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REVIEW ARTICLE

Global Research Trends on Ecosystem Service Valuation Using Remote Sensing (1990–2024)

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Abstract

Ecosystem service valuation (ESV) provides a scientific basis for balancing ecological conservation and socioeconomic development. With the rapid progress of Earth observation technologies, remote sensing has become an essential tool for quantifying and mapping ecosystem services at multiple spatial and temporal scales. However, a comprehensive understanding of the global research landscape on ecosystem service valuation using remote sensing remains limited. In this study, this study conducted a bibliometric analysis of publications retrieved from the Web of Science Core Collection between 1990 and 2024. A total of 1172 articles were identified through a systematic search strategy integrating ecosystem service valuation and remote sensing keywords. The analysis employed performance indicators (e.g., publication output, citation trends, and core journals), collaboration networks (countries, institutions, and authors), and keyword co-occurrence to reveal research hotspots and emerging frontiers. The results show a steady growth of publications, with a significant surge after 2010 driven by the application of MODIS, Landsat, and Google Earth Engine in large-scale ESV studies. China, the United States, and several European countries play dominant roles in terms of both output and international collaboration. Research hotspots have shifted from conceptual frameworks and regional case studies to methodological innovations, such as spatial modeling, integration of remote sensing with ecosystem accounting frameworks, and applications in ecological security and sustainable development. This study highlights the increasing importance of remote sensing in advancing ecosystem service valuation and provides insights into future directions, including high-resolution monitoring, machine learning integration, and policy-oriented assessments.

Keywords: remote sensing, ecosystem service valuation, bibliometric analysis, natural capital accounting.

1 Introduction

Ecosystem service valuation (ESV) provides an evidence base for balancing ecological conservation with socioeconomic development by translating biophysical service supply and use

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into decision-relevant metrics [8, 9, 14, 15, 22]. Over the past three decades, the rapid maturation of Earth observation has transformed how ESV can be implemented in practice: long time-series archives (e.g., Landsat, MODIS, Sentinel) and cloud platforms (e.g., Google Earth Engine) now enable synoptic, repeatable, and multi-temporal assessments from local to global scales [16, 17, 41, 42]. Remote sensing thus functions as both a measurement system—retrieving land cover, biomass, vegetation indices, surface temperature, inundation, and coastal morphology—and as an integrative scaffold that links ecological processes with valuation and accounting frameworks [7, 10, 18, 24].

A series of domain reviews underscores this transition while also revealing fragmentation. A broad systematic synthesis of remote sensing of ecosystem services documented the expanding use of satellite data to map service proxies and to monitor change, yet it largely emphasized biophysical assessment rather than economic valuation pathways [3, 11, 25]. Method-focused surveys for specific contexts—for example, urban vegetation and grasslands—catalogued sensors, spectral features, and modelling algorithms (including machine learning) that support service quantification, but they tended to concentrate on single ecosystems or application scenes, often stopping short of connecting remote sensing outputs to valuation schemes or ecosystem/natural-capital accounting [11]. Complementing these is a bibliometric analysis of vegetation spatiotemporal dynamics and driving forces (1987–2024), which charted research growth and thematic structure for vegetation change per se; however, that line of work did not target the valuation of ecosystem services or its interface with remote sensing. Taken together, prior syntheses have clarified the technical repertoire and ecosystem-specific advances but leave open a field-level view of how remote sensing and ESV have co-evolved, which actors and outlets organize the knowledge base, and where methodological frontiers are emerging [28].

This study addresses that gap by providing a comprehensive bibliometric mapping of global research on ESV using remote sensing over 1990–2024. Using a curated corpus from the Web of Science Core Collection (exported as "Full Record + Cited References"), this study combine performance analysis with science-mapping to answer five questions: (RQ1) How have publication and citation trajectories evolved, and where are the inflection points? (RQ2) Which journals and disciplines channel knowledge production and exchange, and how cross-disciplinary are the citation flows? (RQ3) What is the intellectual base (cited references, authors, and sources) that underpins remote-sensing–enabled ESV? (RQ4) How are collaboration structures (countries, institutions, authors) configured, and what do they imply for knowledge diffusion and agenda-setting? (RQ5) What are the dominant themes, how have they evolved over time, and which methodological frontiers (e.g., cloud platforms, machine learning, carbon/habitat integration, coastal and flood-risk applications) are currently ascendant [1, 6, 7, 25]?

Our contributions are threefold. First, this study assemble and document a reproducible corpus for the intersection of remote sensing and ESV, enabling transparent trend analysis across three decades [17, 41]. Second, This study delineate the field's organizational and intellectual architecture—identifying core journals, cross-disciplinary citation pathways, keystone references and author communities, and the hub-and-spoke collaboration patterns that mobilize this knowledge globally [32, 33]. Third, this study map the conceptual structure and its temporal evolution, showing a migration from mapping- and case-led studies toward model-based, platform-enabled valuation that couple's carbon and habitat services and extends to water/coastal risk contexts [3, 10, 18, 37]. By synthesizing these layers, the paper offers a consolidated baseline and an agenda for the next phase of remote-sensing–enabled ESV, emphasizing high-resolution multi-sensor fusion with explicit uncertainty propagation, stronger causal evaluation, tighter linkage to ecosystem/natural-capital accounting and socioeconomic data, and open, reproducible cloud workflows.

The remainder of the paper is organized as follows. Section 2 details the data and bibliometric methods. Section 3 reports result for performance trends, source landscape and disciplinary flows, intellectual base, collaboration structures, and conceptual evolution. Section 4 discusses drivers of growth, methodological implications, policy relevance, limitations, and priorities, and Section 5 concludes.

