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Review

The Evolution of Landscape Ecology in the Democratic Republic of the Congo (2005–2025): Scientific Advances, Methodological Challenges, and Future Directions

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Abstract

Since 2005, landscape ecology has emerged as a structured scientific field in the Democratic Republic of Congo, notably shaped by the contributions of Professor Jan Bogaert. The evolution of research in this field can be divided into three main phases. The first phase (2005–2012) focused on the quantitative analysis of forest fragmentation using Geographic Information Systems and landscape metrics. From 2013 to 2019, research approaches broadened to include the social sciences, marking a shift toward a socio-ecological perspective on landscapes. Since 2020, the field has increasingly adopted holistic frameworks that integrate climatic factors and forward-looking modeling. Key research themes now include ecological flows across landscape mosaics, land-use dynamics, and the anthropogenic transformation of ecosystems. However, several challenges persist, including the lack of long-term temporal datasets, uneven geographic coverage, and limited integration of local knowledge systems. Notable advances have been made through high-resolution remote sensing and participatory methods, although their application is still limited by technical and financial constraints. This manuscript advocates for stronger interdisciplinary collaboration, improved field methodologies, and the development of context-appropriate tools to support sustainable and locally grounded landscape management in the Congolese context.

Keywords: DRC; fragmentation; interdisciplinarity; landscape ecology; modelling; remote sensing/GIS

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1. Introduction

Landscape ecology, first conceptualized by Carl Troll in 1939, has evolved into a transdisciplinary science at the intersection of ecology, geography, conservation biology, and spatial planning [1]. By analyzing the interactions between spatial patterns and ecological processes, it provides a robust framework for understanding ecosystem dynamics under anthropogenic pressures [2–4]. Since the 1980s, the field has expanded rapidly through innovations in remote sensing, geospatial analysis, and multiscale modeling approaches [5–7].

However, the foundational assumptions and paradigms of landscape ecology have predominantly emerged from relatively stable socio-ecological contexts in the Global North [8]. In contrast, the Democratic Republic of the Congo (DRC) presents a fundamentally different set of biophysical and institutional landscape dynamics that challenge these frameworks [9].

The DRC contains the world's second-largest tropical forest massif, characterized by exceptional biodiversity, vast ecological heterogeneity, and complex human–environment interactions [10]. Yet, this landscape is profoundly shaped by structural instability, including recurrent armed conflicts, governance vacuums, weak institutional oversight, and intense dependence on natural resource extraction [11,12].

These conditions have produced hyper-fragmented ecosystems where industrial and artisanal mining, illegal logging, conflict-affected forests, and unplanned urban sprawl intersect chaotically [13]. For example, in mining-rich regions such as Katanga and Tshopo, overlapping concessions and protected areas drive abrupt forest loss [14–18], habitat isolation [19], and soil contamination [20,21]. The absence of effective spatial planning fosters anarchic urban expansion, further fragmenting peri-urban ecosystems [22]. Such spatial configurations create natural laboratories for studying ecological tipping points and landscape collapse—phenomena inadequately captured by traditional linear models of disturbance and recovery.

Moreover, post-conflict dynamics generate nonlinear ecological feedback, evidenced by spontaneous reforestation during periods of armed insecurity when agricultural pressures temporarily decline [9,11]. These trajectories challenge classical degradation narratives and call for more adaptive, context-sensitive modeling frameworks. Another defining feature is the complex interplay between global extractive pressures and local land-use practices. The expansion of industrial and artisanal mining of cobalt, copper, and timber often undermines traditional agroforestry systems, which have historically been crucial for maintaining biodiversity and soil fertility [23]. Nonetheless, local ecological knowledge continues to influence land-use decisions [24], highlighting that resilience in the DRC is simultaneously ecological, cultural, and institutional.

Emerging landscape trajectories in the DRC challenge conventional narratives of ecological degradation. Rather than conforming to linear models of disturbance and recovery, these trajectories reveal more complex, dynamic patterns that demand adaptive and context-sensitive modelling frameworks. A critical characteristic of this context is the interplay between global extractive forces and localized land-use practices. The rapid expansion of industrial and artisanal mining—particularly for cobalt, copper, and timber—frequently undermines traditional agroforestry systems that have historically played a vital role in preserving biodiversity and maintaining soil fertility [23].

However, despite increasing pressures from global markets and extractive industries, local ecological knowledge continues to shape land-use decisions in significant ways [24]. This underscores the deeply intertwined cultural and ecological dimensions of resilience in Congolese landscapes. These findings suggest that resilience is not a static ecological property but an emergent phenomenon shaped by overlapping institutional, socio-cultural, and environmental processes.

