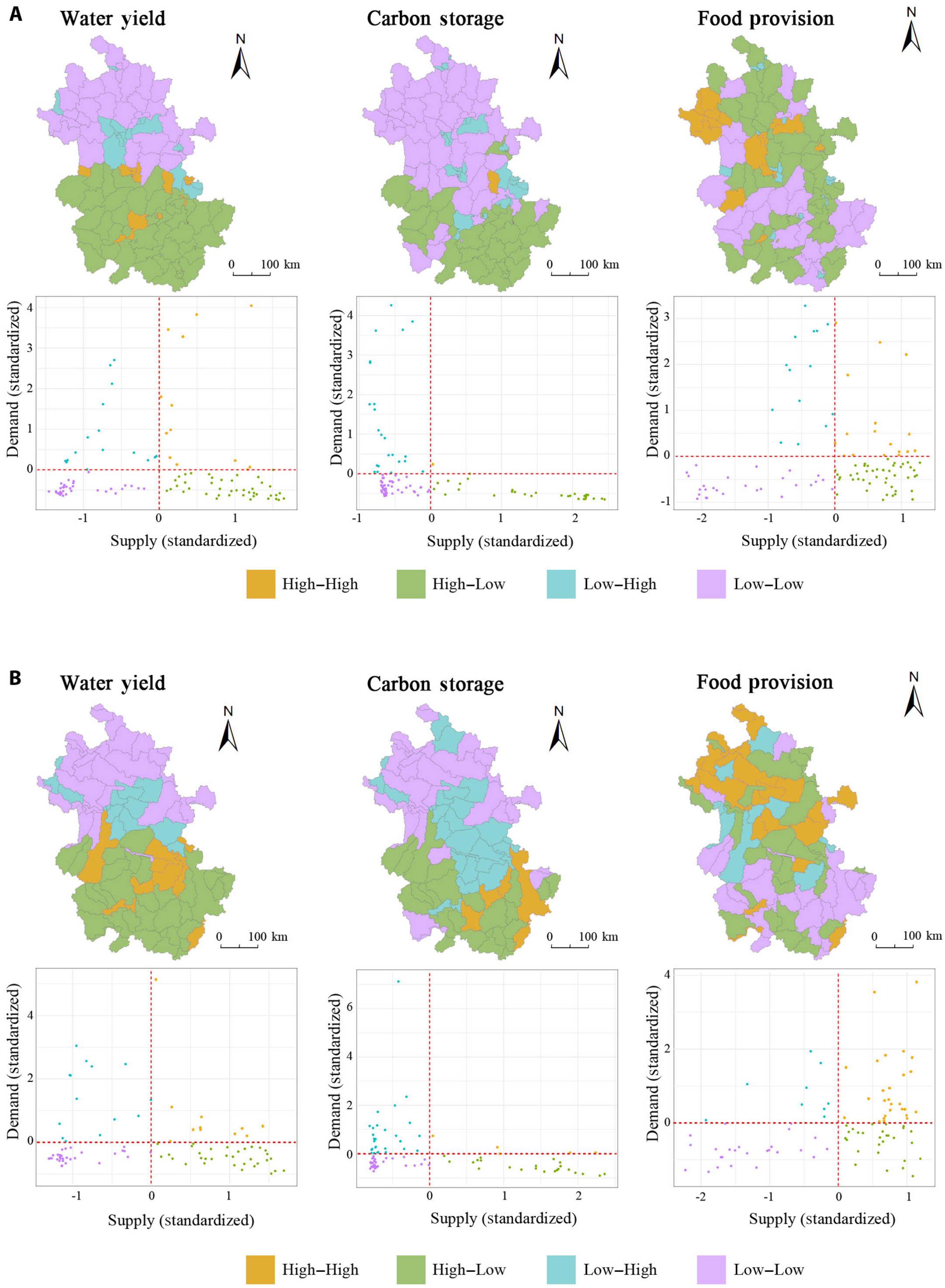


**Fig. 6.** Spatial matching modes of WEF in Anhui Province at (A) the county scale and (B) the sub-watershed scale.

reaching 30.34%, while high supply–low demand accounted for 31.46%, low supply–high demand accounted for 10.11%, and low supply–low demand accounted for 28.09%.

A cross-scale comparison shows that the county scale highlights broad regional trends, where most areas fall into high supply–low demand or low supply–low demand categories, reflecting a general mismatch between resource provision and utilization. By contrast, the sub-watershed scale reveals finer spatial heterogeneity, exposing more localized high supply–high demand areas for F and clearer resource stress zones for W and E. This demonstrates that the county scale is more effective in identifying macro-level imbalances, whereas the sub-watershed scale provides more nuanced insights into ecological fragility and management priorities.

