



Review

Social resilience of tropical forest ecosystems: A systematic review of core principles and their application

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ABSTRACT

Tropical forest systems (TFSS), play a crucial role in maintaining the planet's ecological balance, supporting life on Earth, and providing different ecosystem services, which are vulnerable to environmental (e.g., severe droughts) and human-induced disturbances (e.g., deforestation). The resilience concept is usually considered in evaluating a forest system under these severe disturbances. However, while resilience evaluations have mainly focused on engineering and ecological perspectives, the integration of social core resilience principles (3SRPs)- learning and experimentation (P5), participation (P6), and polycentric governance (P7)- remains limited. This study performs a systematic review of papers published between 2000 and 2024, focusing on social resilience in tropical forest systems to assess the application of the 3SRPs, following the (PRISMA) framework for systematic reviews, and identify the research gaps in social-based resilience studies. The keywords “resilience”, “forest”, and “ecosystem services” were searched in the “Web of Science” and “Scopus” databases from 2000 to 2024. The 24-year timeframe captures the evolution of resilience theory from early ecological foundations to contemporary social-ecological applications. The results show that despite the recognition of social aspects in selected studies (49), 55% of studies have considered one social principle, 12% studies taken two principles into account (i.e., P6 and P7), and only 8% of reviewed studies have incorporated all three social principles together in their assessments. Social aspects such as stakeholders' participation and governance are often overlooked, with the majority of evaluations focusing on ecological criteria. There is a crucial need for an integrated approach that considers social and ecological criteria to assess forest resilience, with an emphasis on the effective application of 3SRPs.

1. Introduction

1.1. Tropical forests as social-ecological systems

Tropical forests are vital systems that provide irreplaceable environmental, economic, and social benefits on a global scale. These forests cover about 7% of the Earth's surface and host more than half of the

world's terrestrial biodiversity (Myers, 1992). Some of the most important roles of tropical forests include mitigating climate change, supporting many species, and contributing to human well-being (Borma et al., 2022). The Amazon rainforest alone stores approximately 150–200 billion tons of carbon, underscoring its significance in global climate regulation (Nobre et al., 2016). Beyond carbon storage, tropical forests regulate regional and global hydrological cycles. They contribute

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to atmospheric moisture, which plays a vital role in shaping rainfall patterns and supports water availability for agricultural productivity (Nyasulu et al., 2024) and also protects the soil from erosion processes.

The economic benefits of tropical forests are substantial, and they provide timber, non-timber forest products such as fruits, nuts, and medicinal plants, and support industries like tourism and pharmaceuticals (Young, 2021). Indigenous communities and local populations rely on these forests for their livelihoods, as well as sustaining culturally-rooted customs, behaviors, values, beliefs, and traditional knowledge (Londres et al., 2023).

Despite the importance of tropical forests, they face severe threats, primarily from deforestation and climate change (FAO, 2020). FAO (2020) estimates that the world loses approximately 10 million hectares of forest annually, with tropical regions accounting for the majority. Deforestation not only leads to biodiversity loss but also disrupts the carbon cycle, exacerbating global warming. About 8% of global carbon emissions currently come from tree cover loss in tropical forests (World Resources Institute, 2018). The global distribution of tropical forests is shown in Fig. 1a. Fig. 1b illustrates global population density, revealing

a notably high concentration of people in tropical forest regions. Addressing the compounded pressures of biodiversity loss, carbon emissions, and population demands in these regions requires a robust understanding of resilience and their ability to withstand and recover from both anthropogenic and natural disturbances.

Another important factor to consider while studying forests is that these systems are not isolated; they are living, dynamic spaces shaped by the people who rely on them and, in turn, influence the forests near them (Fig. 2). Hence, the study of these large-scale ecological systems is deeply intertwined with social aspects.

Large-scale systems (i.e., forests) encompass physical, ecological, hydrological dimensions, and climatic aspects, as well as socio-economic parameters. A comprehensive understanding of these kinds of systems requires acquiring in-depth knowledge of their physical and ecological structure, followed by other studies such as the integration of socio-analyses and human dimensions. While ecological studies serve as a crucial foundation in unraveling the biophysical nature of forest systems, incorporating social perspectives can extend these findings. Rather than suggesting that the absence of social considerations renders

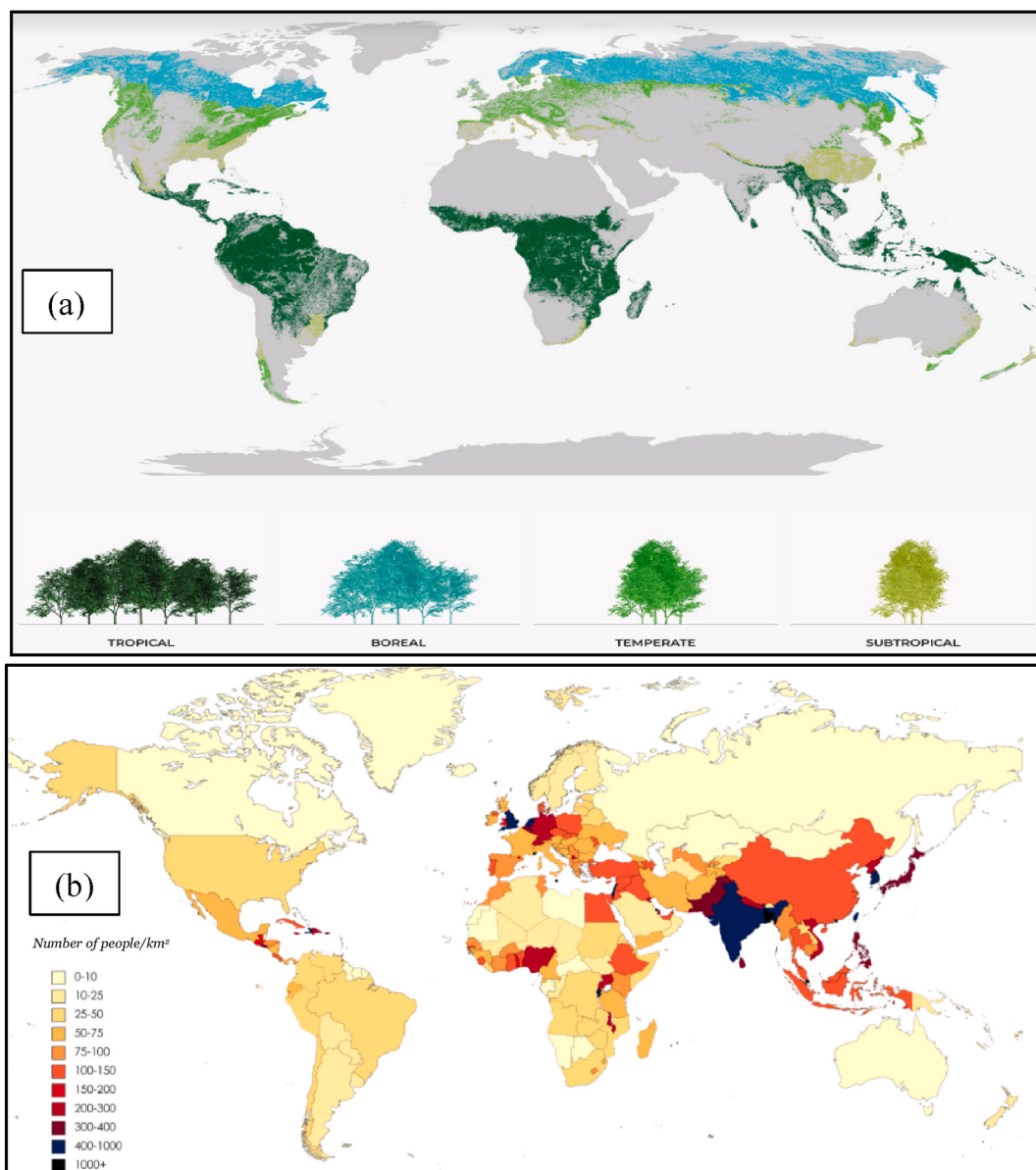


Fig. 1. a) The global distribution of forest types, including tropical forests (Tropical: 45.5%, Boreal: 27.3%, Temperate: 16.2%, and Subtropical: 11%) (GFW, 2024); b) The global population density (Wikipedia contributors, 2024).

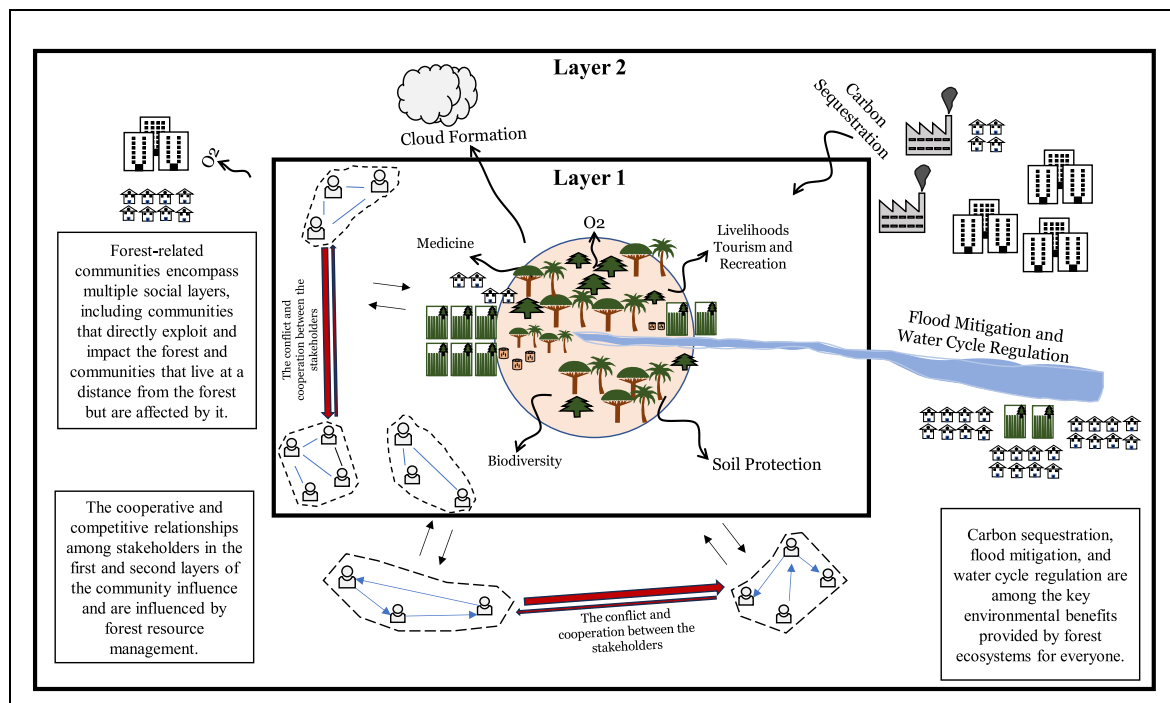


Fig. 2. Examples of intertwined connections between human and forest systems. Stakeholders and society interact directly (Layer 1) and indirectly (Layer 2) with forest systems. The red arrows show the conflict or cooperation between stakeholders that affect the condition of the forest ecosystem. The arrow width refers to the intensity of conflict or cooperation.

ecological research disconnected from reality, it is more constructive to view social studies as complementary, which provides essential context and a fuller picture, especially when addressing resilience, governance, and human-ecosystem interactions. This paper presents the social dimension as an extension that builds upon prior ecological foundations rather than as a replacement.

1.2. Resilience principles

Resilience is traditionally conceptualized through three primary approaches: engineering, ecological, and social-ecological resilience (Krell, 2019; Hlásny et al., 2021; Heinemann, 2010; Anamaghi et al., 2025). Engineering resilience concentrates on a system's recovery time, assuming a return to its original equilibrium state after temporary shocks (Bryant et al., 2019), while ecological resilience emphasizes a system's capacity to absorb changes and potentially transition to new stable states (Holling, 1973; Eklom et al., 2012; Pomara and Lee, 2021). Social-ecological resilience represents a more comprehensive framework, focusing on the interconnected capacities of human and natural systems to sustain desired service levels during disruptions (Behboudian et al., 2023, 2024; Tampekis et al., 2023). Researchers have extensively explored these resilience concepts across various domains, particularly in forest systems, investigating responses to disturbances like fire, insect outbreaks, and climate variations (Li et al., 2022; Chambers et al., 2023; Rodríguez-Rodríguez et al., 2023; Yang et al., 2024; Garate-Quispe et al., 2024). With this in mind, social resilience refers to the capacity of communities, institutions, and governance systems to adapt, learn, and reorganize in response to social-ecological disturbances. It is underpinned by principles such as participation, learning and experimentation, and polycentric governance, which enable systems to absorb shocks, innovate, and transform. Social resilience complements biophysical resilience (e.g., diversity and redundancy) by addressing human dimensions, including information exchange, and institutional flexibility to sustain functionality and well-being under uncertainty (Biggs et al., 2012; Behboudian et al., 2023).

