Environmental Science and Ecotechnology 23 (2025) 100496

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Original Research

Optimizing soil conservation through comprehensive benefit assessment in river basins

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ARTICLE INFO

Article history:
Received 13 April 2024
Received in revised form
7 October 2024
Accepted 7 October 2024

Keywords:
Ecosystem service flow
Soil conservation
Off-site benefit
Key areas

ABSTRACT

Land degradation from water erosion poses a significant threat to water security and ecosystem stability, driving global efforts in soil conservation. Quantitative assessment of soil conservation benefits—both on-site and off-site—is crucial for guiding effective conservation strategies. However, existing methodologies often fall short in quantifying the value of these combined benefits. Here, we present a comprehensive framework for quantifying soil conservation service flows in monetary terms, evaluating the effectiveness of both on-site and off-site measures. Applying this framework to the Yellow River Basin (YRB), we employ cost-avoidance algorithms related to soil fertility maintenance, dredging cost reduction, and mitigation of nonpoint source pollution. Our results reveal that while many areas contribute to both on-site and off-site benefits, over half of the YRB relies predominantly on off-site services. By strategically enhancing key regions—which constitute 30% of the basin—we demonstrate that the overall soil conservation service supply can increase by 64.2% over the multi-year average from 2001 to 2020 compared to a consideration of on-site only. These findings underscore the essential role of off-site services in fully understanding soil conservation needs, particularly in large river basins, and the identified priority areas can offer valuable insights for optimizing soil conservation efforts.

1. Introduction

The world's large river basins are facing serious water erosion problems [1], undermining their functioning and the ecosystem services they provide. Notable examples include suspended sediment pollution in the Mekong River Basin [2], the negative impacts of agricultural production in the Nile River Basin [3], and water-sediment imbalance in the Yellow River Basin (YRB) [4]. Water erosion is a major driver of land degradation, which is projected to increase by 10% globally by the end of the 21st century [5,6] and is already threatening the sustainable development of socio-ecological systems in these large river basins.

The United Nations (UN) Decade on Ecosystem Restoration aims to promote global ecological restoration and achieve land degradation neutrality by 2030 [7]. Soil conservation measures are widely considered effective solutions to curb soil erosion in changing environmental conditions [8,9]. These measures include ecological and engineering interventions, such as reforestation, terracing, and mulching [10]. When effectively implemented in large river basins, such measures can mitigate on-site soil degradation, reduce off-site diffuse pollution, and prevent the decline of reservoir capacity caused by sediment transport downstream [8]. However, most studies conducted thus far have focused on modeling, cost analysis, drivers, and risk-impact of soil conservation [11–16] while neglecting important issues such as interregional benefit transfers, extraterritorial ecosystem impacts, and tele-coupling between regions [17,18]. These factors, which refer to the transmission of positive ecosystem service outcomes, advantages, or gains between different regions, are particularly relevant in large river basins. For instance, vegetation situated in the upper reaches of a river mitigates sediment transport, enhancing

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https://doi.org/10.1016/j.ese.2024.100496
2666-4984/

soil quality in downstream agricultural fields through soil conservation measures [19,20]. Failure to quantify these inter-regional impacts can undervalue certain areas where soil conservation measures are being applied, preclude the accurate identification of relevant stakeholders, and ultimately hinder the fairness of payment for ecosystem service policies. This remains a major gap in soil erosion and conservation research, limiting the effectiveness of policy implementation across large river basins.

While soil conservation is inherently a local process, its impacts extend both on- and off-site through hydrological pathways within expansive river basins. A compelling example of this phenomenon is evident in the Loess Plateau region of China, where large-scale afforestation efforts successfully intercepted local soil, preventing its entry into the Yellow River and mitigating downstream reservoir siltation [21]. Addressing soil erosion and land degradation in large river basins requires a spatial perspective, recognizing the on- and off-site benefits of soil conservation measures. This transition from local to regional impacts and ecosystem improvements to benefits for stakeholders can be conceptualized using the soil conservation service flow (SCSF, Fig. 1). The SCSF, lacking a specific transfer carrier, naturally disperses to connected areas along sediment transport pathways. While the physical transport of sediment offers a biophysical foundation for quantifying SCSF, it should not be conflated with the SCSF itself. Existing studies primarily focus on quantifying soil erosion, sediment transport, and the effects of soil conservation on these processes [5,6,22,23], overlooking the important mechanism of SCSF, particularly at the river basin scale in terms of service supply values and associated benefits.

We introduce the concept and analytical framework of SCSF, a tool designed to support the planning of soil conservation and land degradation control measures across large river basins. Using monetized value methods, we visually quantified SCSF and its change trends. Soil conservation ecosystem services refer to soil retention by ecosystems, preventing sediment from entering water bodies and causing damage [24]. Water erosion displaces soil into rivers, directly affecting humans by losing soil nutrients *in situ*, reservoir siltation, and water quality deterioration downstream [25–27]. This, in turn, affects soil structure, organic matter content, crop yields, infrastructure, and other types of water pollution [28,29]. Therefore, we chose the three metrics with the most direct impacts for our calculations: maintenance of soil fertility (MSF), reduction of dredging project costs (RCD), and nonpoint source pollution mitigation (NSPM). The valorization of these three metrics effectively represents the transport of benefits from soil conservation both *in situ* and downstream and is relevant for studying soil conservation service flows.