## Resource governance pattern at dual scale

The study results showed marked spatial differences in the supply–demand patterns and management priorities of WEF in Anhui Province (Figs. 7 and 8). At the county scale, W supply zones were concentrated in the southern and western counties, F production zones dominated the agriculturally developed east and north, while E production was mainly distributed in the west and southeast. Surplus zones covered about 83% of the total area, reflecting overall abundance, but pressure zones appeared in the central part of Anhui due to rapid urbanization, and deficit zones clustered in the west and north. Priority zones for management were concentrated in central regions, while improvement and concern zones were scattered across the north. In terms of governance types, CC (core zone + concern zone) accounted for 4.76% of counties; SC (surplus zone + concern zone) accounted for 28.57%; SP accounted for 5.71%, all of which are located in the southern area; PC (pressure zone + priority zone) accounted for 12.38%; SG (surplus zone + growth zone) accounted for 6.67%; DI (deficit zone + improvement zone) accounted for 0.95%; SI (surplus zone + improvement zone) accounted for 22.87%; and DC (deficit zone + concern zone) accounted for 18.09%.

At the sub-watershed scale, W supply zones remained concentrated in the south and west, but in smaller patches compared to the county scale; F production zones in the north and east were also fragmented, while E production was scattered in the

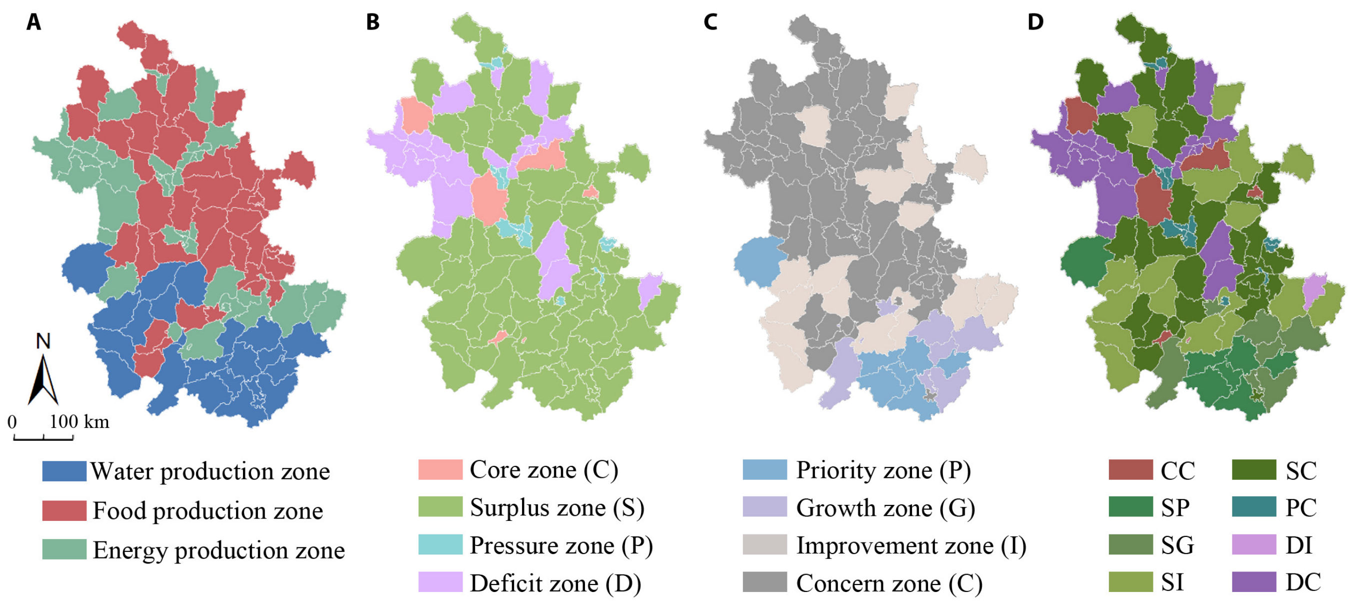


**Fig. 7.** Spatial classification and governance strategies of WEF at the county scale in Anhui Province. (A) Resource partitioning. (B) Matching typology. (C) Priority strategy. (D) Integrated governance.

