frontiers | Frontiers in Forests and Global Change

TYPE Systematic Review
PUBLISHED 13 November 2025
DOI 10.3389/ffgc.2025.1623266

OPEN ACCESS

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RECEIVED 05 May 2025
ACCEPTED 14 October 2025
PUBLISHED 13 November 2025

CITATION
Tabi Eckebil PP, Mintah F, Bürgi M, Akinyemi FO, Sonwa DJ and Ifejika Speranza C (2025) Tropical ecosystem multifunctionality assessment and insights for sustainable land management: a systematic literature review using the driver-pressure-state-impact-responses framework. *Front. For. Glob. Change* 8:1623266. doi: 10.3389/ffgc.2025.1623266

Tropical ecosystem multifunctionality assessment and insights for sustainable land management: a systematic literature review using the driver-pressure-state-impact-responses framework

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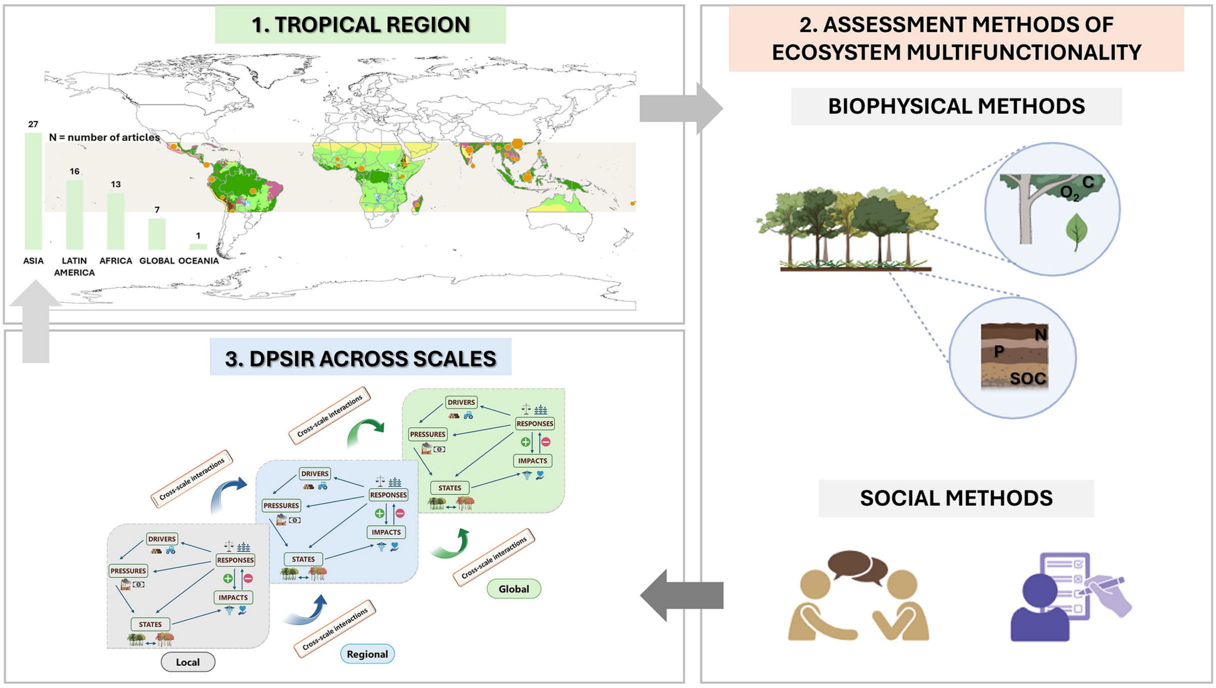
A systematic review of studies on tropical ecosystem multifunctionality (EMF) reveals the main factors influencing ecosystems' ability to provide multiple functions and services. We examined forty publications to determine the methodological approaches used to assess the multifunctionality of tropical ecosystems. The DPSIR helped to identify the drivers, pressures, state, impacts and responses shaping EMF. Biophysical-based methods dominate in calculating multifunctional indices using average and threshold values, while the use of social science-based methods is low. Most identified drivers are direct, such as land-use change, whereas pressures arise from human activities and environmental stressors. Biotic and abiotic factors affecting ecological conditions directly impact human well-being. Most responses are concentrated at the national level and neglect the local level, particularly those policies that support integrated landscape approaches. The inadequate integration of social dimensions and local levels in EMF calls for holistic approaches that balance attention to social needs and ecosystem health, thereby enhancing sustainable land management.

KEYWORDS

ecosystem multifunctionality, tropical ecosystems, ecosystem benefits, ecosystem functions, landscape multifunctionality, sustainable land management, DPSIR

1 Introduction

Tropical terrestrial ecosystems play a crucial role in Earth's natural processes by contributing almost a third of the global carbon cycle, including photosynthesis and biomass production (Mitchard, 2018). These ecosystems are rich in biodiversity and endemism, housing a significant portion of the world's species and providing several ecosystem services that enhance human well-being (Gardner et al., 2009; FAO and UNEP, 2020; Pillay et al., 2022). However, human activities such as agricultural expansion, logging, and climate change are undermining the functions of these ecosystems, particularly tropical forests (Laurance, 2013; Lewis et al., 2015; Edwards et al., 2019; Akinyemi and Ifejika Speranza, 2022). With increasing human pressure on these ecosystems, there is a need to secure their ability to provide multiple ecosystem services simultaneously (Manning et al., 2018).



GRAPHICAL ABSTRACT

Ecosystem multifunctionality (EMF) is defined as the ability of ecosystems to provide multiple ecosystem functions and services simultaneously (Gamfeldt and Roger, 2017; Garland et al., 2021). EMF underscores the importance of biodiversity in regulating ecosystem processes and ensuring ecosystem resilience amid environmental changes (Byrnes et al., 2014). In this study, we adopt an integrative approach to EMF, encompassing both "ecosystem function-multifunctionality" and "ecosystem service-multifunctionality" (Manning et al., 2018: 429). Ecosystem functions refer to the biological, physical and geochemical processes occurring in an ecosystem, while ecosystem services refer to the benefits humans derive from ecosystems (Manning et al., 2018; Trivedi et al., 2018).

EMF has been examined from an ecological perspective, often focusing on biodiversity assessments to understand biophysical processes (Manning et al., 2018). Yet, the predominant focus on ecological diversity and functions makes it challenging to fully appreciate the dynamic interactions and feedback loops between humans and nature. This highlights the need to integrate additional perspectives, such as those of stakeholders alongside the ecological perspective. Achieving this requires conducting interdisciplinary research to comprehend the complex human-nature interactions impacting EMF, and their societal implications (Bennett et al., 2015; Díaz et al., 2015; Kühne and Duttmann, 2020).

Achieving optimal EMF often involves balancing ecological goals, such as biodiversity conservation, with societal goals, like agricultural productivity and economic development. Trade-offs arise because actions that enhance one ecosystem service may reduce another. For instance, intensive agricultural practices can increase food production but may lead to habitat loss and decreased biodiversity (Trubins, 2023). Similarly, biodiversity conservation policies may restrict land use options for local communities, impacting their livelihoods (Schaafsma and Bartkowski, 2020). EMF also depends on sustainable land management (SLM), which involves managing land (soil, water, vegetation, and wildlife) to preserve intact ecosystems while ensuring that productive land remains viable for the present and future (Cowie et al., 2024). SLM aims to balance these competing objectives by considering stakeholders' diverse values and needs (Van Wensem et al., 2017; Jaskulak, 2022).

Despite ongoing research on the multifunctionality of tropical ecosystems, significant gaps remain. Important aspects still lacking include the key factors influencing these ecosystems, the trade-offs involved, and current limitations in EMF assessment approaches. Specifically, there is insufficient consideration of how local stakeholders perceive and value these ecosystems (Hölting et al., 2020b). Additionally, the continuing degradation of land and natural resources show that new insights are needed for sustainable land management and for managing the trade-offs in environmental and monetary value exchange (Haregeweyn et al., 2023). Measuring and valuing ecosystem functions and services in tropical regions is particularly challenging due to data limitations and the complexities involved in interpreting outcomes for decision-making (de Groot et al., 2012; Stürck and Verburg, 2017). Therefore, a comprehensive understanding of EMF is essential for guiding SLM practices, and for ensuring ecosystem health in the tropics and societal benefits.

This contribution thus reviews evidence on the multifunctionality of terrestrial tropical ecosystems. The research questions guiding our analysis are:

a What methods are used to analyze the multifunctionality of terrestrial tropical ecosystems?
b What factors drive the current conditions of terrestrial tropical ecosystems and threaten their multifunctionality?

c What insights can be gained for an informed land management that fosters the multifunctionality of terrestrial tropical ecosystems?
d To what extent does the DPSIR framework identify cause-effect relationships that affect EMF

The following sections outline our methodology, present the research results, and discuss the implications for SLM that promotes EMF and societal benefits.