Resilience is a complex concept describing a system's ability to respond and adapt to disturbances (Biggs et al., 2012; Tampekis et al., 2023; Behboudian et al., 2024). Biggs et al. (2012) proposed seven pivotal resilience principles: maintaining diversity and redundancy (P1), managing connectivity (P2), monitoring slow variables and feedback (P3), understanding systems as complex adaptive systems (CAS) (P4), encouraging learning and experimentation (P5), broadening participation (P6), and promoting polycentric governance systems, for enhancing, building, and evaluating resilience (P7) in social-ecological systems. Scholarly investigations have employed diverse methodological approaches, including index-based frameworks (Bryant et al., 2019), landscape modeling (Mina et al., 2022), remote sensing techniques (Yang et al., 2024), and scenario-building strategies (Sarkki et al., 2017; Sakellariou et al., 2023), to assess and enhance the system's resilience. The overarching objective of most resilience research studies is to develop adaptive management strategies that enable ecological and social-ecological systems to navigate increasingly complex environmental challenges, with a critical focus on understanding and enhancing their capacity to persist and transform in response to dynamic global changes (Baho et al., 2017; Cantarello et al., 2017; Turner et al., 2022; Nikinmaa et al., 2023; Sakellariou et al., 2023).

Encouraging learning and experimentation (P5), broadening participation (P6), and promoting polycentric governance (P7) (Biggs et al., 2012; Behboudian et al., 2023) are critical for evaluating social resilience because they address the human and institutional capacities necessary to navigate uncertainty and change. Learning enables communities to adapt by integrating new knowledge from past disruptions and fostering innovation in crisis response. Participation ensures inclusive decision-making, empowering diverse stakeholders to contribute their perspectives and resources. Polycentric governance, with its nested and networked structure, allows for flexible, multi-scale coordination, improving responsiveness to localized and systemic challenges. Together, these three principles strengthen a system's ability to self-organize, recover, and transform in the face of shocks, ensuring long-term social resilience (Behboudian et al., 2021).

Tropical forests are increasingly recognized as social-ecological

systems, where ecological dynamics and human governance, livelihoods, and cultural practices are deeply intertwined (Berkas et al., 2000; Folke et al., 2005; Ostrom, 2009; Chazdon and Guariguata, 2016). Resilience in tropical forest systems (TFSs) cannot be fully understood through engineering and ecological perspectives alone. Social factors play a pivotal role, as forests directly benefit human communities while being significantly influenced by human activities (Berkas et al., 2000; Folke et al., 2005). Incorporating social considerations alongside ecological and engineering approaches provides a more holistic understanding of resilience, especially when addressing interconnected human-environment systems (Ostrom, 2009; Liu et al., 2007). A comprehensive assessment of forest resilience necessitates the integration of three core social resilience principles (3SRPs) (Biggs et al., 2012): (i) learning and experimentation, which considers the dynamic nature of the systems and necessitates a continuous updating of knowledge through experimentation and systematic monitoring (Armitage et al., 2008); (ii) participation, which emphasizes inclusive stakeholder engagement in decision-making (Reed et al., 2018); and (iii) polycentric governance, which supports coordinated actions across multiple governing bodies at different levels (Nagendra and Ostrom, 2012).

TFSs are vulnerable to unanticipated problems like severe droughts, and their adaptive management depends on encouraging learning and experimentation (P5). Stakeholders can investigate cutting-edge methods of resource management and restoration through ongoing learning, which will increase the resistance of TFSs under disruptions (Chazdon et al., 2016). Broadening participation (P6) is another important principle that is crucial to guarantee the representation and appreciation of the viewpoints of indigenous peoples and local communities. This kind of involvement encourages shared ownership of forest management techniques, lowers conflict, and improves sustainability (Tengö et al., 2014). Finally, promoting polycentric governance (P7) makes it easier for local, regional, and national stakeholders to coordinate. This method offers the adaptability required to tackle various scale-specific issues in TFSs (Galaz et al., 2008). In light of this, local villages oversee forest areas under government supervision, adhering to explicit guidelines for roles and resource distribution among several tiers of government. By encouraging collaborations between different stakeholders, decision-making networks between the stakeholders improve the polycentric governance. The decision-making can be improved by identifying key stakeholders and streamlining information flow through the use of methods such as social network analysis (SNA) (Bodin et al., 2016; Emami-Skardi et al., 2021; Sharifian et al., 2022).

Encouraging learning and experimentation (P5) is a vital principle for the adaptive management of tropical forest systems, which are inherently dynamic and subject to unforeseen challenges such as climate change or socio-economic shifts. By fostering an environment of continuous learning, stakeholders can explore innovative approaches to restoration and resource management, thereby enhancing the resilience of TRFs to disturbances. For instance, adaptive management frameworks serve as a practical tool by incorporating pilot projects in reforestation programs. These projects test the resilience of various tree species to changing rainfall patterns, relying on an iterative process of monitoring, feedback, and adjustments to refine outcomes over time.

Similarly, community-led monitoring programs empower local populations to take an active role in biodiversity, carbon sequestration, and water resource tracking. Citizen science initiatives, supported by scalable tools like mobile applications, enable communities to collect and share vital data with policymakers, bridging the gap between grassroots knowledge and decision-making. Cross-sector knowledge exchange further enhances these efforts by bringing together indigenous knowledge holders, scientists, and policymakers. Through workshops and collaborative platforms, these groups can co-design forest management plans that integrate diverse perspectives and expertise.

Broadening participation (P6) underscores the importance of inclusive decision-making to ensure that a variety of perspectives,

particularly those of indigenous peoples and local communities, are represented and valued. Such participation not only fosters trust and cooperation but also promotes shared ownership of forest management practices, reducing conflicts and enhancing sustainability. Stakeholder mapping and engagement provide a structured approach to this inclusivity, actively involving farmers, loggers, conservationists, and government agencies in land-use planning. Participatory tools like focus groups and consensus-building workshops can facilitate collaboration and ensure all voices are heard.

Community-based forest management programs, like those in Brazil's Amazon (de Andrade et al., 2022), exemplify this principle by granting local communities co-management rights to forest areas. These initiatives incentivize sustainable practices and empower cooperatives through financial and technical support, enabling equitable decision-making and sustainable harvesting. Similarly, participatory budgeting models offer community members the opportunity to decide how conservation funds are allocated, whether for ecotourism infrastructure or reforestation projects. Transparent mechanisms for fund tracking ensure accountability and build trust among stakeholders.

Promoting polycentric governance (P7) integrates multiple levels of authority, facilitating coordination across local, regional, and national stakeholders. This approach provides the flexibility needed to address diverse and scale-specific challenges in TFSs. Decentralized forest governance models, such as Indonesia's community forestry programs, demonstrate the power of this approach. In these programs, local villages manage forest areas under government supervision, guided by clear protocols for responsibilities and resource-sharing among different governance levels.

Collaborative decision-making networks further enhance polycentric governance by fostering partnerships between diverse stakeholders (Ahmadi et al., 2019; Arabatzis et al., 2024). For example, multi-stakeholder forums in Costa Rica bring together conservation NGOs, government agencies, and private landowners to develop joint reforestation policies (Wallbott and Florian-Rivero, 2018). Using tools like network analysis, these forums identify key actors and streamline information flow to optimize decision-making. Additionally, integrated land-use planning leverages Geographic Information Systems (GIS) to visualize land-use trade-offs, enabling agricultural, urban, and conservation planners to collaborate effectively at a landscape level, as seen in the Amazon basin. (Young and Gilmore, 2017).

These principles are essential for bridging the gap between ecological resilience (maintaining diversity and redundancy, managing connectivity, monitoring slow variables and feedback, fostering systems as complex adaptive systems) and societal needs, ensuring that forest management strategies are sustainable and equitable (Biggs et al., 2012).

To analyze an issue from a social perspective, it is necessary to examine the relationships among individuals within society and the interactions between society and the environment, particularly in tropical forests. Regarding this point, a comprehensive social study of the interplay between forests and society should consider four key dimensions: a) the impact of forest conditions (e.g., biodiversity and ecosystem health) on the well-being and practices of dependent communities; b) the effects of human activities like urbanization and resource extraction on forest health; c) the role of stakeholder interactions, including conflicts and collaborations, in influencing forest management and sustainability; and d) the reciprocal influence of forests in shaping stakeholder dynamics, either fostering cooperation or exacerbating conflict among diverse groups, including local communities, government agencies, non-governmental organizations (NGOs), and private entities. Other factors such as economic context, historical context, policy impacts, incentive mechanisms, and adaptive management might be taken into account in forest systems (Skardi et al., 2020; Emami-Skardi et al., 2021).

If a study addresses all of the above-mentioned four key dimensions, it can be considered a social study of forest-related dynamics. However,

it is important to recognize that the scope and social depth of such studies can vary significantly. Depending on the level of analysis and focus, studies may fall into different categories or classes, ranging from localized assessments to broader, system-wide investigations.

Despite their importance, social resilience principles mostly remain inadequately addressed in the literature (Biggs et al., 2012; Behboudian et al., 2023). Previous studies have largely focused on ecological and physical criteria (Holling, 1973; Folke et al., 2005), with only a minority incorporating social resilience principles. Even among those that incorporate social criteria, the focus is typically limited to just one principle, neglecting the interconnectedness of learning, participation, and governance. This narrow focus has hindered the development of integrated frameworks that reflect the multifaceted nature of TFSs and their interactions with human communities. This review addresses this gap by systematically evaluating the application of all seven resilience principles (P1-P7) in tropical forest studies, with a main focus on social dimensions (P5-P7).

1.3. Study aims

The specific objectives are: (i) to review and analyze previous studies regarding resilience assessment and resilience-related criteria evaluation in TFSs, with a particular focus on principles related to social resilience; (ii) to identify the most studied tropical forest disturbances; and (iii) discuss the limitations of previous studies in forest resilience, including gaps in applying social resilience principles, and examine the intellectual structure of the field using co-citation analysis to suggest directions for future research. Through a systematic analysis of the literature, existing challenges and opportunities are identified for integrating social principles into resilience assessments with a particular focus on principles related to social resilience, where applicable, to assess the degree to which these dimensions are represented within the broader landscape of tropical forest resilience studies.

2. Materials and methods

This systematic review paper follows the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, widely acknowledged as an effective tool for conducting literature reviews (Page et al., 2021). The “Web of Science” and “Scopus” databases from 2000 to 2024 were used in the data retrieval process. To ensure consistency, identical search strings were employed simultaneously across both databases. Searches were performed within the titles, abstracts, and keywords of relevant literature. Exclusions were applied to non-English articles and grey literature, such as book sections and dissertations, due to inconsistent reporting of social-ecological linkages. Utilizing a high sensitivity but low specificity search strategy, the search string was meticulously devised to encompass resilience assessment and ecosystem services in forest systems. The keywords employed in the specified databases included “resilience”, “forest”, and “ecosystem services”, which led to the finding of 2642 papers ultimately. This precision in the search strategy ensured that only the most relevant literature was included in the study. The broad initial search followed best practices for systematic reviews of complex socio-environmental systems (Knight et al., 2021), while subsequent screening ensured precision through geographic (tropical) and biome filters, Methodology filters (empirical assessments), and social-ecological integration criteria.

During the screening stage, the title, abstract, and keywords of the retrieved papers were investigated to select relevant papers. The screening criteria are as follows.

1. The articles must consider at least one of the three main resilience concepts (engineering, ecological, and social-ecological) in Tropical Forest Systems (TFSs).

2. The article should utilize a resilience assessment method in tropical forests.
3. The language of the papers should be English.

Following the title, abstract, and keywords screening process, only 61 records were retained. In the next step, and as a result of utilizing two databases, several duplicate papers were identified after taking the screening tools into account. These papers were stored in an Excel sheet for duplicate detection. Following the elimination of duplicates after screening all papers, 49 records remained. As depicted in Fig. 3, these 49 papers were deemed suitable for an in-depth review in the final stage, investigating the consideration of the social-related principles and the considered disturbances (i.e., droughts, fire, and land use change) in TFSs.