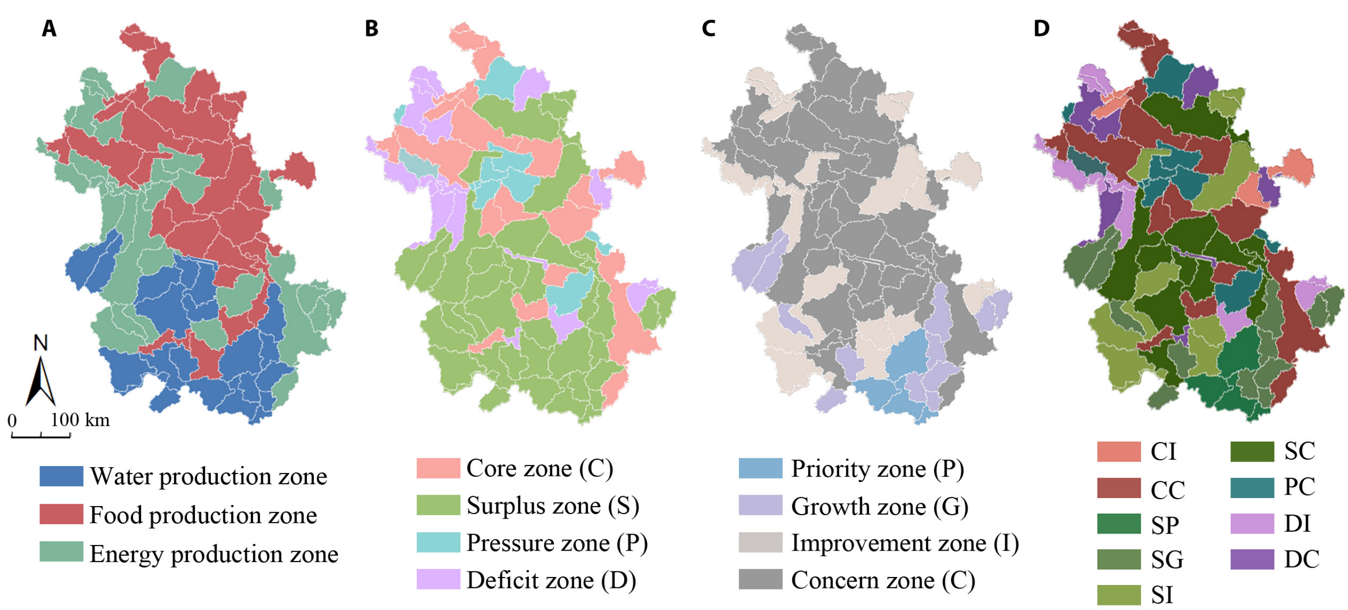


**Fig. 8.** Spatial classification and governance strategies of WEF at the sub-watershed scale in Anhui Province. (A) Resource partitioning. (B) Matching typology. (C) Priority strategy. (D) Integrated governance.

southeast and west. Surplus zones still dominated but were smaller and more dispersed, while pressure and deficit zones were more evident in fragile ecological areas of central and northern sub-watersheds. Coordination between W, E, and F was strongest in the southern sub-watersheds, whereas most central and northern sub-watersheds required targeted optimization. Governance patterns also differed: CI accounted for 5.62% of sub-watersheds, SC (surplus zone + concern zone) accounted for 14.6%, CC accounted for 17.98%, PC accounted for 10.48%, SP accounted for 9.5%, DI accounted for 10.48%, SG accounted for 15.17%, DC accounted for 6.67%, and SI accounted for 9.5%. Notably, DC zones were more prominent at this scale, capturing resource-scarce and ecologically vulnerable sub-watersheds that were less visible in county-scale analysis.

The comparison between county and sub-watershed scales revealed clear differences in the spatial patterns and governance priorities of the WEF nexus. At the county scale, resource supply and surplus zones dominated in large, continuous patches, masking localized deficits. In contrast, the sub-watershed scale exposed more fragmented distributions and highlighted ecologically fragile deficit zones in central and northern areas. Governance types were also more diversified at the sub-watershed scale, with DC and SI zones more prominent than at the county scale.

## Discussion

### Trade-offs and synergies among WEF supply–demand

This study highlighted both synergies and trade-offs that influence sustainable resource management through revealing the complex interrelationships between WEF supply and demand. The trade-offs between W–F and E–F supply stemmed from the competition for limited water and energy inputs in production-oriented systems, where intensive irrigation and fertilizer use enhanced food output but reduced ecological water availability and energy efficiency [38]. Such imbalances might disrupt natural hydrological and nutrient cycles, or weaken ecosystem resilience. In contrast, the synergy between W–E supply reflected their mutual ecological reinforcement. Stable water yields sustained hydropower generation and energy system stability, while sufficient energy inputs facilitated water extraction, distribution, and purification, thereby maintaining the ecological functions of aquatic systems [39].

Ecologically, the coexistence of trade-offs and synergies implied that enhancing one service can undermine or reinforce others depending on landscape configuration, ecosystem capacity, and management intensity [20,40]. Recognizing these ecological linkages is crucial for designing adaptive strategies that maintain system integrity while meeting human needs. Strengthening W–E cooperation, promoting eco-efficient agriculture, and protecting hydrological ecosystems can collectively improve the resilience and sustainability of the WEF nexus across scales [41].

### WEF supply–demand matching mechanism and scale effect

The scale-dependent characteristics of the WEF nexus highlight how administrative and natural boundaries jointly influence the coordination of resource supply and demand. At the administrative scale, integrated demand-side policies, such as joint water and energy planning or demand reduction strategies, are more effectively coordinated. Meanwhile, at the natural scale, targeted supply-side interventions such as optimizing land-use patterns to reduce W–F and E–F conflicts are better suited to the ecological realities of resource distribution. This dual-scale perspective not only captures the spatial variability of WEF relationships but also offers a novel pathway for linking socio-economic planning with ecological conservation in multiscale resource governance.