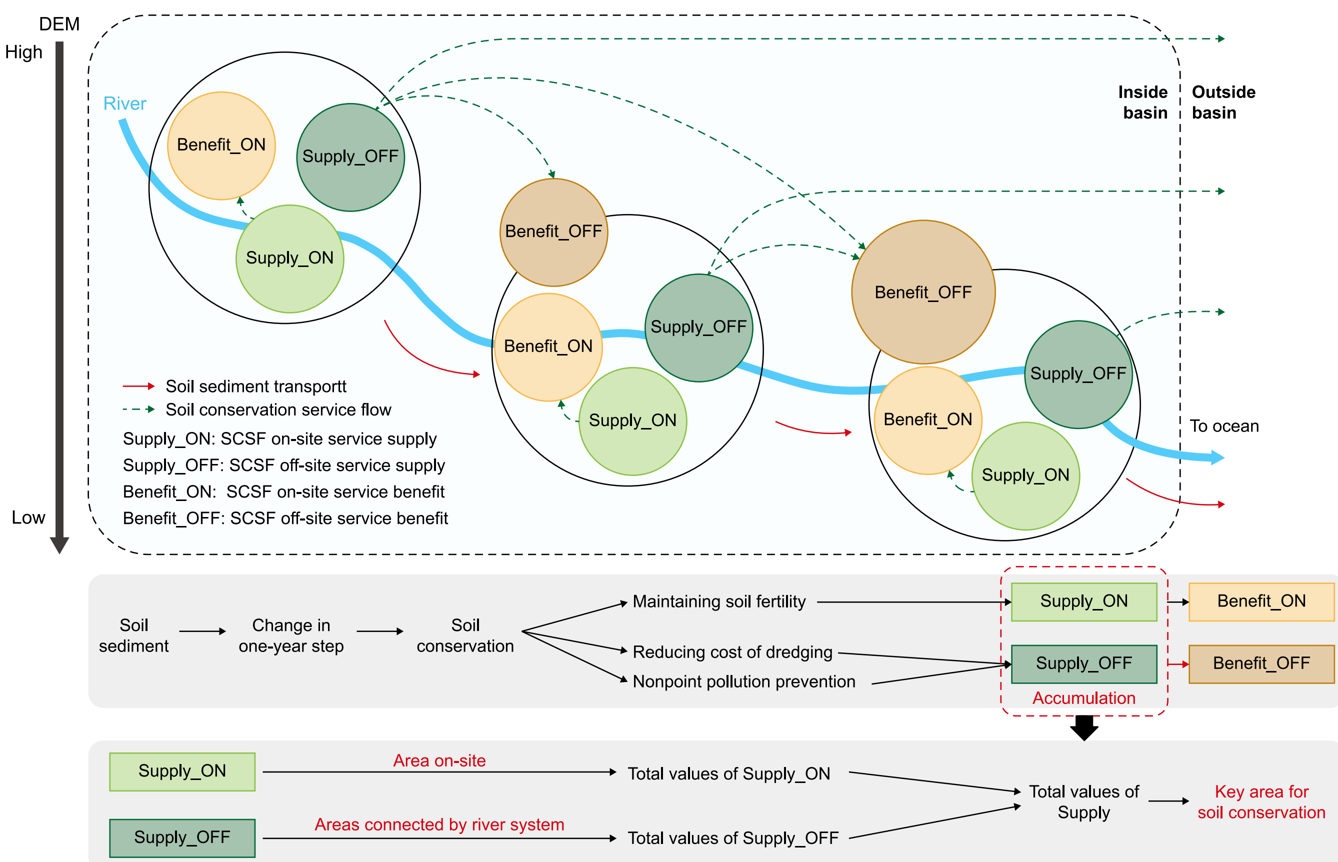

Fig. 1. Framework for evaluating soil conservation service flow (SCSF) introduced in this study. This framework is organized into three distinctive components. In the initial segment, delineated by the top dashed box outlining the watershed boundary, the framework elucidates the concept and progression of SCSF. The blue curve represents the river's flow from higher to lower elevations, while three black circles symbolize diverse units that the river traverses. Each black circle contains four concentric circles (light green, dark green, light yellow, and dark yellow), signifying the service value supplied and benefited for the on-site (Supply_ON and Benefit_ON) and off-site (Supply_OFF and Benefit_OFF) areas, respectively. The dark green dashed line indicates the paths of service values between units. DEM: digital elevation model. The second part, depicted by the gray rectangular area in the middle, presents a si mplified approach to calculating supply and benefit values. Here, Benefit_ON is expressed through the maintenance of soil fertility value, which is quantitatively equal to Supply_ON. Benefit_OFF encompasses reducing dredging project costs and nonpoint source pollution mitigation, quantified by aggregating the Supply_OFF generated in all connected upper-reach areas. The third part, indicated by the gray rectangular area at the bottom, focuses on diagnosing key areas for soil conservation by integrating Supply_ON and Supply_OFF from different units.

Our main objective is to formulate a soil conservation service flow research framework and test its applicability using the YRB as a case study. To this end, the on-site supply, on-site benefit, off-site supply, and off-site benefit values of soil conservation services in each subunit will be calculated separately. In addition, we aim to identify key ecological functional areas for soil conservation based on the quantified service flow and assess their dependence on off-site benefits. Over the years, multiple efforts to address soil erosion in the YRB have been carried out [30]. However, the benefits of these actions across the entire basin have not been fully studied and recognized, which could impact future ecological restoration planning (Supplementary Material Fig. S1). Our new spatial coupling perspective for defining and visually quantifying SCSF (Fig. 1) underscores the importance of on- and off-site conservation values in combatting land degradation and effectively achieving land degradation neutrality and sustainable development goals across large river basins.

2. Materials and methods

2.1. The framework for analyzing soil conservation service flow

The pathways through which service supply and benefits flow across different units constitute the SCSF. “Supply” refers to the value that soil conservation offers to human society, while “benefit” denotes the value society derives from these conservation efforts. Each “unit” represents a part of a basin as a pixel or geographic sub-basin. We measure the supply value for each unit through on-site (Supply_ON) and off-site (Supply_OFF) service supply, and the benefit value is expressed by on-site (Benefit_ON) and off-site (Benefit_OFF) service benefit. The on-site benefit value is directly derived from the on-site supply value, rendering them numerically equal. However, the off-site benefit value requires accumulating all values transmissible along the hydrological path to that unit, which is why the service flow approach provides a more accurate calculation of these values.