This synthesis disrupts dominant resilience paradigms, particularly the Press–Pulse Disturbance (PPD) framework, which assumes coherent institutions, clearly defined ecological thresholds, and linear cycles of disturbance and recovery. In socio-ecologically fragmented settings such as the DRC—characterized by governance vacuums, political volatility, and extractive development—these foundational assumptions often collapse. Such empirical realities raise an important theoretical question:

How do Congolese landscapes—marked by extreme fragmentation, resource extraction, and institutional instability—challenge resilience models like the PPD framework, which are premised on predictability, linearity, and institutional coherence?

Since the mid-2000s, a body of research—especially by Professor Jan Bogaert and colleagues—has sought to respond to these limitations. Their work combines high-resolution spatial analysis, biodiversity monitoring, and participatory approaches to more effectively capture the dynamic and contested nature of land-use in the DRC [23,24]. Rather than adhering to a single conceptual framework, this research advocates for flexible, critically reflexive models capable of integrating socio-political contingency, ecological fragmentation, and local knowledge systems.

This article presents a diachronic and critical review of landscape ecology research in the DRC from 2005 to mid-2025. We trace the institutional development of the field, its thematic evolution, and key conceptual tensions. We argue that the Congolese case compels a fundamental revision of landscape ecological theory, particularly in relation to plural, uncertain, and politically embedded ecological realities.

Moreover, the role of landscape ecology in shaping socio-ecological transitions extends beyond the measurement of fragmentation. In settings like the DRC, where spatial patterns significantly influence governance outcomes, landscape ecology has the potential to act as a mediating science for sustainability transitions [25]. The DRC's hyper-fragmented landscapes resemble "transition arenas" described in the Geography of Sustainability Transitions (GST) literature—spaces where competing land-use logics and governance regimes interact in unpredictable ways. However, existing frameworks rarely account for informal land-use systems or customary governance, particularly in underrepresented Global South contexts [25].

We hypothesize that the anthropogenic and political pressures shaping Congolese landscapes give rise to non-linear ecological feedback, which conventional models such as the PPD framework fail to capture. Specifically, we advance the following predictions:

1. Conventional fragmentation indices (e.g., FRAGSTATS) will underestimate the ecological impacts of small-scale, high-frequency disturbances (e.g., artisanal mining, shifting cultivation), due to their fine spatial resolution and temporal variability.
2. Periods of armed conflict will be associated with temporary reforestation—resulting from reduced agricultural activity—followed by rapid deforestation during post-conflict reconstruction phases. These cycles create pulsed disturbance regimes that deviate from linear recovery assumptions.
3. Landscapes under customary or informal governance regimes will demonstrate greater ecological resilience to fragmentation than those under weak, contested, or externally imposed formal governance systems due to stronger local stewardship and adaptive capacity.

2. Materials and Methods

This review follows a narrative and exploratory approach designed to reconstruct the evolution of landscape ecology in the DRC between 2005 and 2025. Although we did not apply a formal systematic review protocol such as PRISMA or ROSES, our methodology was guided by clear and transparent principles to ensure coherence, traceability, and thematic relevance.

The literature search was conducted across multiple sources to account for the diversity and fragmentation of scientific production in the region. We used international databases such as Google Scholar and Scopus but also consulted local university archives and research center collections, particularly those affiliated with Congolese institutions. This allowed us to include regionally produced knowledge that is often overlooked in global indexing systems.

To identify relevant publications, we combined thematic and geographical keywords associated with landscape ecology and its applications in the DRC. The search included studies addressing spatial patterns, land use change, ecological connectivity, conservation strategies, and landscape-scale processes. We focused on documents published between

2005 and 2025, covering both English- and French-language literature, in order to reflect the multilingual reality of scientific discourse in the country.

Publications were included in the synthesis if they engaged explicitly with landscape ecological concepts or methods and demonstrated empirical or conceptual relevance to the Congolese context. While peer-reviewed articles formed the core of the corpus, we also considered gray literature—such as technical reports and institutional publications—provided they originated from recognized academic, governmental, or non-governmental organizations. We excluded opinion pieces, editorials, or documents lacking substantive ecological content.

Rather than applying rigid exclusion filters, we prioritized thematic relevance and conceptual depth, aiming to capture the full range of perspectives that have contributed to landscape ecological thinking in the DRC. Given the dispersed and often interdisciplinary nature of the literature, a systematic protocol risked omitting significant contributions, particularly those embedded in applied or locally grounded research. Our approach therefore favors analytical flexibility while maintaining a rigorous interpretative framework. This methodological positioning strengthens the credibility of the synthesis while remaining sensitive to the epistemological and institutional specificities of the Central African research landscape.