2 Methodology

2.1 Literature Search Strategy

To ensure comparability with related bibliometric studies, This study used the Web of Science Core Collection (SCI-Expanded) as the sole data source

[27] and set the search window to 1990–2024 to capture long-term trends in how remote sensing has been applied to ecosystem service valuation (ESV). Records were exported in "Full Record + Cited References" format for subsequent bibliometric and science-mapping analyses [1, 38]. The search targeted the intersection of ESV/valuation and remote sensing/earth observation by combining two keyword clusters with AND and linking synonyms within each cluster with OR [10] (stemming and common abbreviations allowed). The ESV/valuation cluster included "ecosystem service*," "ecosystem services valuation," "ecosystem valuation," "monetary valuation," "economic valuation," "benefit transfer," "value transfer," "willingness to pay," "ecosystem accounting," "SEEA-EA," "natural capital accounting," "InVEST," "ARIES," and "SolVES," [21] while the remote sensing/EO cluster included "remote sensing," "earth observation," satellite, "Google Earth Engine"/GEE, Landsat, MODIS, Sentinel, AVHRR, LiDAR, SAR, and ICESat [12, 17, 20, 41]; indicative RS variables permitted in titles/abstracts/keywords included NDVI, EVI, LAI, LST, SIF, FAPAR, ET, NPP, and GPP [19, 29, 36]. An example WoS Topic query was: TS = ((<ESV/valuation cluster>) AND (<remote sensing/EO cluster> OR)). No document-type or language restrictions were applied at retrieval; during screening, only peer-reviewed English-language Articles and Reviews were retained to ensure metadata quality and tool compatibility [26, 31]. This study excluded items whose titles clearly indicated unrelated domains (e.g., major biomedical, chemical, or physical terms such as disease, cancer, cell, polymer, catalyst, spectroscopy, crystallography, isotope, hematology, cardiology, cosmology, black hole), studies that conducted remote-sensing mapping without valuation/accounting components, studies that performed valuation without remote-sensing/EO data, conference abstracts, non–peer-reviewed items, and records without accessible full text. Screening proceeded in two stages: first, deduplication and title/abstract screening against two necessary conditions—explicit involvement of ESV (valuation/accounting/value transfer, etc.) and use of remote-sensing/EO data (sensor/platform/index/resolution); second, full-text verification of the valuation approach (e.g., market-based, replacement cost, CVM/value transfer, or SEEA-EA integration) and remote-sensing specifications (sensor/platform/indices/resolution), with reasons for exclusion documented (e.g., non-English full text, missing methodological details). Names of authors, institutions, and countries were standardized and keywords were harmonized [19, 25] (e.g., "ecosystem accounting/SEEA-EA/natural capital accounting" consolidated under "ecosystem accounting"; "Google Earth Engine/GEE" unified as "GEE"). The finalized WoS plain-text file supported analyses of publication and citation trends, country/institution/author collaboration networks, keyword co-occurrence and burst detection, and cited-reference co-citation networks. Following this protocol, 1,172 publications were retained for analysis, consistent with the sample size reported in the abstract.

2.2 Bibliometric Analysis

The "Bibliometric Analysis" section details a reproducible workflow that converts retrieved records into the science-mapping outputs reported in this study. This study first delineated the analytic scope—remote-sensing–enabled ecosystem service valuation (ESV)—and the observation levels (document, author, institution, country), then compiled a corpus from the Web of Science Core Collection (SCI-Expanded, 1990–2024) exported as "Full Record + Cited References," yielding 1,172 publications after screening. Records were curated in R (v4.x) with bibliometric/bibliophagy (v4.x), including author/institution/country name disambiguation, keyword harmonization (e.g., "Google Earth Engine" ; "ecosystem accounting/SEEA-EA" unified), and fractional counting for multi-authored and multi-country items. This study constructed performance indicators (publication and citation trajectories, journal concentration) and three families of networks aligned with the figures: co-authorship maps for authors, institutions, and countries (COA/ORG/Collaborating Countries); co-citation structures representing the intellectual base at the document, journal, and author levels (DCA/JCA/ACA) [23, 34]; and conceptual structures based on keyword co-occurrence with cluster, timeline, and time-zone/overlay views (CO-DESC) [5, 39]. Association-strength normalization and Louvain community detection were used for conceptual networks [30, 38]; co-citation graphs were pruned when necessary for readability. Visualizations were produced with bibliometric/bibliophagy and ggplot2/Origin, while Cite Space supported timeline and overlay rendering. In all graphs, node size encodes frequency or link strength, edge width indicates tie weight, and color gradients convey temporal slices. Sensitivity checks on thresholds and

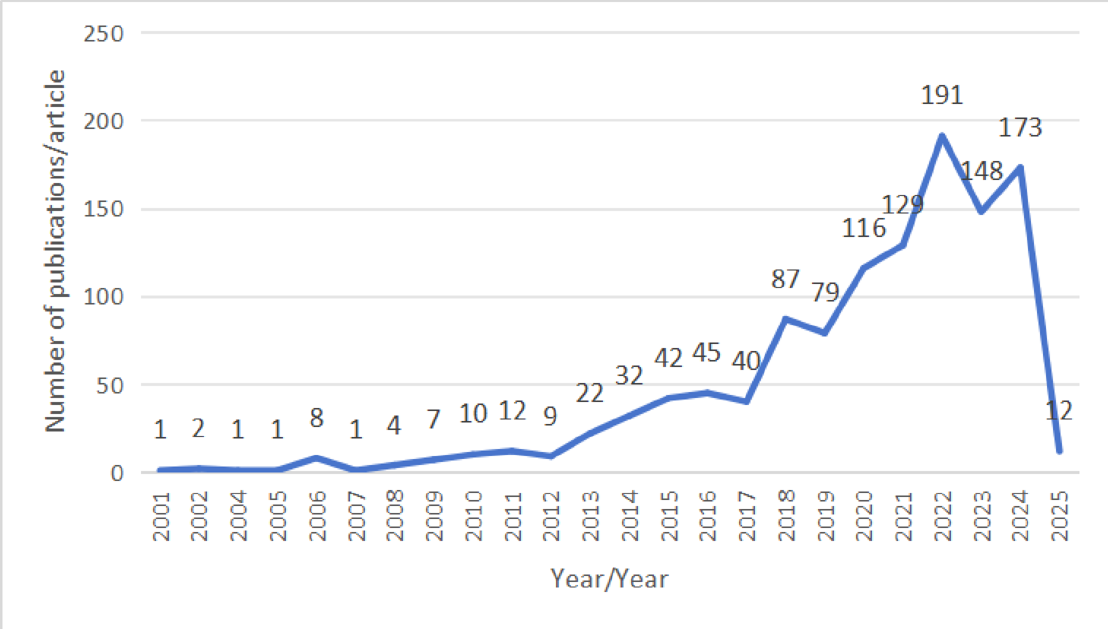

Figure 1. Annual publication trends in remote-sensing–enabled ecosystem service valuation (2001–2025).

normalizations confirmed the stability of the main patterns emphasized later—namely the post-2010 acceleration associated with MODIS/Landsat/GEE, the leading roles of China, the United States, and several European countries, and the shift from early conceptual/case work toward methodological innovation and policy-oriented applications.

