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Review

Evolving approaches and data availability for understanding the impact of land-use change on ecosystem services

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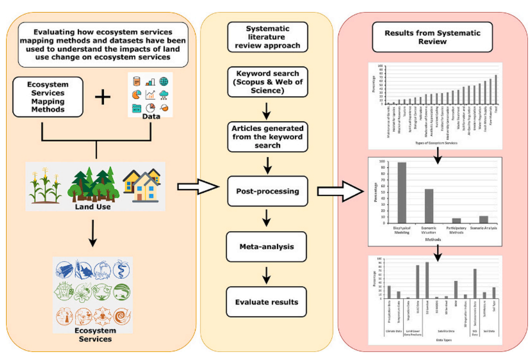
HIGHLIGHTS

- Maps 23 distinct types of ecosystem services across global studies
- Asia (especially China) leads with 51 % of the case studies
- Biophysical models in 98 % and economic valuation in 55 % of reviewed studies
- Machine learning in 27 % of studies enhanced mapping of cultural services

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding how land-use change alters the flow of ecosystem services is critical for sustainability policy and planning. We conducted a systematic review of 459 peer-reviewed articles published between 2001 and March 2024 to (a) catalogue which ecosystem services have been studied and their geographic distribution, (b) trace methodological innovations in mapping, and (c) assess the integration of emerging data streams. Our analysis identified 23 ecosystem services spanning provisioning (food, water, raw materials), regulating (climate regulation, erosion control, flood protection), and cultural (recreation, aesthetics), with provisioning services most often mapped individually but regulating services dominating in category-level assessments. Regionally, Asia (especially China) contributed over half (51 %) of the case studies, while case studies in Europe, Africa, and the Americas are also increasing, aided by international collaborations in nearly 30 % of the studies. Biophysical modeling (98 % of papers) and economic valuation (55 %) remain foundational, supplemented by scenario analysis (11 %), participatory mapping (8 %), and a growing adoption of machine-learning techniques (27 %). Data diversity has expanded beyond Landsat (used in 90 % of studies) and land-cover products (84 %) to include Sentinel, Moderate Resolution Imaging Spectrometer (MODIS), elevation and topographic data, climate grids, soil moisture, and citizen-science platforms. Despite advances, persistent uncertainties arise from scale

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mismatches, data proxies, and model rigidity. We highlight emerging ensemble and hybrid approaches that blend advanced analytics with local knowledge, and call for capacity building in data-scarce regions. These directions promise more accurate, equitable, and actionable assessments to guide nature-based land-use decisions-makings.

1. Introduction

Land-use change from agricultural expansion and urban sprawl to deforestation has negatively affected key ecosystem services across the globe (Athukorala et al., 2024; Belay et al., 2022). By replacing forests and wetlands with croplands or urban infrastructure, we have weakened nature's capacity to regulate climate, clean water, control soil erosion, and supply food (Ocloo et al., 2024; Sannigrahi et al., 2018). A 4 % rise in global deforestation in 2022 compared to previous years reduced carbon sequestration in the biosphere by accelerating atmospheric CO_2 accumulation and amplifying climate warming (Japelaghi et al., 2022; Zhang et al., 2023). In China's Yangtze River Delta, for example, agricultural fields were shown to deliver lower carbon and water-regulating services compared to adjacent natural forests (Tao et al., 2018). In tropical regions such as the Amazon and Congo Basin, heavy rains interacting with land-use change exacerbate soil erosion and nutrient loss (Lhoest, 2020). This reduces agricultural yields and overloads waterways with fertilizer runoff that triggers eutrophication in waterways (Machado et al., 2019; Zhou et al., 2019). Such widespread declines in ecosystem services underscore the urgent need for comprehensive insights into how land conversion alters nature's benefits to people (Peng et al., 2020).

To quantify these impacts, researchers have developed a suite of mapping approaches spanning biophysical, scenario-based, economic valuation, and participatory methods (Asante-Yeboah et al., 2024; Thorn et al., 2017). Biophysical models characterize the spatial distribution and quality of services, while scenario analyses explore how decision-making and subsequent future land use trajectories might reshape ecosystem functions and related services (Assennato et al., 2022; Vermaat et al., 2020). Economic valuation converts service flows into monetary units for direct comparison with other economic activities, and participatory mapping integrates local perceptions often overlooked by purely statistical models (Marino et al., 2023; Pullanikkatil et al., 2016). These frameworks are operationalized through toolboxes such as the Integrated Valuation of Economic Services and Tradeoffs (InVEST) which fuses biophysical modeling and scenario analysis with economic metrics across terrestrial, freshwater, marine, and coastal realms (Elliot et al., 2020; Kertész et al., 2019). The Soil and Water Assessment Tool (SWAT) which specializes in watershed-scale hydrology (Khan et al., 2019; Wang et al., 2022), and the Artificial Intelligence for Environment and Sustainability (ARIES) which leverages artificial intelligence to synthesize diverse data streams into holistic service assessments have all been used in environmental monitoring (Martínez-López et al., 2019; Mayer et al., 2022). These diverse tools enable researchers to apply different mapping approaches depending on their specific research objectives and the socio-ecological context, providing scientifically robust frameworks for understanding how land use changes affect the provisioning of ecosystem services.

Despite these advances, significant challenges persist. Studies disproportionately address provisioning and regulatory services, whereas cultural services such as recreation and aesthetic values remain under-researched due to their often intangible and subjective nature (Xin et al., 2023; Zhang et al., 2015). Methodological heterogeneity in assessment frameworks, temporal scales, spatial resolutions, and valuation metrics hampers synthesis across studies (Calzolari et al., 2016; Englund et al., 2017). Monetary valuations are especially difficult to assess when services lack clear market proxies, leading to inconsistent results (Cabana et al., 2020), and even technical indicators for the same service vary widely between studies and locations (Miedema Brown and Anand, 2022). Data constraints further amplify uncertainties, as reliance on indirect proxies, uneven spatial resolution, and a lack of temporal profiles mean that most analyses offer snapshots rather than long-term trends (Almeida et al., 2024; Haas and Ban, 2017). Geographic biases compound these gaps, with Africa, South America, and Southeast Asia remaining data-scarce relative to well-monitored developed areas. This is particularly problematic as these regions often encompass the world's highest concentrations of biodiversity and globally critical ecosystem services, such as carbon storage, which directly underpin millions of livelihoods (Radeloff et al., 2024). Consequently, tradeoffs and synergies among services across different contexts are poorly understood (Dade et al., 2019; Petroni et al., 2022).

Emerging data sources and computational techniques have shown promise in bridging these gaps. High-resolution remote sensing, open-access global datasets, and machine-learning algorithms can advance biophysical models and extend service mapping into traditionally data-poor landscapes (Arunyawat and Shrestha, 2018; Shoyama and Yamagata, 2014). Although InVEST is applicable to data-rich regions (Assennato et al., 2022; Xiao et al., 2023), artificial intelligence and big-data frameworks now offer pathways to generate novel observations and reduce uncertainty in both data-poor and data-rich contexts (Hoque et al., 2020; Thorn et al., 2017). The use of ensemble approaches, where the results of many models are used to define a range of possible outcomes to reduce uncertainty, has improve predictive robustness in ecosystem services assessments (Lu and Li, 2024). By leveraging statistical techniques that integrate diverse datasets and algorithms such as decision trees, neural networks, and regression models, ensembles produce composite predictions that better capture spatial and temporal variabilities in service provisioning (Chan et al., 2011; Locatelli et al., 2011).

This multifaceted strategy allows researchers to account for a wide range of ecological responses, including species interactions, ecosystem health, and socio-economic impacts, and to guide sustainable land-use practices through scenario analysis (Sun et al., 2017). Furthermore, hybrid approaches extend ensemble methods by formally integrating quantitative and qualitative data, such as local knowledge (Sinare et al., 2016). This creates an iterative process where stakeholder insights directly shape the models, ensuring they reflect on-the-ground realities. Especially useful in data-scarce regions, this co-production of knowledge builds culturally relevant and scientifically rigorous conservation strategies (Li and Wang, 2023). By combining these perspectives, hybrid frameworks enhance scenario forecasting, sharpening our understanding of how land-use choices affect ecosystem services (Stürck et al., 2018; Tao et al., 2018). Together these advanced frameworks can be leveraged to build sophisticated scenario forecasting models, which further refine our grasp of how alternative land-use pathways will influence service dynamics.

Recognizing these advances, we examine the evolving suite of methods and datasets deployed to assess land use change impacts on ecosystem services. Specifically, we aim to: (a) identify which ecosystem services have been studied in recent years, including whether different trends have emerged across different geographic regions; (b) analyze emerging trends in methods used to understand land use change impacts on ecosystem services; and (c) assess whether recent advances in data types and sources are being effectively integrated into current research. By highlighting both progress and persistent blind spots, we seek to guide more equitable, comprehensive, and data-informed analyses of how land use decisions shape the benefits derived from nature.

2. Methods

To catalogue the ecosystem services studied, trace methodological innovations, and evaluate the use of novel data streams, we adopted a multi-phase workflow. First, we conducted a systematic literature search across Scopus and Web of Science database, targeting peer-reviewed articles published between 2001 and March 2024. Following duplicate removal and relevance screening, we distilled the resulting articles to a core set of studies. We then extracted and standardized critical metadata and methodological details into a structured database. Finally, we organized each study's mapping approach into five thematic categories (biophysical modeling, economic valuation, participatory mapping, scenario analysis, and machine-learning applications) to enable a rigorous, comparative analysis of how land-use change impacts on ecosystem services have been quantified and valued.

2.1. Systematic literature search

We carried out a systematic review to synthesize how land-use change affects ecosystem services. Two major citation databases, Scopus and Web of Science were queried with the Boolean string "land AND use AND change OR land AND cover AND change AND ecosystem AND services." We selected these platforms because together they encompass the bulk of peer-reviewed research on our topic. To trace the evolution of ecosystem services mapping, we examined articles published from January 2001 to March 2024. This period spans from the release of the groundbreaking Millennium Ecosystem Assessment (MA) which first globally assessed ecosystem services to the modern era of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), a permanent body whose mission is to connect science and policy for conservation. Our initial query returned 12,718 records from Scopus and 202,253 from Web of Science. To avoid over-representing one database, we extracted the top 350 most relevant articles from each source, 700 in total, based on each database's internal relevance ranking. All records were imported into Mendeley Reference Manager, where we removed 164 duplicates. The remaining 536 unique articles underwent title and abstract screening against our inclusion criteria: original, empirical studies of land use/land cover change impacts on ecosystem services. We excluded reviews, conference proceedings, and book chapters, eliminating 77 additional records. The final outcome comprised of 459 peer-reviewed articles. Fig. 1 depicts the methodological workflow for the review. Our workflow mirrors best practices in systematic reviews (Ayompe et al., 2021; Manley et al., 2022a).