Most existing frameworks for identifying key ecosystem service areas overlook the significance of off-site service flows [31–33]. Our framework distinguishes itself by integrating on- and off-site supply values, offering a complete and precise quantification of soil conservation's true value for each unit. Including service flows makes the framework more comprehensive, ensuring that the contribution of different areas is properly evaluated, rationalizing the delineation of key areas, and offering spatial guidance for future environmental management and conservation projects.

Considering limitations in data acquisition and assessment methods, including long-term series data on soil composition, infrastructure development, and aquatic biodiversity, we selected MSF as the on-site SCSF indicator and both RCD and NSPM as the off-site SCSF indicators. These metrics are pivotal for evaluating the feasibility and applicability of our framework [34] (Fig. 1).

While acknowledging necessary simplifications in the theoretical and methodological aspects of the SCSF, focusing on terrain, vegetation, rainfall, and soil processes—along with the highlighted service flow benefits like MSF, RCD, and NSPM—makes our approach valuable for tackling land degradation control, ecosystem restoration, and environmental management in large river basins.

2.2. Data sources

We sourced precipitation data covering the period 2000–2020 from the dataset of daily surface climate values in China [35]. We acquired a digital elevation model from the MERIT dataset [36]. The normalized difference vegetation index (NDVI) values for the years 2000–2020 were retrieved from the MODIS MOD13A3 NDVI Monthly L3 data [37]. Soil erodibility factor data were obtained from the National Earth System Science Data Center [38]. Sediment load data, measured in 14 tributary sub-basins from 2000 to 2020, were compiled from the Yellow River Conservancy Commission of the Ministry of Water Resources [39]. Land use data spanning the same period were sourced from the European Space Agency's Climate Change Initiative-Land Cover (ESA's CCI-LC) dataset [40]. Information on soil nutrient concentrations (N, P, and K) for different land use types was extracted from Table 1 in the literature [41]. Data on fertilizer prices per acre for crops like corn, wheat, and soybeans were taken from the National Compilation of Cost-Benefit Information for Agricultural Products using national average data across different years [42]. Consumer Price Index data were obtained from the National Bureau of Statistics [43]. See Table S1 in the Supplementary Materials for a detailed breakdown of data sources and specifications.

2.3. Soil retention assessment in each pixel

The modified universal soil loss equation [11] and the sediment connectivity index were employed to calculate the annual soil loss. The difference in soil loss between the current year and the previous one was taken as the soil retention amount for the current year. A negative value indicates a net increase in soil erosion, signifying no soil retention for that year. Since the negative effects of soil erosion on downslope land plots are mitigated by landscape connectivity and decrease with increasing flow path length, we quantified and mapped overland sediment generation and delivery to the stream using the following equations:

$$SE_i = R_i \times K_i \times LS_i \times C_i \times P_i \tag{1}$$

$$ST_i = SE \times SDR_i \tag{2}$$

$$SDR_i = \frac{SDR_{\max}}{1 + \exp\left(\frac{IC_0 - IC_i}{k}\right)} \tag{3}$$

$$SC_i = ST_{i-1} - ST_i \tag{4}$$

where SE_i is soil erosion (Mg ha^{-1} yr^{-1}); R_i is the rainfall erosivity factor (MJ mm h^{-1} ha^{-1} yr^{-1}) calculated according to Ref. [44]; K_i is the soil erodibility factor (Mg h MJ^{-1} mm^{-1}, the data source can be found in Table S1 in the Supplementary Materials); LS_i is the topographical factor (dimensionless) calculated according to Ref. [44]; C_i is the vegetation cover factor (dimensionless) [45]; P_i is soil conservation practice (dimensionless, the default for this study is 1); ST_i is sediment transport in one year (Mg ha^{-1} yr^{-1}); i represent the year (2000–2020); and SDR is the sediment delivery ratio (dimensionless). It is the proportion of eroded material reaching the river, a function of sediment connectivity derived from the conductivity index IC. $SDR_{\max}$ is the maximum theoretical SDR; IC indicates the probability of sediment being mobilized and transported from a point in the catchment, which is related to the topography and surface cover of the upstream catchment and downstream flow path; and IC_0 and k are calibration parameters that define the shape of the SDR–IC relationship (detailed information can be found on the official InVEST website at http://releases.naturalcapitalproject.org/invest-userguide/latest/en/sdr.html). Meanwhile, SC_i is the annual soil retention (Mg ha^{-1} yr^{-1}).

We validated the simulation data by comparing it year-over-year with the annual measured sediment transport data from 14 sub-basins in the YRB (Supplementary Material Fig. S1). The Nash coefficient and the coefficient of determination (r^2) were used as

Table 1
Monetary value for soil conservation service flow
Descriptive statistics of multi-year average supply and benefit value of different services. YRB is the value for the whole basin. SCSF is the value for the sum of services.

Service type	MSF (USD ha^{-1})	RCD (USD ha^{-1})		NSPM (USD ha^{-1})		SCSF (USD ha^{-1})	
	Supply_ON/Benefit_ON	Supply_OFF	Benefit_OFF	Supply_OFF	Benefit_OFF	Supply	Benefit
YRB	9.44	0.20	4270	1.12	23330	10.83	27620
Upstream	6.84	0.15	2820	0.80	15440	7.82	18270
Midstream	12.58	0.27	4760	1.50	25850	14.42	30620
Downstream	5.34	0.12	19620	0.66	107160	6.27	126790

evaluation indicators of the simulation metrics [46], yielding average values of 0.53 and 0.78, respectively (Supplementary Material Fig. S2). In addition, we applied the published GLASS AVHRR FVC (1982–2021) data to validate the FVC calculated in this study. A total of 100 random points across the basin were selected, and the FVC values corresponding to different years were extracted at these points for correlation analysis and Nash coefficient calculation. The results showed a Nash coefficient of 0.71 and an r^2 of 0.86 (Supplementary Material Fig. S3).