For each paper, we coded: (1) resilience concept (engineering/ecological/social-ecological), (2) disturbances studied, and (3) principles applied (P1-P7). Social principles (P5-P7) were operationalized as P5 (Learning and experimentation), P6 (Participation), and P7 (polycentric governance). To identify whether a paper addressed the social resilience principles, including learning and experimentation (P5), participation (P6), and polycentric governance (P7), a full-text review of each article has been conducted. Papers were coded manually using a qualitative content analysis approach. Indicators of P5 included information exchange (Behboudian et al., 2023), centrality measures (i.e., in-degree centrality), knowledge sharing, and learning approach (Emami-Skardi et al., 2021). P6 was identified through explicit reference to community engagement, participatory decision-making, interest in cooperation, or stakeholder inclusion (Biggs et al., 2012). Finally, P7 was coded when studies mentioned multiple governance levels, polycentric governance, institutional coordination, centrality-based indicators (i.e., betweenness), or decentralized forest management (see Table S3 in the supplementary material). To ensure consistency, a subset of papers ($n = 10$) was independently reviewed and cross-coded by two team members, resolving discrepancies via consensus.

Given the importance of stakeholder relationships in social resilience, we used social network analysis (SNA) and its results (i.e., centrality measures) as an analytical framework to assess how interactions among actors were represented in the reviewed studies (Biggs et al., 2012; Emami-Skardi et al., 2021; Behboudian et al., 2023). Specifically, we looked for references to centrality indicators, such as in-degree, out-degree, betweenness, and bridging roles, as proxies for participation levels (P6), knowledge exchange (P5), and institutional coordination (P7) (Ahmadi et al., 2019; Emami-Skardi et al., 2021). Centrality metrics were coded only where explicitly used or where relational dynamics could be reasonably inferred based on reported interactions. More details about centrality measures and SNA can be found in Ahmadi et al. (2019).

The review encompassed publications from 2000 to 2024 to achieve three objectives. The first objective is historical context that captures foundational ecological resilience studies (pre-2012) alongside post-2012 social-ecological integrations (Biggs et al., 2012). Secondly, temporal trends identify shifts in methodological approaches (e.g., from qualitative frameworks to mixed-methods; see Section 3.1.1). Finally, completeness ensures representation of long-term case studies (>10 years) that are critical for assessing resilience (Seddon et al., 2016). This extended period is appropriate to contextualize recent advances in social-ecological resilience within the broader trajectory of forest resilience research.

While the inclusion criteria allowed papers focusing on any of the three primary resilience concepts (engineering, ecological, or social-ecological), the analysis specifically tracked whether social resilience principles (P5–P7) were addressed, regardless of a study’s primary resilience framework. This approach allows for understanding how frequently social dimensions appear in the wider resilience literature on TFSs, even if not as the central focus.

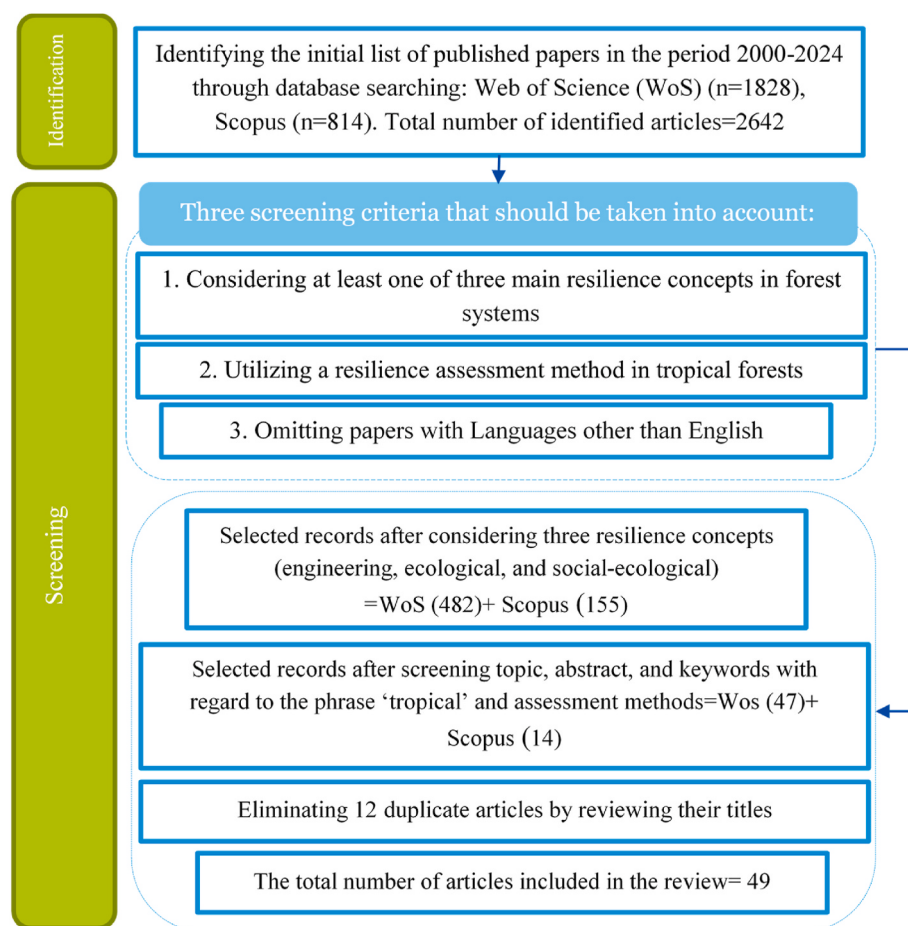


Fig. 3. A flowchart of selecting articles for in-depth review based on the PRISMA framework (The initial search yielded 2642 records using the search strings detailed in Section 2.).

3. Results

3.1. Statistical analysis

3.1.1. Spatiotemporal distribution of tropical forest systems' resilience studies

Fig. 4 presents the publication time distribution of the 49 papers selected for the systematic review. These papers discuss different resilience assessment methods and criteria developed for tropical forests.

About 58% of the selected papers were published after 2019. This trend underscores the growing recognition of the significance of incorporating resilience assessment aspects into tropical forest systems (TFSS). It should be mentioned that although the literature search covered the period from 2000 to 2024, no studies meeting the inclusion criteria were published between 2000 and 2007.

This systematic literature review offers a global perspective, as reflected in the distribution of the case studies, with 29%, 25%, 18%, and 16% of the selected papers focusing on case studies located in North

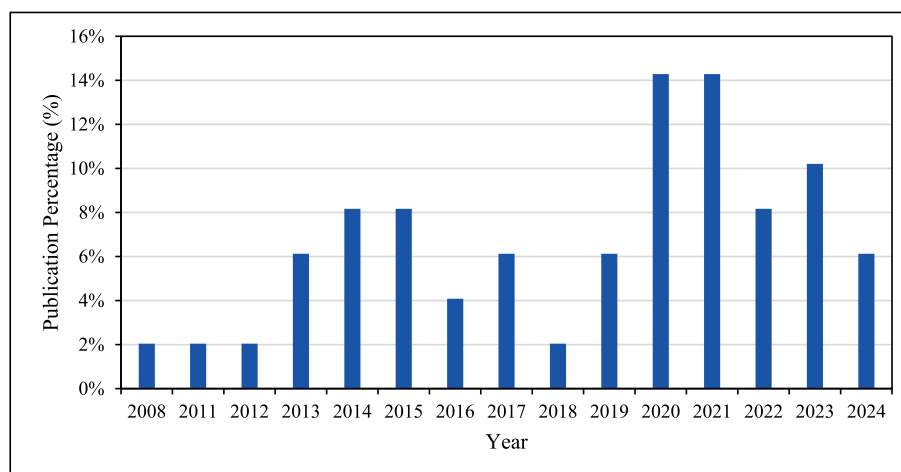


Fig. 4. The publication time distribution of the selected 49 papers for the systematic review.

America, Asia, Global-scale, and South America, respectively (Fig. 5). The predominance of studies in North America and Asia suggests a regional bias, potentially driven by funding availability, institutional priorities, or the presence of large-scale tropical forest ecosystems (geographical clusters). For example, North America's leadership in governance and environmental strategies (Amaris and Ruiz, 2023) may explain its high representation, while Asia's focus on fire and land use change reflects regional environmental pressures. Conversely, the underrepresentation of South America, despite hosting the Amazon basin (Piponiot et al., 2019), highlights a critical gap in research coverage for one of the most biodiverse regions, and only 16% of studies have considered these areas. The five most frequently considered countries for case studies are China, Indonesia, Costa Rica, and Brazil (Fig. 5).

3.1.2. Primary resilience approach

Regarding the resilience concept, most of the selected papers have focused on ecological resilience (79.6%), and less on engineering (24.5%) and social-ecological (16.0%) resilience. Furthermore, only 6% of reviewed papers have considered engineering and ecological resilience concepts together, while 14% have simultaneously applied the principles of ecological and social-ecological resilience. There are no papers that have jointly evaluated the three primary resilience approaches (i.e., engineering, ecological, and social-ecological concepts). This indicates that practically every research study that uses the idea of social-ecological resilience has properly evaluated both ecological and social aspects. In general, the engineering and, more specifically, the social-ecological resilience have not been sufficiently evaluated in the previous research, even though for the forest system, both social and ecological factors should be considered in resilience assessment. The percentage of papers that have considered different resilience concepts is presented in Table 1. Three distinct typologies emerge: (1) Ecological-centric (79.6% of studies), focusing on biophysical metrics; (2) Hybrid (14%), integrating ecological and social dimensions; and (3) Engineering-driven (24.5%), emphasizing stability. While 79.6% of studies focused on ecological resilience (P1-P4), only 16% incorporated social-ecological resilience (P5-P7). However, among social-ecological studies, 87% also addressed ecological principles, suggesting nascent integration (Table 1)

3.1.3. Disturbances affecting tropical forest systems (TFSs)

Fig. 6 illustrates the distribution of key stressors impacting tropical forests, as identified in the reviewed literature, across different continents and globally. The figure highlights six primary types of disturbances, including climate change, fire, insect outbreaks, drought, land use change, and wind disturbances. Among these disturbances, climate change and fire appear as the most extensively studied disturbances

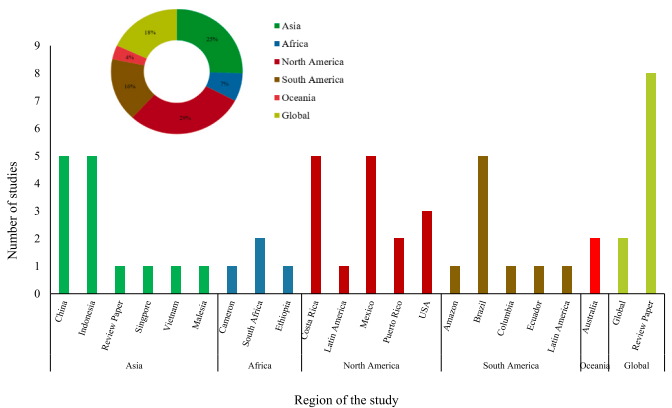


Fig. 5. Continent-Country scale spatial distribution of case studies of the reviewed papers (Global and Review Paper in the x-axis represent the global scale of the research, and the type of the study.).

Table 1
The percentage of papers that have considered different resilience concepts.

Concept	The % of reviewed papers		
	Engineering Resilience	Ecological Resilience	Social-Ecological Resilience
Engineering Resilience	24.5	6	0
Ecological Resilience	6	79.6	14
Social-Ecological Resilience	0	14	16

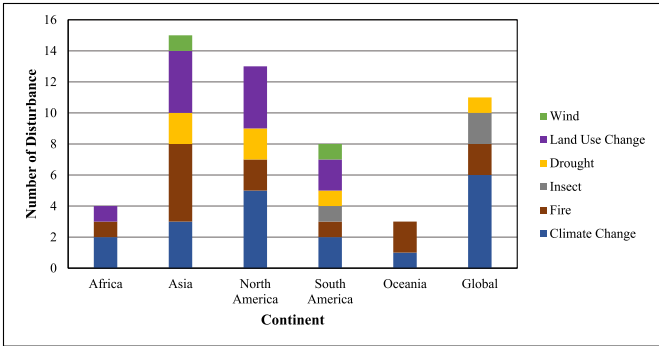


Fig. 6. Number and type of disturbances affecting tropical forests worldwide.

globally (35% and 24%, respectively), with notable research emphasis in Asia and North America. Drought and land use change are also featured prominently in the analysis, particularly in Asia and South America. Conversely, wind disturbances and insect outbreaks have been relatively less studied but are still significant in specific regions such as North America. However, certain critical disturbances such as forest clearing (Chazdon and Guariguata, 2016) and hunting (Tagg et al., 2020) have been rarely studied in the tropical forest resilience literature. These underrepresented disturbances warrant further investigation to provide a more comprehensive understanding of their impacts on TFSs.