3 Results

3.1 Publication performance

Employing a bibliometric approach, this study charts the developmental trajectory of global research on ecosystem service valuation (ESV) using remote sensing and the enabling factors that have shaped its expansion. Over the observation window 2001–2024, annual scholarly output evolved from a prolonged low baseline in the early 2000s to a sustained expansion after 2010, with production rising from 10 items in 2010 to 173 in 2024 (compound annual growth ≈ 22.6%). A structural uplift is evident around 2018 (87 vs. 40 in 2017), followed by a high plateau that peaks in 2022 (191) and remains elevated through 2023–2024 (148–173). The sharp drop recorded for 2025 (12) is a partial-year artifact due to the search cut-off rather than a substantive contraction. This growth pattern coincides with wider access to long time-series satellite archives (e.g., Landsat, MODIS), the diffusion of cloud platforms such as Google Earth Engine, and the rising policy salience of ecosystem/natural-capital accounting and sustainability agendas, which collectively lowered analytical barriers and facilitated large-area, multi-temporal ESV applications (Figure 1).

3.2 Source landscape & disciplinary context

To situate remote-sensing–enabled ESV within its publication venues and disciplinary flows, this study first examined the cited-source co-citation network (Figure 2). The map resolves several well-defined clusters. A methods/remote-sensing cluster is anchored by Remote Sensing of Environment, ISPRS Journal of Photogrammetry and Remote Sensing, International Journal of Applied Earth Observation and Geoinformation, and International Journal of Remote Sensing, reflecting the technical backbone of satellite data processing. An environmental science & management cluster centers on Science of the Total Environment, Journal of Environmental Management, Environmental Monitoring and Assessment, and Ecological Indicators, which concentrates evidence synthesis, monitoring, and assessment workflows. A third cluster connects ecology, valuation, and land-use/policy, with Ecological Economics, Ecosystem Services, Landscape Ecology, Landscape and Urban Planning, Global Environmental Change, and Land Use Policy shaping the bridge to economic valuation and governance. Domain-specific outlets such as Agriculture, Ecosystems & Environment and Forest Ecology and Management supply ecosystem-focused applications, while general-science journals (PNAS, Nature, Science) appear as prestige anchors with broad cross-cluster reach. Bridging positions are consistently occupied by Remote Sensing

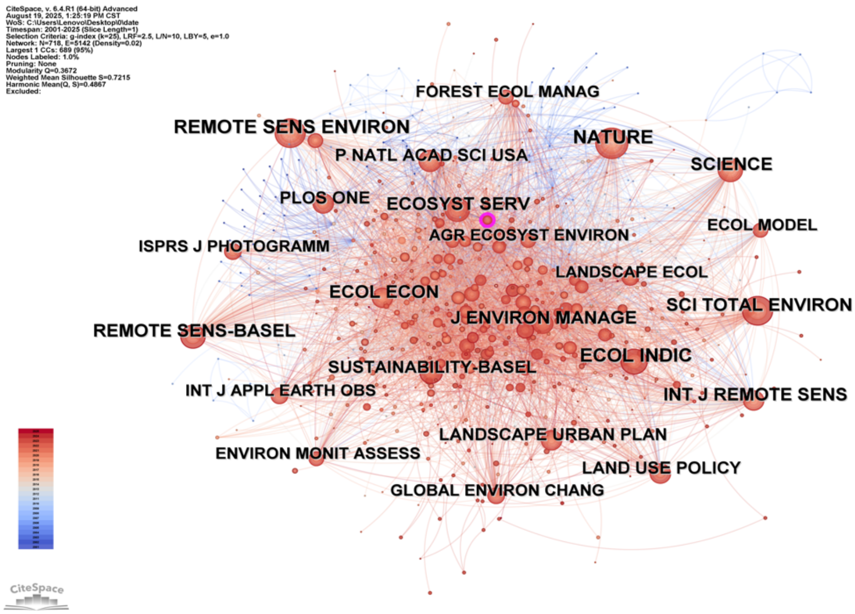

Figure 2. Journal co-citation network in remote-sensing–enabled ecosystem service valuation.

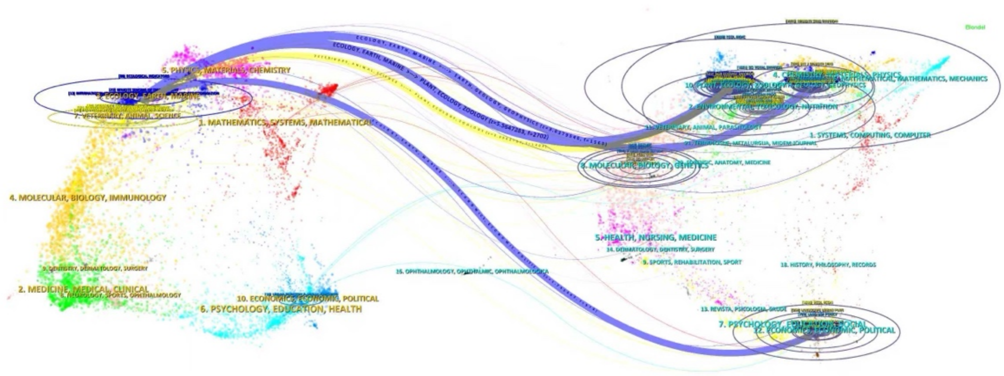

Figure 3. Thematic evolution of research on remote-sensing–enabled ecosystem service valuation (1990–2024).

of Environment, Science of the Total Environment, and Ecological Indicators, underscoring the dual methodological–policy orientation of the field.

The journal dual-map overlay (Figure 3) corroborates this structure and makes the cross-disciplinary citation currents explicit: dominant ribbons run from ECOLOGY/EARTH/MARINE publishing venues on the citing side to ENVIRONMENT/ECOLOGY knowledge bases on the cited side, while secondary but meaningful streams flow into SYSTEMS/COMPUTING/COMPUTER and, to a lesser extent, PHYSICS/MATERIALS/CHEMISTRY. These trajectories indicate that ESV studies increasingly lean on environmental-ecological theory while drawing methodological support from computational and quantitative domains, consistent with the field's shift from concept- and case-led work to scalable modeling and policy-relevant assessment described elsewhere in this study.