2.2. Data capture and analysis

We developed a structured spreadsheet to systematically extract and harmonize key metadata and methodological details from each of the 459 selected articles. For every study, we recorded the lead author's name, their institutional affiliation country, the geographic focus of the research, and the year of publication to allow temporal trend analysis. We then catalogued the ecosystem service categories and specific service types addressed, ranging from carbon sequestration and water regulation to soil retention and recreational values and noted the original classification framework used by each paper. To facilitate cross-study comparisons, we used the IPBES system of material, non-material, and regulating contributions, which offers a comprehensive, people-centered perspective on nature's benefits (Tengö et al., 2017). Next, we captured the principal mapping methods and software tools such as InVEST, SWAT, and ARIES alongside the data inputs and sources employed (for example, remote sensing layers, in-situ measurements, and socio-economic statistics). We also documented the spatial scale and resolution at which each study was conducted (from catchment-level analyses to national assessments) and the temporal scope, distinguishing between single-year snapshots and multi-year trend evaluations. Finally, we recorded whether and how studies incorporated valuation, either in biophysical units or monetary terms to reflect human benefits that may not directly transact in markets. We then classified each paper's mapping approach into one of five detailed categories:

Biophysical modeling: This approach entails process-based and spatially explicit simulations such as SWAT's watershed hydrology modules, InVEST's carbon-flux and water-yield models, or dynamic vegetation models that quantify ecosystem functions in physical units (e.g., tons of carbon sequestered, cubic meters of runoff).

Economic valuation: Encompasses both market-based and non-market techniques such as cost–benefit analyses, hedonic pricing, market-price methods to contingent valuation and benefit-transfer approaches that convert service flows into monetary metrics for direct comparison with other economic activities.

Participatory mapping: Integrates community and stakeholder knowledge through tools like participatory GIS, focus-group mapping exercises, and structured interviews, capturing cultural, recreational, and aesthetic services that resist purely quantitative measurement.

Scenario analysis: Employs land-change projection models (e.g., CLUE-S, Land Change Modeler) and integrated assessment frameworks built on socioeconomic storylines or climate scenarios, exploring how alternative land-use pathways might reshape service bundles and their trade-offs over time.

Machine learning: (advanced computational techniques used to analyze complex datasets and identify patterns that may be difficult to discern through traditional methods). This was to identify the different articles that incorporated machine learning into their study. While there was an overlap between machine learning and other methods, we decided to keep this as a separate class to highlight how ecosystem mapping methods have evolved over the years.

3. Results

Drawing on 459 peer-reviewed studies published from 2001 through 2024, this section distills the evolving landscape of land use change and ecosystem services research. We begin by characterizing which services researchers have mapped, how attention to provisioning, regulating, and cultural services has shifted over time, and where on the globe these analyses are concentrated (Section 3.1). We then examine the methodological toolkit spanning biophysical modeling, economic valuation, scenario analysis, participatory mapping, and the growing role of machine learning, and how these approaches have been combined and applied across service categories (Section 3.2). Finally, we assess the data foundations underpinning these studies, detailing the climate, land cover, remote-sensing, socioeconomic, and soil datasets and their sources, and tracing how data diversity has expanded over our review period (Section 3.3).

3.1. Ecosystem service types, temporal and spatial trends

We found 23 distinct types of ecosystem services evaluated in the studies reviewed, spanning material services (e.g., food and water supply), regulating services (e.g., climate regulation, erosion control), and non-material services (e.g., recreation, tourism). The most frequently mapped ecosystem service types were: food provisioning (76 % of studies), raw-material extraction (66 %), and water provision (61 %). By contrast, habitat provisioning (5 %) and maintenance of genetic-diversity (3 %) received scant attention (Fig. 2).

When recast into the IPBES framework, regulating services were the most frequently assessed category (92 % of articles), followed by material services (85 %), while non-material or cultural services were less frequently assessed (66 %). The percentages are not mutually exclusive, as a single article may assess multiple service categories (Fig. 3). Evaluating the annual distribution of each ecosystem service category

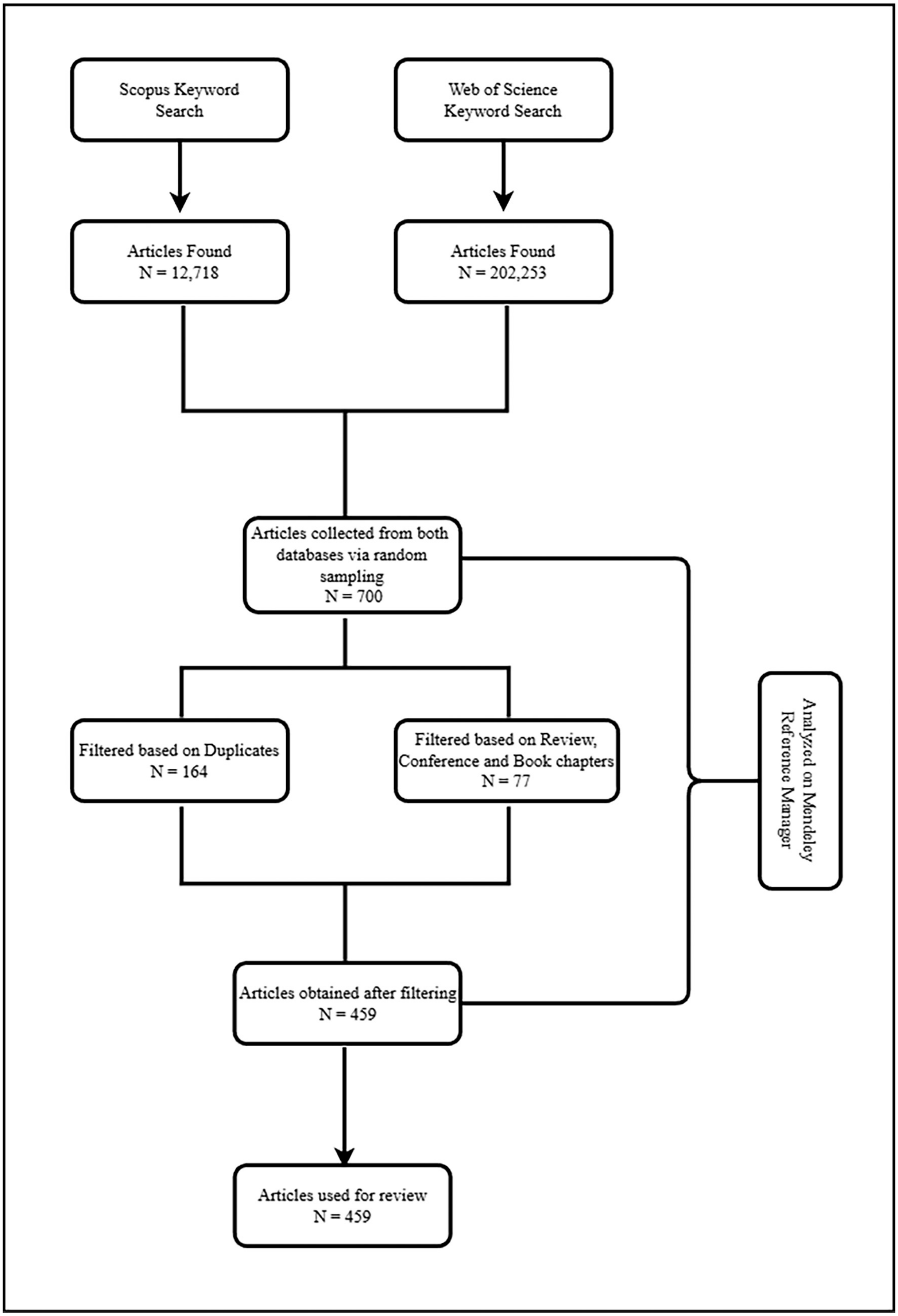

Fig. 1. Flowchart highlighting the steps used in the systematic review.

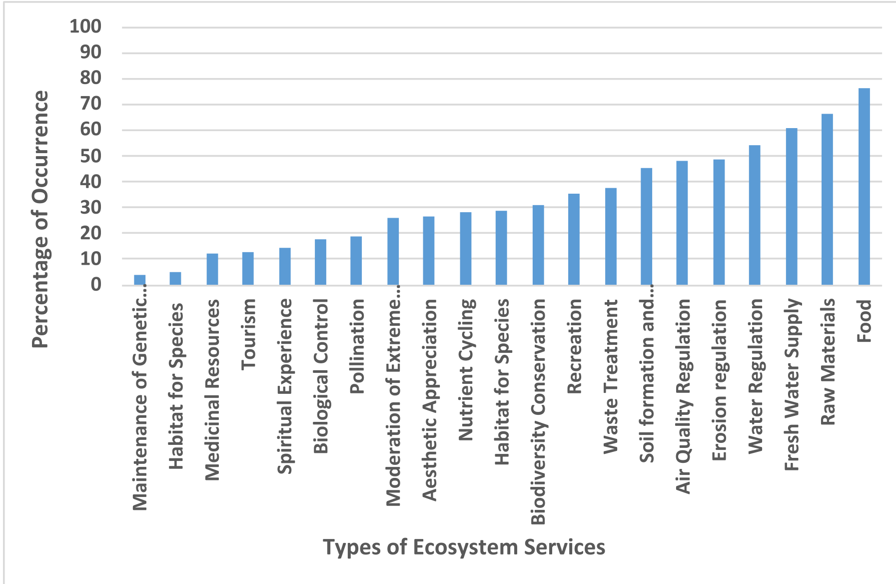

Fig. 2. Percentage of studies referencing specific ecosystem services types in the reviewed literature from 2001 to 2024 ($n = 459$).