The analysis of the literature review highlights that Asia accounts for the highest number of case studies (15), primarily focused on disturbances caused by fire, land use change, and climate change. North America follows closely with 13 studies, emphasizing climate change, land use change, and fire. Studies in South America, home to vast tropical forests, exhibit a more balanced focus on disturbances, with a notable number of studies dedicated to investigating climate change and land use change. Africa encompasses relatively fewer case studies, with climate change being the most prominent studied disturbance. Oceania has a minimal number of studies, with disturbances primarily attributed to fire and climate change. On a global level, climate change emerges as the most studied disturbance, followed by insects and fire, underscoring their overarching impact on tropical forests worldwide. In a country-scale analysis, Indonesia has investigated the highest number of disturbances related to fire, while studies in the USA have focused on the impacts of climate change. Conversely, countries such as Ethiopia and Vietnam have scrutinized very few disturbances across all categories, highlighting significant variability in the distribution of environmental stresses globally.

3.2. Application of the resilience principles

The number of reviewed papers using the seven core resilience principles is presented in Fig. 7. The selected papers have mostly focused on ecological principles, i.e., P1, P2, P3, and P4 (respectively 55%, 20%, 43%, and 61%). Only 18%, 23%, and 14% of the reviewed papers have taken social-based resilience principles, i.e., P5, P6, and P7,

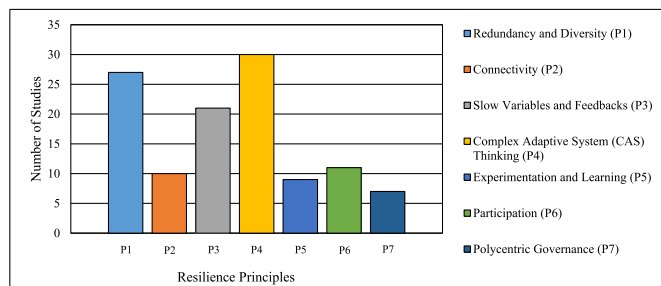


Fig. 7. The number of reviewed papers that have addressed any of the seven core resilience principles.

respectively, into account. A detailed description of the mentioned principles can be found in the supplementary material. Furthermore, a comprehensive overview of the selected papers in terms of the author(s), publication year, study area, resilience concepts, disturbances, and core resilience principles that have been used for resilience assessment in tropical forests is presented in Table S2 in the supplementary material. Notably, 42 studies (e.g., Galván-Cisneros et al., 2023; Benítez et al., 2023) successfully bridged ecological and social resilience dimensions, validating the search strategy's precision in identifying integrated frameworks.

Our analysis reveals a relatively limited evaluation of three social resilience principles, including encouraging experimentation and learning (P5), encouraging participation (P6), and promoting polycentric governance (P7) within the context of social network analysis and stakeholder analysis methods.

Experimentation and learning (P5), investigated in nine studies, has been largely overlooked, despite its essential role in enabling adaptability and innovation in resilience strategies. Available studies have primarily focused on qualitative assessments of P5, with little consideration given to the application of centrality indices, such as in-degree centrality, to evaluate this principle. These studies have investigated, for example, the local inhabitants' shared knowledge about ecosystem services; qualitatively assessed the preferences for specific vegetation types in neighborhoods; and envisioned the role of conservation NGOs as bridging organizations, which enables fostering alliances between stakeholders and facilitates information transfer about incentives.

Participation (P6), addressed by 11 out of 49 studies, requires additional research into participatory governance and community involvement as resilience mechanisms. A closer look at these studies reveal that while P6 have been qualitatively examined, a systematic method have not been developed to assess stakeholder involvement or collaboration. Similarly, elevating the status of naturally regenerating forests to a legitimate land use is suggested as a means to integrate multiple stakeholders into social-ecological processes, overcoming the stigmas of degradation and abandonment. Despite these valuable insights, the absence of quantitative methods or structured frameworks for evaluating P6 highlights a critical gap.

Polycentric governance (P7) principle appears in only seven studies, signaling the least attention among all principles, despite its potential for fostering flexibility and coordination across scales. For promoting polycentric governance, the literature underscores the importance of considering social, legal, economic, and political factors that influence governance systems. It also emphasizes the role of scientific studies in demonstrating how forests contribute to ecosystem services, such as maintaining environmental quality through carbon sequestration and regulating water and energy cycles. Moreover, the need for appropriate governance instruments to mitigate land-use conflicts and promote sustainable outcomes is a recurring theme (Biggs et al., 2012). Therefore, deeper insights into stakeholder interactions, participation dynamics, and quantitative approaches to evaluate polycentric governance are needed (Arabatzis et al., 2024). Despite these contributions, the lack of quantitative metrics highlights an opportunity to advance the

evaluation of P5, P6, and P7 by integrating social network analysis techniques and centrality indices.

The few studies (4 out of 49) that addressed all three social resilience principles (P5–P7) share several notable features. These include the use of mixed-method approaches combining qualitative and quantitative tools, explicit attention to stakeholder dynamics and power relations, and a multi-level governance framework. For instance, Santillán-Carvantes et al. (2023) used a holistic approach to mapping social-ecological land systems that incorporates multiple dimensions, including physical, biological, and socio-economic factors, to inform sustainable development strategies. They applied limited participation, adaptive management, governance structures, local engagement, and governance interactions. Such studies offer valuable examples of how to operationalize an integrated approach to social resilience in tropical forest contexts.

The limited inclusion of social resilience principles (P5–P7) in tropical forest studies, with only 16% adopting a social-ecological approach, reflects a persistent disciplinary divide in resilience research. This gap exists despite decades of theoretical consensus that forests function as coupled human-natural systems (Berkes et al., 2000; Folke et al., 2005) and empirical evidence demonstrating that polycentric governance (P7) directly mediates forest recovery rates (Chazdon and Guariguata, 2016), Participation (P6) reduces conflict and improves compliance (Nagendra and Ostrom, 2012), and Learning and Experimentation (P5) fosters adaptation to climate shocks (Reyes-García et al., 2019).

Our findings align with broader critiques of 'social blindness' in resilience assessments and reveal tropical forests as a critical frontier for integration. For instance, among the few studies that did apply social-ecological frameworks (e.g., Santillán-Carvantes et al., 2023; Tanguay and Bernard, 2020), reported enhanced adaptive capacity through co-designed monitoring systems (linking P5 and P3), nested governance institutions (P7 operationalization), and equity-focused benefit sharing (P6 implementation).

The reviewed literature demonstrates varying degrees of engagement with the seven core resilience principles in social-ecological systems. Complex adaptive system (CAS) thinking (P3) is the most frequently addressed principle, with 30 studies incorporating it. This highlights its centrality in framing social-ecological systems as dynamic and interlinked networks requiring holistic approaches. The principle of redundancy and diversity (P1) is the second most frequently addressed, featured in 27 studies, indicating its foundational role in bolstering resilience by ensuring system robustness through overlap and functional diversity. The principle of slow variables and feedback (P3) appears in 21 studies, suggesting a moderate focus on the importance of understanding gradual changes and their long-term impacts on systems. Connectivity (P2), discussed in 10 papers, plays a critical role in maintaining adaptive capacities, though it remains underexplored compared to redundancy (P1).

The uneven distribution of focus across principles underscores the challenges and opportunities for future research. While redundancy (P1), CAS thinking (P4), and slow variables (P3) are relatively well-explored, significant gaps remain in social resilience principles, i.e., participation (P6), governance (P7), and learning and experimentation (P5). These gaps highlight the need for more comprehensive studies that integrate underrepresented principles, ensuring a balanced and systematic application of resilience thinking in social-ecological systems. Expanding such research would not only deepen theoretical understanding but also provide practical frameworks for addressing real-world challenges.

3.3. Evaluation of the selected papers according to their journals and citations

Studies focusing on resilience in TFSs have been published in 30 different journals. Table 2 provides an overview of the journals of the reviewed journal papers and their impact factors. The SCImago Journal

Table 2

Details of the journals in which the selected papers have been published.

Journal name	SCImago Journal Rank (SJR)	Quartile*	Impact Factor (IF)	Author(s)	No. of papers
Forest Ecology and Management	1.531	Q1	5.3	Benítez et al. (2023) Galván-Cisneros et al. (2023) Piponirot et al. (2019) Mesa-Sierra et al. (2020) Zanini et al. (2021) Ding and Zang (2021) Meli et al. (2017) Yang et al. (2024) Chen and Chen (2021)	9
Global Change Biology	4.327	Q1	10.863	Sala and Maestre (2014) Brando et al. (2019)	2
Ecological Applications	1.946	Q1	5.317	Rosenfield et al. (2023) Montoya et al. (2021) Hapsari et al. (2018)	3
Remote Sensing of Environment	3.851	Q1	13.8	Smith et al. (2014) Xie et al. (2023) Meng et al. (2021)	3
Biological Conservation	2.527	Q1	6.021	Brosi et al. (2008) Willis et al. (2013)	2
Conservation Biology	2.629	Q1	7.862	Cajaiba et al. (2020) Kleinschroth and Healey (2017)	2
Global Ecology and Biogeography	3.055	Q1	6.73	Freudenberger et al. (2012) Townsend and Masters (2015)	2
Environmental Management	1.304	Q2	4.865	Islam et al. (2020) Santillán-Carvantes et al. (2023)	2
Landscape and Urban Planning	2.696	Q1	8.119	Drillet et al. (2020)	1
Ecological Indicators	1.841	Q1	6.263	Sun et al. (2013)	1
Environmental Reviews	2.326	Q1	10.02	Soubry et al. (2021)	1
Urban Forestry & Urban Greening	1.286	Q1	4.885	Rockwell et al. (2022)	1
Biotropica	0.925	Q1	2.967	Chazdon and Guariguata (2016)	1
Nature Climate Change	8.118	Q1	28.66	Flores and Staal (2022)	1
Journal of Hydrology: Regional Studies	0.905	Q2	4.069	Dutra et al. (2022)	1
Science Advances	6.239	Q1	14.95	Reid et al. (2017)	1
Nature	15.993	Q1	47.728	Seddon et al. (2016)	1
Journal of Applied Ecology	2.924	Q1	6.938	Şekercioglu et al. (2015) Medeiros et al. (2024)	2
Quaternary Science Reviews	1.936	Q1	4.983	Biagioni et al. (2015)	1
Geoderma	1.959	Q1	6.114	Carrillo-Saucedo and Gavito (2020)	1
Biodiversity and Conservation	1.023	Q1	3.791	Tagg et al. (2020)	1
Sustainability Science	1.598	Q1	5.349	Munoz-Erickson et al. (2014)	1
Agricultural Systems	2.285	Q1	6.12	Tscharntke et al. (2011)	1
Agroforestry Systems	0.587	Q1	2.453	Tanguay and Bernard (2020)	1
Frontiers in Ecology and Evolution	1.452	Q1	4.493	Ramdzan et al. (2022)	1
Ecological Engineering	1.317	Q1	4.9	McKenna et al. (2019)	1
Marine Policy	1.414	Q1	4.96	Sale et al. (2014)	1
Ecology and Society	1.242	Q1	4.404	Boissière et al. (2013) González-Cruz et al. (2015)	2
Agriculture, Ecosystems & Environment	2.349	Q1	6.576	Picasso and Pizarro (2024)	1
Ecosphere	1.01	Q1	2.878	Zinnert et al. (2021)	1

Rank (SJR) serves as a metric for assessing the validity and quality of the reviewed articles (Nazari and Kerachian, 2024). The reviewed papers have been mostly published in the Forest Ecology and Management (9 papers), Ecological Applications (3 papers), and the Remote Sensing of Environment (3 papers). Only two of the selected papers were published in Q2 journals, while the majority were published in Q1, according to the Quartile ranking scale. Journals with the highest impact factors include Nature (IF = 47.73) and Nature Climate Change (IF = 28.66). Global-scale studies are given priority by high-impact journals like Nature, whereas applied ecology is the main focus of regional magazines like Forest Ecology and Management.