2 Materials and methods

2.1 Study design and protocol for conducting a systematic literature review

2.1.1 The drivers, pressures, state, impacts and responses (DPSIR) framework

The DPSIR framework has been found to be effective in describing factors driving ecosystem change and their causal relationships (Kyere-Boateng and Marek, 2021). It has also been used to evaluate ecosystem services (Naveedh Ahmed et al., 2020) and to identify policy priorities for land and natural resources management (Quevedo et al., 2023). This framework integrates ecological, biological, and socioeconomic perspectives ensuring a comprehensive assessment of ecosystems (Carr et al., 2007; Ness et al., 2010). Applying the DPSIR framework in this review is essential as it integrates science, policy, and practice and helps pinpoint critical issues that may impede the overall functioning of ecosystems (Carnohan et al., 2023; Figure 1).

In this review, we define "*Direct drivers*" as human activities such as land use changes that have an immediate impact on ecosystems, whereas "*Indirect drivers*" refer to activities triggered by broader societal forces such as industrial development. "*Pressures*" are the forces exerted on ecosystems, categorized into *environmental pressures* and *human behavioral pressures*. The resulting changes in ecosystem conditions are the "*State*." The consequences of these changes on terrestrial tropical ecosystems are termed "*Impacts*," while "*Responses*" refer to the societal actions taken or policies proposed to mitigate or adapt to these impacts (Maxim et al., 2009; Fitz et al., 2022). The analysis in this paper is structured according to the Drivers–Pressures–States–Impacts–Responses framework, as the framework enables identifying how drivers, pressures, impact and responses interact, and how such interactions create synergies and trade-offs for EMF over time and space.

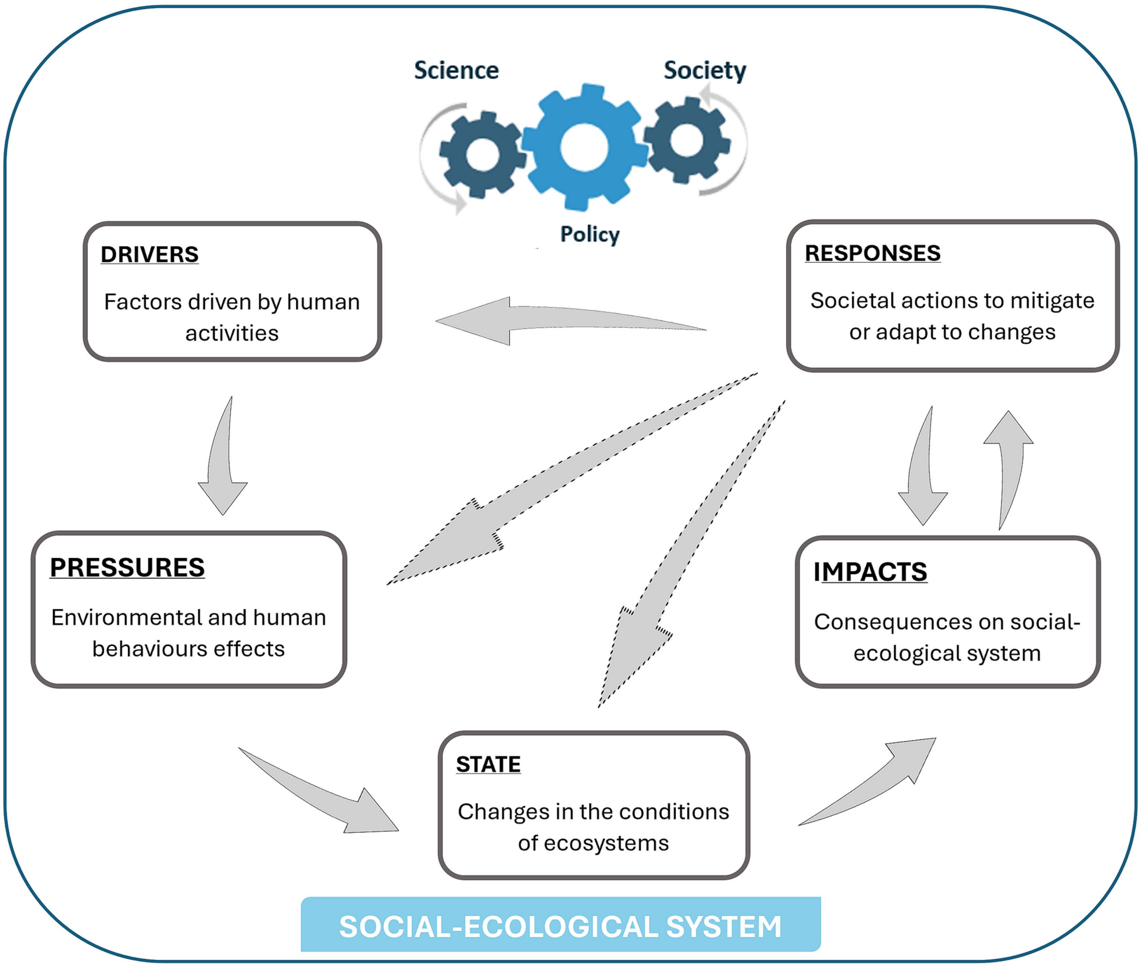


FIGURE 1
DPSIR framework applied to social-ecological systems (Carnohan et al., 2023; Smeets and Weterings, 1999).

2.1.2 Protocol and articles selection process

In this systematic literature review, we explored publications on EMF with a specific focus on terrestrial tropical ecosystems. Our review followed the Protocol, Search, Appraisal, Synthesis, Analysis, and Reporting approach. This six-step approach is recognized for its comprehensive, systematic, and reproducible nature, minimizing bias and enhancing the reliability of findings (Haddaway et al., 2020).

2.1.2.1 Protocol

The protocol aims to clearly outline the study's scope, background, research gaps, and scale (Mengist et al., 2020; Page et al., 2021). We first investigated the methods used to assess EMF. Subsequently, using the DPSIR framework, we analysed the drivers and pressures affecting the multifunctionality of terrestrial tropical ecosystems, the conditions of these ecosystems and the impacts of the changes on humans and nature. The responses derived served as insights for SLM aimed at enhancing the multifunctionality of tropical ecosystems, while considering societal effects.

2.1.2.2 Search

To capture a wide range of publications that align closely with the study's scope and objectives, we developed multiple search strings by combining relevant keywords using the syntax [TITLE-ABS-KEY]. As "Ecosystem Multifunctionality" (EMF) refers to the capacity of ecosystems to provide multiple functions and services simultaneously, we incorporated the term "Landscape Multifunctionality" (LMF), which extends this notion to broader spatial scales reflecting research emphasizing the importance of valuing landscapes for balancing biodiversity conservation and human needs. Then, "Ecosystem Services" (ES) denotes the specific benefits that people derive from diverse ecosystems. We searched multiple databases, including Web of Science, Scopus and Science Direct. The search strings are structured as follows:

i Seach to capture articles on EMF/LMF at the tropical region: TITLE-ABS-KEY (("Ecosystem multifunction*" AND "tropical*" AND "ecosystem*") OR ("Ecosystem multifunction*" AND "tropics") OR ("Landscape multifunction*" AND "tropical*" AND "ecosystem*") OR ("Landscape multifunction*" AND "tropics") OR ("Ecosystem multifunction*" AND "tropical ecosystem*") OR ("Landscape multifunction*" AND "tropical ecosystem*") OR ("Ecosystem multifunction*" AND "tropical*" AND "region*") OR ("Ecosystem multifunction*" AND "tropical*" AND "area*") OR ("Landscape multifunction*" AND "tropical*" AND "region*") OR ("Landscape multifunction*" AND "tropical*" AND "area*")).

ii Search to capture articles on EMF/LMF including the benefits: TITLE-ABS-KEY (("Ecosystem multifunction*" AND "function*" AND "tropic*") ("Ecosystem multifunction*" AND "ecosystem service*" AND "tropic*") OR ("Ecosystem multifunction*" AND "benefit*" AND "tropic*") OR ("Ecosystem multifunction*" AND "contribut*" AND "tropic*") OR ("Ecosystem multifunction*" AND "advantage*" AND "tropic*") OR ("Ecosystem multifunction*" AND "value*" AND "tropic*")) OR (("Landscape multifunction*" AND "function*" AND "tropic*") ("Landscape multifunction*" AND "ecosystem service*" AND "tropic*") OR ("Landscape multifunction*" AND "benefit*" AND "tropic*") OR ("Landscape multifunction*" AND "contribut*" AND "tropic*") OR ("Landscape multifunction*" AND "advantage*" AND "tropic*") OR ("Landscape multifunction*" AND "value*" AND "tropic*")).

iii Search to capture studies on EMF/LMF, including Nature's contributions to people: TITLE-ABS-KEY (("Ecosystem multifunctionality" AND "Nature's contribution*") OR ("Landscape multifunctionality" AND "Nature's contribution*")).

The search step resulted in 499 articles (see the details in Supplementary Table S1).