Both county and sub-watershed governance frameworks exhibited distinct advantages under the dual-scale comparative analysis. At the county scale, the continuity of WEF production zones reflected the strong influence of administrative boundaries that facilitated macro-level planning and policy implementation [2]. In contrast, the sub-watershed scale better captures the impact of natural conditions and hydrological processes on resource supply. Factors such as topography, soil fertility, and river networks can influence the spatial clustering and trade-offs of ESs. These factors led to varying distribution patterns and synergistic or competitive relationships within the same sub-watershed. Thus, the WEF supply–demand matching mechanism cannot be fully represented at a single scale. Its spatial variability and interconnections required both administrative-scale regulation and hydrological-scale ecological analysis to provide a more comprehensive and refined resource management approach.

### Integrated governance recommendations

Future governance of WEF resources in Anhui Province should combine administrative and ecological perspectives to balance supply and demand while reducing trade-offs (Fig. 9). County-scale planning is more effective for policy coordination and resource allocation among administrative units, whereas the sub-watershed scale better reflects ecological processes, hydrological linkages, and localized resource conflicts. Management strategies should therefore be adapted to the characteristics and governance strengths of each scale.

The SP zones possess abundant WEF resources with relatively high coordination, meaning ecological and socio-economic systems are mutually reinforcing. The main challenge is to utilize surplus sustainably without degrading ecosystem capacity. At the county scale, diversification of agricultural and energy structures should be supported to reduce over-dependence on water-intensive crops, ensuring that surplus flows benefit regional food and energy security [18]. At the sub-watershed scale, attention should be given to restoring degraded riparian zones, building ecological corridors, and improving upstream–downstream water allocation to maintain hydrological connectivity and protect surplus conditions.

DC zones are the most vulnerable areas, characterized by chronic shortages and poor coordination, often leading to ecological degradation and socio-economic stress. The key is to secure ecological baselines while rebuilding ecosystem capacity [42]. At the county scale, strict quotas on water and energy use are necessary to reduce extraction pressure, while investment in efficient irrigation reduces demand on already stressed ecosystems. At the sub-watershed scale, reforestation and wetland restoration improve water retention, infiltration, and evapotranspiration balance, directly addressing the structural ecological deficits that drive scarcity [43].

In SC zones, despite resource abundance, the weak coordination means there exist ecological imbalances or inequities. The challenge is to transform excess into ecological fairness. At