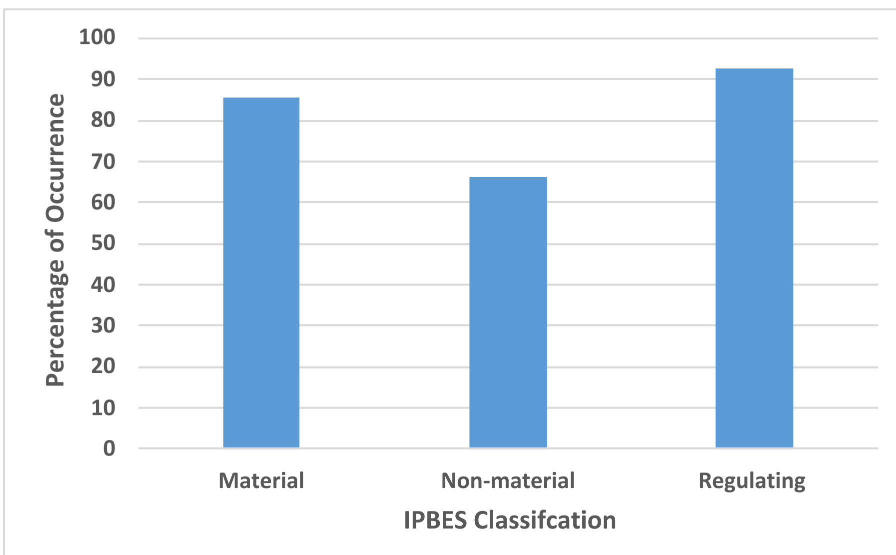

Fig. 3. Percentage of Reviewed Articles (n = 459) Addressing IPBES Ecosystem Service Categories (2001–2024).

showed that material services studies dominated the earliest research, comprising 100 % of publications in 2001 (based on the single paper captured that year). Over time, their prevalence fluctuated, declining to a low of 27 % in 2009 before rising to 46 % in 2012. Meanwhile, cultural services peaked at 33 % of studies in 2004–2005 and again in 2007 but then dropped sharply to 18 % in 2011. Interest in them resurged in later years, with cultural services returning to a peak of 33 % in both 2020 and 2022. Regulating services grew significantly between 2011 and 2015, accounting for 43–50 % of annual publications. Despite this upward trend, their share temporarily dropped to 26 % in 2012, which coincided with the rebound in material-service studies that same year (Fig. 4).

Our review also mapped where these studies were conducted, revealing work across 57 countries but with a heavy concentration in just a few. Studies led by lead authors from China accounted for 51 % of the sample, followed by Ethiopia (5.5 %) and the United States (4.5 %) (Figs. 5 and 6). In contrast, studies led with authors from Austria, Costa Rica, Morocco, Turkey, and Botswana each contributed just 0.3 %. To evaluate the extent of research being conducted by researchers from a country, other than where the institution was based, we compared lead authors' institutional countries with their study locations (Fig. 7) and found that 17 of the 57 nations (29 %) featured analyses taking place outside of their home country. Chinese institutions led this trend with 21 externally focused or global studies (but these represented just 10 % of its total studies given its large output); Algeria's entire research output consisted of 5 studies all focused in Europe. Germany had 46 % contribution to international studies (5 of its 13 studies), while the United Kingdom had 45 % contribution to international research (5 of 11 studies). The United States had 21 % contribution to international studies (3 of its 19 studies).

3.2. Ecosystem services mapping methods

Our review identified four principal mapping approaches across the

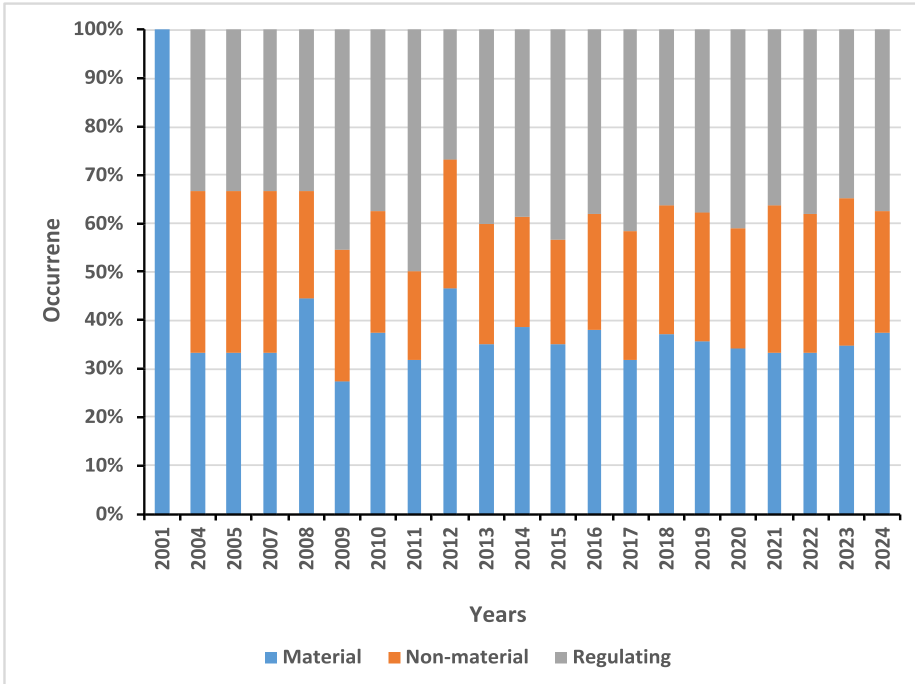

Fig. 4. Yearly Distribution of IPBES Ecosystem Service Categories in Reviewed Literature (n = 459).

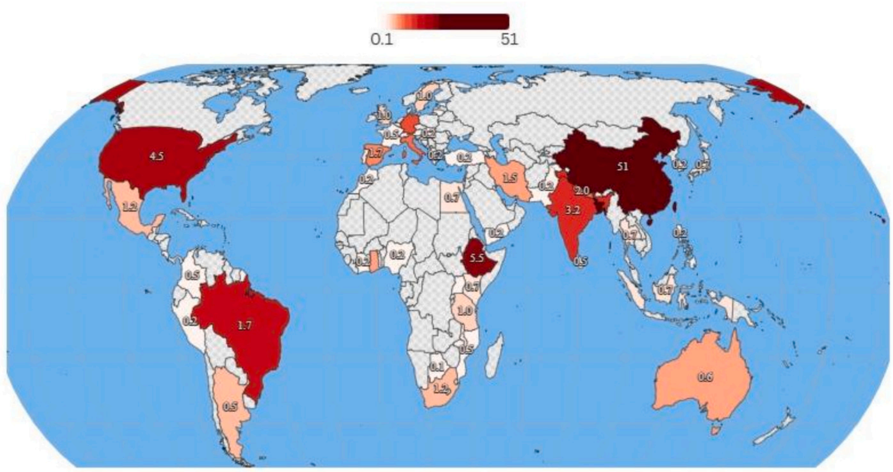

Fig. 5. Spatial distribution of ecosystem services studies for first author geographic origin.

459 articles: biophysical modeling, economic valuation, scenario analysis, and participatory methods (Fig. 8). Biophysical models dominated, appearing in 98 % of the studies, followed by economic valuation in 55 %. Scenario analysis featured in 11 %, while participatory mapping was the least common at 8 %. Machine learning (ML) techniques were incorporated in 27 % of studies, with the use of ML growing steadily since it first appeared in our sample in 2009 (Fig. 9). By 2022, nearly one-quarter of papers (24 %) employed ML. A diverse suite of algorithms underpins this trend: Random Forests was the most widely used algorithm (33 % of ML-enabled studies), followed by Artificial Neural Networks (17 %) and Multi-Layer Perceptron (15 %). Less frequent were Naïve Bayes classifiers (3 %) and k-Nearest Neighbors (1 %) (Fig. 10). Authors typically layered ML predictions atop biophysical or scenario models to boost accuracy and reduce uncertainty (Mienye et al., 2024).

Integration of multiple mapping methods emerged early: dual-method studies have been employed since 2001, and by 2009 a handful of papers combined three or more approaches in a single analysis (Fig. 11). Prior to 2008, research relied primarily on biophysical approaches (55 % of that period's studies) and economic valuation (45 %), with scenario and participatory methods gaining traction by 2011. When we examined the methods used across ecosystem service categories (provisioning, regulating, and cultural), biophysical modeling and economic valuation approaches proved the most versatile, covering 25–60 % and 22–32 % of category-specific studies, respectively (Fig. 12). Scenario analysis and participatory mapping accounted for only 2–5 % of studies within any service group.

3.3. Datasets and sources in ecosystem services mapping

Mapping ecosystem services depends on a combination of input data spanning climate, land cover, remote sensing, socioeconomic, and soil information (Fig. 13). In terms of climatological data, precipitation data were most widely used (32 % of studies), followed by temperature (18 %). The land cover class was dominated by land use/land cover (LULC)

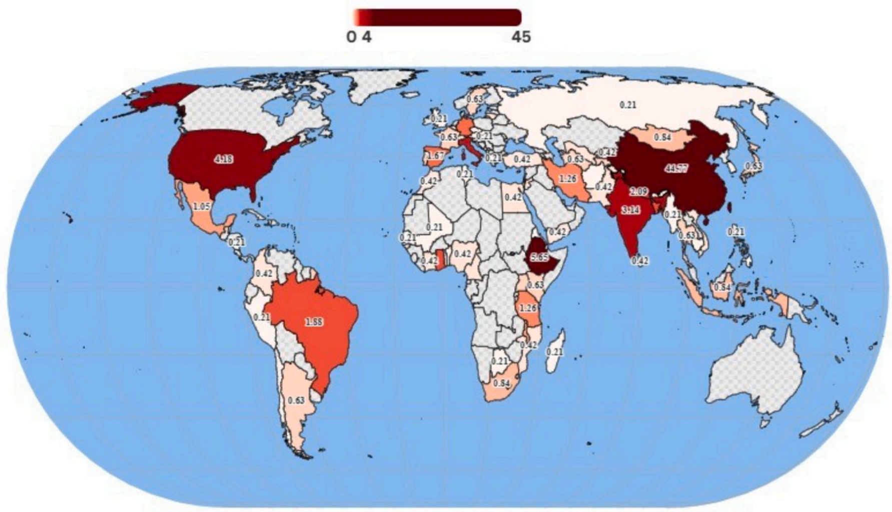

Fig. 6. Spatial distribution of study regions for the different ecosystem services and their percentages captured in the review.