2.1.2.3 Appraisal

We appraised the 499 selected articles based on the aim and objectives of this study, applying specific inclusion and exclusion criteria. The inclusion criteria were that papers have to be empirical studies on EMF, LMF, ecosystem functions, services, and benefits in terrestrial tropical ecosystems across various scales. Conversely, the exclusion criteria filtered out literature reviews, duplicated articles, studies outside the tropics (e.g., sub-tropical, temperate, and polar), studies focused on soil micro-food web issues and articles that did not address terrestrial ecosystems (e.g., marine, freshwater). Additionally, we excluded non-English articles; however, exceptionally, we included some global-scale studies and reported results related only to terrestrial tropical ecosystems (Figure 2).

2.2 Documents coding and data analysis

2.2.1 Synthesis

A total of 40 papers were selected, coded, and categorized regarding the DPSIR components addressed, the methods used to assess EMF, the ecosystem types, case studies reviewed locations, and the year of publication. Additionally, factors identified in the reviewed articles as contributing to, enhancing or reducing EMF were coded using MaxQDA software 2024.

The first author developed the codebook through a combination of deductive reasoning based on predefined indicators and inductive insights gained through extensive reading of articles and familiarity with the topic. The initial codebook was reviewed by the co-authors and refined after coding a preliminary set of articles. One co-author independently coded half of the selected articles using the finalized codebook. At this first stage, a minimum agreement of 60% of coding between both authors was achieved. In the second stage, discrepancies among the authors' coding were systematically discussed to refine the analysis with a final agreement of 70% being achieved. This achieved agreement is slightly below an agreement level over 80%, generally recommended to ensure the trustworthiness and credibility of the findings (Kurasaki, 2000).

2.2.2 Analysis

The analysis evaluated the current methods used for EMF assessment and their limitations. Additionally, we examined the Drivers, Pressures, State, Impacts, and Responses (DPSIR) in terrestrial tropical ecosystems across the 40 selected articles. This approach assessed the current conditions and the threats to ecosystems, as well as the factors determining their multifunctionality. It also evaluated the impacts of

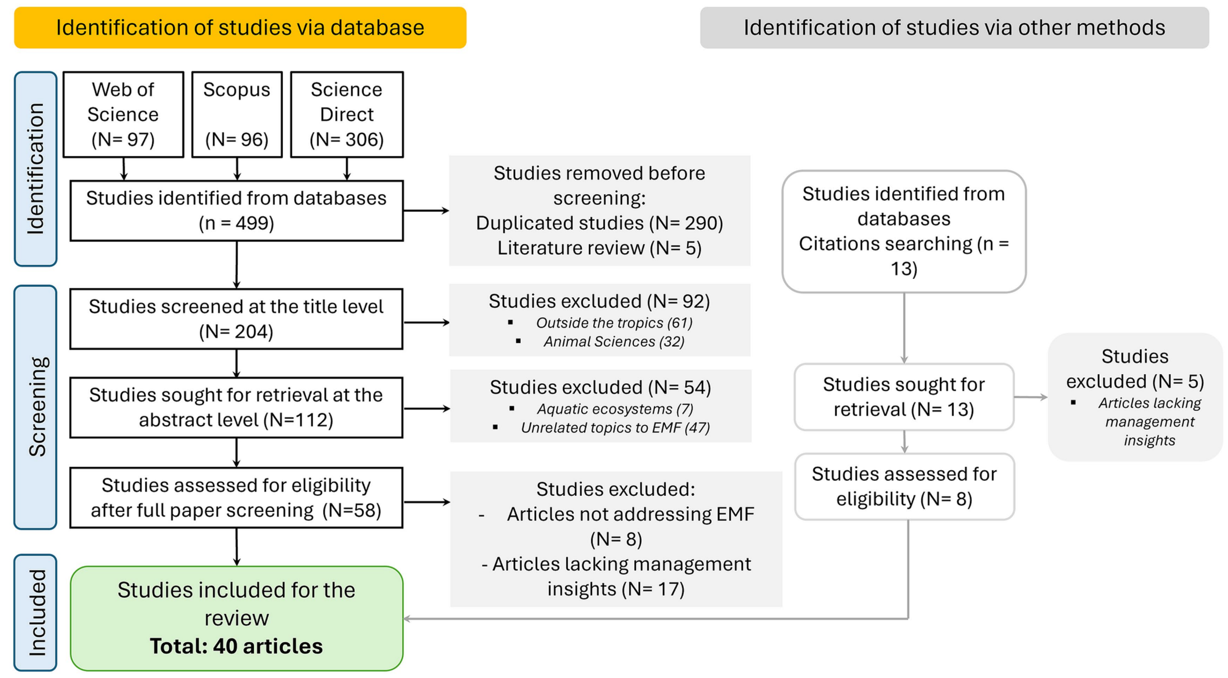


FIGURE 2
Flow diagram of systematic review for Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Haddaway et al., 2022).

changes on living and non-living components and the effects on human well-being. Finally, the analysis highlighted responses aimed at mitigating the negative effects and identified conditions for positive outcomes, including trade-offs between ecological functions and societal needs.

2.2.3 Report

We used content analysis to analyse the data. First, we mapped the reviewed case studies and tracked the annual publication trends. Next, we carried out a bibliographic network analysis to visualize the co-occurrence of keywords related to EMF. Subsequently, we identified the factors influencing EMF in tropical regions, presented the assessment methods and examined response strategies that aligned with SLM. In the discussion section, we elaborated critical aspects missing from existing assessments and suggested ways of making the evaluation more holistic. Additionally, we derived insights for SLM highlighting its relevance for broader societal implications.

3 Results

3.1 Overview of the reviewed articles

The 40 articles analysed captured about 64 different case studies reviewed in the tropics and distributed according to ecoregions as described by Dinerstein et al. (2017) and Figure 3.

The reviewed articles encompass studies across diverse ecosystems such as forests, drylands, pastures, and integrated landscapes combining forests with farmlands and pastures. The case studies reviewed were categorized per year of publication and ecosystem types (Figure 4).

The bibliographic network analysis displayed four nodes or clusters: (i) *Biodiversity*; (ii) *Management*; (iii) *Agroforestry* and (iv) *Land-use* (Figure 5). The *biodiversity* cluster, the largest in the network, emphasizes the central role of ecological components in EMF studies, particularly ecosystem functions, plant functional traits, and soil organic carbon. Its size and connectivity highlight biodiversity as the foundation for understanding multifunctionality in tropical systems. The *management* cluster serves as a bridge, linking practices, such as biodiversity conservation, ecosystem services, and multifunctional landscapes. This suggests that management practices are frequently framed as linking ecological processes and policy or governance interventions. The *agroforestry* cluster connects ecological restoration, landscape multifunctionality, and sustainable forest management, indicating growing recognition of agroforestry as a multifunctional land-use strategy. Finally, the *land-use* cluster, though smaller, links to various land-use practices and captures debates on shifting cultivation, agricultural intensification, and conservation strategies, reflecting the tensions between production-oriented practices and ecological sustainability. These clusters highlight a dynamic research environment where biodiversity is fundamental to EMF. Moreover, studies on land use and agroforestry uncover intriguing trade-offs co-benefits, and new opportunities contributing to a more comprehensive understanding of EMF within social-ecological contexts.

3.2 Methods used to assess tropical ecosystem multifunctionality

Three main methods to assess EMF have been identified in the reviewed papers. The following provides a comprehensive