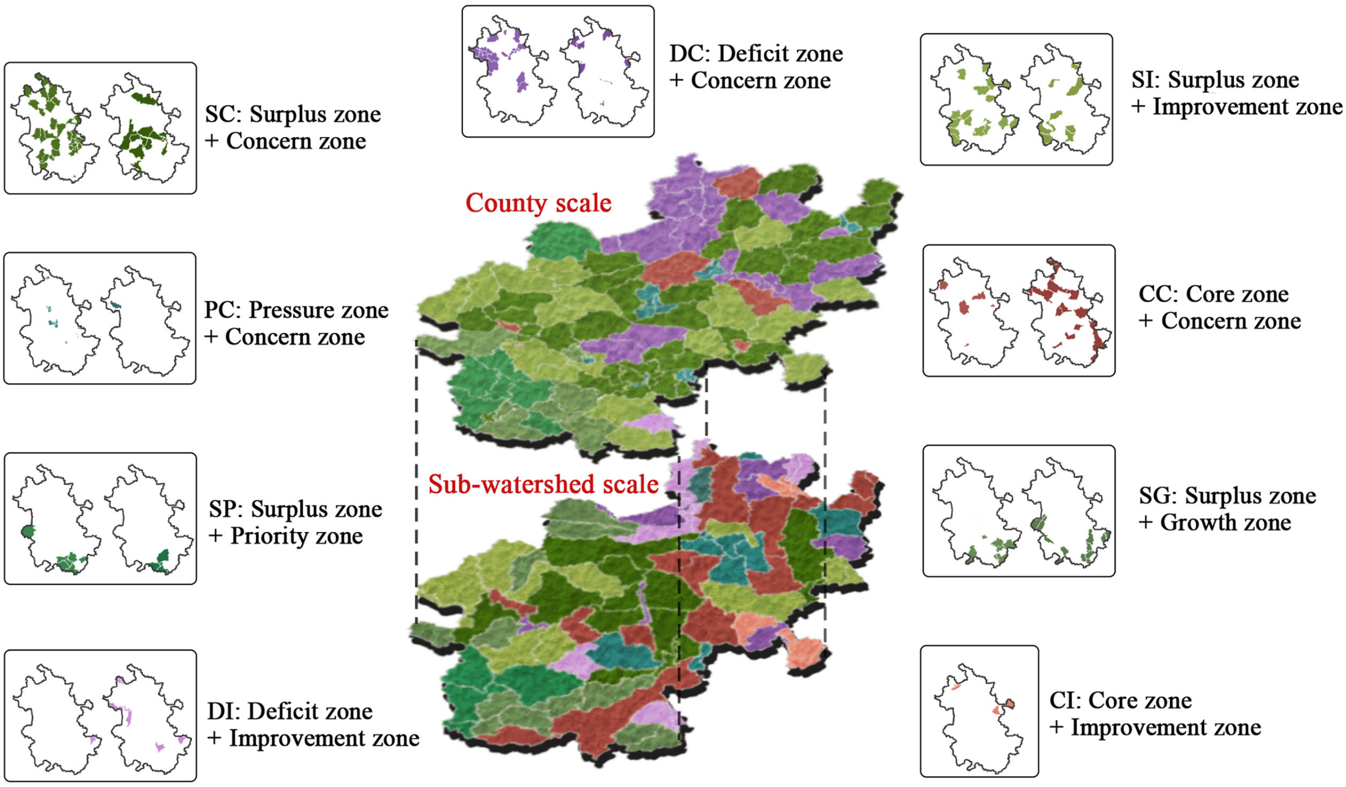


**Fig. 9.** Zones for WEF at the county and sub-watershed scales in Anhui Province.

the county scale, governments can promote renewable energy and sustainable farming to prevent ecological overshoot and safeguard long-term capacity. Sub-watershed should include implement water conservation and erosion control programs to protect soil–water interactions, while biodiversity restoration prevents ecological decline under surplus-driven expansion.

The SI zones have abundant resources but structural inefficiencies like spatial mismatches or transmission losses. The focus should be on removing ecological bottlenecks that hinder balanced use. At the county scale, counties can improve efficiency in agricultural value chains to minimize post-harvest losses, thereby reducing unnecessary resource throughput [44]. At the sub-watershed scale, measures should focus on adaptive land-use planning and conservation-oriented agriculture to maintain landscape multifunctionality, ensuring surpluses are ecologically stable.

In CC zones, ecological and economic values are both high, but poor coordination threatens long-term sustainability. These areas face the highest risk of ecological externalities. At the county scale, the policy should safeguard high-value ecosystems through ecological red lines and recognize their role in carbon sequestration, water regulation, and habitat provision. Sub-watershed strategies should maintain landscape connectivity, restore habitat patches, and limit fragmentation to protect biodiversity and resource supply.

In DI zones, deficits are severe but arise mainly from structural issues, meaning restoration and redesign can yield major ecological gains. County governments can promote drought-tolerant crops, water reuse systems, and renewable energy. At the sub-watershed scale, small-scale water conservation facilities, slope stabilization, and erosion control can help alleviate natural constraints on supply.

The SG and CI zones are in transitional states where growth potential is coupled with ecological stress points. The task is to guide growth along ecologically sustainable pathways. At the county scale, initiatives can integrate eco-tourism, circular economy models, and green technologies to support growth while protecting the environment. Sub-watershed management should diversify ESs, strengthen watershed-scale water regulation, and enhance resilience to climate variability.

The PC zones are under severe pressure with weak coordination, making them ecologically fragile and socially conflict-prone. The counties should enforce allocation plans to prevent the collapse of basic provisioning services and adopt non-conventional water sources to reduce pressure on natural ecosystems. At the sub-watershed scale, ecological flows as a minimum ecological constraint should be guaranteed, while upstream–downstream compensation mechanisms address ecological inequities in water availability.

Embedding these targeted, scale-specific measures into the zoning framework allows governance to draw on both the administrative advantages of counties and the ecological accuracy of sub-watersheds [45]. Such a dual-scale approach can improve resource allocation, reduce conflicts, and safeguard ecological security under ongoing socio-economic change and climate pressure.

## Limitations and future research directions

Despite offering a comprehensive analysis of ES supply and demand in the context of WEF at county and sub-watershed scales, this study still faces certain limitations. First, W and E supply estimations primarily relied on the InVEST model and F supply was estimated through NDVI values combined with statistical data. However, model simplifications and parameter uncertainties may introduce data accuracy limitations. Future research could improve regional resource estimations by incorporating higher-resolution meteorological data [46] and soil characteristic models [47] for better calibration. Second, this study focused on annual average supply–demand matching without fully exploring the spatial and temporal transfer processes of ESs. Future studies could integrate ES flow theories and models to address this gap [48]. Finally, future research should also consider other critical ESs beyond the 3 key WEF components, such as biodiversity and soil retention [31]. Expanding the comprehensive evaluation framework in this way would contribute to a more holistic regional resource management strategy.