3.3 Intellectual base

The intellectual backbone of remote-sensing–enabled ESV is organized around four tightly connected strands. First, a valuation-framework core is anchored by canonical works associated with Costanza and de Groot, together with contributions by Daily, which stabilize concepts, typologies, and monetary assessment logics for ecosystem services. Second, a remote-sensing/methods strand links these frameworks to operational mapping through references connected to satellite time-series processing and workflow standardization—most visibly the

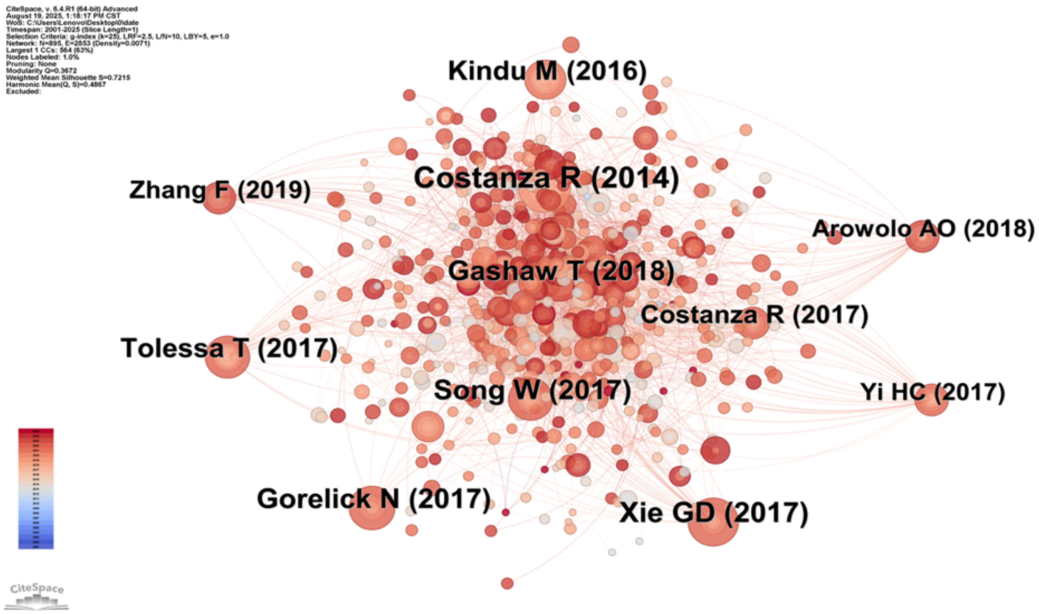

Figure 4. Author co-citation network in remote-sensing–enabled ecosystem service valuation research.

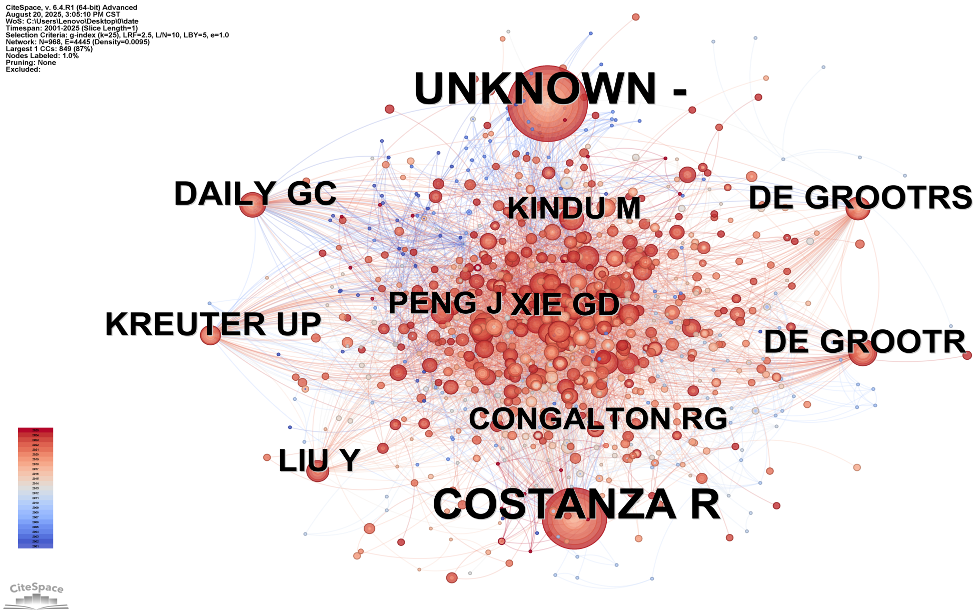

Figure 5. Thematic evolution of research on remote-sensing–enabled ecosystem service valuation (1990–2024).

Google Earth Engine paper (Gorelick 2017) and accuracy-assessment practice rooted in Congalton's work. Third, a large regional empirical cluster draws on land-use/land-cover change and coefficient-based valuation, with prominent nodes for Xie G.D., Song W., Peng J., and Liu Y. (China), and a parallel Ethiopian line featuring Kindu M., Tolessa T., and Gashaw T.; additional case-based anchors include Arowolo A.O. and Zhang F. These communities collectively document the field's transition from localized case studies to scalable assessments. Fourth, policy-relevant outlets (e.g., Ecosystem Services, Ecological Economics, Land Use Policy) connect empirical evidence to governance and planning, forming bridges to decision contexts.