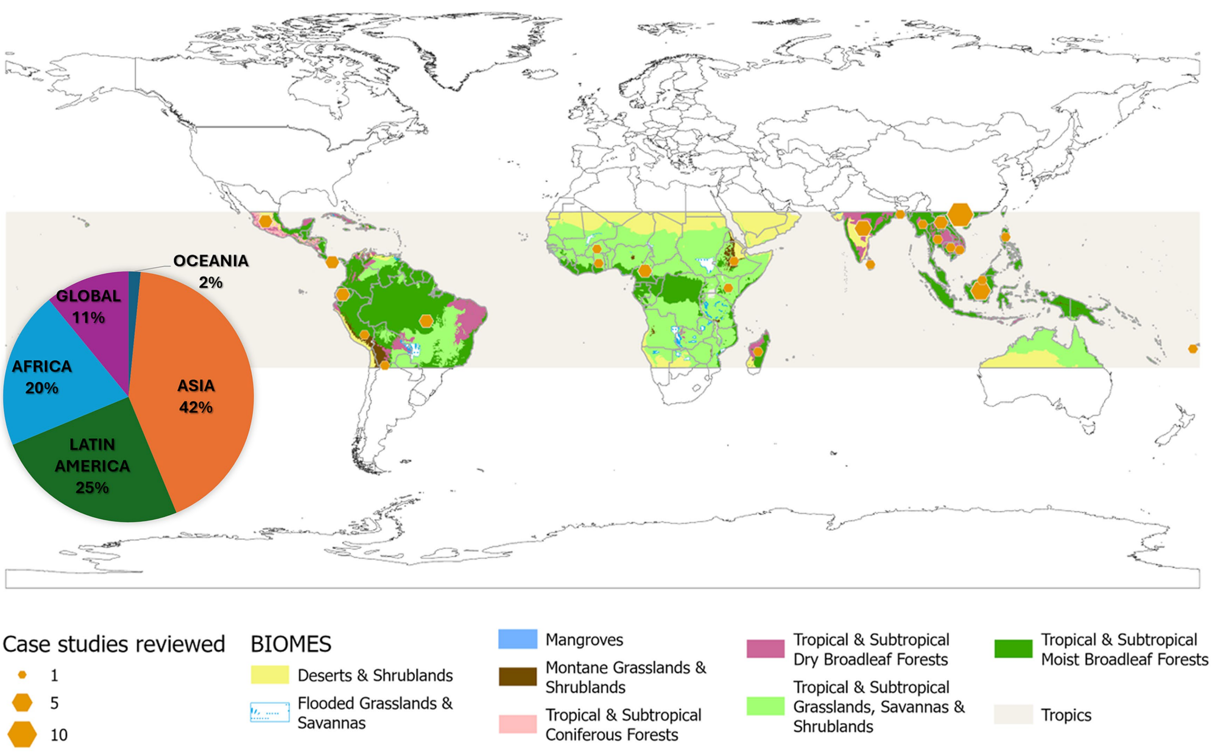


FIGURE 3
A mapped distribution of the case studies from the 40 articles reviewed across various biomes between 2010 and 2024.

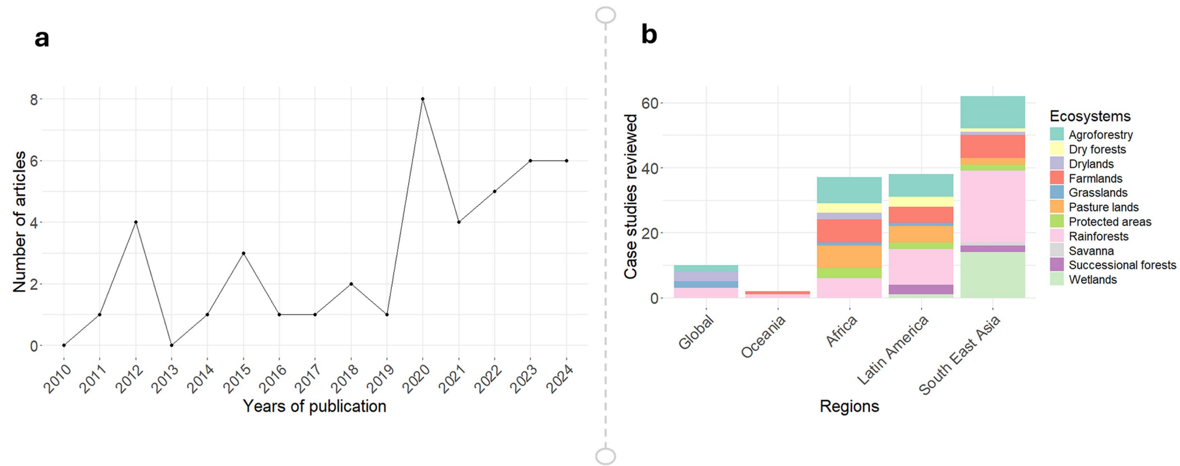


FIGURE 4
Distribution of the case studies from the 40 articles reviewed per year and ecosystem types between 2010 and 2024. **(a)** Publications on EMF in the tropics between 2010 and 2024. **(b)** Case studies reviewed by ecosystem types and regions.

overview of how these methods have been applied in the 40 reviewed articles.

3.2.1 Biophysical-based methods

Most of the evaluated papers (28 out of 40) assessed multifunctionality using various biophysical methods. These assessments rely either on the averaging method (a calculation of a multifunctionality index value) or the threshold method (evaluating a threshold functionality in response to an abrupt change). At the tree community level, functional traits serve as key indicators (Li et al., 2022). At the forest scale, a broader range of variables is examined, including tree species richness (Maestre et al., 2012; Sircely and Naeem, 2012), rare species (Tang et al., 2023), biodiversity dominance (Lohbeck et al., 2016; Zemp et al., 2023) and abiotic drivers (Wang et al., 2022). Moreover, climatic factors such as mean annual precipitation and mean annual

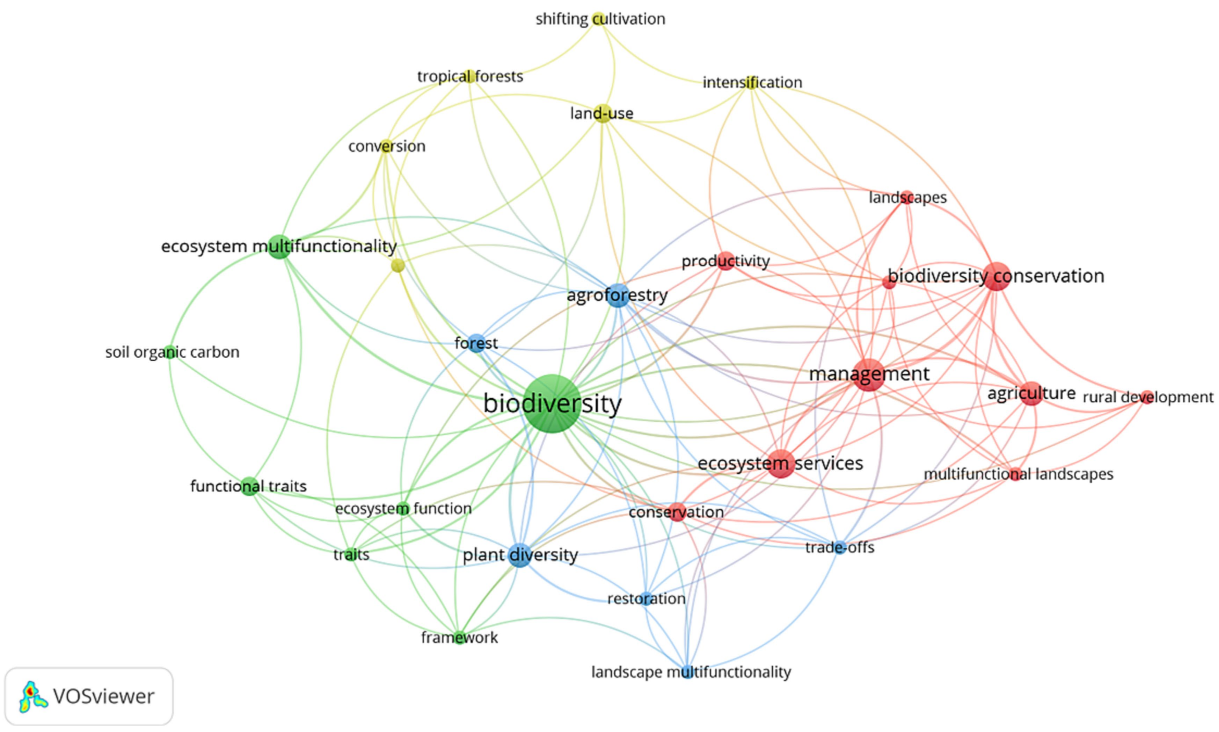


FIGURE 5
Semantic network analysis of the terms referring to EMF in tropical regions from the 40 articles reviewed between 2010 and 2024.

temperature and soil factors play crucial and specific roles in EMF. Their influence varies depending on the ecosystem type. For instance, in semi-arid ecosystems, higher precipitation is positively correlated with increased EMF, as it enhances nutrient availability through microbial activity. In contrast, excessive rainfall in humid ecosystems can lead to nutrient leaching, potentially reducing EMF.

Land-use allocation modeling and multi-objective optimization have been employed to gain deeper insights into the ecological and socioeconomic factors that drive current land-use decisions. Potential transformation scenarios are simulated using optimization approaches that model the transition toward an optimal multifunctional land-use composition (von Groß et al., 2024). Within a social-ecological system, the model facilitates a rapid evaluation of trade-offs between ecological and socioeconomic functions and services (Grass et al., 2020; Reith et al., 2020; Law et al., 2021).

3.2.2 Social science-based methods

Only 8 out of 40 assessed papers exclusively use methods from the social sciences. Commonly, perception-based approaches are employed through participatory methods such as interviews, surveys and participatory mapping collaboratively with local stakeholders (Estrada-Carmona et al., 2014; Atela et al., 2015; Heinze et al., 2022). These exercises often involve ranking the preferred use of specific ecosystem services and benefits derived from nature, offering valuable insights into how different stakeholders perceive and utilize these services. This enables a better understanding of how ecosystem services are utilized while emphasizing the importance of local knowledge and stakeholder perspectives (Zanzanaini et al., 2017; Duncan et al., 2020). Lastly, capturing people's perceptions is appropriate for formulating conservation policies and how they can be translated into actions (de Brito et al., 2020).