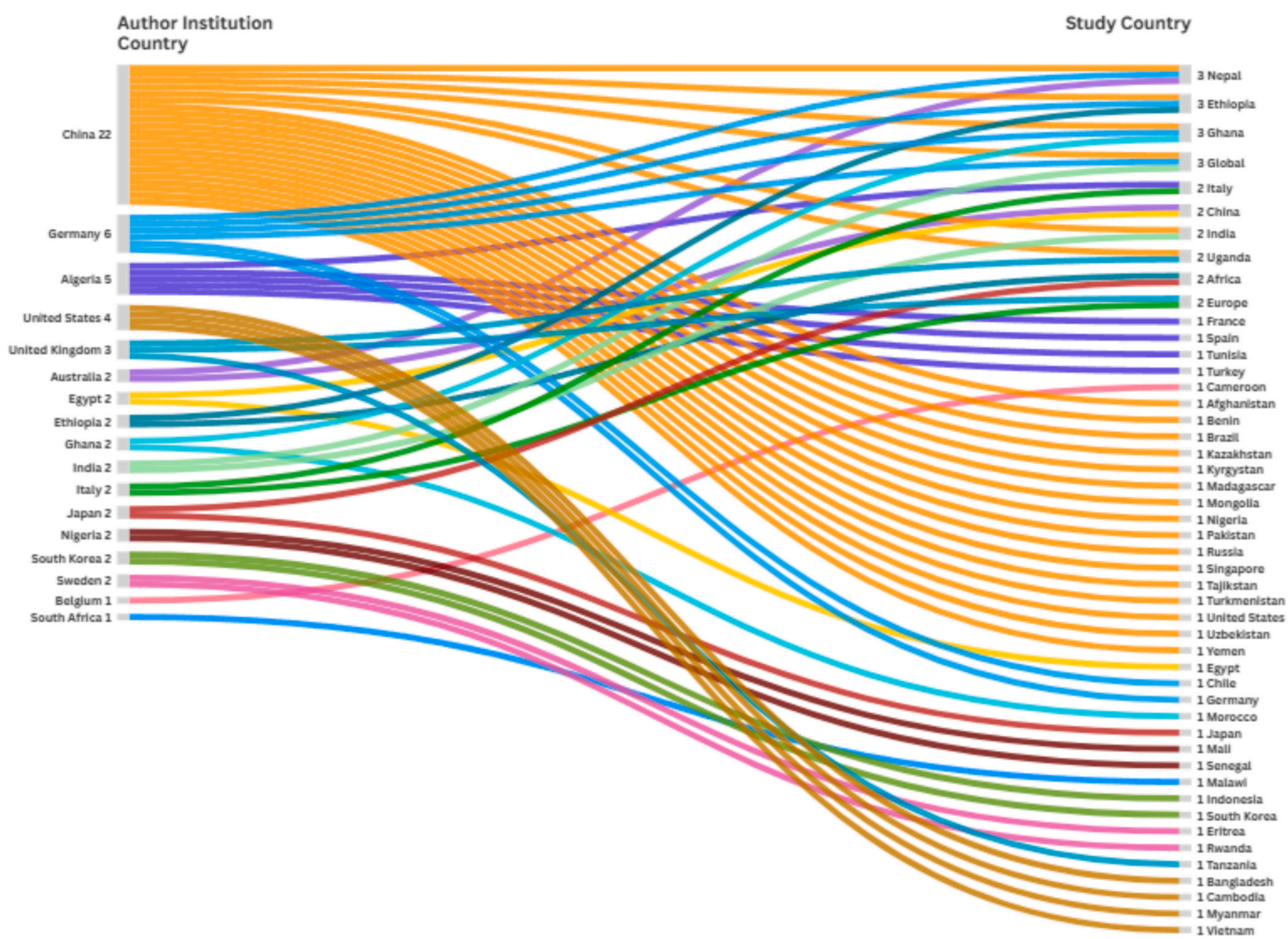

Fig. 7. Geographic Connections in Ecosystem Services Research: Lead Author Institution Country to Study Country. This Sankey diagram illustrates the geographic connections in ecosystem services research, showing the flow of studies from the lead author's institutional country (left) to the primary study country (right). The width of the bands is proportional to the number of studies, representing the exact count for each institution-to-study country pair. The numbers displayed adjacent to the country names in this figure represent the total count of studies where that country served as either the lead author's institution base or the study's geographic focus as depicted in this diagram. It is important to note that this visualization highlights major flows and connections, and thus the sum of the numbers directly labeled on the diagram's nodes does not represent the full total of 459 viewed articles.

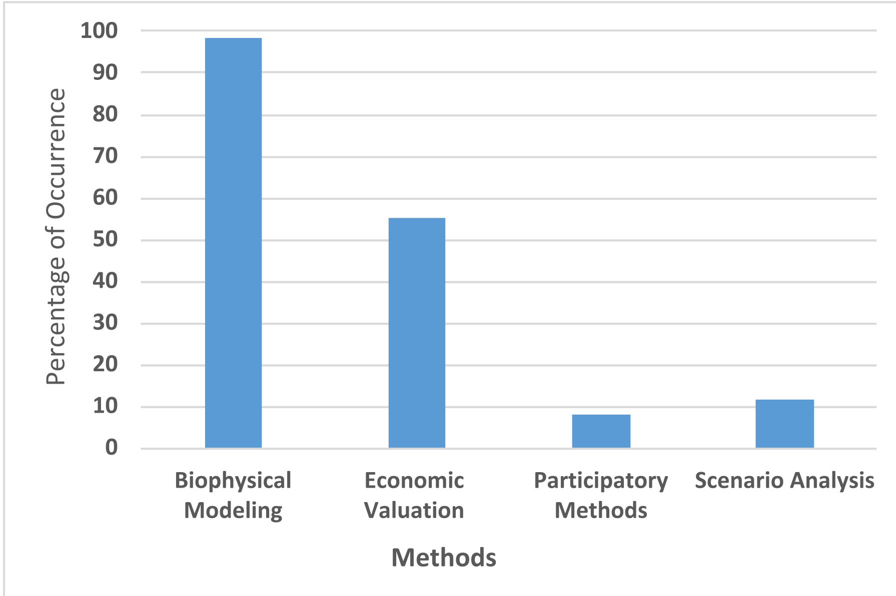

Fig. 8. Percentage distribution of the different mapping methods captured in the review.

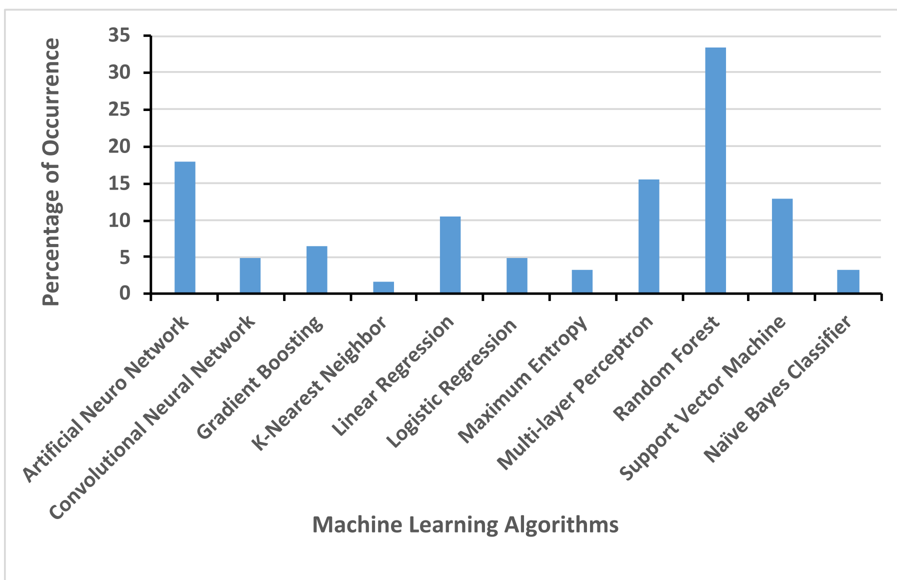

Fig. 9. Percentage distribution of machine learning algorithms captured in the review.

products (84 %), which are typically derived from remote sensing but analyzed here as distinct thematic inputs given their direct relevance to ecosystem service models. Standalone vegetation metrics (such as Normalized Difference Vegetation Indices and Enhance Vegetation Indies) appeared less frequently. For direct remote sensing inputs, Landsat imagery had the highest occurrence (90 %), followed by digital elevation models (DEMs, 43 %), with MODIS, Sentinel missions, and derived vegetation indices playing smaller roles. Socioeconomic datasets such as population density and market-value statistics from sources like the Food and Agriculture Organization (FAO) data portal and World Health Organization (WHO) featured prominently (21 and 6 % respectively), reflecting growing interest in human–environment interactions. Soil datasets such as soil types (28 %) and soil-moisture (16 %) were also moderately used in the review.

Temporal trends highlight an increasing diversity of data types from 2001 to 2024 (Fig. 14). In the early period (2001–2007), studies distributed their inputs evenly among LULC products, Landsat imagery, and socioeconomic data (each 33.3 %). The middle phase (2008–2015) ushered in diversification of data types: precipitation, DEMs, temperature, and Sentinel each featured in 5–10 % of papers, as reliance on socioeconomic data (4 %), LULC (6 %) and Landsat (9 %) was reduced. The most recent years (2016–2024) show an increase in methodological sophistication, with individual studies integrating up to eleven distinct data types (Fig. 14). Notably, a diverse range of inputs including MODIS, soil-moisture, soil-type, vegetation indices, and hydrologic datasets collectively accounted for 10–15 % of the data used in the studies, highlighting the field's expanding data palette.