## Conclusion

This study applied a dual-scale WEF nexus framework to analyze ES supply and demand in Anhui Province from 2000 to 2020. By integrating county and sub-watershed perspectives, the framework captured both broad administrative patterns and ecological processes, offering a more comprehensive understanding of resource imbalances. The results reveal clear divergence among the 3 sectors. W supply increased by over 90% while demand doubled, indicating substantial though uneven improvements across counties, especially in the southwest. F supply expanded by more than 60% as demand declined by nearly 40%, reflecting gains in agricultural efficiency. In contrast, E supply remained nearly stagnant, with demand rising by 340%, leaving severe shortages concentrated in the rapidly developing central and eastern regions. Scale comparison highlighted that county-scale assessments are effective for policy coordination and resource allocation, while sub-watershed analysis is critical for detecting localized hotspots and ecological trade-offs. Furthermore, the coexistence of W–F and E–F trade-offs and W–E synergies revealed in WEF supply underscored the importance of recognizing ecological linkages within the WEF nexus. The scale effect identified high-pressure zones that would be overlooked by a single spatial framework, thereby enhancing the precision of intervention strategies. By incorporating the findings from both scales into a unified zoning framework, this study not only mapped the current WEF imbalances but also proposed a practical pathway to combine administrative coordination with ecological integrity in resource governance. The approach can be applied to other regions where managing resources across different spatial scales is essential for achieving sustainable development under rapid socio-economic and environmental change.

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**Author contributions:** X.L.: Conceptualization, methodology, investigation, data curation, and writing—original draft. X.Z.: Conceptualization, supervision, project administration, and funding acquisition. Q.S.: Methodology and data curation. Z.Y.: Data curation. H.W.: Data curation. S.G.: Conceptualization and writing—review and editing.
**Competing interests:** The authors declare that they have no competing interests.

## Data Availability

The data used in the paper are available upon request to the corresponding author as the raw data are not publicly archived.

## Supplementary Materials

Supplementary Text
Tables S1 to S5

## References

1. Ding T, Chen J, Fang L, Ji J, Fang Z. Urban ecosystem services supply-demand assessment from the perspective of the water-energy-food nexus. *Sustain Cities Soc*. 2023;90:Article 104401.
2. Albrecht TR, Crootof A, Scott CA. The water-energy-food nexus: A systematic review of methods for nexus assessment. *Environ Res Lett*. 2018;13(4):Article 043002.
3. Tiffen M, Mortimore M, Gichuki F. *More people, less erosion: Environmental recovery in Kenya*. Nairobi (Kenya): ACTS Press; 1994.
4. Duan W, Chen Y, Zou S, Nover D. Managing the water-climate-food nexus for sustainable development in Turkmenistan. *J Clean Prod*. 2019;220:212–224.
5. Byrnes JEK, Gamfeldt L, Isbell F, Lefcheck JS, Griffin JN, Hector A, Cardinale BJ, Hooper DU, Dee LE, Emmett Duffy J, et al. Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions. *Methods Ecol Evol*. 2014;5(2):111–124.
6. Jiang L, Wu S, Liu Y, Yang C. Grain security assessment in Bangladesh based on supply-demand balance analysis. *PLOS ONE*. 2021;16(5):Article e0252187.
7. Zhang X, Wang Y, Yuan X, Shao Y, Bai Y. Identifying ecosystem service supply-demand imbalance for sustainable land management in China's loess plateau. *Land Use Policy*. 2022;123:Article 106423.
8. Biba S. The goals and reality of the water–food–energy security nexus: The case of China and its southern neighbours. *Third World Q*. 2016;37(1):51–70.
9. Kurian M. The water-energy-food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environ Sci Pol*. 2017;68:97–106.
10. Scanlon BR, Fakhreddine S, Rateb A, de Graaf I, Famiglietti J, Gleeson T, Grafton RQ, Jobbagy E, Kebede S, Kolusu SR. Global water resources and the role of groundwater in a resilient water future. *Nat Rev Earth Environ*. 2023;4(2):87–101.
11. Miralles-Wilhelm F. Development and application of integrative modeling tools in support of food-energy-water nexus planning—A research agenda. *J Environ Stud Sci*. 2016;6:3–10.
12. Rillig MC, Van der Heijden MG, Berdugo M, Liu Y-R, Riedo J, Sanz-Lazaro C, Moreno-Jiménez E, Romero F, Tedersoo L, Delgado-Baquerizo M. Increasing the number of stressors reduces soil ecosystem services worldwide. *Nat Clim Chang*. 2023;13(5):478–483.
13. Xia H, Yuan S, Prishchepov AV. Spatial-temporal heterogeneity of ecosystem service interactions and their social-ecological drivers: Implications for spatial planning and management. *Resour Conserv Recycl*. 2023;189:106767.
14. Chen W, Chi G. Urbanization and ecosystem services: The multi-scale spatial spillover effects and spatial variations. *Land Use Policy*. 2022;114:Article 105964.