3.2.3 Mixed methods approach

Mixed methods integrate qualitative and quantitative approaches to analyse complex interactions between nature and humans or environment and society. In the reviewed articles, mixed methods often combine ecological assessments, spatial analysis, and modeling with participatory approaches, interviews, and surveys within four articles. Mixed methods typically bridge the gap between empirical ecological data and human perspectives facilitating the identification of trade-offs and the development of more effective conservation and land-use policies (Ribeiro et al., 2019; Ahammad et al., 2024).

In summary, different methods are used to assess EMF. The previously described methods highlight advantages and disadvantages and pinpoint the crucial lack of primary data and direct stakeholder participation in assessing EMF (Pinillos et al., 2020).

3.3 Factors affecting the conditions of tropical ecosystems and their multifunctionality

The factors driving and threatening the current conditions of tropical ecosystems and strategies for enhancing their multifunctionality using the DPSIR indicators, are summarized in Table 1. The percentages reflect the occurrence of the terms across the 40 articles reviewed.

TABLE 1 Factors influencing ecosystem multifunctionality and strategies for its enhancement from the 40 articles reviewed.

DPSIR framework	Indicators		Percentages (%)
Drivers	Indirect drivers (25.1 ≈ 25%)	Complexity of the governmental institutions	3.3
		Population growth and people's needs	8.5
		Ecosystem management practices and decisions	8.5
		Government policies and strategies	4.7
	Direct drivers (74.9 ≈ 75%)	Livestock production	4.7
		Shifting cultivation	6.2
		Subsistence agriculture	6.2
		Agricultural intensification and expansion	20.9
		Logging	8.1
		Natural resources exploitation	5.2
		Climate change	3.3
		Land use changes	20.4
Pressures	Human behavior pressures (55.3 ≈ 55%)	Industrial development and urbanization	28.9
		Market demands	26.3
	Environmental pressures (44.7 ≈ 45%)	Emission or pollution	10.5
		Hazards	21.1
		Use of chemicals and fertilizers	13.2
State	(100%)	Disrupted abiotic conditions	10.6
		Disrupted biotic conditions	3.0
		Declined habitat and biodiversity	51.5
		Degraded land and soil	13.6
		Fragmented landscape	21.2
Impacts	Socioeconomic impacts on humans (49.3 ≈ 49%)	Insecure land tenure	10.7
		Reduce ability to maintain health and safety	6.7
		Reduced human well-being, societal equity and livelihoods	32.0
	Impacts on the ecosystem (50.7 ≈ 51%)	Reduced ecosystem services provision	5.3
		Habitat and biodiversity loss	29.3
		Disrupted biophysical processes	16.0

(Continued)

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TABLE 1 (Continued)

DPSIR framework	Indicators		Percentages (%)
Responses	Local level (20.7 ≈ 21%)	Promotion of ecosystem services	2.6
		Education and technical training	2.6
		Community-based ecosystem management	2.3
		Promoting income-generating activities	3.2
		Sustainable use of natural resources	2.3
		Improving sustainable livelihood strategies and good quality of life	7.6
	National level (66.8 ≈ 67%)	Promotion of equity and welfare for future generations	2.6
		Enhancing food security	1.5
		Conservation and development projects	5.0
		Multi-stakeholder engagement /multi-scale governance	7.9
		Cross level-communication	2.0
		Government support or subsidies	1.7
		Inclusion of Indigenous and local knowledge (ILK) /stakeholders' values and perspectives	2.9
		Reforestation /restoration /afforestation /agroforestry	13.1
		Strengthening rules and regulations /law enforcement	3.5
		Establish new policies (i.e., Biodiversity protection)	6.1
		Enhance land management /Planning /Landscape approach	20.4
	International level (12.5 ≈ 12%)	Climate change /REDD+ mechanisms	7.3
		Product certification /market mechanisms development	2.3
		Payment for Environmental Services (PES)	2.9

REDD+: Reducing emissions from deforestation and forest degradation in developing countries through conservation, sustainable management of forests and enhancement of forest carbon stocks.

3.3.1 Drivers

The reviewed articles identified direct drivers (75%) and indirect drivers (25%) that negatively impact EMF. The primary direct drivers include land-use changes, particularly agricultural intensification and expansion. Frequent logging contributes to landscape transformation, reducing natural forest cover and leading to more fragmented and less diverse forest ecosystems. Population growth and ecosystem management practices are the major indirect drivers reported, leading to increased land demand or conversion. These socio-cultural and economic factors play a crucial role in shaping landscapes. The articles reviewed reveal that forests are often extensively converted into large-scale monocultures, mixed plantations, or agroforestry systems dominated by rubber, oil palm, and soybeans, primarily to meet international market demands.

3.3.2 Pressures

Pressures have been classified into environmental pressures (55%) and human behavior pressures (45%). Among environmental pressures, hazards (21%), such as flooding, were identified as a major factor. These hazards are primarily driven by vegetation cover loss due to deforestation, increased runoff, nutrient leaching, and soil structure instability. Such disruptions hinder ecosystem functions resulting in reduced multifunctionality. Additionally, pollutant emissions (10%) contribute significantly to air pollution and declining air quality. Furthermore, infrastructure construction (29%) has been reported to negatively impact soil properties, disrupting water availability and nutrient cycling.

3.3.3 State

The decline in habitat and biodiversity have been identified as a significant issue (51%), primarily driven by wildlife habitat destruction and forest resource depletion. The second key factor assessed in studies evaluating ecosystem health is soil condition, which is impacted by abiotic resource depletion (10%), which comprise reductions in nitrogen (N), phosphorus (P), and soil organic carbon (SOC), all of which play essential roles in ecosystem functioning. Indeed, fine roots (usually less than 2 mm in diameter) constitute a significant portion of total forest biomass and are critical in nutrient and water uptake. The increase in fine root production associated with agroforestry enhances SOC sequestration, facilitated by soil decomposers. Conversely, intensive land use accelerates soil degradation, diminishing biotic resource activity. The reviewed articles indicate that disruption of biotic resources (3%), particularly the decline of soil microfauna responsible for organic decomposition and energy flow, can result in the loss of aboveground biodiversity and SOC. These factors trigger cascading effects across trophic levels, ultimately affecting ecosystem functioning.

3.3.4 Impacts

Impacts were analysed from two perspectives: ecosystem impacts (51%) and socioeconomic impacts on human communities (49%). Habitat and biodiversity loss, along with disrupted biophysical processes, are often precursors to the decline of EMF. Deforestation and monoculture plantations reduce species diversity in ecosystems, compromising their ability to deliver essential ecosystem services. In addition to land use, pedo-morphology also plays a critical role in the supply of ecosystem services. Disruptions in biophysical processes due to various drivers jeopardize ecosystem services, reducing livelihood opportunities and negatively affecting human well-being. Importantly, ecosystem services hold significant social value for people, including cultural, spiritual, and educational benefits, playing a vital role in people's good quality of life. Consequently, these impacts have far-reaching consequences, threatening the environment and society.

3.3.5 Responses

Among the responses to enhance EMF, 21% were identified at the local level, 67% at the national level and 12% at the international level and their cross-scale interactions.

3.3.5.1 Local level: dominance of measures to improve livelihoods and quality of life

Improving livelihoods and well-being (7%) is essential at the local level, as highlighted in the reviewed articles. Key strategies include community-based management, promoting alternative sources of income, and integrating Indigenous and local knowledge alongside stakeholder perspectives in the valuation of nature. For example, maintaining or enhancing hedgerows has been recognized for supporting ecosystem health and providing multiple benefits to local communities.

3.3.5.2 National level: policies and regulations for an integrated landscape approach

The most significant responses documented at the national level include land management measures and landscape approach initiatives (20%), reforestation, restoration, afforestation, and agroforestry (13%), as well as the establishment of new policies supporting biodiversity conservation and carbon emission reduction (6%). To effectively implement these strategies, the reviewed articles emphasize the need for a more integrated landscape approach that addresses complex land management challenges by balancing conflicting land use demands, aligning policies, and involving diverse stakeholders. This approach aims to promote sustainable and equitable outcomes for both society and the environment (Reed et al., 2015). The reviewed articles underscore the need for conservation measures to protect natural and old-growth tropical forests to safeguard biodiversity and enhance EMF. Additionally, protecting endemic species habitats along the interfaces between natural forests and agricultural lands can help mitigate the negative impacts of land conversion.

3.3.5.3 International level: mechanisms to tackle global climate change

Climate mitigation is a global priority that requires urgent attention. Key measures include Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanisms (7%), product certification and market-based mechanisms (2%), and Payment for Environmental Services (PES) (3%). These governance instruments share a common objective: promoting economic incentives through SLM to support conservation efforts. Multifunctional ecosystems offer a valuable framework for implementing PES by enhancing the market value of certified products from landscapes that comply with environmental regulations. Such landscapes, therefore, contribute to biodiversity conservation and foster societal benefits.