To provide better network visualization and capture the connections between the key papers and authors over time, we have utilized the VOSviewer software (Van Eck and Waltman, 2010) for investigating the collected papers from the Web of Science. According to the citation network of the 49 reviewed papers, which illustrates the citation link between every two items where one item cites the other, only four papers have cited each other (Sun et al., 2013; Chazdon and Guariguata, 2016; Meli et al., 2017; Hapsari et al., 2018). It can be connected to Fig. 4, where there are more publications after 2019. In other words, the

surge in publications after 2019 coincides with the IPCC's emphasis on ecosystem resilience, suggesting policy-driven research agendas. However, the lack of citation networks (only four papers cite each other) indicates fragmented knowledge exchange, necessitating stronger interdisciplinary collaboration.

In the next step, a co-citation network is presented (Fig. 8) where items (i.e., reviewed papers) are connected based on being cited together by other items. This network analysis helps identify influential references and conceptual linkages, providing valuable insights into the intellectual structure and recurring themes across the reviewed literature. Nodes in the network represent individual references, with their size reflecting citation frequency and their connections indicating co-citation relationships. The color-coded clusters (thematic clusters) identify thematic groupings that highlight the key research areas or frameworks within the reviewed literature. For instance, the red cluster focuses on restoration ecology and related frameworks, while the green cluster represents ecosystem dynamics and resilience studies. The blue cluster appears to concentrate on broader ecological or methodological approaches. The representative papers for the red cluster (restoration ecology and tropical forest dynamics) are Chazdon, R.L. (2008),

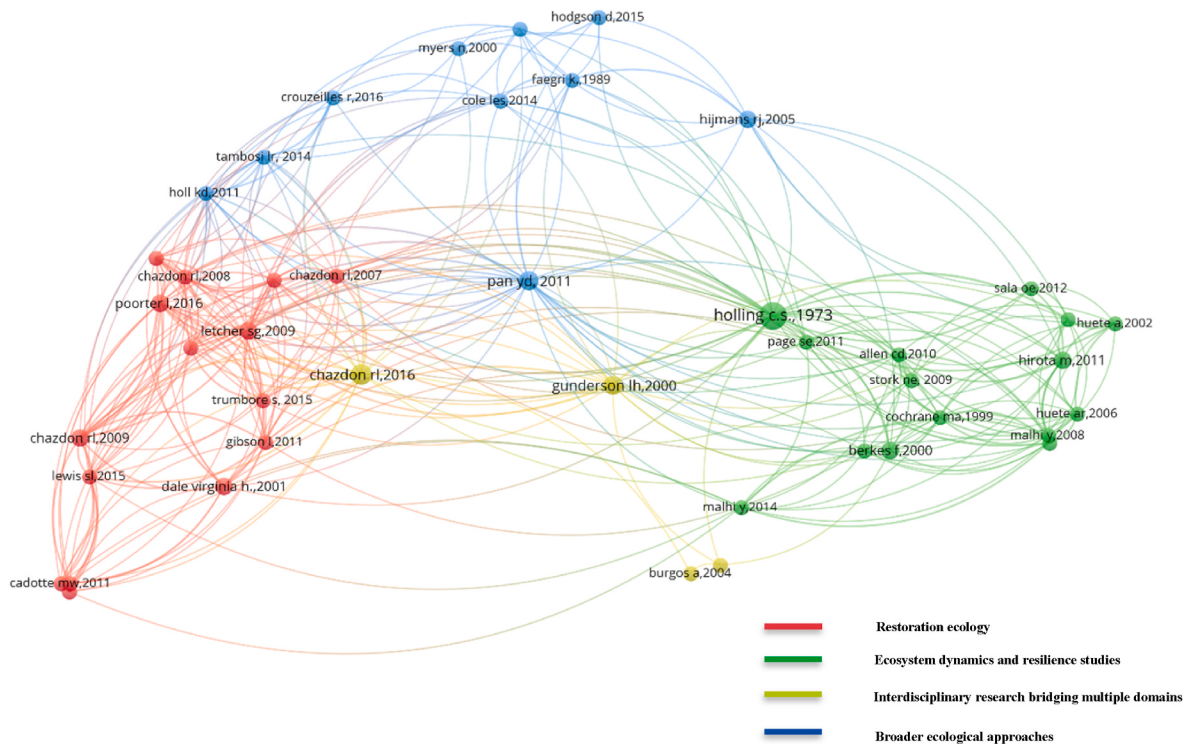


Fig. 8. Co-citation network with at least three citations. Different colors indicate different clusters and the nodes' sizes are proportional to the counts of the co-citations.

Chazdon et al., (2009), Letcher and Chazdon (2009), and Holl and Aide (2011). The green cluster (ecosystem dynamics and resilience) has Holling, C.S. (1973), Berkes et al. (2000), Gunderson, L.H. (2000), Hirota et al. (2011), and Malhi et al. (2014) as the most representative studies. Blue Cluster (climate and broader ecological approaches) contains ; Myers et al. (2000), Hijmans et al. (2005), Crouzeilles et al. (2016), and Cole et al. (2014) as the most important articles.

The red cluster (restoration ecology) dominates the literature, reflecting a strong focus on post-disturbance recovery, while the green cluster (ecosystem dynamics) underscores foundational theories like Holling's resilience framework. The blue cluster's emphasis on climate suggests growing interdisciplinary integration, yet the sparse overlap between clusters indicates siloed research approaches. It should be noted that restoration ecology (red cluster), ecosystem dynamics and resilience (green cluster), broader ecological approaches (blue cluster), and interdisciplinary research (yellow cluster) mostly align with P1 (redundancy and diversity), P3 (Slow variables and Feedback), P4 (CAS Thinking), and P6 (Participation)-P7 (polycentric governance), respectively (Table 3). While all these four clusters emphasize P1-P4, reflecting a biocentric approach, their neglect of social principles (P5–P7) underscores a disciplinary blind spot in participatory restoration frameworks.

Table 3
A summarize of cluster-resilience principle links in Fig. 8.

Cluster	Dominant Principles	Underrepresented Principles
Restoration Ecology (Red)	P1, P4	P5, P6, P7
Ecosystem Dynamics (Green)	P2, P3	P6, P7
Climate Studies (Blue)	P4	P5, P7
Interdisciplinary (Yellow)	P6, P7	P5 (quantitative methods)

4. Discussion

4.1. Limitations of resilience principles studies

Given the number and nature of disturbances stressing Tropical Forest Systems (TFSS), such as climate change, fire and drought (Fig. 7), and the alarming loss of tropical forests over the last decades (FAO, 2020), it is crucial to evaluate the resilience of TFSS regarding core principles of resilience and their related criteria. The accuracy of this assessment can be enhanced by using all crucial ecological and social resilience principles (Nikinmaa et al., 2023). These principles allow for considering social and ecological factors since a forest system is a social-ecological system. Furthermore, the co-citation network (Fig. 8) reveals four thematic clusters: restoration ecology (red), ecosystem dynamics (green), climate-focused studies (blue), and interdisciplinary work (yellow). The dominance of restoration ecology aligns with the high frequency of ecological resilience studies (79.6%), while the sparse overlap between clusters suggests disciplinary silos. Geographically, North American studies disproportionately address climate change (35%), whereas Asian cases emphasize fire and land use (24%), reflecting regional priorities. Methodologically, quantitative approaches dominate, yet social resilience principles (P5–P7) remain underrepresented, highlighting a need for mixed-methods frameworks.

Social resilience in TFSS is deeply shaped by how information, resources, and decisions flow among actors. Social network analysis (SNA) offers a powerful lens for capturing these dynamics (Ahmadi et al., 2019). Measures such as centrality and connectivity not only illuminate who holds influence or acts as a knowledge bridge, but also help operationalize principles like participation (P6) and polycentric governance (P7). Thus, incorporating network-based perspectives provides conceptual and practical tools for diagnosing social resilience (Behboudian et al., 2021). Recent approaches in considering the social aspects of resilience assessment (such as stakeholder analysis and social network analysis) have made it possible to define more efficient criteria for P5-P7 principles. In addition, the availability of numerical and simulation

models, remote sensing, and observational data makes it possible to include P1–P4 principles and significantly improve the accuracy of resilience evaluation and enhancement results.

The underrepresentation of social principles may reflect a disciplinary legacy that views forests as ecological rather than social-ecological systems. Only 6% of studies combined all three resilience concepts (Table 1), suggesting a fragmented epistemological framework. In addition, institutional incentives such as the preference for 'high-impact' ecological data in grant proposals and publications may marginalize social resilience research. For instance, only 2 of 49 papers were published in Q2 journals (Table 2), which often host interdisciplinary work. Finally, the scarcity of mixed-methods frameworks (e.g., combining agent-based modeling with participatory mapping) exacerbates the gap. Only Muñoz-Erickson et al. (2014) and Sale et al. (2014) bridged this divide, using game theory for P6–P7.

The underrepresentation of social principles (P5–P7) likely reflects disciplinary divides and methodological challenges (e.g., quantifying governance networks in Ahmadi et al. (2019)). Yet, their absence in 82% of studies (Fig. 7) underscores a critical gap, as tropical forests face escalating human pressures (FAO, 2020).

Beyond the observed frequencies, our findings highlight a conceptual disjunction in the tropical forest resilience literature. While ecological and engineering resilience are often operationalized through quantifiable metrics (e.g., biodiversity loss, recovery time), social resilience principles require interpretive frameworks that engage with power, agency, and institutional complexity. The marginal integration of P5–P7 suggests that resilience research on TFSs has yet to fully embrace the relational and political dimensions of social-ecological systems. This reflects a broader tension in resilience theory: between system-based approaches and actor-oriented perspectives. Addressing this gap offers a path toward more holistic and transformative resilience assessments.

Finally it should be mentioned that the limited number of studies that addressed all 3SRPs provide instructive cases for advancing resilience research. Their methodological diversity and commitment to inclusivity underscore the potential for richer, more context-sensitive assessments of social resilience. These cases suggest that adopting a systems-thinking approach, alongside stakeholder engagement and multi-level institutional analysis, is key to capturing the complexity of tropical forest systems.

4.2. Limitations of different social resilience assessments

Resilience in forest systems cannot be sufficiently explained by engineering and ecological perspectives alone. Despite being greatly influenced by human activity, forests directly benefit human populations, which makes social issues crucial. Combining ecological and engineering approaches with social considerations can yield a more thorough knowledge of resilience, especially when working with interconnected human-environment systems. A comprehensive assessment of forest resilience requires the integration of three core social resilience principles, including encouraging learning and experimentation (P5), broadening participation (P6), and polycentric governance (P7) for improving the resilience and sustainability of TFSs. However, their limited incorporation in the reviewed studies (18%, 23%, and 14% in Fig. 8) highlights a significant research gap. Tropical forests are highly dynamic and complex systems facing immense uncertainties due to climate change, deforestation, and socio-economic pressures. Integrating continuous learning and experimentation (P5) in tropical forest management will enable adaptive strategies that respond effectively to changing conditions and enhance restoration success. Similarly, broadening participation (P6) ensures that the perspectives and interests of diverse stakeholders, such as local communities, conservation organizations, and policymakers, are incorporated into decision-making processes, fostering cooperative actions for sustainable forest management. Adopting polycentric governance frameworks (P7), characterized by multiple interconnected governing authorities at different scales, is

especially important in TFSs, as it promotes governance flexibility and coordination across local, regional, and global levels. Emphasizing these principles in future research will strengthen the foundation for managing tropical forests sustainably in the face of increasing challenges and disturbances. In recent years, there has been good development in improving the accuracy and application range of resilience evaluation methods (Fig. 4). Therefore, more resilience-based criteria and sub-criteria can be taken into account in TFSs.

The underrepresentation of social resilience principles (P5–P7) in the literature (i.e., only 7 out of 49 studies addressing P7) (Table S2) and none applying quantitative metrics like centrality indices for P5, reflects deeper methodological and regional biases. Fig. 6 highlights how regional threats (e.g., fire in Asia, climate change in North America) disproportionately shape research priorities, favoring ecological modeling (P1–P4) over participatory governance (P6–P7). For instance, while 24% of Asian studies focused on fire disturbances (Fig. 6), none employed social network analysis to evaluate stakeholder collaboration (P6), revealing a disconnect between localized threats and holistic solutions. This pattern suggests that methodological inertia (e.g., reliance on remote sensing for P1–P4) and institutional preferences for quantifiable data marginalize social dimensions, even in regions like Indonesia and Brazil where stakeholder conflicts are central to deforestation (Section 3.1).