2.4. Calculation for soil conservation service flow

Based on the annual soil retention ($SC_i > 0$), the on-site MSF value, off-site RCD value, and off-site NSPM value were used to calculate the SCSF for each pixel. Supply_ON and Supply_OFF were calculated as follows:

(1) Supply_ON

2.4.1. Maintenance of soil fertility (MSF)

We chose the soil nutrition value corresponding to N, P, and K as the benefit of soil fertility conservation. The following formula was used to calculate the price [47]:

$$M = \sum\nolimits_j SC \times C_j \times P_j \quad (j = \mathrm{N, P, K}) \tag{5}$$

where M is the economic benefit of fertilizer conservation (USD ha^{-1}); SC is the amount of soil retention (t ha^{-1}); C_j is the N, P, and K contents in different land use types (kg t^{-1}); and P_j is the price for N, P, and K in the market (USD t^{-1}).

The prices corresponding to different fertilizer categories were obtained by dividing the average fertilizer purity per acre by fertilizer prices per acre for corn, wheat, and soybeans in different years.

(2) Supply_OFF

2.4.2. Dredging project costs (RCD)

The shadow price method was applied to calculate the value of silt-decreasing intervention [48]:

$$D = 24\% \times SC \times \frac{Pr}{\rho} \tag{6}$$

where D is the economic benefit of reducing the cost of dredging (USD ha^{-1}); SC is the amount of soil retention (t ha^{-1}); Pr is the cost of earth excavation in China (USD m^{-3}); and ρ is the volume weight of the soil (t m^{-3}).

The cost of excavation per unit area in China (in 2018) is estimated to be CNY 18.93 m^{-3} [49], where CNY represents Chinese currency (CNY 7.28 = USD 1.00, exchange rate at September 14, 2023). We then combined this price with the consumer price index to calculate the cost price of different years [49].

2.4.3. Nonpoint source pollution mitigation (NSPM)

Soil erosion leads to the displacement of nutrients from the land surface, which are then carried by runoff into rivers and transported to lower reaches through river systems. When the concentration of these nutrients surpasses the carrying capacity of the water environment, they will pollute the land. The accounting value can be calculated as follows:

$$B = \sum_{j=1}^{2} SC \times C_j \times d_j \times P_w \tag{7}$$

where B is the economic benefit of nonpoint source pollution mitigation (NSPM, USD ha^{-1}); SC is the amount of soil retention (t ha^{-1}); C_j is the content of N and P in sediment; d_j is the diffusion rate and refers to the contribution rate of soil retention to nitrogen and phosphorus in water (for N: 3.0; for P: 2.0 [50]); and P_w is the cost to treat the wastewater of nitrogen and phosphorus (USD t^{-1}).

To calculate the cost to treat wastewater, we used the equivalent values of ammonia nitrogen (0.8 kg) and total phosphorus (0.25 kg) in the standard and calculation method for sewage charge collection (https://www.mee.gov.cn/ywgz/fgbz/gz/200302/t20030228_86250.shtml). We used the following formula:

$$NE = \frac{EM}{E} \tag{8}$$

where NE is the number of equivalents of a pollutant; EM refers to the emissions of a pollutant (kg), i.e., $SC \times C_i \times d_i$; and E is the release quantity value corresponding to one equivalent of the pollutant (kg). The amount of the sewage charge is equal to the sum of the pollution equivalents multiplied by USD 0.096.

The total supply of soil conservation service flow for each unit is the sum of MSF, RCD, and NSPM.

(1) Benefit _ON

Supply_ON is the source for Benefit _I, which are numerically equal.

(2) Benefit _OFF

Since sediment flow is contingent on the pathways through which upstream soil erosion transmits risks downstream, the value of benefits derived from upstream soil retention must also accumulate along the same pathways. In this study, we model the accumulation of these benefits using the DEM-based D8 algorithm [51] to simulate the flow path of sediment deposits.

2.4.4. Dredging project costs (RCD)

$$R_u = \sum_m D \tag{9}$$

where R_u is the economic benefit of reducing the cost of dredging from upstream (USD ha^{-1}); D is the economic benefit of reducing the cost of dredging (USD ha^{-1}); and m is all upstream cells connected through the hydrological path.

2.4.5. Nonpoint source pollution mitigation (NSPM)

$$B_u = \sum_n B \tag{10}$$

where B_u is the economic benefit of mitigating nonpoint source pollution from upstream (USD ha^{-1}); B is the economic benefit of mitigating nonpoint source pollution (USD ha^{-1}); and n is all upstream cells connected through the hydrological path.

The total benefit of soil conservation service flow for each unit is the sum of MSF, RCD, and NSPM.

2.5. Diagnosing important areas for soil conservation

At the sub-basin scale, we performed a spatial ranking based on the values of on-site (Supply_ON), off-site service (Supply_OFF), and total (Supply_ON + Supply_OFF) supply, respectively. First, the value of the Supply_ON of each sub-basin needs to be calculated in conjunction with the total area of the *in situ* sub-basin. Second, the Supply_OFF value of each sub-basin needs to be calculated in conjunction with the lower benefit area. We used the hydrological connectivity network to determine this, which defines the relationships between sub-basins. This network can help identify the downstream benefit areas connected to each sub-basin, as delineated in previous research [52]. Finally, we calculated the spatial ranking of the total supply value by summing the on- and off-site values.