Analyzing the results of the DPSIR assessment for each ecosystem (Figure 6) reveals a significant knowledge gap regarding savanna ecosystems, which have received comparatively fewer studies. In contrast, studies on forest ecosystems are notably most prevalent,

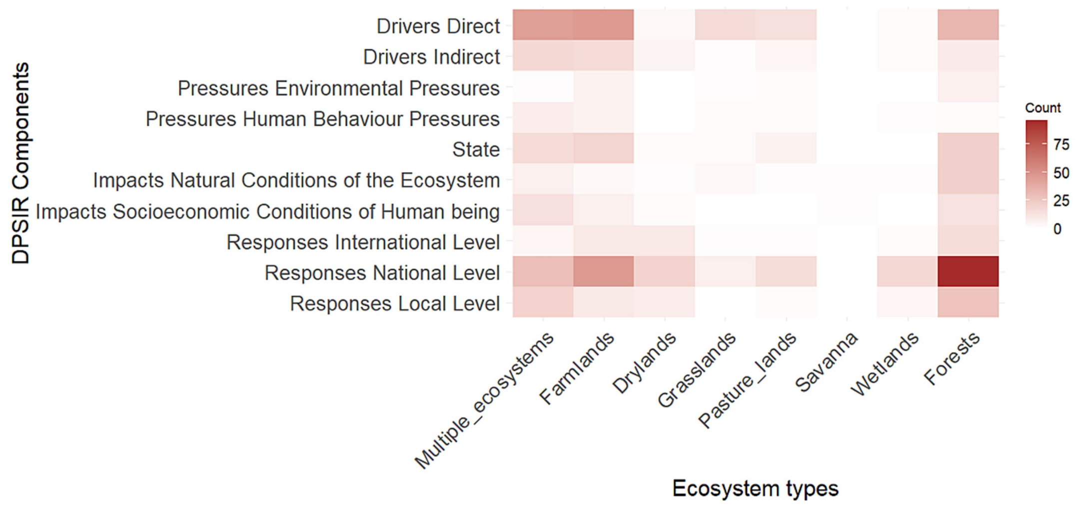

FIGURE 6
DPSIR components influencing multifunctionality across tropical ecosystem types from the 40 articles reviewed between 2010 and 2024.

particularly regarding responses at the national level. This indicates that forests are a primary focus in studying multifunctionality in tropical regions. Following forests, farmlands also represent an important area of interest, highlighting the considerable impact of agricultural activities on land use and ecosystem dynamics.

The DPSIR framework thus provides a valuable conceptual lens for assessing EMF in the tropics, as it helps to unpack the complexity underlying multifunctional ecosystems. Moreover, it highlights that the sustainability of tropical landscapes depends not only on mitigating drivers and pressures, but also on anticipating the responses that shape ecosystem states and their associated impacts (Table 2).

3.4 The DPSIR framework as a basis for addressing cause–effect relationships concerning ecosystem multifunctionality

As DPSIR is widely applied in studying policy-practice interventions and outcomes for the environment, it is important to assess the extent it enables addressing cause-effect relationships regarding EMF. First, applying the DPSIR framework to EMF in tropical regions underscores not only the interlinkages between drivers, pressures, state, impacts, and responses, but also the dynamic feedback and trade-offs that shape these relationships. It makes such interactions explicit, thereby revealing cascading feedback loops across its components. Second, the analysis shows that synergies and trade-offs not only occur at one scale, but that cross-scale interactions exist between the local, national and international that frequent conflicts between agriculture and environmental conservation, especially in regions undergoing severe deforestation of tropical forests, nevertheless, land-use zoning can improve social-ecological outcomes and support multifunctionality across both local and regional landscapes (Law et al., 2021). Hence, drivers that occur at the global level such as demand for timber can trigger increased local exploitation of forests thus affecting their EMF or those of their associated landscapes. Third, there is also a time dimension to DPSIR interactions. A lag effect in one of its components could affect "impacts" and the "state" of an ecosystem. The lag effect shows the delay in time before a driver or pressure could have an effect/impact on the state of a variable. While some drivers may have immediate impacts, others might take time. Also, for an impact to occur certain thresholds have to be reached and this depends on the characteristics of the focus ecosystem. For example, a study in the Amazon revealed that between 1970 and 2009, the landscape underwent gradual fragmentation and shifts in spatial configuration (from forest cover to fruits trees plantation), largely driven by global market incentives that shaped intergenerational livelihood opportunities at the local level (Palacios-Abrantes et al., 2022).

The DPSIR can thus be understood as a general system dynamics model that shows the cause effect relationships at a synthetic level. System dynamic models enable qualitative and quantitative analysis of cause-effect relationships in social-ecological systems and have been applied to study interactions between the DPSIR components. This review shows that the DPSIR can be enhanced by adding cross-scale interactions, positive/negative feedback loops, and time lags as shown in Figure 7.

3.5 Insights for sustainable land management and the enhancement of EMF in tropical ecosystems

The responses from DPSIR analysis in the 40 articles evaluated addressed sustainable land management (SLM) and have been grouped into four main insights and detailed in Table 3: (1) Promoting community-led initiatives for SLM, (2) Participatory governance, (3) Policies promoting the sustainable use of natural resources, (4) Diversified land-use practices.

This analysis indicates that most of the insights are on diversification of land use practices ($n = 81$), including measures such as restoration, afforestation and agroforestry. The next most important insight for SLM emphasizes the promotion of policies aimed at sustainable use of natural resources ($n = 40$). This includes

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TABLE 2 Unpacking DPSIR: trade-offs, feedback, and multifunctionality in tropical ecosystems.

DPSIR Components	Local (short-term)	Local (medium-term)	Regional (short-term)	Regional (long-term)	Global (long-term)	Affected ecosystem functions/Services	Trade-offs/Synergies	Responses/ Feedback loops
Driver (D)								
Indirect drivers	Population growth	People's needs	Ecosystem management practices and decisions	Government policies and strategies	Climate change	Provisioning and regulation services	Trade-off: ↑provisioning services (e.g., food) → ↓Regulating services (e.g., carbon storage)	Policy incentives for agroforestry → reduce the intensity of land use change
Direct drivers	Agricultural intensification and expansion	Land use changes	Natural resources exploitation	Logging				
Pressure (P)								
Human behavior pressures	Industrial development and urbanization		Market demands		CO_2 emission and pollution	Biodiversity Habitat, nutrient cycling, water and quality	Trade-off: socioeconomic conditions↑ → natural resource conditions↓	Policy incentives for tree planting → water and air regulation
Environmental pressures	Use of chemicals and fertilizers		Hazards					
State (S)	Disrupted biotic and abiotic conditions	Declined habitat and biodiversity	Degraded land and soil	Fragmented landscapes	Altered biological diversity and decomposers	Productivity, energy flow	Aggravation: disrupted biogeochemical cycles accelerate ecosystem collapse	Policy incentive for soil restoration → improves soil conditions and fertility
Impact (I)								
Socioeconomic impacts on humans	Reduced human well-being, societal equity and livelihoods		Disrupted biophysical processes		Global biodiversity loss	Provisioning and cultural, regulating services	Aggravation: Insecure land tenure escalates unsustainable resource management	Laws and regulations enforcement for sustainable land management → Enhanced ecosystem services
Impacts on the ecosystem	Reduced ecosystem services provision		Disrupted biophysical processes					
Response (R)								
Local level	Improving sustainable livelihood strategies and good quality of life	Education and technical training	Sustainable use of natural resources	Community-based ecosystem management	New policies for biodiversity protection, and REDD+ mechanisms	Multiple ecosystem services and functions are enhanced	The combined effect of sustainable practices enhances livelihoods and quality of life	Responses create feedback loops that influence drivers and pressures
National level	Restoration and agroforestry practices	Inclusion of Indigenous and local knowledge (ILK)	Enhance land management and Landscape approach	Multi-stakeholder engagement and multi-scale governance		International regulations to enhance overall ecosystem services and functions	Global and regional science-policy frameworks providing guidance for conservation and sustainable land management	Policy incentives for diversified landscapes → enhanced ecosystem functions and services
International level	Payment for environmental services (PES)		Certification/market mechanisms development					