As mentioned earlier in Section 3.1, China, Indonesia, Costa Rica, and Brazil are the most considered countries as the location of the case studies in the literature review. For instance, China's tropical forests face severe fragmentation due to agricultural expansion, infrastructure development, and urbanization, leading to significant biodiversity loss (Sasaki et al., 2024). Furthermore, Indonesia has one of the highest rates of deforestation, primarily due to palm oil plantations and illegal logging (Cisneros et al., 2021). Additionally, peatland fires exacerbate carbon emissions and cause significant ecological damage (Edwards et al., 2020). Costa Rica's tropical forests face threats from climate change, leading to shifts in biodiversity and the extinction of endemic species, such as the golden toad (Ferreira, 2024). Brazil faces massive deforestation in the Amazon due to logging, agriculture, and infrastructure projects like highways and dams (Pinto et al., 2024). These activities significantly affect global carbon cycles and biodiversity. Finally, deforestation due to agricultural expansion, cattle ranching, and infrastructure development puts Mexico's tropical forests under significant pressure (Durand and Lazos, 2004). Although programs like Reducing Emissions from Deforestation and Forest Degradation (REDD) aim to combat deforestation and promote sustainable forest management, they face technical, legal, and governance challenges (Guizar-Coutiño et al., 2022).

The focus on countries with high deforestation rates (e.g., Brazil) may skew research toward ecological crises (P1–P4) rather than governance solutions (P7), as local stakeholders are often excluded from policy design (Guizar-Coutiño et al., 2022), and leads the research trend toward a case study bias. Another challenge regarding the social principles evaluation can be attributed to data accessibility. While remote sensing enables global-scale resilience monitoring (P1–P4), social data (e.g., for P5–P7) remains hyper-local and rarely interoperable, hindering comparative analyses.

Given the involvement of diverse stakeholders from sectors such as agriculture, municipal services, industry, and the environment in multi-purpose forest-based ecosystem services, it is advisable to develop operating policies that account for their conflicting interests and the impacts of their decisions on TFSs. In addition, given the growing significance of addressing disputes in service usage in forests under extreme events, it is essential to incorporate social aspects into the management of TFSs. The social aspects of these systems have been addressed in only a few studies, notably those by Muñoz-Erickson et al. (2014), Sale et al. (2014), Tanguay and Bernard (2020), and Santillán-Carvantes et al. (2023). Employing game theory and agent-based modeling techniques can effectively tackle these complexities in future

research (Behboudian et al., 2024). Arguably, the most lucrative opportunity for future research resides in utilizing different data sources and the outputs of numerical models to evaluate the resilience of TFSs. The rapid expansion of databases offers unprecedented opportunities to enhance the input data used in quantifying existing resilience principles and in the evaluation of social-ecological resilience. To operationalize social principles, it is recommended to utilize stakeholder surveys to quantify P5–P7 (Yang et al., 2024) and develop metrics for participation (e.g., decision-making diversity) and governance (e.g., network centrality).

It is important to note that not all studies were expected to address social resilience explicitly. However, by examining the prevalence of P5–P7 across the broader resilience literature in TFSs, this study highlights the relative infrequency with which these principles are considered, pointing to a gap in integrative approaches rather than a shortfall in individual studies.

4.3. Policy and practice implications

This review highlights actionable pathways to translate resilience principles into policy and practice. First, forest certification schemes (e.g., Forest Stewardship Council) could integrate social-ecological resilience criteria by requiring assessments of polycentric governance (P7) and stakeholder participation (P6) alongside biodiversity metrics (P1–P4). For instance, certification audits might evaluate whether local communities are included in fire management planning which is a gap evident in Asian studies (Fig. 6). Second, conservation interventions (e.g., REDD) should mandate resilience-based monitoring frameworks that combine remote sensing (for P1–P4) with participatory mapping (for P5–P7), as demonstrated by Muñoz-Erickson et al. (2014). Finally, national guidelines could adopt our typology of resilience principles (Table 1) to prioritize underrepresented social dimensions in high-risk regions like the Amazon (where only 16% of studies addressed P7). By aligning funding incentives with interdisciplinary resilience assessments, policymakers can bridge the gap between ecological data and governance realities.

5. Conclusion

Evaluating the resilience of Tropical Forest Systems (TFSs) is essential to understanding their capacity to withstand and recover from disturbances, such as climate change, fire, and drought, ensuring the sustainability of their ecological functions (e.g., biodiversity support) and the livelihoods of communities that depend on them. The results of this review highlight that there has not been a comprehensive approach to resilience evaluation in TFSs. Our systematic literature review has revealed several key insights.

- Most reviewed papers have utilized the four ecological resilience principles (P1: maintaining diversity and redundancy (55%); P2: managing connectivity (20%); P3: managing slow variables and feedback (43%); and P4: fostering complex adaptive system (CAS) thinking (61%)) for evaluating resilience in TFSs.
- Only 6% of the reviewed papers have employed all four ecological resilience principles together, all of which have been published after 2021. However, 37% of the papers have mutually considered P1 and P4, 26% of the reviewed papers have taken P3 and P4 into account in resilience evaluation, whereas P2 and P4 have been considered in 14% of the papers.
- There has not been a comprehensive application of social resilience principles, as denoted by the low number of papers focusing on learning and experimentation (P5) (18%), broadening participation (P6) (23%), and polycentric governance (P7) (14%), in TFSs studies. The underrepresentation of the social principles in the literature highlights a critical gap in resilience evaluation.

- Compared to the ecological resilience principles, where 37% of studies considered P1 and P4 together, 26% accounted for P3 and P4, and 14% included P2 and P4, the integration of social resilience principles remains notably lower.
- The resilience principles have been addressed in most papers associated to different disturbances, such as climate change, fire, drought, land use, insect outbreaks, and wind, which shows that the resilience criterion is an important concept to evaluate the sustainability of a system under key stressors.
- Furthermore, broadening participation (P6) surpasses other social resilience principles (P5 and P7) in the number of reviewed papers that incorporate this principle into resilience evaluations.
- Quantitative methods dominate ecological resilience studies (79.6%), whereas social-ecological resilience (16%) relies heavily on qualitative case studies. Only 6% of papers integrate engineering and ecological resilience, revealing a methodological divide. Future research could bridge this gap by combining network analysis (e.g., centrality metrics for P5–P7) with ecological modeling.
- The underrepresentation of social principles (P5–P7) in our corpus reflects a disciplinary legacy favoring biophysical metrics, not their irrelevance to forest resilience.

Our review reveals a pure imbalance: while ecological principles (P1–P4) anchor tropical forest resilience assessments, social principles (P5–P7) remain marginal. Closing this gap requires (1) funding interdisciplinary teams, (2) leveraging emerging tools (e.g., social network analysis), and (3) centering equity in resilience frameworks. Only then can governance and participation be meaningfully integrated into forest management.

Future research can improve forest resilience evaluations by employing forest-based simulation models (e.g., Lund-Potsdam-Jena managed Land (LPJmL)) and social attachments (i.e., social network analysis) (Skardi et al., 2020). Using climate change scenarios such as Shared Socioeconomic Pathways (SSPs) can support evaluation efforts and enhance future resilience more effectively. Applying a polycentric governance framework (e.g., Behboudian et al., 2023) to P7 could bridge the gap between ecological and institutional research. Furthermore, considering the expansion of simulation and computing tools and also better access to ground and satellite-based databases, future research should prioritize enhancing resilience by emphasizing all seven core principles, defining a set of appropriate criteria for each principle, and incorporating social aspects in enhancing the resilience of TFSs. Epistemological shifts are needed to treat social resilience as foundational, not additive.

CRediT authorship contribution statement

Massoud Behboudian: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Conceptualization. **Mohammad Javad Emami-Skardi:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Sara Anamaghi:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Carla Sofia Santos Ferreira:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Lan Wang-Erlandsson:** Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Conceptualization. **Rares Halbac-Cotoară-Zamfir:** Writing – review & editing, Methodology, Conceptualization. **Zahra Kalantari:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2025.127319>.

Data availability

Data will be made available on request.