In the cited-reference co-citation network (Figure 4), these strands appear as densely knit clusters with high-degree, high-betweenness nodes such as Costanza (2014), Xie (2017), and Gorelick (2017) acting as structural pivots; the color gradient indicates that many keystone items concentrate from 2014 onward, reflecting the consolidation of valuation frameworks and the diffusion of cloud-based analytics. The cited-author co-citation network (Figure 5) corroborates the same architecture at the author

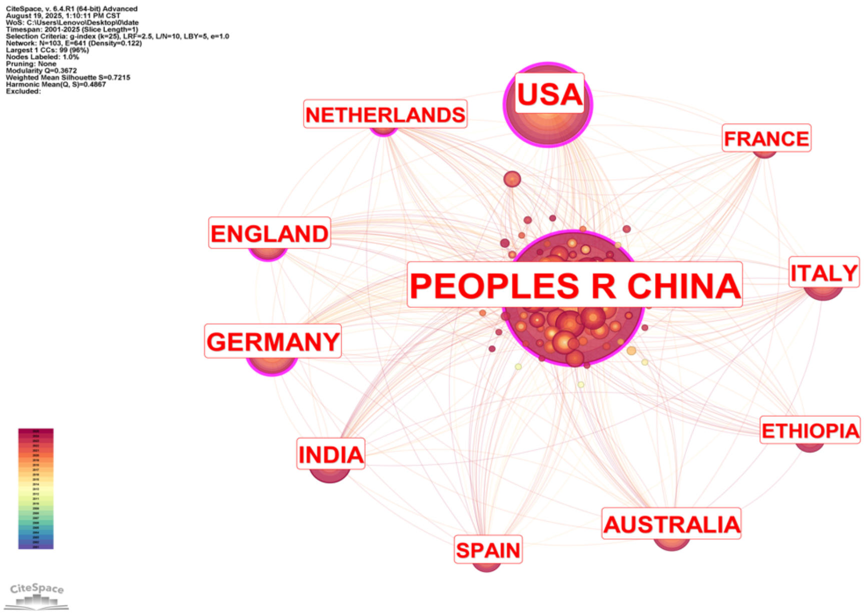

Figure 6. Author co-citation network in remote-sensing–enabled ecosystem service valuation research.

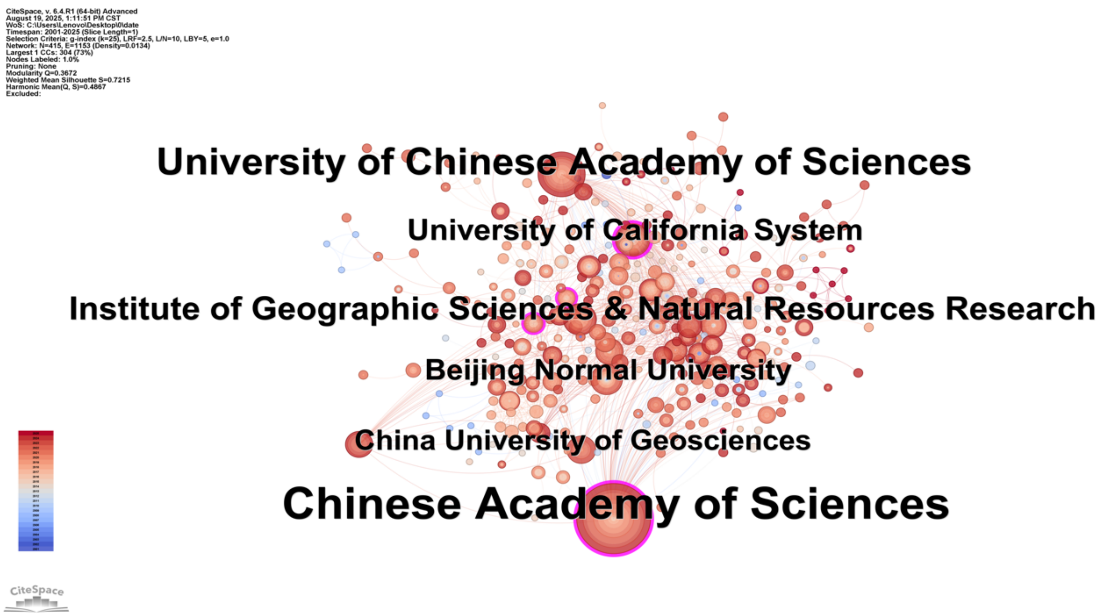

Figure 7. Author co-citation network in remote-sensing–enabled ecosystem service valuation research.

level: cores around Costanza/de Groot/Daily (theory and valuation), Xie/Song/Peng/Liu(large-scale empirical applications), and Kindu/Tolessa/Gashaw (Horn-of-Africa land-change valuation), with Congalton and related methodologists providing cross-cluster ties. Occasional nodes labeled "UNKNOWN" arise from incomplete metadata aggregation and are not interpreted substantively. Taken together, the two maps indicate a mature knowledge base in which valuation theory, remote-sensing methodology, and regional application have become mutually reinforcing, enabling the post-2010 surge documented elsewhere in this study.

3.4 Collaboration structure

The At the country level, the co-authorship map exhibits a highly centralized topology with China occupying the largest and most connected node, followed by the United States and a set of European economies (Germany, England/UK, the Netherlands, France, Italy, Spain). Australia, India, and Ethiopia appear as active contributors with multiple cross-regional ties. The thickness and multiplicity of links between China and North America/Europe indicate sustained international collaboration rather than isolated bilateral exchanges (Figure 6).

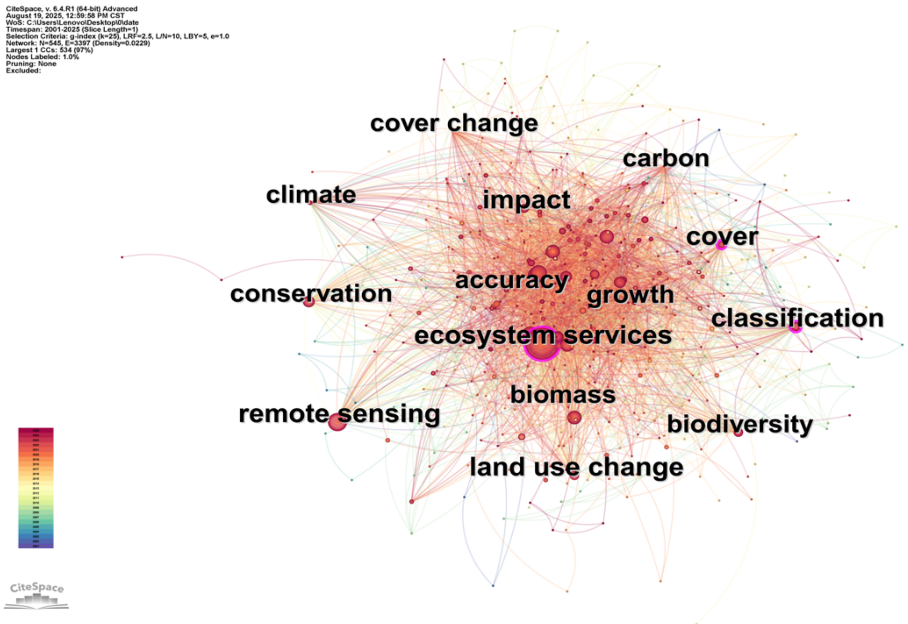

Figure 8. Keyword co-occurrence network in remote-sensing–enabled ecosystem service valuation research.