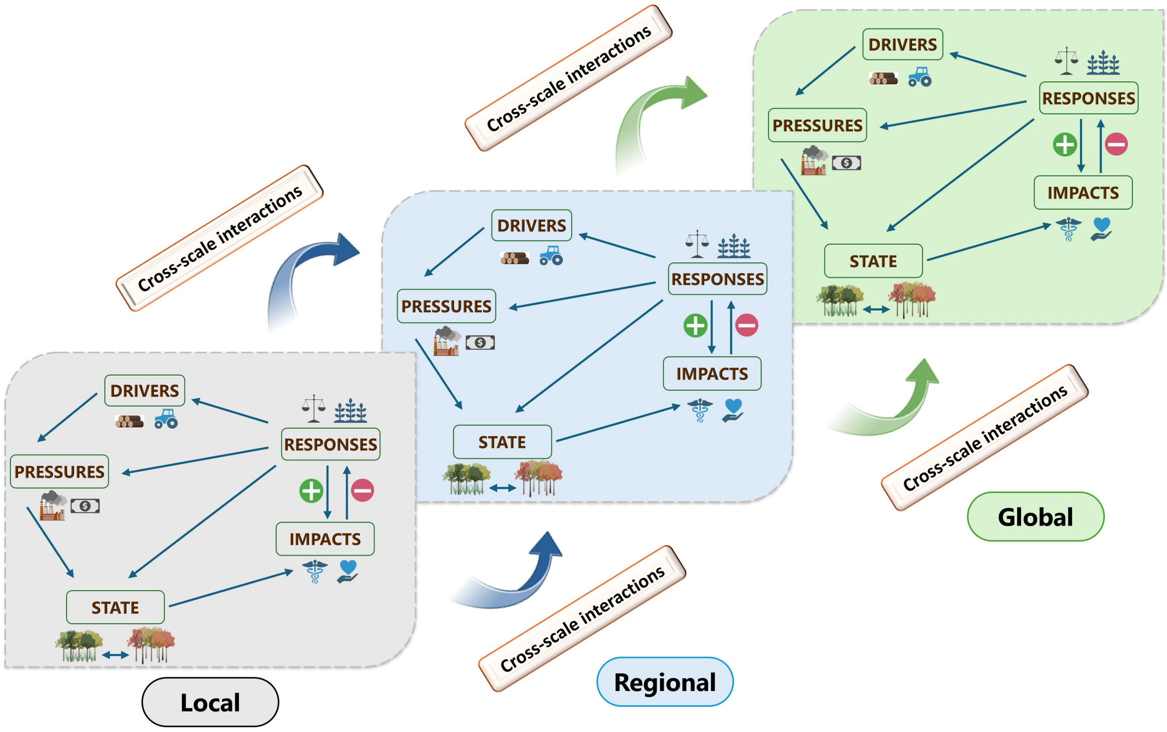

FIGURE 7
Spatial–Temporal analysis of EMF in the tropics using the DPSIR framework.

TABLE 3 Recommended responses based on DPSIR as insights for sustainable land management (SLM).

SLM insights	Implications	Number of studies
Promoting community-led initiatives for SLM	Locally driven action where communities take charge of designing and implementing initiatives	29
Participatory governance	Multi-stakeholder engagement, including local communities and policymakers	36
Policies promoting the sustainable use of natural resources	Land-use policies with biodiversity conservation and climate adaptation strategies	40
Diversified land-use practices	Restoration, afforestation and agroforestry	81

policies for biodiversity conservation and climate change adaptation, such as certification mechanisms and payment for environmental services. Subsequently, the inclusion of multi-stakeholders at multiple levels refers to the third insight, the participatory governance for SLM ($n = 36$). This insight implies he involvement of local communities, policymakers, conservation project managers and researchers. Lastly, the insight on promoting community-led initiatives for SLM, emphasizes focus on local communities ($n = 29$). This insight acknowledges the values of incorporating Indigenous and local knowledge as well as community-based ecosystem management.

Although each of these insights addressed specific aspects, they often intersect across multiple levels of governance. For instance, participatory governance requires the involvement of diverse stakeholders at local, national, and international scales. Similarly, policies supporting the sustainable use of natural resources may be initiated at national or international levels but implemented locally. Conversely, a bottom-up approach where community-led initiatives for SLM emerge locally can shape new policies that, in turn, influence management strategies at the national level.

4 Discussion

4.1 Methods used in analyzing multifunctionality – key findings and research gaps

The reviewed articles indicate that widely implemented biophysical methods emphasize ecological functions as key variables in assessing multifunctionality. Threshold-based and averaging methods are commonly employed to calculate a multifunctionality index. These approaches typically involve either aggregating ecosystem functions and services or applying multivariate models (Byrnes et al., 2014; Allan et al., 2015). For instance, plant functional traits and species dominance influence the level of multifunctionality. Lohbeck et al. (2016) highlight that species traits are less important than dominance in determining species functionality in disturbed forests such as secondary forests. In contrast, Wood et al. (2015), show that in agricultural landscapes, the interplay between biodiversity, ecosystem functions, and trait species is crucial for enhancing multifunctionality. Additionally, functional diversity in mixed species plantations is associated with various functional traits enhancing multifunctionality. However, the effects of functional diversity can vary significantly depending on tree species and the type of plantation (Li et al., 2022). Given the wide range, of ecosystem function variables, the determination of a functional trait for a given function remains ambiguous (Hoelting et al., 2019). There is currently no standardized method regarding assessing EMF in ecology and land system science (Trogisch et al., 2017; Garland et al., 2021; Hölting et al., 2020a). The findings from this review show that achieving EMF is context and target dependent.

Mixed method approaches combine biophysical and social methods and, to some extent, modeling. However, these methods often fail to integrate approaches that value people's perspectives in ecosystem or landscape assessments. Relying solely on biophysical methods presents limitations, primarily due to uncertainties in assessing ecosystem services caused by data scarcity (Hamel and Bryant, 2017). Few studies employ longitudinal data or experimental designs (Giling et al., 2019) and long-term data collection for effective ecosystem management remains a significant challenge (Carpenter et al., 2009). An integrated assessment approach can yield better outcomes to meet the Sustainable Development Goals (SDGs) van Soest et al. (2019). In that vein, frameworks such as Nature-based Solutions (NbS) and Access and Benefit-Sharing (ABS) could be considered. However, while these frameworks focus on multifunctionality, it is crucial to recognize the potential contributions of social science methods to these assessments. Responses indicate the need for a more integrative and holistic approach that actively involves different stakeholder groups (Hölting et al., 2020a, 2020b). One of them could be Nature's Contributions to People (NCP) from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

4.2 Driving factors of multifunctionality in tropical ecosystems

4.2.1 Biotic and abiotic factors driving multifunctionality

Our analysis, grounded in the DPSIR framework, underscores the intricate interconnectedness of human-nature interactions and reveals critical challenges and opportunities in promoting EMF. The identified drivers of EMF can be differentiated into biotic and abiotic factors.

Biotic factors include tree functional traits, which are widely recognized for their role in providing various ecosystem functions and services that support overall multifunctionality. Their impact is influenced mainly by their size and the diversity of species present, which collectively enhance biodiversity across multiple trophic levels, thereby promoting the EMF (Schuldt et al., 2018; Kearsley et al., 2019). It is well known that trees allocate a substantial amount of their photosynthates to their root systems. Because fine roots have a rapid turnover rate, they contribute up to 70% of the net primary productivity in forest ecosystems (Kernaghan, 2013). They are intricately linked to other functional traits, such as mycorrhizal associations, which generally enhance nutrient uptake (Dallstream et al., 2023). However, human-induced land use change, such as mining, deforestation, and conversion of forests to agricultural lands, reduces fine root production, threaten tropical ecosystems multifunctionality, and disrupts these belowground processes (Awoonor et al., 2023).

Among the abiotic factors, soil constituents are important determinants of EMF. A decline in nutrient cycling leads to lower soil organic carbon (SOC) sequestration, lowering the likelihood of high tree species richness and ultimately diminishing EMF. It is worth noting that decisions on land management practice can significantly influence the multifunctionality of landscapes. For example, implementing agroforestry systems as an alternative to slash-and-burn (Tremblay et al., 2015) or restoring mined lands into an agroforestry plantation (König et al., 2022), can enhance the ability of such landscapes to improve the quantity and quality of functions and services. Further, an increase in soil fertility and yield through excessive inputs of chemicals and fertilizers rich in nitrogen can induce soil acidification. This leads to nutrient imbalance, a modification in soil microbiota and soil matter, and consequently, a decrease in multifunctionality (Liu et al., 2013). Environmental factors, mainly temperature and precipitation, are also important abiotic factors determining EMF. Mean annual rainfall is crucial for ecosystem functioning in drylands, supporting microbial litter decomposition and nutrient release. In contrast, mean annual temperature plays a larger role in biophysical processes, and extreme temperature or precipitation can negatively impact ecosystem functioning. This underscores the delicate balance within tropical ecosystems, where both temperature and precipitation are critical drivers of biophysical processes that sustain ecosystem functions (Wu et al., 2011).

4.2.2 Spatial–temporal dimensions of tropical ecosystem multifunctionality

Our review revealed important regional and temporal variations in EMF research across tropical ecosystems. In Latin America, studies have largely concentrated on the promotion of forest restoration, particularly agroforestry practices and the associated trade-offs. A strong emphasis has been placed on the benefits of restoration activities as a strategy to reduce deforestation while supporting human wellbeing (Reith et al., 2022; Reith et al., 2020). Whereas, in Asia and the African continent, research has focused more on the influence of functional traits to EMF under diverse land use conditions—protected areas, mono and mixed species plantations—highlighting the important role of biodiversity in enhancing multifunctionality (Li et al., 2021; Sircely and Naeem, 2012). Additionally, studies across the three continents examined the extent to which stakeholders' perceptions shape decision-making in contexts where the value of nature's contributions to people is particularly salient within agriculture-dominated landscapes (Ellis et al., 2019).