References

- Ahmadi, A., Kerachian, R., Rahimi, R., Skardi, M.J.E., 2019. Comparing and combining social network analysis and stakeholder analysis for natural resource governance. *Environ. Dev.* 32, 100451.
- Amaris, E.M., Ruiz, M., 2023. Governance structures and environmental security strategies in the Caribbean region. *Security Strategies in Latin America and the Caribbean: Building Resilience*, p. 81.
- Anamaghi, S., Behboudian, M., Emami-Skardi, M.J., Kåresdotter, E., Ferreira, C.S. S., Destouni, G., Kalantari, Z., 2025. Research efforts and gaps in the assessment of forest system resilience: a scoping review. *Ambio* 1–18.
- Arabatzis, G., Kolkos, G., Stergiadou, A., Kantartzis, A., Tampekis, S., 2024. Optimal allocation of water reservoirs for sustainable wildfire prevention planning via AHP-TOPSIS and forest road network analysis. *Sustainability* 16 (2), 936.
- Armitage, D., Marschke, M., Plummer, R., 2008. Adaptive co-management and the paradox of learning. *Glob. Environ. Change* 18 (1), 86–98.
- Baho, D.L., Allen, C.R., Garmestani, A.S., Fried-Petersen, H.B., Renes, S.E., Gunderson, L. H., Angeler, D.G., 2017. A quantitative framework for assessing ecological resilience. *Ecol. Soc.* 22 (3), 1.
- Behboudian, M., Kerachian, R., Pourmoghim, P., 2021. Evaluating the long-term resilience of water resources systems: application of a generalized grade-based combination approach. *Sci. Total Environ.* 786, 147447.
- Behboudian, M., Anamaghi, S., Mahjouri, N., Kerachian, R., 2023. Enhancing the resilience of ecosystem services under extreme events in socio-hydrological systems: a spatio-temporal analysis. *J. Clean. Prod.* 397, 136437.
- Behboudian, M., Anamaghi, S., Kerachian, R., Kalantari, Z., 2024. Comparison of three group decision-making frameworks for evaluating resilience time series of water resources systems under uncertainty. *Ecol. Indic.* 158, 111269.
- Benítez, G., Ruelas-Monjardín, L.C., Von Thaden, J., Acosta-Rosado, I., Alvarado-Castillo, G., Equihua, M., 2023. Carbon storage in a peri-urban neotropical forest: assessing its potential and patterns of change over half a century. *Urban For. Urban Green.* 86, 11. Article 128009.
- Berkes, F., Colding, J., Folke, C., 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecol. Appl.* 10 (5), 1251–1262.
- Biagioni, S., Wündsche, M., Haberzettl, T., Behling, H., 2015. Assessing resilience/sensitivity of tropical mountain rainforests towards climate variability of the last 1500 years: the long-term perspective at Lake Kalimpa (Sulawesi, Indonesia). *Rev. Palaeobot. Palynol.* 213, 42–53.
- Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., et al., 2012. Toward principles for enhancing the resilience of ecosystem services. *Annu. Rev. Environ. Resour.* 37 (1), 421–448.
- Bodin, Ö., Robins, G., McAllister, R.R., Guerrero, A.M., Crona, B., Tengö, M., Lubell, M., 2016. Theorizing benefits and constraints in collaborative environmental governance: a transdisciplinary social-ecological network approach for empirical investigations. *Ecol. Soc.* 21 (1).
- Boissière, M., Locatelli, B., Sheil, D., Padmanaba, M., Sadjudin, E., 2013. Local perceptions of climate variability and change in tropical forests of Papua, Indonesia. *Ecol. Soc.* 18 (4).
- Borma, L.S., Costa, M.H., da Rocha, H.R., Arieira, J., Nascimento, N.C.C., Jaramillo-Giraldo, C., Ambrosio, G., Carneiro, R.G., Venzon, M., Neto, A.F., van der Hoff, R., 2022. Beyond carbon: the contributions of South American tropical humid and subhumid forests to ecosystem services. *Rev. Geophys.* 60 (4), 2021RG000766.
- Brando, P.M., Silvério, D., Maracahipes-Santos, L., Oliveira-Santos, C., Levick, S.R., Coe, M.T., et al., 2019. Prolonged tropical forest degradation due to compounding disturbances: implications for CO₂ and H₂O fluxes. *Glob. Change Biol.* 25 (9), 2855–2868.
- Brosi, B.J., Daily, G.C., Shih, T.M., Oviedo, F., Durán, G., 2008. The effects of forest fragmentation on bee communities in tropical countryside. *J. Appl. Ecol.* 45 (3), 773–783.
- Bryant, T., Waring, K., Sánchez Meador, A., Bradford, J.B., 2019. A framework for quantifying resilience to forest disturbance. *Front. For. Glob. Change.* 2, 56.
- Cajaliba, R.L., Périco, E., da Silva, W.B., Caron, E., Buss, B.C., Dalzochio, M., Santos, M., 2020. Are primary forests irreplaceable for sustaining Neotropical landscapes' biodiversity and functioning? Contributions for restoration using ecological indicators. *Land Degrad. Dev.* 31 (4), 508–517.
- Cantarello, E., Newton, A.C., Martin, P.A., Evans, P.M., Gosal, A., Lucash, M.S., 2017. Quantifying resilience of multiple ecosystem services and biodiversity in a temperate forest landscape. *Ecol. Evol.* 7 (22), 9661–9675.
- Carrillo-Saucedo, S.M., Gavito, M.E., 2020. Resilience of soil aggregation and exocellular enzymatic functions associated with arbuscular mycorrhizal fungal communities along a successional gradient in a tropical dry forest. *Mycorrhiza* 30 (1), 109–120.
- Chambers, J.C., Brown, J.L., Bradford, J.B., Board, D.I., Campbell, S.B., Clause, K.J., et al., 2023. New indicators of ecological resilience and invasion resistance to support prioritization and management in the sagebrush biome, United States. *Front. Ecol. Evol.* 10, 1009268.
- Chazdon, R.L., 2008. Beyond deforestation: restoring forests and ecosystem services on degraded lands. *science* 320 (5882), 1458–1460.
- Chazdon, R.L., Guariguata, M.R., 2016. Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. *Biotropica* 48 (6), 716–730.
- Chazdon, R.L., Peres, C.A., Dent, D., Sheil, D., Lugo, A.E., Lamb, D., et al., 2009. The potential for species conservation in tropical secondary forests. *Conserv. Biol.* 23 (6), 1406–1417.
- Chen, X., Chen, H., 2021. Comparing environmental impacts of Chinese Torreya plantations and regular forests using remote sensing. *Environ. Dev. Sustain.* 23 (1), 133–150.
- Cisneros, E., Kis-Katos, K., Nuryartono, N., 2021. Palm oil and the politics of deforestation in Indonesia. *J. Environ. Econ. Manag.* 108, 102453.
- Cole, L.E., Bhagwat, S.A., Willis, K.J., 2014. Recovery and resilience of tropical forests after disturbance. *Nat. Commun.* 5 (1), 3906.
- Crouzeilles, R., Curran, M., Ferreira, M.S., Lindenmayer, D.B., Grelle, C.E., Rey Benayas, J.M., 2016. A global meta-analysis on the ecological drivers of forest restoration success. *Nat. Commun.* 7 (1), 11666.
- de Andrade, R.A., Sacomano Neto, M., Candido, S.E.A., 2022. Implementing community-based forest management in the Brazilian Amazon Rainforest: a strategic action fields perspective. *Environ. Polit.* 31 (3), 519–541.
- Ding, Y., Zang, R.G., 2021. Effects of thinning on the demography and functional community structure of a secondary tropical lowland rain forest. *J. Environ. Manag.* 279 (9). Article 111805.
- Drillet, Z., Fung, T.K., Leong, R.A.T., Sachidanandam, U., Edwards, P., Richards, D., 2020. Urban vegetation types are not perceived equally in providing ecosystem services and disservices. *Sustainability* 12 (5), 14. Article 2076.
- Durand, L., Lazos, E., 2004. Colonization and tropical deforestation in the Sierra Santa Marta, southern Mexico. *Environ. Conserv.* 31 (1), 11–21.
- Dutra, D.J., Elmiro, M.A.T., Ribeiro, S.M.C., 2022. Association between forest resources and water availability: temporal analysis of the Serra Azul stream sub-basin. *An. Acad. Bras. Ciênc.* 94 (3), e20201289.
- Edwards, R.B., Naylor, R.L., Higgins, M.M., Falcon, W.P., 2020. Causes of Indonesia's forest fires. *World Dev.* 127, 104717.
- Eklblom, A., Gillson, L., Risberg, J., Holmgren, K., Chidoub, Z., 2012. Rainfall variability and vegetation dynamics of the lower Limpopo Valley, Southern Africa, 500 AD to present. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 363, 69–78.
- Emami-Skardi, M.J., Momenzadeh, N., Kerachian, R., 2021. Social learning diffusion and influential stakeholders identification in socio-hydrological environments. *J. Hydrol.* 599, 126337.
- FAO, 2020. Global Forest Resources Assessment 2020. Food and Agriculture Organization of the United Nations.
- Ferreira, M.N., 2024. Conservation priorities mapping—a first step toward building area-based strategies. *Front. Sci.* 2, 1440501.
- Flores, B.M., Staal, A., 2022. Feedback in tropical forests of the Anthropocene. *Glob. Change Biol.* 28 (17), 5041–5061 [Review].
- Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.* 30, 441–473.
- Freudenberger, L., Hobson, P.R., Schluck, M., Ibisch, P.L., 2012. A global map of the functionality of terrestrial ecosystems. *Ecol. Complex.* 12, 13–22.
- Galaz, V., Olsson, P., Hahn, T., Folke, C., Svedin, U., 2008. The problem of fit among biophysical systems, environmental and resource regimes, and broader governance systems: insights and emerging challenges. In: *Institutions and Environmental Change*. MIT Press, pp. 147–182.
- Galván-Cisneros, C.M., Montaña, L.R.S., Ojeda-Rodríguez, A.E., Meira-Neto, J.A.A., 2023. Structures of tropical dry forests in the Andes: forest conservation, composition and the role of fabaceae and myrtaceae. *Cerne* 29 e-1033189.
- Garate-Quispe, J., Herrera-Machaca, M., Pareja Auquipata, V., Alarcón Aguirre, G., Baez Quispe, S., Carpio-Vargas, E.E., 2024. Resilience of aboveground biomass of secondary forests following the abandonment of gold mining activity in the southeastern Peruvian Amazon. *Diversity* 16 (4), 233.
- GFW, 2024. Global Forest Watch, Interactive Map. Retrieved December 18, 2024, from <https://www.globalforestwatch.org>.