Regarding data source, approximately 90 % of studies draw on the United States Geological Survey (USGS) Platform, encompassing datasets such as satellite imagery (e.g., Landsat), DEMs, and hydrological data (Fig. 15). Simultaneously, 70 % of papers augment these broad-scale sources with locally generated datasets. Among international

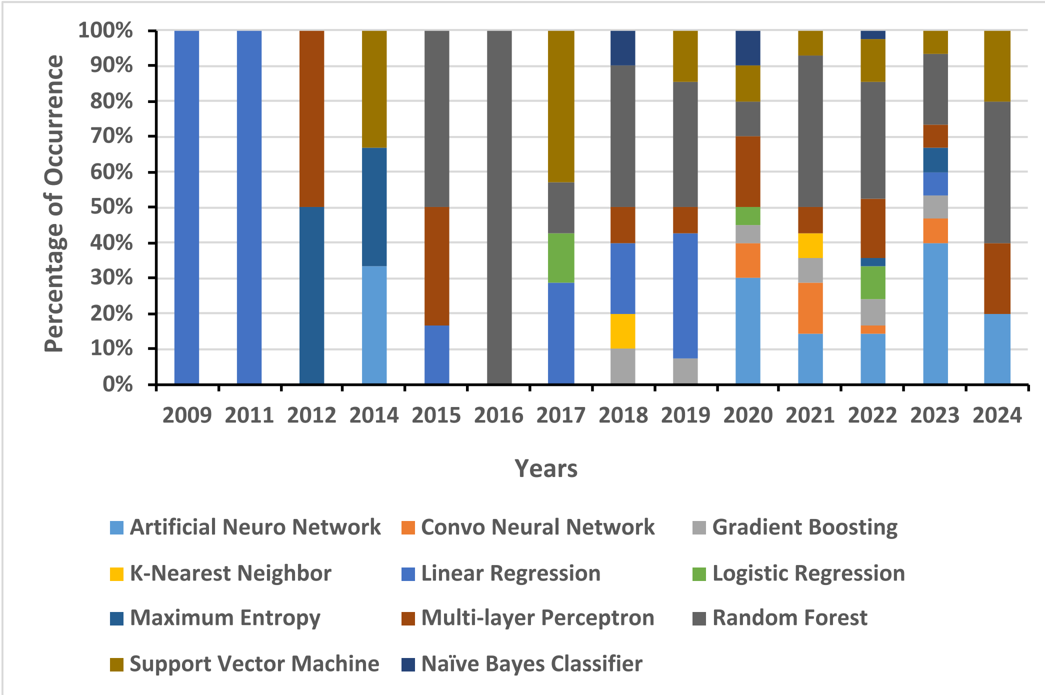

Fig. 10. Evolution of machine learning algorithms captured in the review.

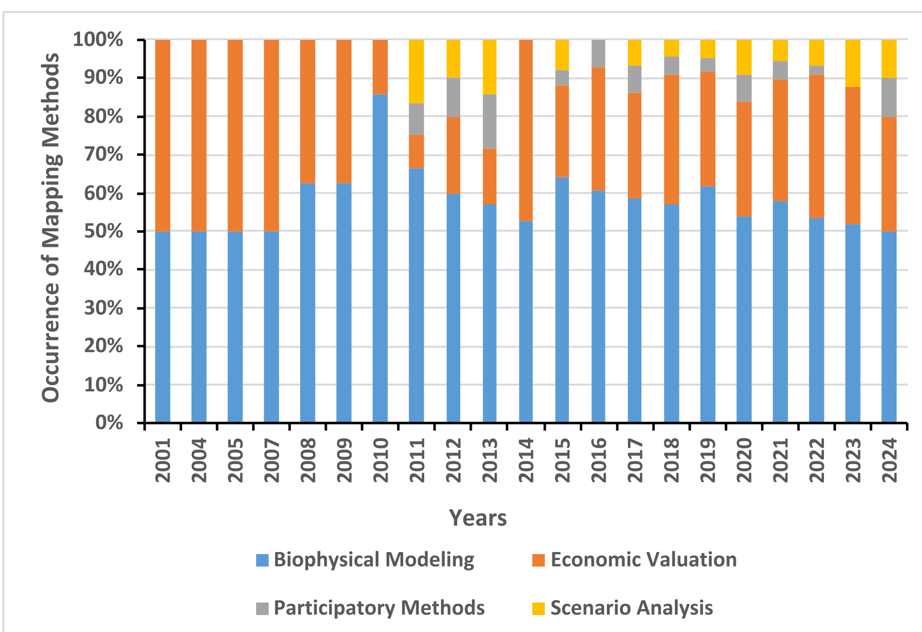

Fig. 11. Evolution of mapping methods over the years captured in the review.

repositories, the FAO supplies about 21 % of data types, while WorldClim underpins 20 % of high-resolution climate variables. Other noteworthy, albeit less common, sources include the European Space Agency's (ESA) Copernicus program (8 %), the WHO data portal (5 %), and Global rainfall archives (3 %).

4. Discussion

In this study, we sought to understand the evolution of approaches and data that have been utilized by different researchers across the globe to understand the impacts of land-use change on ecosystem services modeling. In addition, we assessed where the expertise is in relation to the ecosystem services mapped.

4.1. *Studies of ecosystem services and their distribution*

Ecosystem services research has greatly expanded over the past two decades, documenting 23 distinct service types ranging from genetic-diversity maintenance and medicinal resources to tourism, waste treatment, erosion control, climate regulation, and food provision (Fig. 2). This breadth reflects an evolving consensus that ecosystems deliver a tapestry of material and non-material benefits critical for

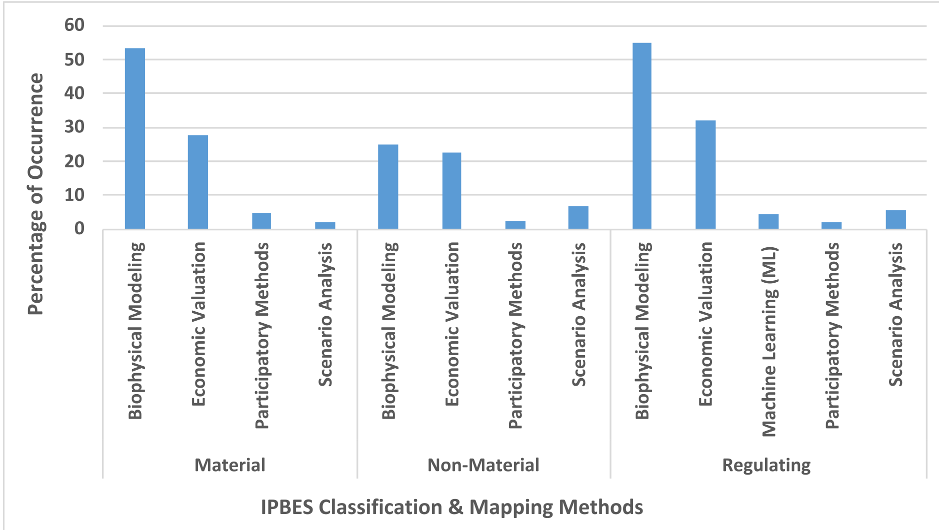

Fig. 12. Efficiency of mapping methods used in mapping the different ecosystem categories.

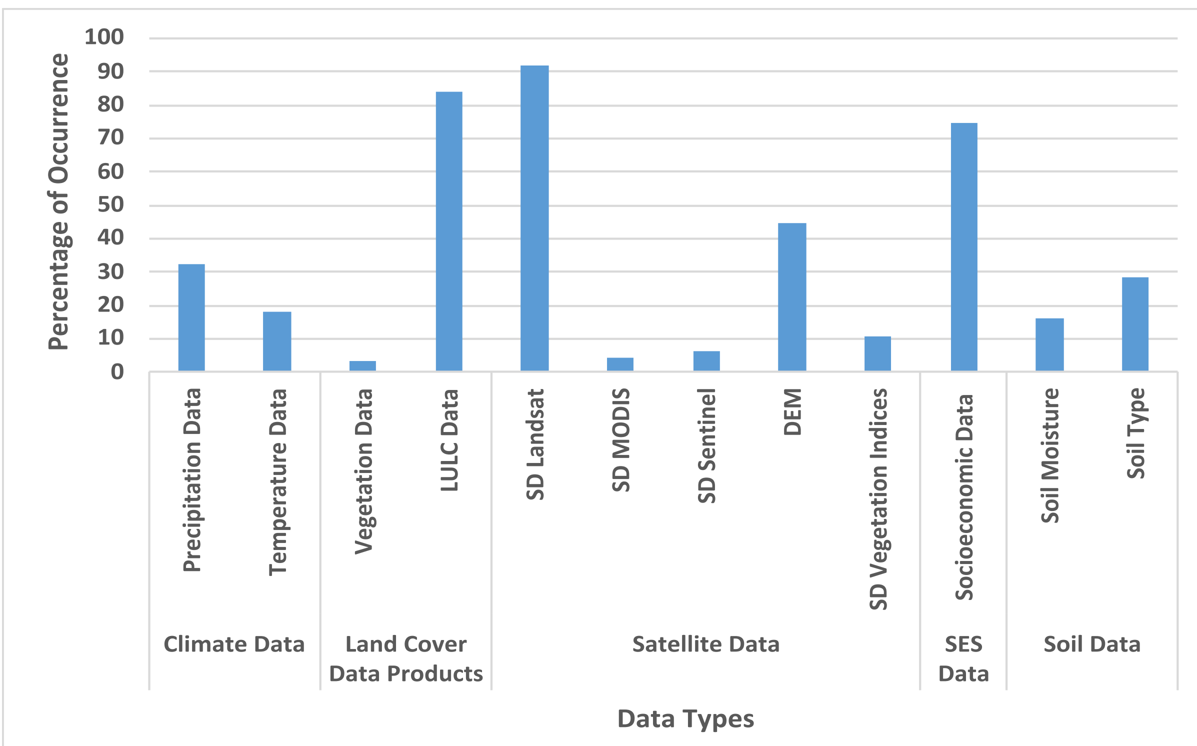

Fig. 13. List of data types captured in the review.

evidence-based decisions at all governance levels (Cortés-Calderón et al., 2021; Tolessa et al., 2017). Although material services such as food and water supply dominate individual service counts, regulatory services, particularly water purification, carbon sequestration, and pollination emerge as the most frequently studied category under the IPBES framework (Fig. 3). This underscores their central role in maintaining a healthy ecosystem (Ma and Zhang, 2023; Yang et al., 2024). Yet mounting evidence points to troubling declines: the global capacity for ecosystems to regulate climate, water, and floods has declined globally over the years due to intensified exploitation (Chaplin-Kramer et al., 2019). For example, Argentina's Pampas region lost 35 % of its erosion-control service between 2001 and 2018 (Lara et al., 2023). Meanwhile, population growth and economic expansion drive escalating demand for food, water, and timber, further stressing regulatory foundations and cementing material services' prominence in both research and policy (Ankur et al., 2022; Pechanec et al., 2019; Yang et al., 2023).