3. Landscape Ecology in the DRC (2005–2025): The Trajectory of an Emerging Discipline

Between 2005 and 2025, landscape ecology in the DRC has gradually established itself as a structured scientific discipline at the intersection of spatial analysis, functional ecology, and land management. This disciplinary consolidation began with the arrival of Professor Jan Bogaert in 2005, which marked a pivotal moment in the field's development. His pioneering contributions introduced a level of methodological rigor that had previously been lacking, while also fostering a collaborative research environment with local institutions.

The first wave of studies (2005–2012) established the conceptual foundation of landscape ecology in the Congo Basin, focusing primarily on forest fragmentation and the spatial structure of ecosystems [14,15,26]. These early investigations relied heavily on GIS, landscape metrics, and quantitative analytical methods. This exploratory phase was reinforced by targeted ecological assessments, particularly examining the impacts of logging, mining activities, and the resulting loss of ecological connectivity [27–29].

Between 2013 and 2019, the field matured, with research priorities shifting toward analyzing interactions between natural dynamics and anthropogenic pressures. Greater emphasis was placed on ecosystem services [30], (peri)urban dynamics [31–33], and modeling deforestation processes [34]. This period also marked a gradual integration of social sciences, signaling a move toward more cross-cutting and transdisciplinary approaches.

Since 2020, the discipline has experienced methodological diversification and expanded its analytical scope. Key themes now include climate change integration, prospective modeling, evaluation of protected area effectiveness, and ecological restoration strategies [9,16–18,35,36]. Current studies adopt holistic perspectives that bridge local and regional scales, while developing decision-support tools to aid territorial planning [13,37,38].

Professor Jan Bogaert's most significant contribution lies in establishing a scientific school in the DRC, characterized by analytical rigor and the mentoring of a new generation of researchers. His approach, initially focused on ecosystem spatialization, has evolved into a systemic vision that incorporates socio-environmental dimensions. Today, landscape ecology in the DRC stands at a critical crossroads: it must consolidate its scientific achievements and enhance its societal relevance to become a strategic driver for conservation, environmental governance, and sustainable territorial development.

4. Scientific Dynamics of Landscape Ecology in the DRC (2005–2025)

Since 2005, the development of landscape ecology in the DRC has been accompanied by a marked increase in scientific output. While initially limited, this growth accelerated significantly after 2015, driven by the expansion of international collaborations and the establishment of multidisciplinary research programs. Publication activity peaked in 2018 and 2020, corresponding, respectively, to the release of major synthesis papers and the completion of high-impact integrative projects (Figure 1). The year 2024 set a new record for the number of publications, confirming this upward trajectory and reflecting both the growing expertise of local research teams and the alignment of scientific priorities with global environmental challenges.

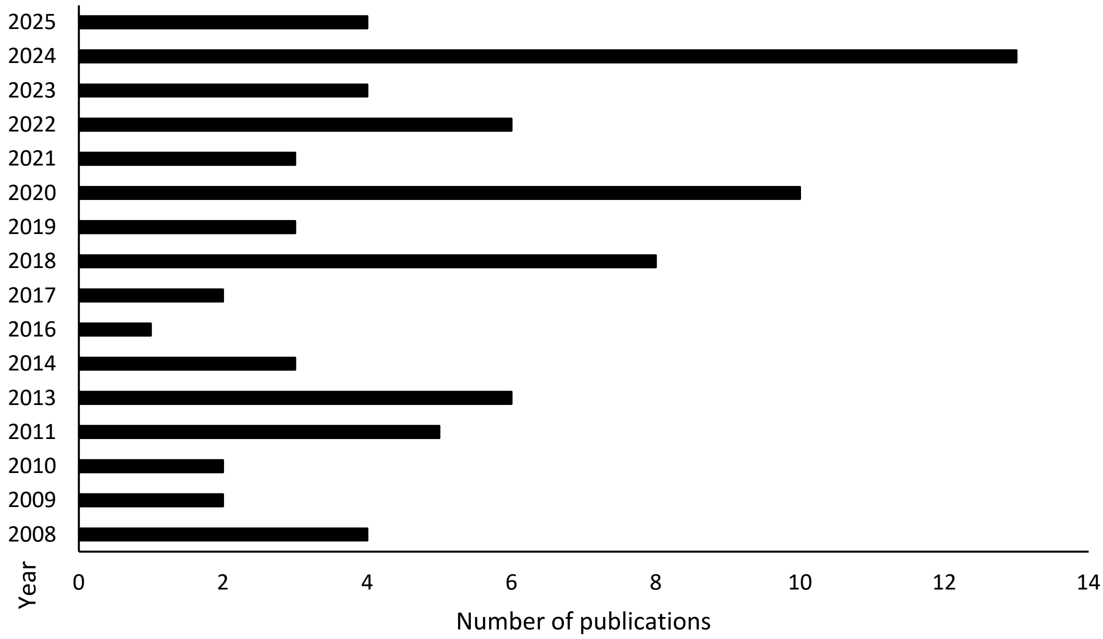

Figure 1. Distribution of Published Landscape Ecology Studies by Year in DRC (n = 76).