- González-Cruz, G., García-Frapolli, E., Casas, A., Dupuy, J.M., 2015. Responding to disturbances: lessons from a Mayan social-ecological system. *Int. J. Commons* 9 (2), 831–850.
- Guizar-Coutiño, A., Jones, J.P., Balmford, A., Carmenta, R., Coomes, D.A., 2022. A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. *Conserv. Biol.* 36 (6), e13970.
- Gunderson, L.H., 2000. Ecological resilience—in theory and application. *Annu. Rev. Ecol. Systemat.* 31 (1), 425–439.
- Hapsari, K.A., Biagioni, S., Jennerjahn, T.C., Reimer, P., Saad, A., Sabiham, S., Behling, H., 2018. Resilience of a peatland in Central Sumatra, Indonesia to past anthropogenic disturbance: improving conservation and restoration designs using palaeoecology. *J. Ecol.* 106 (6), 2473–2490.
- Heinimann, H.R., 2010. A concept in adaptive ecosystem management: an engineering perspective. *For. Ecol. Manag.* 259 (4), 848–856.
- Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.: J. Roy. Meteorol. Soc.* 25 (15), 1965–1978.
- Hirota, M., Holmgren, M., Van Nes, E.H., Scheffer, M., 2011. Global resilience of tropical forest and savanna to critical transitions. *Science* 334 (6053), 232–235.
- Hlásný, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J., et al., 2021. Bark beetle outbreaks in Europe: state of knowledge and ways forward for management. *Curr. For. Rep.* 7 (3), 138–165 others.
- Holl, K.D., Aide, T.M., 2011. When and where to actively restore ecosystems? *For. Ecol. Manag.* 261 (10), 1558–1563.
- Holling, C.S., 1973. Resilience and Stability of Ecological Systems.
- Islam, M.A., Paull, D.J., Griffin, A.L., Murshed, S., 2020. Assessing ecosystem resilience to a tropical cyclone based on ecosystem service supply proficiency using geospatial techniques and social responses in coastal Bangladesh. *Int. J. Disaster Risk Reduct.* 49 (17), Article 101667.
- Kleinschroth, F., Healey, J.R., 2017. Impacts of logging roads on tropical forests. *Biotropica* 49 (5), 620–635 [Review].
- Knight, T., Price, S., Bowler, D., Hookway, A., King, S., Konno, K., Richter, R.L., 2021. How effective is ‘greening’ of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure and the ‘urban heat island effect’? An updated systematic review. *Environ. Evid.* 10 (1), 12.
- Krell, R., 2019. Resilience. In: *The Handbook of Psychoanalytic Holocaust Studies*. Routledge, pp. 41–51.
- Letcher, S.G., Chazdon, R.L., 2009. Rapid recovery of biomass, species richness, and species composition in a forest chronosequence in northeastern Costa Rica. *Biotropica* 41 (5), 608–617.
- Li, H., Speer, J.H., Thapa, I., 2022. Analyzing resilience in the Greater Yellowstone Ecosystem after the 1988 wildfire in the Western U.S. using remote sensing and soil database. *Land* 11 (8).
- Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Taylor, W.W., 2007. Complexity of coupled human and natural systems. *Science* 317 (5844), 1513–1516. <https://doi.org/10.1126/science.1144004>.
- Londres, M., Schmink, M., Börner, J., Duchelle, A.E., Frey, G.P., 2023. Multidimensional forests: complexity of forest-based values and livelihoods across Amazonian socio-cultural and geopolitical contexts. *World Dev.* 165, 106200.
- Malhi, Y., Gardner, T.A., Goldsmith, G.R., Silman, M.R., Zelazowski, P., 2014. Tropical forests in the Anthropocene. *Annu. Rev. Environ. Resour.* 39 (1), 125–159.
- McKenna, P., Erskine, P.D., Glenn, V., Doley, D., 2019. Response of open woodland and grassland mine site rehabilitation to fire disturbance on engineered landforms. *Ecol. Eng.* 133, 98–108.
- Medeiros, N.F., Ordóñez-Parra, C.A., Buisson, E., Silveira, F.A.O., 2024. Systematic review of field research reveals critical shortfalls for restoration of tropical grassy biomes. *J. Appl. Ecol.* 61 (6), 1174–1186.
- Meli, P., Holl, K.D., Benayas, J.M.R., Jones, H.P., Jones, P.C., Montoya, D., Mateos, D.M., 2017. A global review of past land use, climate, and active vs. passive restoration effects on forest recovery. *PLoS One* 12 (2), e0171368.
- Meng, Y.Y., Liu, X.N., Wang, Z., Ding, C., Zhu, L.H., 2021. How can spatial structural metrics improve the accuracy of forest disturbance and recovery detection using dense Landsat time series? *Ecol. Indic.* 132, 12. Article 108336.
- Mesa-Sierra, N., Escobar, F., Laborde, J., 2020. Appraising forest diversity in the seasonally dry tropical region of the Gulf of Mexico. *Rev. Mex. Biodivers.* 91.
- Mina, M., Messier, C., Duveneck, M.J., Fortin, M.J., Aquilué, N., 2022. Managing for the unexpected: building resilient forest landscapes to cope with global change. *Glob. Change Biol.* 28 (14), 4323–4341.
- Montoya, E., Matthews-Bird, F., Brooks, S.J., Gosling, W.D., 2021. Forests protect aquatic communities from detrimental impact by volcanic deposits in the tropical Andes (Ecuador). *Reg. Environ. Change* 21 (2), 14, 53.
- Muñoz-Erickson, T.A., Lugo, A.E., Quintero, B., 2014. Emerging synthesis themes from the study of social-ecological systems of a tropical city. *Ecol. Soc.* 19 (3).
- Myers, N., 1992. *The Primary Source: Tropical Forests and Our Future*. W. W. Norton & Company.
- Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A., Kent, J., 2000. Biodiversity hotspots for conservation priorities. *Nature* 403 (6772), 853–858.
- Nagendra, H., Ostrom, E., 2012. Polycentric governance of multifunctional forested landscapes. *Int. J. Commons* 6 (2). <https://doi.org/10.18352/ijc.321>.
- Nazari, M., Kerachian, R., 2024. Optimal operation of reservoirs considering water quantity and quality aspects: a systematic state-of-the-art review. *Water Resour. Manag.* 38 (15), 5911–5944.
- Nikinmaa, L., Lindner, M., Cantarello, E., Gardiner, B., Jacobsen, J.B., Jump, A.S., Parra, C., Plieninger, T., Schuck, A., Seidl, R., Timberlake, T., 2023. A balancing Act: principles, criteria and indicator framework to operationalize social-ecological resilience of forests. *J. Environ. Manag.* 331, 117039.
- Nobre, C.A., Sampaio, G., Borma, L.S., Castilla-Rubio, J.C., Silva, J.S., Cardoso, M., 2016. Land-use and climate change risks in the Amazon and the need for a novel sustainable development paradigm. *Proc. Natl. Acad. Sci.* 113 (39), 10759–10768.
- Nyasulu, M.K., Fetzer, I., Wang-Erlandsson, L., Stenzel, F., Gerten, D., Rockström, J., Falkenmark, M., 2024. African rainforest moisture contribution to continental agricultural water consumption. *Agric. For. Meteorol.* 346, 109867.
- Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325 (5939), 419–422.
- Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hofmann, T.C., Mulrow, C.D., Brennan, S.E., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Int. J. Surg.* 88, 105906.
- Picasso, V., Pizarro, D., 2024. Silvopastoral transitions in Latin America: toward diverse perennial systems. *Agrofor. Syst.* 1–6.
- Pinto, L.G., Amaral, S., Metzger, J.P., Rosa, M., Adorno, B., Goncalves, G., 2024. Alarming patterns of mature forest loss. In: *The Brazilian Atlantic Forest*.
- Piponi, C., Rödig, E., Putz, F.E., Rutishauser, E., Sist, P., Ascarrunz, N., Blanc, L., Deroire, G., Descroix, L., Guedes, M.C., Coronado, E.H., Huth, A., Kanashiro, M., Licona, J.C., Mazzei, L., d’Oliveira, M.V.N., Peña-Claros, M., Rodney, K., Shenkin, A., de Souza, C.R., Vidal, E., West, T.A.P., Worter, V., Hérault, B., 2019. Can timber provision from Amazonian production forests be sustainable? *Environ. Res. Lett.* 14 (6), 064014, 10.
- Pomara, L.Y., Lee, D.C., 2021. The role of regional ecological assessment in quantifying ecosystem services for forest management. *Land* 10 (7).
- Ramdzan, K.N.M., Moss, P.T., Heijnis, H., Harrison, M.E., Yulianti, N., 2022. Application of palaeoecological and geochemical proxies in the context of tropical peatland degradation and restoration: a review for Southeast Asia. *Wetlands* 42 (7), 95 [Review].
- Reed, M.S., Vella, S., Challies, E., De Vente, J., Frewer, L., Hohenwallner-Ries, D., Van Delden, H., 2018. A theory of participation: what makes stakeholder and public engagement in environmental management work? *Restor. Ecol.* 26, S7–S17. <https://doi.org/10.1111/rec.12541>.
- Reid, J.L., Wilson, S.J., Bloomfield, G.S., Cattau, M.E., Fagan, M.E., Holl, K.D., Zahawi, R. A., 2017. How long do restored ecosystems persist? [Proceedings Paper]. *Ann. Mo. Bot. Gard.* 102 (2), 258–265.
- Reyes-García, V., García-del-Amo, D., Benyei, P., Fernández-Llamazares, Á., Gravani, K., Junqueira, A.B., Soleymani-Fard, R., 2019. A collaborative approach to bring insights from local observations of climate change impacts into global climate change research. *Curr. Opin. Environ. Sustain.* 39, 1–8.
- Rockwell, C.A., Crow, A., Guimaraes, E.R., Recinos, E., La Belle, D., 2022. Species richness, stem density, and canopy in food forests: contributions to ecosystem services in an urban environment. *Urban Plan.* 7 (2), 139–154.
- Rodríguez-Rodríguez, J.C., Fenton, N.J., Kembel, S.W., Mestre, E., Jean, M., Bergeron, Y., 2023. Drivers of contrasting boreal understorey vegetation in coniferous and broadleaf deciduous alternative states. *Ecol. Monogr.* 93 (3).
- Rosenfield, M.F., Jakovac, C.C., Vieira, D.L.M., Poorter, L., Brancalion, P.H.S., Vieira, I.C. G., de Almeida, D.R.A., Massoca, P., Schietti, J., Albernaz, A.L.M., Ferreira, M.J., Mesquita, R.C.G., 2023. Ecological integrity of tropical secondary forests: concepts and indicators. *Biol. Rev.* 98 (2), 662–676.
- Sakellariou, S., Sfougaris, A., Christopoulou, O., Tampekis, S., 2023. Spatial resilience to wildfires through the optimal deployment of firefighting resources: impact of topography on initial attack effectiveness. *Int. J. Disaster Risk Sci.* 14 (1), 98–112.
- Sala, O.E., Maestre, F.T., 2014. Grass-woodland transitions: determinants and consequences for ecosystem functioning and provisioning of services. *J. Ecol.* 102 (6), 1357–1362.
- Sale, P.F., Agardy, T., Ainsworth, C.H., Feist, B.E., Bell, J.D., Christie, P., et al., 2014. Transforming management of tropical coastal seas to cope with challenges of the 21st century. *Mar. Pollut. Bull.* 85 (1), 8–23.
- Santillán-Carvantes, P., Balvanera, P., Thomsen, S., Mora, F., Pérez-Cárdenas, N., Cohen-Salgado, D., et al., 2023. Spatial characterization of social-ecological systems units for management in Tropical Dry Forests. *Landscape Ecol.* 38 (12), 4303–4323.
- Sarkki, S., Ficko, A., Wielgolaski, F.E., Abraham, E.M., Bratanova-Doncheva, S., Grunewald, K., et al., 2017. Assessing the resilient provision of ecosystem services by social-ecological systems: introduction and theory. *Clim. Res.* 73 (1–2), 7–15.
- Sasaki, N., Zhang, L., Meadows, J., Seo, J.W., Boehmer, H.J., 2024. Dynamics of Asia’s and Australasia’s forests in a changing world. *Front. For. Glob. Change.* 7, 1474882.
- Seddon, A.W.R., Macias-Fauria, M., Long, P.R., Benz, D., Willis, K.J., 2016. Sensitivity of global terrestrial ecosystems to climate variability. *Nature* 531 (7593), 229.
- Şekercioglu, Ç.H., Loarie, S.R., Oviedo-Brenes, F., Mendenhall, C.D., Daily, G.C., Ehrlich, P.R., 2015. Tropical countryside riparian corridors provide critical habitat and connectivity for seed-dispersing forest birds in a fragmented landscape. *J. Ornithol.* 156, 343–353.
- Sharifian, H., Emami-Skardi, M.J., Behzadfar, M., Faizi, M., 2022. Water sensitive urban design (WSUD) approach for mitigating groundwater depletion in urban geography; through the lens of stakeholder and social network analysis. *Water Supply* 22 (6), 5833–5852.
- Skardi, M.J.E., Kerachian, R., Abdolhay, A., 2020. Water and treated wastewater allocation in urban areas considering social attachments. *J. Hydrol.* 585, 124757.
- Smith, A.M., Kolden, C.A., Tinkham, W.T., Talhelm, A.F., Marshall, J.D., Hudak, A.T., et al., 2014. Remote sensing the vulnerability of vegetation in natural terrestrial ecosystems. *Rem. Sens. Environ.* 154, 322–337.
- Soubry, I., Doan, T., Chu, T., Guo, X.L., 2021. A systematic review on the integration of remote sensing and GIS to Forest and grassland ecosystem health attributes, indicators, and measures. *Remote Sens.* 13 (16), 3262 [Review].
- Sun, Z.Y., Ren, H., Schaefer, V., Lu, H.F., Wang, J., Li, L.J., Liu, N., 2013. Quantifying ecological memory during forest succession: a case study from lower subtropical forest ecosystems in South China. *Ecol. Indic.* 34, 192–203.

- Tagg, N., Kuenbou, J.K., Laméris, D.W., Meigang, F.M.K., Kekeunou, S., Epanda, M.A., Dupain, J., Mbohli, D., Redmond, I., Willie, J., 2020. Long-term trends in wildlife community structure and functional diversity in a village hunting zone in southeast Cameroon. *Biodivers. Conserv.* 29 (2), 571–590.
- Tampekis, S., Sakellariou, S., Palaiologou, P., Arabatzis, G., Kantartzis, A., Malesios, C., et al., 2023. Building wildland–urban interface zone resilience through performance-based wildfire engineering. A holistic theoretical framework. *Euro-Mediterranean journal for environmental integration* 8 (3), 675–689.
- Tanguay, L., Bernard, S., 2020. Ecoagricultural landscapes in the dieng mountains of central Java; A study of their evolution and dynamics. *J. Rural Stud.* 77, 169–184.
- Tengö, M., Brondizio, E.S., Elmqvist, T., Malmer, P., Spierenburg, M., 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. *Ambio* 43 (5), 579–591.
- Townsend, P.A., Masters, K.L., 2015. Lattice-work corridors for climate change: a conceptual framework for biodiversity conservation and social-ecological resilience in a tropical elevational gradient. *Ecol. Soc.* 20 (2), 11, 1.
- Tscharntke, T., Clough, Y., Bhagwat, S.A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., Wanger, T.C., 2011. Multifunctional shade-tree management in tropical agroforestry landscapes - a review. *J. Appl. Ecol.* 48 (3), 619–629 [Review].
- Turner, B., Devisscher, T., Chabaneix, N., Woroniecki, S., Messier, C., Seddon, N., 2022. The role of nature-based solutions in supporting social-ecological resilience for climate change adaptation. *Annu. Rev. Environ. Resour.* 47 (1), 123–148.
- Van Eck, N., Waltman, L., 2010. Software survey: vosviewer, a computer program for bibliometric mapping. *Scientometrics* 84 (2), 523–538.
- Wallbott, L., Florian-Rivero, E.M., 2018. Forests, rights and development in Costa Rica: a political Ecology perspective on indigenous peoples' engagement in REDD+. *Conflict Secur. Dev.* 18 (6), 493–519.
- Wikipedia contributors, 2024. File:PopulationDensityMapPerSquareKilometre.png. Wikipedia. Retrieved July 2, 2025, from. <https://en.wikipedia.org/wiki/File:PopulationDensityMapPerSquareKilometre.png>.
- Willis, K.J., Bennett, K.D., Burrough, S.L., Macias-Fauria, M., Tovar, C., 2013. Determining the response of African biota to climate change: using the past to model the future. *Phil. Trans. Biol. Sci.* 368 (1625), 20120491.
- World Resources Institute, 2018. By the numbers: the value of tropical forests in the climate change equation. <https://www.wri.org>.
- Xie, Q.Y., Moore, C.E., Cleverly, J., Hall, C.C., Ding, Y.L., Ma, X.L., Leigh, A., Huete, A., 2023. Land surface phenology indicators retrieved across diverse ecosystems using a modified threshold algorithm. *Ecol. Indic.* 147, 110000, 13.
- Yang, Q., Huang, Z., Wu, L., Guo, B.B., Liu, M.L., Xue, X.J., Li, X.Y., Liu, X.N., 2024. Resilience changes of carbon stocks to quantify the long-term effects of ecological engineering projects in subtropical forests of China based on satellite-derived net ecosystem production time series and inventory data. *Land Degrad. Dev.* 35 (7), 2329–2344.
- Young, C.E.F., 2021. The economics of tropical rainforest preservation. In: Oxford Research Encyclopedia of Environmental Science.
- Young, J., Gilmore, M., 2017. Participatory uses of geospatial technologies to leverage multiple knowledge systems within development contexts: a case study from the Peruvian Amazon. *World Dev.* 93, 389–401.
- Zanini, A.M., Mayrinck, R.C., Vieira, S.A., de Camargo, P.B., Rodrigues, R.R., 2021. The effect of ecological restoration methods on carbon stocks in the Brazilian Atlantic Forest. *For. Ecol. Manag.* 481 (11), 118734.
- Zinnert, J.C., Nippert, J.B., Rudgers, J.A., Pennings, S.C., González, G., Alber, M., Baer, S. G., Blair, J.M., Burd, A., Collins, S.L., Craft, C., Di Iorio, D., Dodds, W.K., Groffman, P.M., Herbert, E., Hladik, C., Li, F., Litvak, M.E., Newsome, S., O'Donnell, J., Pockman, W.T., Schalles, J., Young, D.R., 2021. State changes: insights from the US long term ecological research network. *Ecosphere* 12 (5), e03433, 29.