Although non-material services such as recreation, aesthetic values, and spiritual benefits have received less attention historically, their study has surged in recent years. This shift mirrors a broader understanding that human well-being encompasses both psychological and social dimensions alongside material and regulatory needs (Richards and Friess, 2015). Research now links biodiverse green spaces to improved mental health, reduced stress, and stronger community bonds

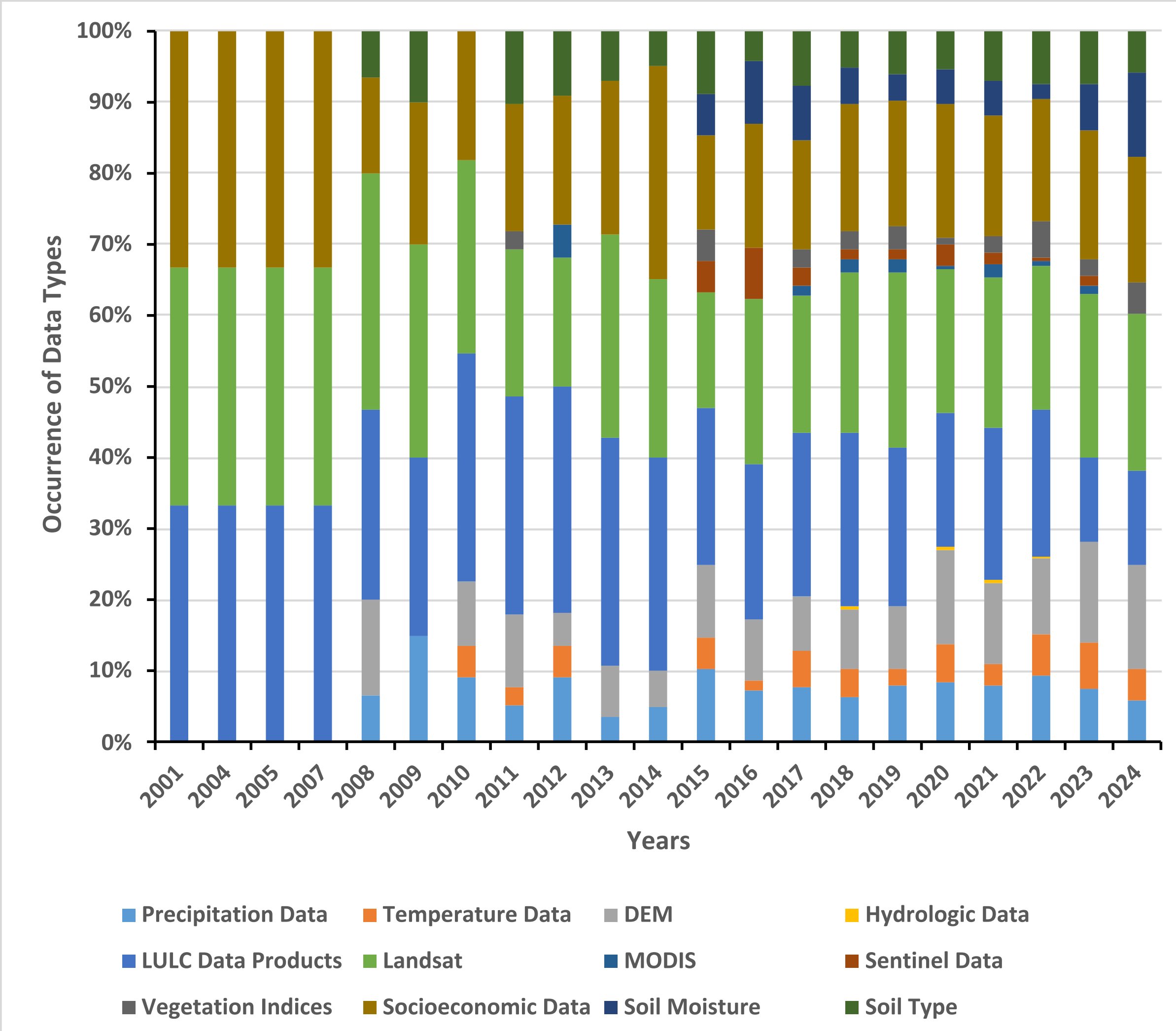

Fig. 14. Evolution of data types used use in the review from 2000 to 2024.

(Fomba et al., 2024; Lonsdorf et al., 2021). Moreover, the rise of ecotourism and nature-based recreation highlights the demand for these intangible benefits and spurs their inclusion in management frameworks (Eekhout et al., 2020). Crucially, all service categories are interdependent: regulating functions like erosion control underpin soil fertility for food production, yet deforestation for agriculture undermines those very controls. Similarly, vibrant recreational landscapes depend on intact regulatory and provisioning systems. Recognizing these synergies and trade-offs calls for both integrated analyses and methods that confront this interconnectedness and integrated policies that safeguard the entire spectrum of ecosystem benefits and prevent cascading service losses (Makwinja et al., 2022).

Geographically, China in particular dominates the ecosystem-service literature, accounting for over half of the case studies we reviewed (Figs. 5 and 6). This focus reflects strong government investment in environmental science, alongside rapid land-use changes driven by economic growth, and a large resource-dependent populations (Li et al., 2019). The identification of locations with high and low delivery of ecosystem services is critical to China's *Master Plan for National Key Ecosystem Protection and Restoration Major Projects*, a roughly $400B plan for ecosystem service improvement nationwide between 2021 and 2035 (Sino-German Environmental Partnership, 2020). Substantial funding, dedicated research centers, reporting requirements, and strong academic collaborations between different government ministries have vastly expanded China's domestic capacity for ecosystem-service mapping (Riao et al., 2020; Wang et al., 2015).

Under the *Master Plan* policies such as the Ecological Redline Mandate require detailed assessments of water regulation and soil conservation to delineate protected areas (Peng et al., 2020). Similarly, urbanization pressures across Asia have spurred studies on flood regulation and carbon sequestration to guide risk mitigation (Deng et al., 2021). Europe has also leveraged ecosystem services mapping to guide land-use decisions. For example, Schirpke and Tasser (2021), quantified 19 services across 52 Alpine ecoregions to reveal shifting supply trends, while Haines-Young et al. (2012) produced continent-wide indicators of service potential and land-use impacts for 27 nations. In Central America, Tobar López et al. (2022) combined biophysical quantification with economic valuation, drawing on satellite imagery and socioeconomic datasets to chart how provisioning, regulating, and cultural services have evolved over time.

In Africa, researchers have increasingly spotlighted the continent's critical role in global and local ecosystem functions. Egoh et al. (2012) demonstrated the importance of carbon sequestration and water regulation in governance frameworks is essential for sustainable outcome. Similarly, Zhou et al. (2014) showed that the Congo Basin forests are critical for providing services such as biodiversity, carbon, and water regulations. Fenta et al. (2020) applied benefit-transfer methods to reveal the substantial economic losses from land degradation in the

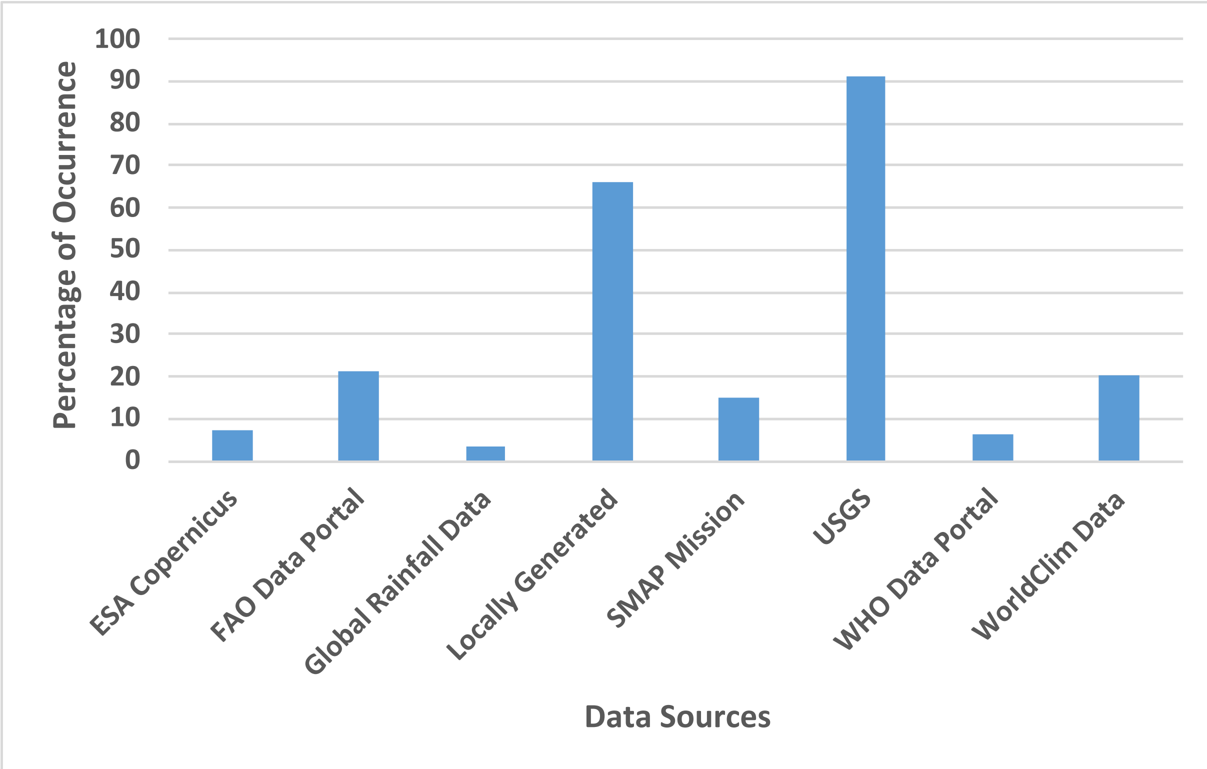

Fig. 15. Distribution of data sources captured in the review.