3. Results

3.1. Monetary value for soil conservation service flow

The multi-year average (2001–2020) for soil conservation service supply and benefit values across the YRB, along with upstream, midstream, and downstream regions, were derived by calculating the average values of MSF, RCD, and NSPM for all pixels, upstream pixels, midstream pixels, and downstream pixels, respectively. The diverse unit prices and calculation methods for on- and off-site supply yield a multi-year average value for Supply_ON (MSF: USD 9.44 ha^{-1}) that substantially surpasses that of Supply_OFF (RCD: USD 0.20 ha^{-1}, NSPM: USD 1.12 ha^{-1}). However, a comparative analysis of the multi-year averages for Benefit_ON and Benefit_OFF reveals a striking contrast. The unit area value for off-site benefits (RCD: USD 4270 ha^{-1}, NSPM: USD 23330 ha^{-1}) significantly exceeds the on-site value (MSF: USD 9.44 ha^{-1}) (Table 1).

From a spatial perspective, the midstream region of the YRB emerges as the most significant contributor across all service supply categories (MSF: USD 12.58 ha^{-1}, RCD: USD 0.27 ha^{-1}, NSPM: USD 1.50 ha^{-1}). Due to the cumulative impact of upstream flow on the lower reaches of the YRB, downstream areas experienced markedly higher benefit values than upstream and midstream regions. The multi-year average downstream benefit reaches USD 19620 ha^{-1} for RCD and USD 107160 ha^{-1} for NSPM. This spatial trend is consistent across the total SCSF as well. The overall service supply for the YRB is estimated at USD 10.83 ha^{-1}, with the midstream region contributing the highest value at USD 14.42 ha^{-1}, followed by the upstream at USD 7.82 ha^{-1}. The total service benefit for the YRB stands at USD 27620 ha^{-1}, with downstream areas leading in off-site benefit, boasting the highest value of USD 126790 ha^{-1} (Table 1).

There has been a substantial rise in the benefits of all three services from 2001 to 2020. Specifically, MSF, RCD, and NSPM have grown substantially, with increases of 176%, 128%, and 42%, respectively. Remarkably, RCD also experienced a significant surge in supply value ($p < 0.05$), marking an 83% increase (Fig. 2). When examining sub-regions within the YRB, the upstream area displayed a significant rise in both service supply and benefit across all categories ($p < 0.05$). Additionally, the off-site benefit of RCD exhibited a notable increase downstream ($p < 0.05$) (Supplementary Materials Figs. S4 and S5). Analyzing the SCSF, both supply and benefit demonstrate significant upward trends over time ($p < 0.05$), with increases of 137% and 56%, respectively (Fig. 2). Specifically, service supply experienced a substantial increase in upstream areas, while service benefit witnessed significant growth in both upstream and midstream regions within the YRB ($p < 0.05$) (Supplementary Materials Figs. S4 and S5).

3.2. Off-site benefits are dominantly driven by soil conservation service flow

Through the analysis of multi-year average ratios comparing off-site benefit to total service benefit across different spatial units, our findings revealed that 23.7% of the entire YRB exhibited Benefit_OFF to total benefit ratios exceeding 0.9 (Fig. 3). Furthermore, 54% of regions demonstrated a Benefit_OFF to total benefit ratio surpassing 0.5, underscoring that more than half of the YRB experiences greater off-site benefits than on-site benefits. This highlights the YRB's pronounced reliance on SCSF. These findings emphasize the critical role of service flows in channeling substantial benefits across socio-ecological systems along river flow paths in the YRB.

3.3. Performance of soil conservation measures based on service flows

The multi-year average values for on-site soil conservation supply (Supply_ON) and off-site soil conservation supply (Supply_OFF) in the YRB are USD 754 million and USD 1181 million, respectively, with a combined total of USD 1935 million (Fig. 4f). Spatially, Supply_ON and Supply_OFF exhibit varying magnitudes across different sub-basins, showcasing distinct spatial rankings compared to the total supply (Fig. 4c and d). When identifying key areas based on the top 30% ranking of supply values in different sub-basins within the YRB, considering both on- and off-site supply, the results reveal that the supply value of critical areas increases by 64.2% compared to only considering on-site supply, based on the multi-year average from 2001 to 2020 (refer to Fig. 4). Our findings underscore the significance of incorporating both on- and off-site supply values for a comprehensive evaluation of soil conservation measures. They also indicate that unilaterally considering the value of on- and off-site supplies may lead to inaccurate assessments of the importance of various sub-basins for SCSF. Our holistic approach illustrates how integrating service flows is pivotal for accurately identifying critical areas for soil conservation services and guiding effective land use planning and ecosystem restoration strategies. In this regard, the 15th meeting of the Conference of the Parties to the UN Convention on Biological Diversity adopted the Kunming–Montreal Global Biodiversity Framework, which establishes a series of targets for the conservation of 30% of terrestrial and marine areas by 2030 [53]. Our approach can help design which areas could be protected across large river basins