Over time, three broad phases can be distinguished: an early phase (2010–2015) where scholars emphasized the negative effects of deforestation and climate change which the United Nations Framework Convention on Climate Change (UNFCCC) aim to address through the REDD+ program (Labrière et al., 2015). Then a second phase (2015–2020) marked by the emergence of several targets to protect or restore terrestrial ecosystems and halt land degradation and biodiversity loss, e.g., UN Sustainable Development Goal (Lohbeck et al., 2016); and a more recent period (2020–present) in which integrated landscape approaches, multifunctionality, and governance trade-offs have gained prominence (Law et al., 2021; Pinillos et al., 2020). These spatio-temporal distinctions demonstrate that while tropical ecosystems share common challenges, the research trajectories and policy debates are highly context-dependent, shaped by regional social-ecological dynamics and dynamic global policy agendas.

The socio-economic consequences emphasize the need for inclusive approaches that address both ecological and social dimensions of sustainability.

4.3 Integrative strategies for sustainable land management

Given the critical role of biotic and abiotic factors in supporting EMF, as well as the significant contribution of sustainable land management (SLM) practices in promoting multifunctionality (Neyret et al., 2023), it is essential to recognize the positive feedback of SLM on human well-being and quality of life. However, trade-offs must always be considered in decision-making processes (Grass et al., 2020). The following responses for SLM were derived based on the analysis:

1. Driven by the need to conserve ecosystems, measures such as forest restoration (Fremout et al., 2022; Melo et al., 2023) and agroforestry practices (Reith et al., 2020; Sahle et al., 2021) were highlighted by the DPSIR framework as effective responses for reducing the trade-offs associated with converting natural landscapes to single-uses areas.
2. Different right-holders and stakeholders use tropical ecosystems in diverse ways; for example, while hunters are interested in sustainable wildlife hunting (de Paula et al., 2022), Non-Timber Forest Products (NTFP) collectors, especially women, are often interested in maintaining the sustainable supply of the products as an important part of their livelihood (Viet Quang and Nam Anh, 2006). Logging companies on the other hand are concerned with the quality of timber (Putz et al., 2012). Thus, integrating multiple stakeholders allows for a comprehensive analysis of trade-offs among several land use preferences. This response highlights two key insights for SLM: participatory governance at multiple levels and the promotion of community-led initiatives at the local level.
3. Multifunctional ecosystems offer the advantage to implement market-based mechanisms such as REDD+ (Do and van Noordwijk, 2023) and the Payments for Environmental Services (PES) scheme (Tacconi et al., 2013). To effectively support positive outcomes, these strategies need to be reconsidered, with a dual aim of addressing global warming and promoting ecosystem services and human well-being (Dewi et al., 2013; Labrière et al., 2015). Thus, beyond the articles reviewed, PES has served as a significant incentive for the adoption of agroforestry practices, while simultaneously generating co-benefits for local communities (Mayr et al., 2024). This measure addresses the insight on promoting policies for the sustainable use of natural resources.

As management responses entail trade-offs, monetary valuation should be applied judiciously, both as compensation for environmental damage and as an incentive for sustainable practices.

4.4 Environmental and socio-economic value dynamics in human–nature interactions

Promoting environmental awareness and environmentally friendly behavior to support EMF is crucial. While framing ecosystem services in economic terms can be beneficial for policy formulation and decision-making, it may lower nature's complex value to simplistic market metrics. Thus, other non-economic responses are required. Vuong and Nguyen (2025) introduced the idea of the "Nature Quotient" (NQ) as a way to evaluate how individuals perceive and relate to the natural world. NQ reflects the ability to interpret and integrate knowledge about the links between humans and ecosystems, which in turn supports the development of ecological awareness and motivates environmentally responsible actions (Vuong and Nguyen, 2025). This approach can be operationalized through recommendations highlighted by the reviewed articles, starting at the local level (e.g., updating scholar training programs) and extending to the national level, emphasizing environmental awareness among all stakeholders, from young scholars to practitioners. The notion of Nature Quotient also relates to concepts like environmental awareness, nature care, "*Pachamama*," "*living in harmony with nature*," or to other world views such as those underpinning Indigenous ecological knowledge (IPBES, 2022).

This EMF assessment recognizes the need for a greater inclusion of the social dimension. The Nature's Contributions to People (NCP) concept could make such an important contribution, by incorporating stakeholders' views and perspectives, while operationalizing Indigenous, local, and traditional knowledge to better understand nature-human relationships, and adopt plural values of nature (IPBES, 2019). For example, case studies featured in this review demonstrated that a participatory approach involving all stakeholders is effective for integrating different perspectives in assessing interconnections between the environment and society (Ribeiro et al., 2019; de Brito et al., 2020).

The NCP framework considers values described by existing frameworks in a more pluralistic and inclusive manner, involving a broader range of actors (from the local to national level) with diverse interests in shaping ecosystems (Pascual et al., 2017; Ellis et al., 2019; Kadykalo et al., 2019). Furthermore, the negative contributions of nature to people have been rarely explored in EMF studies and this aspect warrants closer examination (Brauman et al., 2020). This review underscores the limited integration of the social dimension in conservation and land-use policies and recommends its inclusion in EMF assessments to enhance stakeholder representation and promote more comprehensive ecosystem management strategies (Holting et al., 2019; Kockelkoren et al., 2023). As land-use policies and ecosystem management strategies are not value-neutral, their success depends heavily on how they engage diverse stakeholders, particularly local communities whose livelihoods are most directly affected (Sayer et al., 2013). These ethical dimensions underscore that EMF cannot be disentangled from social legitimacy.

Future research could build on these findings by integrating stakeholder perspectives and ethical considerations more systematically and incorporating the NCP framework. This opens avenues for more interdisciplinary studies, fostering a broader understanding of EMF in tropical regions.

4.5 Limitations of this study

This review lays the foundation for a better understanding of factors influencing EMF in tropical ecosystems. Despite the extended key terms we applied in the methodology, limited studies were retrieved for the analysis. This is likely due to the scarcity of empirical research focused on tropical ecosystems. Additionally, the ambiguous distinction between drivers and pressures in the DPSIR framework prompted us to propose our own definition of these terms in this review drawing on previous publications that have utilized the same framework. Finally, while stakeholder-specific data was beyond the scope of our review, it was difficult to directly capture the views, priorities, or experiences of local actors who are central to land use decision-making. Future research should therefore complement our cross-continental synthesis with empirical stakeholder engagement to better integrate ecological, social, and ethical dimensions of sustainable land management. As the study of EMF in terrestrial tropical ecosystems advances, there is a need for further research on how integrative approaches in assessing EMF can better inform SLM.

5 Conclusion

Preserving natural habitats and biodiversity to enhance EMF and sustain nature's benefits for human well-being remains challenging, particularly in tropical regions. While screening the studies for their assessment methods, we identified gaps and proposed approaches to make the assessment more holistic. Biophysical methods commonly employed to measure multifunctionality have limitations in capturing the interactions of multiple functions in the assessment of ecosystem functioning. Mixed method approaches, incorporating stakeholder viewpoints grounded in social sciences, could provide a more comprehensive foundation for SLM, ultimately enhancing EMF. Furthermore, the DPSIR framework helped identify factors affecting the multifunctionality of ecosystems in the tropics. Our analyses revealed that land use changes and agricultural intensification and expansion are the main drivers of ecosystem degradation, negatively impacting nature and humans. The proposed responses to enhance EMF focus on policies that promote an integrated landscape approach and strategies aimed at improving people's quality of life. These responses offer valuable insights for SLM that seeks positive ecological and societal outcomes. Finally, a holistic approach grounded in the diverse values that people hold toward nature can be achieved by applying the IPBES' Nature's Contributions to People concept to assess EMF and inform sustainable land and ecosystem management.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PT: Writing – review & editing, Conceptualization, Writing – original draft, Investigation, Formal analysis, Methodology, Data curation, Visualization. FM: Formal analysis, Writing – review & editing, Methodology, Investigation. MB: Writing – review & editing. FA: Writing – review & editing. DS: Writing – review & editing. CI: Supervision, Conceptualization, Resources, Writing – review & editing, Funding acquisition.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program (grant agreement no. 101001200).

Acknowledgments

This research is part of the SUSTAINFORESTS project. We thank reviewers for their valuable comments on the manuscript. This study contributes to the Initiative Afrique at the University of Bern, the Programme on Ecosystem Change and Society (https://pecs-science.org/) and the Global Land Programme (https://glp.earth/).

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2025.1623266/full#supplementary-material

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