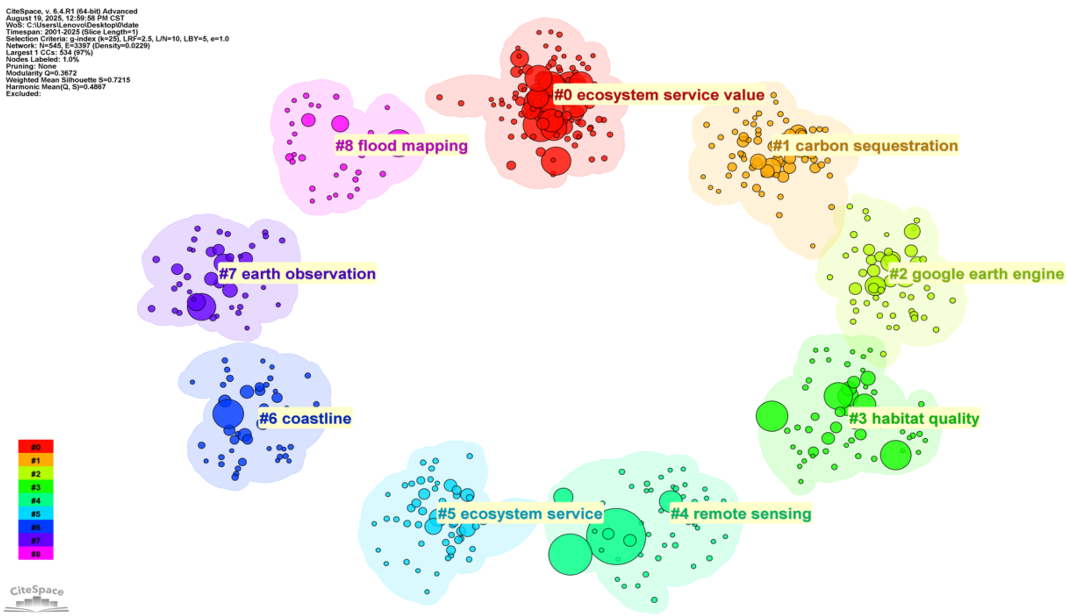

Figure 9. Keyword clustering map of remote-sensing–enabled ecosystem service valuation research.

At the institutional level, the network is organized around several hubs led by the Chinese Academy of Sciences (CAS)and its affiliates (e.g., University of Chinese Academy of Sciences, Institute of Geographic Sciences and Natural Resources Research), accompanied by Beijing Normal University and China University of Geosciences. Outside China, the University of California system functions as a major international bridge, linking Asian and Western partners. The prominence of these hubs, together with numerous medium-sized institutions, suggests a "hub-and-spoke" structure that facilitates large collaborative projects and knowledge diffusion (Figure 7).

At the author level, cohesive teams are visible alongside brokerage positions that connect otherwise separate clusters. Notable high-productivity/high-degree authors include Estoque, Ronald C., Das, Subhasis, Bera, Biswajit, Shit, Pravat Kumar, An, Li, Ban, Yifang, Yu, Le, Chen, Wanxu, Fan, Shuisheng, Baral, Himal, and Peng, Qingxia. The prevalence of cross-national co-authorship within these groups indicates growing internationalization of remote-sensing-enabled ESV research and helps explain the post-2010 expansion

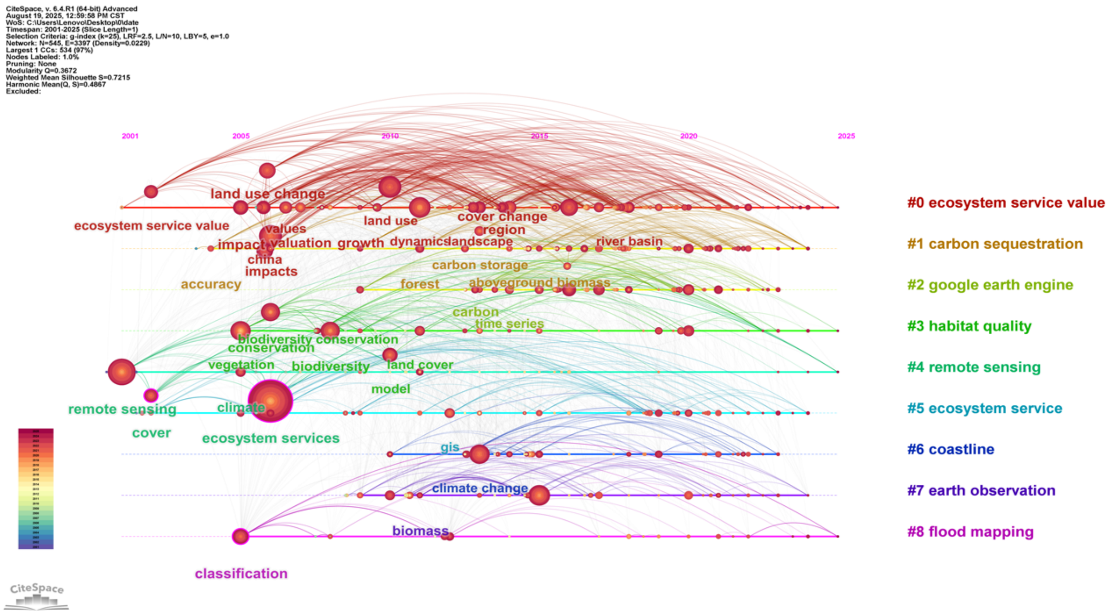

Figure 10. Thematic evolution timeline of remote-sensing–enabled ecosystem service valuation research (1990–2024).