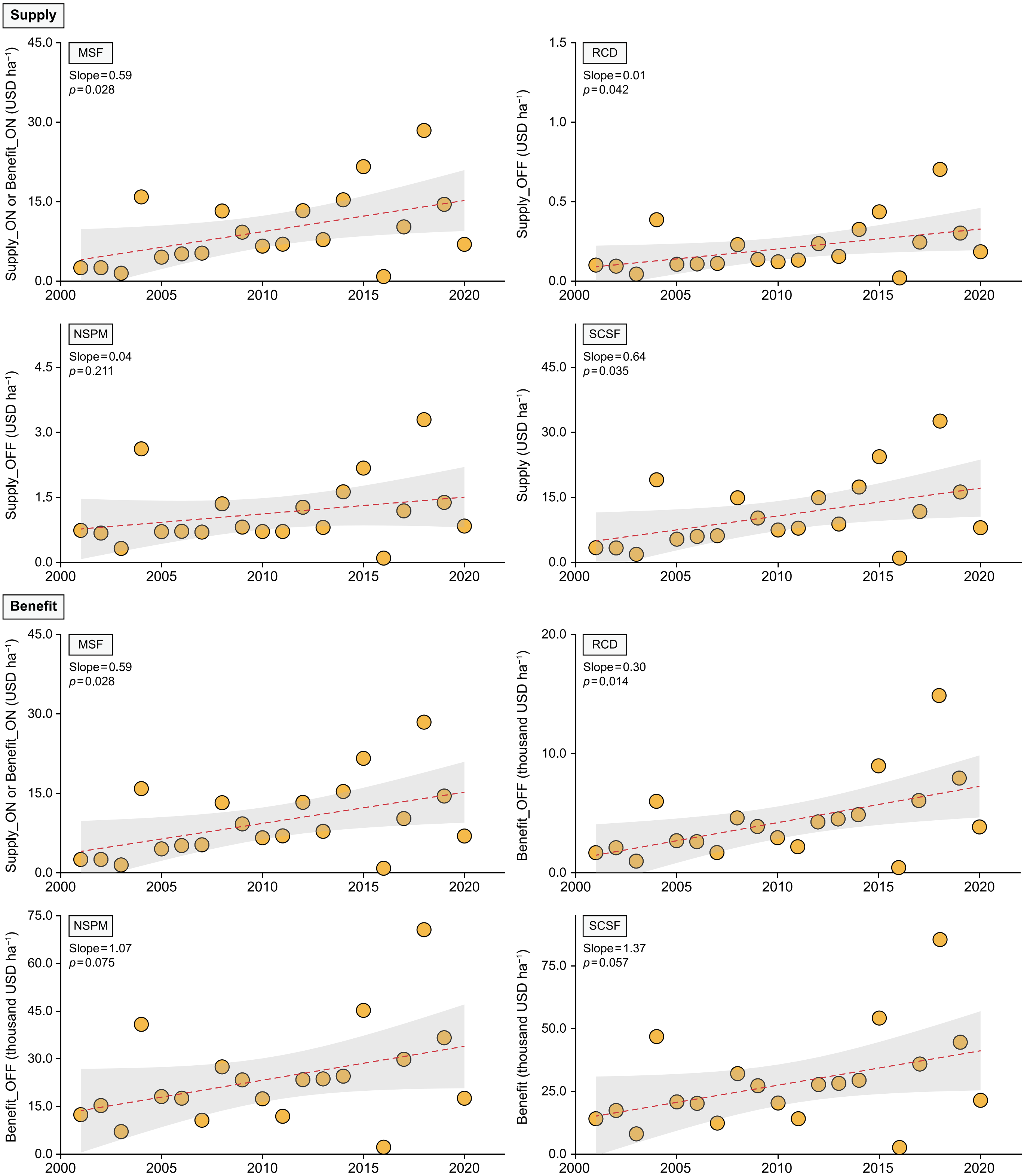

Fig. 2. Evolution of supply and benefit values over time for various Yellow River Basin (YRB) services. MSF: maintenance of soil fertility, RCD: reduction of dredging project costs, NSPM: nonpoint source pollution mitigation, SCSF: total supply values of various services. Please refer to Figs. S4 and S5 in the Supplementary Materials for upstream, midstream, and downstream change trends. The shaded part of the figure represents the 95% confidence interval.

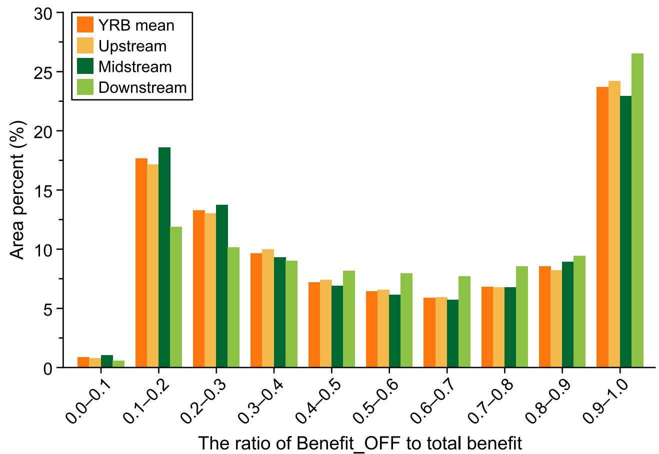

Fig. 3. Ratio of off-site service benefit (Benefit_OFF) to the total service benefit values across the entire Yellow River Basin (YRB) and various regions within the basin. YRB mean, Upstream, Midstream, and Downstream signify the respective overall area percentages of the YRB, the upstream region, the midstream region, and the downstream region, respectively. For a detailed breakdown of the spatial division, please refer to Fig. S1 in the Supplementary Materials.

based on the services they provide.

4. Discussion

4.1. Soil conservation effects based on the service flow

The difference between dynamic soil conservation benefits based on service flow and static assessment primarily lies in off-site supply and benefit. The results demonstrate that the multi-year average off-site benefits in the YRB far surpasses on-site benefits, with 54% of the region relying more on off-site benefits. This highlights how introducing service flow leads to different outcomes in valuing soil conservation services in different regions. For instance, while An et al. conducted a long-term time-series study on soil conservation service functions in the YRB from 2000 to 2018, the results only emphasized the importance of the midstream [54]. However, our study identified the contribution of the upstream to soil conservation supply and the increasing trend through the off-site cumulative effect, designating it as a key area. The significant increase in the total benefit value of soil conservation services over the last two decades stems from the significant increase in on-site MSF benefits and the cumulative value of RCD benefits. Meanwhile, the supply value has also increased significantly and is concentrated in the midstream region. These soil conservation service indicators shifts mainly result from sediment interception [55]. Previous studies have indicated that human activities have been the dominant factor in sediment load changes in the Yellow River from 2000 to 2012, Accounting for 72.2% of the shift [56]. This prominence can be attributed to the robust implementation of diverse soil conservation measures, including initiatives like the Grain to Green Project [57], agricultural conservation measures [58], construction of terraces [59], and vegetation restoration [60]. Vegetation changes throughout the watershed and check dams in the stream network reduced sediment loads by approximately 80% and 20%, respectively [61].