15. Bai C, Zhou L, Xia M, Feng C. Analysis of the spatial association network structure of China's transportation carbon emissions and its driving factors. *J Environ Manag*. 2020;253:Article 109765.
16. Javan K, Altaee A, BaniHashemi S, Darestani M, Zhou J, Pignatta G. A review of interconnected challenges in the water–energy–food nexus: Urban pollution perspective towards sustainable development. *Sci Total Environ*. 2024;912:Article 169319.
17. Heard BR, Miller SA, Liang S, Xu M. Emerging challenges and opportunities for the food–energy–water nexus in urban systems. *Curr Opin Chem Eng*. 2017;17:48–53.
18. Radmehr R, Ghorbani M, Ziaei AN. Quantifying and managing the water-energy-food nexus in dry regions food insecurity: New methods and evidence. *Agric Water Manag*. 2021;245:Article 106588.
19. Zhang Z, Wang Q, Yan F, Sun Y, Yan S. Revealing spatio-temporal differentiations of ecological supply-demand mismatch among cities using ecological network: A case study of typical cities in the "upstream-midstream-downstream" of the Yellow River Basin. *Ecol Indic*. 2024;166:Article 112468.
20. Feng Z, Jin X, Chen T, Wu J. Understanding trade-offs and synergies of ecosystem services to support the decision-making in the Beijing–Tianjin–Hebei region. *Land Use Policy*. 2021;106:Article 105446.
21. Shen J, Li S, Liang Z, Liu L, Li D, Wu S. Exploring the heterogeneity and nonlinearity of trade-offs and synergies among ecosystem services bundles in the Beijing-Tianjin-Hebei urban agglomeration. *Ecosyst Serv*. 2020;43:Article 101103.
22. Tang R, Hou G, Chen Y, Liu X, Chu S, Li L. Spatial and temporal characteristics and driving mechanisms of recreational ecosystem services supply-demand mismatch in rapidly urbanizing areas: Evidence from the Yangtze River Delta. *Ecol Indic*. 2025;171:Article 113153.
23. Xin R, Skov-Petersen H, Zeng J, Zhou J, Li K, Hu J, Liu X, Kong J, Wang Q. Identifying key areas of imbalanced supply and demand of ecosystem services at the urban agglomeration scale: A case study of the Fujian Delta in China. *Sci Total Environ*. 2021;791:Article 148173.
24. Yin D, Yu H, Shi Y, Zhao M, Zhang J, Li X. Matching supply and demand for ecosystem services in the Yellow River Basin, China: A perspective of the water-energy-food nexus. *J Clean Prod*. 2023;384:Article 135469.
25. Yang W, Chen J, Ding T, Yan X, Gong W. Supply-demand security assessment of water-energy-food systems: A perspective on intra-city coupling and inter-city linkages of ecosystem services. *Sustain Cities Soc*. 2024;117:Article 105964.
26. Fu B. On the calculation of the evaporation from land surface. *Sci Atmos Sin*. 1981;5(1):23.
27. Zhang L, Hickel K, Dawes W, Chiew FH, Western A, Briggs P. A rational function approach for estimating mean annual evapotranspiration. *Water Resour Res*. 2004;40(2): doi.org/10.1029/2003WR002710.
28. Zhang D, Huang Q, He C, Wu J. Impacts of urban expansion on ecosystem services in the Beijing-Tianjin-Hebei urban agglomeration, China: A scenario analysis based on the shared socioeconomic pathways. *Resour Conserv Recycl*. 2017;125:115–130.
29. Groten SME. NDVI—Crop monitoring and early yield assessment of Burkina Faso. *Int J Remote Sens*. 1993;14(8):1495–1515.
30. Roznik M, Boyd M, Porth L. Improving crop yield estimation by applying higher resolution satellite NDVI imagery and high-resolution cropland masks. *Remote Sens Appl Soc Environ*. 2022;25:Article 100693.
31. Dou H, Li X, Li S, Dang D, Li X, Lyu X, Li M, Liu S. Mapping ecosystem services bundles for analyzing spatial trade-offs in inner Mongolia, China. *J Clean Product*. 2020;256:Article 120444.
32. Sun Y, Liu S, Shi F, An Y, Li M, Liu Y. Spatio-temporal variations and coupling of human activity intensity and ecosystem services based on the four-quadrant model on the Qinghai-Tibet plateau. *Sci Total Environ*. 2020;743:Article 140721.
33. Xu L, He N, Yu G. A dataset of carbon density in Chinese terrestrial ecosystems (2010s). *China Sci Data*. 2019;4(7):21.
34. Wu Y, Kan H, Deng A. Spatio-temporal correlation and optimization of urban development characteristics and carbon balance in counties: A case study of the Anhui Province, China. *Land*. 2024;13(6):810.
35. Wang L, Huang S, Huang Q, Leng G, Han Z, Zhao J, Guo Y. Vegetation vulnerability and resistance to hydrometeorological stresses in water- and energy-limited watersheds based on a Bayesian framework. *Catena*. 2021;196:Article 104879.
36. Falcon WP, Naylor RL, Shankar ND. Rethinking global food demand for 2050. *Popul Dev Rev*. 2022;48(4):921–957.
37. Rao C, Zhang Y, Wen J, Xiao X, Goh M. Energy demand forecasting in China: A support vector regression-compositional data second exponential smoothing model. *Energy*. 2023;263:Article 125955.
38. Zeng Y, Liu D, Guo S, Xiong L, Liu P, Chen J, Chen H, Yin J, Wu Z, Zhou W. Assessment of the impacts of water resources allocation on the reliability, resilience and vulnerability of the water–energy–food–society (WEFS) nexus system. *Agric Water Manag*. 2024;295:Article 108780.
39. Zhu Y, Zhang C, Fang J, Miao Y. Paths and strategies for a resilient megacity based on the water-energy-food nexus. *Sustain Cities Soc*. 2022;82:Article 103892.
40. Wu Y, Zhang X, Li C, Xu Y, Hao F, Yin G. Ecosystem service trade-offs and synergies under influence of climate and land cover change in an afforested semiarid basin, China. *Ecol Eng*. 2021;159:Article 106083.
41. Benyezza H, Bouhedda M, Rebouh S. Zoning irrigation smart system based on fuzzy control technology and IoT for water and energy saving. *J Clean Prod*. 2021;302:Article 127001.
42. Chen X, Yu L, Du Z, Xu Y, Zhao J, Zhao H, Zhang G, Peng D, Gong P. Distribution of ecological restoration projects associated with land use and land cover change in China and their ecological impacts. *Sci Total Environ*. 2022;825:Article 153938.
43. Yu H, Chen C, Shao C. Spatial and temporal changes in ecosystem service driven by ecological compensation in the Xin'an River Basin, China. *Ecol Indic*. 2023;146: Article 109798.
44. Chen X, Di Q, Jia W, Hou Z. Spatial correlation network of pollution and carbon emission reductions coupled with high-quality economic development in three Chinese urban agglomerations. *Sustain Cities Soc*. 2023;94:Article 104552.
45. Wang X, Dong Z, Sušnik J. System dynamics modelling to simulate regional water-energy-food nexus combined with the society-economy-environment system in Hunan Province, China. *Sci Total Environ*. 2023;863:Article 160993.
46. Bagstad KJ, Cohen E, Ancona ZH, McNulty SG, Sun G. The sensitivity of ecosystem service models to choices of