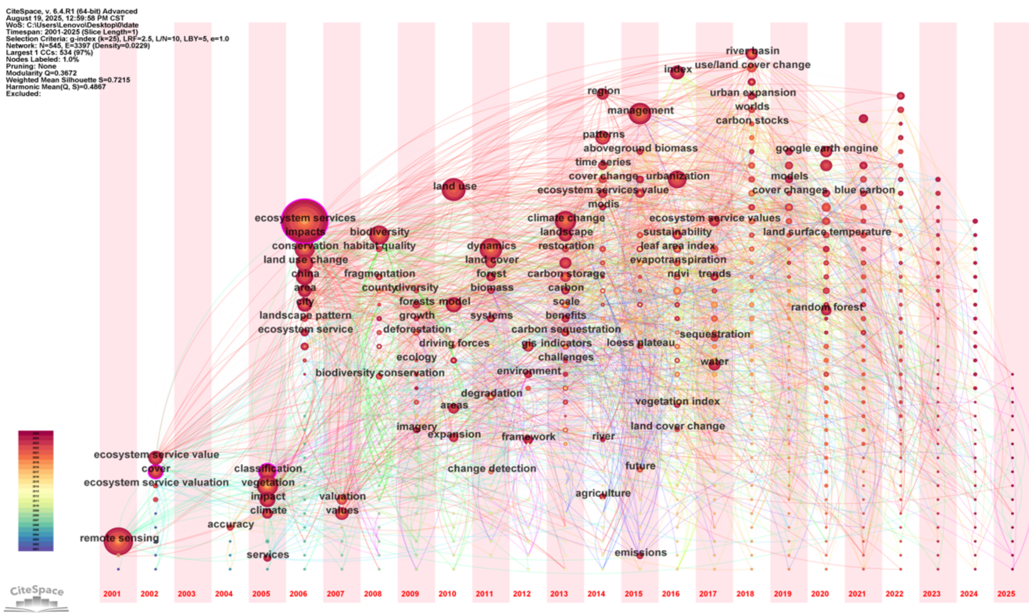

Figure 11. Keyword time-zone view of remote-sensing–enabled ecosystem service valuation research (2001–2024).

documented earlier.

3.5 Conceptual structure & thematic evolution

To characterize how ideas are organized and have evolved in remote-sensing–enabled ESV, this study combined an overall keyword co-occurrence map with clustering, timeline, and overlay views. The overall network (Figure 8) shows a dense core where ecosystem services, land-use change, and remote sensing operate as bridge terms linking methodological streams (classification, accuracy, biomass) with application streams (biodiversity, impact, carbon, conservation).

The cluster view (Figure 9) resolves nine coherent themes: #0 Ecosystem service value (valuation frameworks, land-use/land-cover change, impact evaluation), #1 Carbon sequestration (biomass, carbon storage, forests), #2 Google Earth Engine (cloud platforms and scalable analytics, often with ML), #3 Habitat quality (biodiversity conservation and InVEST-type assessments), #4 Remote sensing (fundamental indices/variables and modeling), #5 Ecosystem service(generic ES applications), #6 Coastline and #8 Flood mapping (coastal/water-risk contexts), and #7 Earth observation(sensor/platform perspective and multi-sensor fusion). The spatial separation of clusters combined with multiple cross-links indicates specialization with substantial methodological exchange.

The timeline view (Figure 10) suggests four phases. An early set-up phase (2001–2009) is dominated by remote sensing, classification, accuracy, and cover. A transition phase (2010–2015) centers on land-use/land-cover change, GIS, and climate change, marking a shift from pure mapping to process analysis. A consolidation phase (2016–2020) brings ecosystem service value, carbon storage/biomass, and habitat quality to the fore, signaling joint treatment of ecological condition and valuation. The frontier phase (2021–2025) features google earth engine, models, random forest, urban expansion, land surface temperature, blue carbon, and water/coastal terms, pointing to computational scaling and policy-relevant risk applications.

The overlay/time-sliced view (Figure 11) corroborates recency: ML and cloud-platform tags are right-skewed (latest), whereas classification, accuracy, and basic cover terms lie to the left (earlier). Overall, the field has migrated from concept- and mapping-driven studies to scalable, model-based valuation that couples carbon and habitat serviceswith cloud/ML toolchains, while expanding into coastal and flood-risk domains—consistent with the post-2010 surge and the methodological–policy linkages shown in previous sections.

3.6 Synthesis of findings

Taken together, the evidence depicts a field that has scaled rapidly since 2010 and consolidated around a dual engine of methodological enablement and valuation frameworks. The strong growth in annual outputs (Figure 1) co-occurs with cross-disciplinary citation flows from ecology/earth-science outlets into environmental-ecology and computational domains (Figure 2), indicating that remote sensing and data-analytic advances—most visibly Landsat/MODIS archives and Google Earth Engine—were translated into ecosystem-service valuation (ESV) through journals that bridge methods and policy. The intellectual base (Figure 3) shows stable pivots—Costanza/de Groot/Daily for valuation concepts, Gorelick/Congalton for scalable analytics and accuracy practice—around which regional empirical traditions (e.g., China, the Horn of Africa) accumulated, providing both theory and tools for large-area, multi-temporal assessments. This knowledge base is enacted through a hub-and-spoke collaboration architecture (Figure 4) dominated by China, the United States, and several European countries, with major institutional bridges (e.g., CAS system, University of California) and cohesive author teams that broker international ties. Conceptually, the domain has migrated from mapping-oriented and case-led work to model-based, policy-relevant valuation, coupling carbon and habitat services and extending to water/coastal risk contexts, while adopting cloud/ML toolchains (Figure 5). In sum, the post-2010 surge is explained by the alignment of data infrastructures, interdisciplinary publication channels, and collaborative capacity, yielding an agenda that now emphasizes high-resolution monitoring, machine-learning integration, and tighter links to ecosystem/natural-capital accounting and sustainability decision-making.

4 Discussion

4.1 Interpreting the trajectory and disciplinary integration

Our results depict a field that has expanded rapidly since 2010 as data infrastructures and policy demand matured in tandem. The diffusion of long time-series satellite archives (e.g., Landsat, MODIS) and cloud platforms (e.g., GEE) lowered the fixed costs of large-area, repeatable analytics, while the policy salience of ecosystem/natural-capital accounting created strong incentives to translate biophysical evidence into decision-relevant valuation. The source landscape and dual-map overlay confirm that knowledge now circulates bidirectionally between environmental/ecological sciences and computational/methodological domains, indicating a structural shift from siloed workflows to integrated pipelines where measurement, modeling, and valuation are co-designed.