In contrast to previous studies, we address the issue of expressing soil conservation service flows solely through sediment accumulation changes [62]. By simulating the virtual service flow process with a monetary approach, we provide a more rational understanding of soil conservation service flow dynamics. Moreover, previous attempts at monetizing service flows have rarely combined them with cumulative effects [63,64]. For example, the Gross Ecosystem Product algorithm proposed by Ouyang et al. considers only static metrics [24]. Our emphasis on off-site supply and benefits due to upstream cumulative effects provides a more objective assessment of soil conservation service values.

4.2. Implications for managing large river basins

Given the intricate dynamics within vast river basins like the YRB, where natural ecosystems, agroecosystems, human populations, and diverse economic activities coexist [65,66], restoration and conservation efforts must extend beyond ecological considerations to reflect their broader implications for human societies [67]. The effectiveness of the UN Decade on Ecosystem Restoration depends on adopting a social-ecological perspective [68]. Our study uniquely acknowledges the value of human-dependent environments by integrating on- and off-site benefits, underscoring the need for ecological restoration that accounts for interconnected natural and socio-economic systems. This approach allows for a comprehensive assessment of ecosystem restoration benefits from a socio-ecological lens. In terms of project evaluation, which has often been contentious [69], our study recognizes the shift from static assessments to dynamic descriptions [70], emphasizing that off-site effects driven by ecosystem service flows play a crucial role in accurately assessing recovery outcomes. For soil conservation services in the YRB, the off-site supply is 1.6 times higher than the on-site supply. Service flows thus contribute to an objective and precise diagnosis of soil conservation, facilitating ecological restoration planning, promoting balanced regional development, and enhancing stakeholder equity [71]. Moreover, service flows influence rankings of soil conservation benefits across different regions (Fig. 4). Our findings reveal that considering both on- and off-site supply increases the supply value of critical areas by 64.2% compared to solely on-site supply considerations. This provides valuable spatial guidance for ecological restoration measures in soil erosion control and can also guide decision-makers in advancing land degradation neutrality goals in the YRB.

While the off-site benefits of soil conservation in the YRB outpace on-site benefits, this does not necessarily imply that soil conservation has significantly contributed to human well-being and soil health. The transported soil, facilitated by water erosion, carries nutrients, carbon, pathogens, and contaminants, potentially creating environmental challenges [13,72,73]. When soil displacement occurs within a spatial unit, negative impacts can propagate along water and value flow paths, adversely affecting the ecological security of downstream areas. Our framework becomes instrumental in pinpointing the sources of ecological and environmental issues like non-point source pollution, sediment dredging, and water contamination, offering practical solutions (Fig. 1). Through hydrological pathways, our approach identifies the upper-reach connectivity zones of each spatial unit as potential erosion sources, while the lower-reach connectivity zones provide information about the range of influence, being erosion sources themselves. For instance, in selecting sites for check dam construction, priority can be given to high-transmission areas to intercept erosion outflow from the source [74]. Once potential erosion sources and the extent of their impact are understood, soil erosion and its associated environmental problems should be prevented and controlled from the source. In the YRB, the middle reaches are most vulnerable to soil erosion, requiring vegetation restoration alongside soil bioengineering measures like terracing and check dam construction. Studies have shown that natural vegetation rehabilitation is the best solution for on-site soil erosion control by strengthening the soil's physical and chemical properties [75,76]. Revegetation of