Sahel and Horn of Africa, while Tiando et al. (2021) assessed threats (such as pollution, acidification and unsustainable fishing) to coastal services in West Africa to inform sustainable management. Our analysis also highlights a surge in geographically diverse research: nearly 30 % of lead authors studied ecosystems beyond their home countries, reflecting an expanding international scope of work. Partnerships led by institutions in China, Algeria, Germany, the U.S., and the U.K. have spurred both biophysical modeling and monetary valuation across diverse contexts (Bryan et al., 2018; Song and Deng, 2017; Temesgen et al., 2018). These efforts are underpinned by targeted funding for understudied regions, capacity-building programs, and interdisciplinary networks (Abd El-Hamid et al., 2022; Li et al., 2022). Moreover, integrating local ecological knowledge through participatory frameworks has proven essential in data-scarce landscapes, reinforcing the value of collaborative, mixed-method approaches (Díaz-Reviriego et al., 2019).

More than half of our studies were from China which represents a biased toward Asia. This is partly because China has been in the forefront of ecosystem services studies, and this trend continues as new environmental laws favors quantifying and valuing ecosystem services for restoration and conservation programs (Liu et al., 2023). This pattern continues as seen in (Manley et al., 2022), in the use of machine learning in mapping ecosystem services where most of the studies and experts were from China. However, although their methods used might be similar, their drivers of ecosystem change (e.g., rapid urban expansion, intensive irrigation) and resulting ecosystem services trade-offs may not reflect conditions in regions such as sub-Saharan Africa or South America (Naidoo et al., 2008; Sutton et al., 2016). In terms of methods, machine learning offers an opportunity that can work well with limited information irrespective of the region. For hydrological studies, we can use regional calibration techniques that take data points from well monitored river basins (gauged watersheds) to improve prediction across the whole region (Auerbach et al., 2016). We can also adapt GIS-based ecosystem services flow mapping, incorporating locally calibrated land-cover scoring to accommodate varying data quality and ensure robustness when transferring models to under-monitored landscapes (Vrebos et al., 2015).

4.2. Ecosystem services mapping methods

Four primary approaches have come to define how researchers map ecosystem services worldwide (Fig. 8): biophysical modeling, economic valuation, scenario analysis, and participatory mapping. Biophysical models implemented in tools like InVEST, SWAT, and ARIES, simulate key functions (carbon storage, water yield, habitat quality, erosion rates) in physical units, offering transparent spatial outputs. For example, (Blumstein and Thompson, 2015) used InVEST to pinpoint hotspots and cold-spots of habitat provisioning, carbon sequestration, water provisioning, and flood regulation. Economic valuation then builds on these biophysical estimates, employing methods such as contingent valuation, benefit transfer, or market-price analyses to assign monetary values to services like pollination, erosion control, or waste treatment, thereby strengthening the economic case for conservation (Mathewos and Aga, 2023; Ureta et al., 2021).

Scenario analysis adds a forward-looking dimension by comparing how alternative land-use pathways, ranging from conservation-oriented to development-driven, affect ecosystem outputs over time. Studies have applied this lens to forecast changes in sediment retention, nutrient cycling, flood protection, and carbon storage under varied policies or climate scenarios (Leh et al., 2013; Yu et al., 2023). Participatory mapping, while less frequently used, brings in community voices and traditional ecological knowledge to, refine maps of cultural and provisioning services that elude purely quantitative methods (Chettri et al., 2021; Fürst et al., 2011). By integrating local perspectives in the mapping process, participatory approaches not only improve data relevance but also foster stakeholder ownership of conservation and land-use decisions (Huq et al., 2019).

ML techniques have increased in popularity over the past decades for understanding the complex, non-linear linkages between environmental drivers and ecosystem service outcomes, boosting both predictive accuracy and spatial detail. In the realm of non-material services, algorithms like random forests, support-vector machines, gradient boosting, and neural networks are increasingly being adopted to map recreation, aesthetic values, and cultural benefits (Lu et al., 2022; Mugiraneza et al., 2019). These methods detect patterns in high-dimensional datasets, whether combining remote-sensing inputs for water-provision forecasts or by integrating socio-economic data for land-use projections (Fu et al., 2024). Furthermore, Google Cloud Vision's pre-trained models has been used to extract visual features from photographs and predict landscape aesthetics (Gosal and Ziv, 2020). Similarly, convolutional neural networks and computer-vision approaches have similarly unraveled the spatial distribution of recreational hotspots, linking landforms and biodiversity to human well-being metrics (Fan et al., 2024; Huai et al., 2022; Nyelele et al., 2023).

Beyond non-material services, ML has also enhanced the mapping of material and regulating services. Hybrid frameworks such as coupling Random Forests models with Markov chains have been used to forecast the distribution and efficiency of services like raw-material supply, biomass stocks, carbon storage, and flood protection under changing land-use regimes (Krause et al., 2019; Yuan et al., 2021). For example, supervised classification algorithms like the Classification and Regression Tree model have been deployed using Google Earth Engine to accurately detect historical forest loss, a critical determinant of carbon storage and raw material supply; this was then coupled with a Multi-Layer Perceptron and Cellular Automata-Markov Chain hybrid model to project future land-cover transitions in regions like the Cross-Sanaga-Bioko coastal forest, thereby informing sustainable forest management (Epie and Hull, 2025). Cellular automata and multi-layer perceptron models have been used to quantify water purification rates, nutrient retention, sediment trapping, and crop-production potential, shedding light on how land-cover transitions impact ecological resilience (Li et al., 2019; Niquisse et al., 2017).

Integrating ML into scenario-analysis workflows further refines future-service projections: Bayesian networks, gradient-boosted trees, and linear models run on simulated land-use paths to anticipate shifts in biodiversity, water regulation, pollination, and soil formation (Hashimoto et al., 2019; Orna et al., 2021; Vickery and Quinn, 2023). Even participatory mapping has benefited from the rapid uptake of machine learning. For example, computer-vision tools now translate hand-drawn community sketch maps into georeferenced layers, and natural-language processing of interview transcripts helps spatially link local perceptions spatially to mapped service values (Broelemann et al., 2016; See et al., 2016). These advances not only bolster technical rigor but also pave the way for more inclusive, data-rich assessments of how land-use decisions shape the full spectrum of ecosystem benefits. By leveraging artificial intelligence and big-data frameworks, researchers can now integrate a wider variety of information from remote sensing inputs to on-site socioeconomic data to analyze regions that were previously data-poor.

4.3. Data availability

Over the past two decades, ecosystem service mapping has increasingly drawn on a wider array of data sources, yet many regions particularly global south and rural areas remain chronically data-poor (Hemati et al., 2020; Xu et al., 2019). These gaps persist due to uneven infrastructure for remote sensing, sparse ground-truthing, and limited funding for local data collection. Consequently, the research community continues to rely heavily on global repositories; chiefly Landsat archives, LULC products, and socioeconomic indicators continue to underpin most studies, with DEMs, MODIS time series, precipitation records, and soil-type surveys also widely used. Although Sentinel-1 and 2 missions appear less frequently used in the reviewed articles, their higher spatial and spectral resolution is gradually gaining traction as researchers acknowledge that robust service assessments demand multiple, complementary data streams (Burkhard and Maes, 2017).

The variation in satellite sensors has driven much of this progress in remote sensing imagery for ecosystem services. Landsat and MODIS provide consistent, multi-decadal coverage essential for mapping carbon stocks, water provision, soil retention, and flood regulation at regional to global scales (Ouedraogo et al., 2016; Tiando et al., 2021). Yet their moderate spatial resolutions (30–500 m) limit fine-scale applications. In contrast, Sentinel-2's 10-m multispectral imagery enhances detection of forest fragmentation, biomass dynamics, and crop patterns, while Sentinel-1's synthetic aperture radar (SAR) delivers cloud-penetrating, day-night mapping that improves biomass and moisture estimates in tropical, cloud-prone landscapes (Almeida et al., 2024; Brandt et al., 2023). Despite these innovations, mismatched resolutions, temporal gaps, and proxy-based indicators introduce uncertainties, highlighting the need for cross-validation, higher-frequency observations, and locally calibrated datasets to strengthen both broad-scale syntheses and site-specific management (Guo et al., 2022).

Gridded climate and topographic layers, including temperature, precipitation, and digital elevation models remain foundational for ecosystem services assessments at multiple scales. For example, Bai et al. (2016) integrated DEM and rainfall data to evaluate water quality, erosion control, and food provision in China's Lake Baiyangdian basin, while Albert et al. (2020) and Samal et al. (2017) used similar datasets to forecast how these services may shift under future climate scenarios. More recently, the emergence of global soil-moisture and soil-type products has resulted in an enhanced ability to map food production, nutrient cycling, water regulation, and carbon storage; with standardized, open-access layers offering broad coverage and improved accuracy (Kusi et al., 2023; Wen et al., 2019).

Citizen science platforms have further enriched ecosystem-service mapping, especially for non-material and habitat functions. Community-generated data feed tools like eBird and Flickr, enabling spatially explicit analyses of recreation and even climate-change impacts (Manley and Egoh, 2024). Chandler et al. (2017) demonstrates how volunteer bird surveys inform biodiversity and habitat assessments, and Suzuki-Ohno et al. (2017) show that crowdsourced bumblebee photographs can reveal pollination potential across Japan. Automated classification of social-media images, as applied by Richards and Friess (2015) in Singapore, illustrates how cost-effective, geographically diverse citizen contributions can fill cultural-service data gaps (Cabral et al., 2016; García-Llamas et al., 2019; Lautenbach et al., 2011).