input data and spatial resolution. *Appl Geogr*. 2018;93: 25–36.
47. Li Z, Xia J, Deng X, Yan H. Multilevel modelling of impacts of human and natural factors on ecosystem services change in an oasis, Northwest China. *Resour Conserv Recycl*. 2021;169:Article 105474.
48. Peng J, Xia P, Liu Y, Xu Z, Zheng H, Lan T, Yu S. Ecosystem services research: From golden era to next crossing. *Trans Earth Environ Sustain*. 2023;1(1):9–19.
49. Yang J, Huang X. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth Syst Sci Data*. 2021;13(8):3907–3925.

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# A Dual-Scale Zoning Strategy for Water–Energy–Food Supply and Demand Ecosystem Services

Xinmiao Liu, Xudong Zhang, Qi Shu, Zengwang Yao, Hailong Wu, and Shenghua Gao

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The water–energy–food (WEF) nexus is essential for balancing resource use, yet most assessments overlook mismatches between administrative boundaries and ecological processes. This study developed a dual-scale framework for 105 counties and 89 sub-watersheds in Anhui Province, China, to quantify WEF supply–demand relationships and guide spatial governance. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, supply–demand index (SDI), 4-quadrant model, and entropy-weighted TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) model were applied to assess water yield, carbon storage, and food production supply–demand relationships. Additionally, a 4-step methodology was developed to delineate management zones. The results showed the following: (a) From 2000 to 2020, water supply increased by about 92% while demand rose by 97%. Food supply grew by 63%, whereas demand declined by 37%. Energy supply remained nearly stable, but demand surged by more than 340%. Both county and sub-watershed scales captured these overall patterns, while the sub-watershed perspective revealed sharper local fluctuations. Cross-service interactions were observed with trade-offs between W–F and E–F and synergies between W–E supply, reflecting the complex ecological coupling within the WEF nexus. (b) Supply–demand matching indicated that water and energy were deficit-dominated and food was surplus-oriented. The food SDI improved more markedly at the sub-watershed scale (0.04 to 0.50) than at the county scale (0.01 to 0.37), showing stronger local recovery and more evident clusters of mismatches. (c) The study area was divided into 3 resource partitioning zones, 4 matching typologies, and 4 priority strategies, and merged into 9 integrated governance zones. This research can give complementary insights from dual scales enabling targeted strategies for integrated WEF management in ecosystems.
Image



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