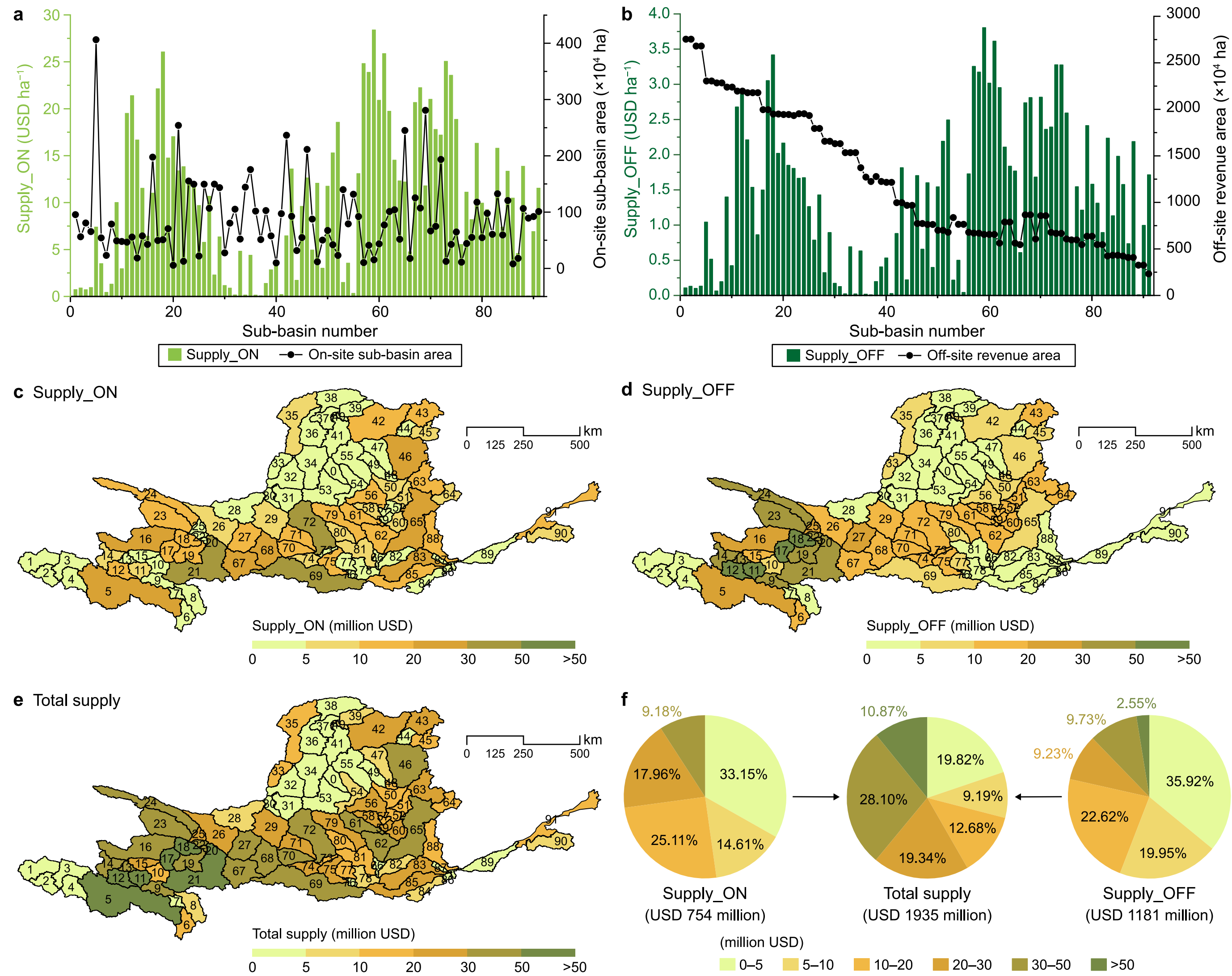

Fig. 4. **a**–**b**, Spatial ranking of on-site supply, off-site supply, and total supply values in the Yellow River Basin (YRB). Panels show the multi-year average of on-site (Supply_ON, **a**) and off-site (Supply_OFF, **b**) service supply per unit area in different sub-basins and corresponding sub-basin (**a**) and sub-basin revenue (**b**) areas. **c**–**e**, The on-site (Supply_ON, **c**), off-site (Supply_OFF, **d**), and total (**e**) service supply spatial ranking (in million USD). **f**, The proportion of different range values in on-site (Supply_ON), off-site (Supply_OFF), and total service supply. The middle number in the pie chart is the total value of the YRB under each supply type.

forests and grasslands accounts for more than 90% of overall hillslope erosion control [77]. The construction of terraces and check dams mainly addresses soil erosion problems for arable lands on hillslopes and gully beds for sediment trapping in mountainous areas, respectively [78,79]. When combined, these strategies can mitigate both soil erosion at the sources and sediment transport along water flow paths from the hill slopes to riverbeds [80]. However, factors such as climate change and the impacts of extreme events, water resource constraints, topographic conditions, and land use suitability should be considered when conducting spatial optimization of soil conservation measures at different spatiotemporal scales [81]. In essence, soil conservation service flows offer a valuable perspective on connectivity and regional considerations for ecological restoration. This approach can seamlessly integrate into decision-making processes and investment planning in public and private sectors, especially in water erosion-prone river basins.

Our theoretical framework and methodology for SCSF are also scalable and adaptable to local needs and conditions in large river basins. For example, soil erosion in the Mekong River Basin is a major environmental issue, triggering land degradation and siltation of river sediments [82]. The upper areas of this basin (in China and The Lao People's Democratic Republic) are highly eroded, and soil conservation measures would yield benefits both locally and in lower reaches like Vietnam [2]. In this case, our research framework can determine the region with the highest impact off-site and identify the linkages between different regions. This can lead to cross-regional cooperation on ecological compensation between countries, thereby providing a theoretical basis for developing fair and objective solutions. Similarly, inadequate soil and water conservation in the Upper Blue Nile basin has led to significant soil erosion, resulting in land degradation and downstream water quality issues [83,84]. In this context, our research framework emphasizes the importance of soil conservation. It offers the possibility of quantifying off-site benefits and providing a rational basis for managing regional soil conservation measures.

However, limitations exist in soil conservation service flow assessments. This study focused on only three components (MSF, RCD, and NSPM) in calculating the value of benefits, overlooking other benefits due to soil conservation, such as stability of the soil structure, maintenance of crop yields, and protection of infrastructure [28,29,85]. Although there are problems of duplicate calculations between different indicators, for example, there is a strong correlation between crop yields and soil fertility maintenance, refining these indicators will improve the reliability of service benefit calculations. Despite these limitations, the study aimed to propose and validate a theoretical framework based on available data. Therefore, despite the constraints above, it remains an important contribution to land degradation control, ecosystem restoration, and environmental management in large river basins.

5. Conclusion

We endeavor to construct a framework for calculating the benefits of soil conservation services based on the service flow concept. The strength of this study lies in its integration of on- and off-site benefits. This framework emphasizes the critical role of off-site benefits in assessing soil conservation service supply capacity and evaluating key ecological functional areas. It is also scalable for broader applications. With the YRB as a case study, our findings reveal that over half of the region is highly dependent on off-site benefits. Strategic improvements in the spatial configuration of key areas—representing 30% of the YRB—could result in a multi-year average (2001–2020) improvement of 64.2% in soil conservation service supply. These findings validate the framework's usability and potential, which can help policymakers and land managers to effectively plan and monitor soil conservation efforts, tackle soil erosion problems, restore degraded ecosystems, and protect and manage natural areas in large river basins, ultimately supporting a more sustainable future.

CRediT authorship contribution statement

Siqi Sun: Writing - Original Draft, Methodology. **Yihe Lü:** Writing - Review & Editing, Conceptualization. **Xiaoming Feng:** Writing - Review & Editing. **Fernando T. Maestre:** Writing - Review & Editing. **Bojie Fu:** Supervision.

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.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 42041005–5). F.T.M. acknowledges support from the University of Alicante (UADIF22-74 and VIGROB22-350) and the Ministerio de Ciencia e Innovación of Spain (PID2020-116578RB-I00).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2024.100496.

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