4.2 Methodological turn: scale, validity, and reproducibility

Conceptual mapping shows a migration from mapping-centric, single-case assessments toward model-based, platform-enabled valuation that couples carbon and habitat services and extends into urban, coastal, and flood-risk contexts. This scaling brings clear benefits—synoptic coverage, temporal depth, and comparability—but also concentrates validity challenges. First, generalizability is often assumed rather than demonstrated: models trained in one biome or governance setting may not transfer to others. Second, uncertainty propagation remains underreported across the chain from land-cover classification and biophysical retrievals to benefit transfer and monetary estimates. Third, reproducibility hinges on versioned data, parameter transparency, and open code—conditions not consistently met even on cloud platforms. As machine-learning adoption grows (e.g., random forests on GEE), rigorous out-of-domain testing, interpretable feature design, and documentation of data lineage become central for decision-grade outputs.

4.3 Collaboration architecture and agenda-setting

Country–institution–author networks display a hub-and-spoke geometry centered on China, the United States, and several European hubs. This configuration accelerates diffusion of sensors, indices, and analytic practices, and it helps explain the post-2010 surge. At the same time, agenda setting can become geographically concentrated, with risks of overlooking data-poor regions that are environmentally critical and socio-economically vulnerable. Strengthening equitable, two-way partnerships and capacity building in under-represented regions would improve external validity, broaden the service portfolio beyond carbon and habitat, and increase the legitimacy of valuation in place-based policy processes.

4.4 Thematic frontiers and policy relevance

The cluster, timeline, and overlay views collectively indicate that the field's current frontier lies at the intersection of carbon accounting (including blue carbon), habitat quality/biodiversity, water and coastal risk, thermal environments (LST), and urban expansion—all strongly policy-relevant. A recurring translation gap remains: many studies culminate in maps or monetary surfaces without closing the loop to concrete instruments (e.g., zoning, subsidy design, restoration prioritization, or loss-and-damage accounting). Embedding explicit decision metrics (e.g., cost-effectiveness, net-present value, no-net-loss) and counterfactual evaluation within valuation workflows would accelerate policy uptake and enable learning-by-doing.

4.5 Agricultural ecosystem services: an emerging integration priority

Agricultural landscapes, covering approximately 38% of terrestrial surface, represent a critical yet underexplored frontier for remote-sensing–enabled ESV. While the literature has concentrated on carbon and habitat services in natural ecosystems, agricultural systems provide multiple provisioning services (food, fiber) alongside regulating functions (pollination, soil conservation, water regulation) that are increasingly monitored via high-resolution sensors (e.g., Sentinel-2, SAR). However, translating crop phenology and field-scale heterogeneity into service valuations remains methodologically challenging, requiring integration of remote sensing with farm-level socioeconomic data, agronomic models, and participatory validation. Future work should develop crop-specific ESV protocols that couple yield mapping with regulating service assessments, establish benchmarks linking plot-scale observations to market and non-market values, and co-design decision tools with agricultural extension services to support climate-smart agriculture and payment-for-ecosystem-services schemes. Agricultural ESV also faces unique construct validity issues: the coexistence of market prices for crops and non-market values for soil health or pollination demands hybrid valuation frameworks whose remote-sensing interfaces require further development.

4.6 Future directions

This study identify five priorities to consolidate rigor and expand impact. Looking ahead, progress will depend on consolidating rigor and widening real-world impact through an integrated agenda that treats validity and equity as first-order design constraints: pursue high-resolution, multi-sensor fusion (optical–SAR–LiDAR, and where relevant SIF/thermal) to better recover service-relevant structure and dynamics [2] while reporting explicit, end-to-end uncertainty budgets that propagate from classification and biophysical retrievals through benefit transfer to monetary estimates [4]; complement correlational mapping with causal and counterfactual evaluation (e.g., difference-in-differences, synthetic controls, matching) so that observed changes can be attributed to policies and shocks with decision-grade credibility [13]; establish common standards for valuation workflows—harmonizing service definitions, coefficient sources, and interfaces with ecosystem/natural-capital accounting (e.g., SEEA-EA) [37], and documenting price bases, discounting, and distributional assumptions via public "model cards" and provenance records; operationalize openness and reproducibility through FAIR data practices, STAC-indexed assets, versioned code and parameters, and containerized, cloud-native pipelines (e.g., GEE/Pangeo), supported by community benchmarks and reference datasets for cross-regional comparability [40]; and, finally, build equitable, co-produced collaborations in under-represented regions and integrate socio-economic and behavioral data (markets, mobility, livelihoods) to analyze beneficiaries, trade-offs, and equity alongside aggregate value, thereby increasing external validity and policy uptake [35].

4.7 Concluding remarks

Remote sensing has become a central engine for scalable, repeatable, and decision-oriented ecosystem service valuation. The field's rapid growth reflects aligned advances in observation, computation, and policy frameworks; its next gains will come from treating validity and equity as first-order design constraints—propagating uncertainty, testing generalization, opening pipelines, and broadening participation—so that valuation products are not merely descriptive but reliably actionable.

5 Conclusion

Beyond mapping how the field has grown, our synthesis suggests a practical pathway for making remote-sensing–enabled ESV decision-grade: co-design workflows with end users (agencies, utilities, NGOs) so that outputs are expressed in fit-for-purpose metrics (e.g., marginal value, cost-effectiveness, no-net-loss) and aligned with MRV requirements for ecosystem/natural-capital accounting; adopt outcome-oriented validation in which valuation products are tested against observed policy actions or investment choices rather than internal accuracy alone; and institutionalize openness via versioned code, STAC-indexed assets, and public "model cards" that document assumptions and uncertainty. Coupled with equitable partnerships in data-poor regions and periodic re-estimation as new sensors and prices arrive, these practices can convert scalable maps into credible, auditable inputs for zoning, restoration prioritization, and climate-biodiversity finance, thereby closing the long-noted gap between descriptive assessment and policy uptake.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Chengyan Gu is an employee of Industry Development and Planning Institute, National Forestry and Grassland Administration, Beijing 100010, China; Zhihui Wang is an employee of Zhejiang Yuanzhuo Technology Co., Ltd., Hangzhou 310000, China. The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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