To promote data equity in Africa, South America, and other underrepresented regions, we recommend: (1) leveraging satellite remote-sensing platforms (e.g., Landsat, Sentinel) and incorporating blue-green infrastructure monitoring to generate consistent land-use and ecosystem-service metrics (Hamel and Tan, 2022); (2) integrating the Soil and Water Assessment Tool (SWAT) with regional parameterization, validated in Peru and Ethiopia to synthesize sparse local measurements into reliable hydrological simulations (Daneshvar et al., 2021; Taye et al., 2023); (3) combining open-access geospatial datasets with statistical regionalization methods to cost-effectively fill critical data gaps (Koskikala et al., 2020); and (4) establishing international data-sharing consortia mirroring SWAT-parameter regionalization approaches to build local modeling capacity and foster collaborative research across data-rich and data-poor contexts (Gitau and Chaubey, 2010).

4.4. Uncertainties and machine learning pitfalls

While these diverse data streams have expanded the scope of ecosystem service mapping, they also introduce layers of uncertainty that complicate interpretation and policy application (Song, 2018). Schulp et al. (2014) illustrated the variability of uncertainty in ecosystem service mapping by providing explicit confidence maps for regions across Europe, indicating where service data was most or least reliable. Their analysis found that while the maps for climate-regulation and recreation maps were produced with high confidence, erosion protection and flood regulation carried much higher uncertainty. Such variation stems from inconsistent indicator definitions, gaps in process understanding, differing study objectives, and heterogeneous data and methods. To clarify these challenges, (Hamel and Bryant, 2017) proposed a unified framework distinguishing among parameter, structural, and scenario uncertainties in water-related models, enabling clearer communication of where and why predictions are inaccurate.

Accurately estimating ecosystem services under changing land use is fraught with layered uncertainties that carry significant policy risks. Predictive models are undermined by ecological complexity, measurement errors, and input data issues, such as classification mistakes and missing time-series records (Tramontana et al., 2015; Warner et al., 2019). These weaknesses limit their ability to capture disruptions from urbanization or variability from economic shifts (Yuan et al., 2019). When policymakers depend on such flawed outputs, the result can be, regulations that misallocate resources and fail to reflect ecological realities, potentially exacerbating environmental degradation (Zhong et al., 2021). To mitigate these risks, we advocate for rigorous input validation, cross-checking satellite-derived maps against field observations, and the adoption of probabilistic modeling techniques that quantify confidence intervals around service estimates.

The complex interplay between land-use change, climate variability, and policy interventions further compounds uncertainty in machine learning forecasts. Population pressures and agricultural intensification create nonlinear ecological responses that purely data-driven models may fail to capture (Wang et al., 2015). Embedding adaptive policy scenarios such as conservation payments aligned with landowner incentives into predictive frameworks can buffer against model error by steering land-use trajectories toward resilient outcomes (Polasky et al., 2011). Future work should incorporate iterative validation loops, where machine learning outputs are regularly recalibrated against new field data and stakeholder feedback, and where scenario ensembles reflect both environmental variability and policy options.

Ensemble modeling has emerged as an alternate solution. Willcock et al. (2018) showed that blending multiple carbon-storage models across South Africa improved accuracy by more than 6 % compared to any single model. Similarly, Martínez-López et al. (2019) embedded a suite of algorithms within the ARIES platform to map non-material and regulating services at three global sites, where consistent outputs eased the detection of trade-offs, synergies, and spatial mismatches. Sensitivity analyses further help identify which parameters drive uncertainty. Chen et al. (2020), for instance, ranked key influences on pollination, carbon stocks, and habitat-suitability maps. Participatory and Bayesian-network approaches also harness expert and local insights to reduce uncertainty on the ground: Grêt-Regamey et al. (2013) demonstrated this in the Swiss Alps, where stakeholder workshops refined models of carbon sequestration, timber production, and avalanche protection. Together, these strategies improve both the credibility and usability of ecosystem service assessments.

ML, while powerful for reducing general uncertainties, introduces its own pitfalls in ecosystem service assessments. Overfitting is a common issue, occurring when models learn idiosyncratic patterns from training data (even in data-rich regions) rather than generalizable relationships, which severely reduces predictive power in new contexts (Kim et al., 2018; Rolnick et al., 2023). Furthermore, ML adoption is hampered by high computational requirements and the need for extensive labeled datasets, particularly in data-poor regions where sparse environmental data can lead to bias by underrepresenting ecologically critical contexts (Ukachukwu et al., 2023; Zhong et al., 2021). Methodological risks also arise from heterogeneous datasets that combine disparate scales and resolutions, yielding conflicting signals, and from spatial mismatches between ecosystem function zones and input layers, which can skew results (Ning et al., 2015; Zhang et al., 2022). Finally, the precision of ML forecasts often obscures underlying uncertainty, reducing interpretability for decision-makers (Tramontana et al., 2015). To mitigate these challenges and improve robustness, future work should deploy hybrid frameworks that combine ML with simpler statistical models or transfer-learning to boost generalizability (Bonas et al., 2024; Davaslioglu and Sagduyu, 2018). These efforts must be paired with rigorous bias-correction protocols, such as single-gauge calibration, in data-scarce environments (Ramadhan et al., 2024), and transparent reporting of training-data characteristics, ensuring the inclusion of stakeholder expertise to ground predictions in local ecological knowledge (Campbell et al., 2025).

4.5. Safeguarding nature

Mapping the services that ecosystems provide, whether through biophysical models, economic valuation, or scenario analyses has become an indispensable compass for conservation and sustainable land-use planning. By quantifying benefits like water purification, carbon storage, and soil retention, these assessments sharpen decision-making and help policymakers weigh trade-offs between development and protection. In China's Poyang Lake Ecological Economic Zone, for example, service-mapping underpinned large-scale reforestation efforts, restoring former agricultural lands to forest and boosting both biodiversity and flood regulation (Deng et al., 2023). Similarly, nature-based solutions such as mangrove restoration not only sequester carbon but also shield coastlines from storms and sea-level rise, illustrating how integrated mapping can align climate resilience with habitat conservation (Camacho-Valdez et al., 2014; Lagrosa et al., 2022).

Real-world applications underscore this impact. In Brazil, service-mapping of water regulation and carbon sequestration guided the establishment of the Atlantic Forest Biosphere Reserve, ensuring protected-area boundaries deliver maximum ecological benefit (Gomes et al., 2020). In the Democratic Republic of Congo, Cameroon, the Republic of Congo, and Equatorial Guinea, payments for ecosystem services and REDD+ initiatives now incentivize communities to reduce deforestation and manage forests sustainably (Ntirumenyerwa Mihigo and Cliquet, 2020). Across these diverse contexts, participatory mapping has woven local knowledge into technical analyses, strengthening community buy-in and ensuring that conservation strategies reflect on-the-ground realities. Together, advances in data availability, methodological diversity, and cross-sector collaboration chart a path toward land-use decisions that safeguard nature's life-support functions for generations to come.

4.6. Methodological constraints and pathways forward

Ecosystem services assessments face several methodological constraints that limit their accuracy and real-world relevance. Widely used biophysical toolkits like InVEST can oversimplify complex ecological interactions and overlook region-specific processes (Vorstius and Spray, 2015). Benefit-transfer methods, which apply economic values across contexts, often produce skewed results by failing to capture local socio-economic realities and relying on scarce data from underrepresented regions (Newbold et al., 2018). Meanwhile, the rise of ML techniques, though promising for pattern detection, introduces some barriers. Heavy computational demands and specialized expertise restrict their use in under-resourced institutions, and in data-poor landscapes they can yield biased predictions that miss critical local ecological traits (Almeida et al., 2024; Mienye et al., 2024).

Compounding these issues are scale mismatches and model rigidity. Many ML and process-based models operate at coarse spatial resolutions, glossing over fine-scale ecosystem dynamics, while their static frameworks struggle to adapt to rapidly changing environmental conditions without frequent recalibration (Lu et al., 2022; Morshed et al., 2022). Overcoming these constraints requires blended approaches that unite advanced analytics with on-the-ground knowledge. Investing in capacity building and co-development with local experts can democratize ML applications, reduce biases, and ensure regionally tailored insights. Hybrid methodologies integrating ML algorithms with participatory data and traditional ecological understanding offer a promising path to more accurate, equitable, and actionable ecosystem-service assessments (Gashaw et al., 2018; Olawade et al., 2024).

5. Conclusion

By systematically reviewing 459 peer-reviewed articles published between 2001 and March 2024, we have charted how ecosystem services research has responded to global land-use change. First, our synthesis shows that scientists now map a far broader suite of services than a decade ago, spanning provisioning (food, water, raw materials), regulating (climate regulation, erosion control, flood protection), and emerging studies of cultural and recreational benefits. Second, methodological innovation is reshaping the field: traditional biophysical and economic-valuation models are now complemented by scenario analysis, participatory mapping, and a growing use of machine-learning algorithms that uncover complex, non-linear relationships and improve predictive accuracy. Third, data diversity has exploded. Open-access satellite archives (Landsat, MODIS, Sentinel), global climate and soil-moisture products, and even citizen-science platforms (eBird, Flickr) have dramatically improved both the spatial reach and the granularity of ecosystem-service assessments.

These advances are reflected in the global footprint of research. Asia, led by China drives the majority of case studies, followed by contributions from Europe, Africa, and the Americas. Importantly, our analysis highlights a growing trend in geographically diverse research: nearly 30 % of lead authors studied ecosystems beyond their home countries. This expansion of research to new locations is helping to close geographic and thematic gaps in the literature by focusing on previously under-studied regions. Looking ahead, the field can build on this momentum by refining hybrid approaches that marry cutting-edge analytics with local ecological knowledge, investing in capacity building for data-poor regions, and designing adaptive, fine-scale models that can keep pace with rapid environmental change. By integrating diverse datasets, stakeholder insights, and methodological innovations, future ecosystem-service research can deliver the actionable intelligence that policy-makers and communities need to balance development, equity, and nature's life-support functions.

CRediT authorship contribution statement

Wesner Njume Epie: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hannah Stouter:** Writing – review & editing. **Julia Lenhardt:** Writing – review & editing. **Lacour M. Ayompe:** Writing – review & editing. **Elsa M. Ordway:** Writing – review & editing, Funding acquisition. **Elizabeth D. Crook:** Writing – review & editing. **Benis N. Egoh:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

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