In terms of spatial coverage, early studies primarily focused on emblematic regions such as the mining areas of Katanga and the peri-urban forests surrounding Kisangani. Over time, the geographical scope of research has expanded to encompass agricultural landscapes, rural–urban interfaces, and buffer zones of protected areas, now covering approximately 50% of the provinces in the Democratic Republic of the Congo (Figure 2). This spatial expansion was accompanied by a methodological refinement, combining macro-regional analyses [13] with fine-scale local assessments [31]. However, certain provinces—particularly in the western and northeastern regions—remain underrepresented, highlighting persistent geographic imbalances in research coverage (Figure 2).

Thematic diversification is also a defining feature of this evolution. While forest fragmentation dominated early research [26,39], current investigations address a wider range of topics: ecological regeneration, functional connectivity, urban landscape dynamics, agroforestry systems, and the functioning of ecosystems [40–43]. This evolution signals a transition toward a systemic reading of socio-ecological interactions.

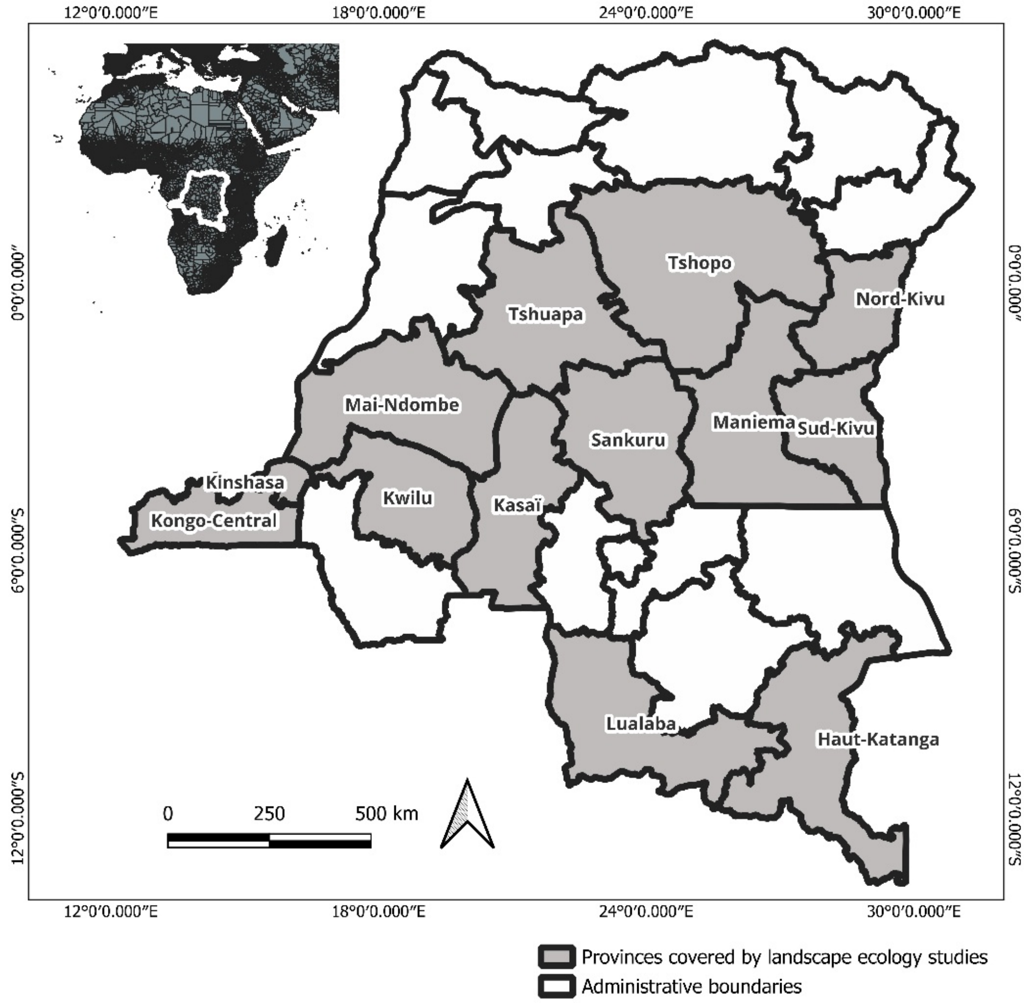

Figure 2. Administrative Provinces Covered by Landscape Ecology Studies in the DRC. Most studies are concentrated in Haut-Katanga province, followed by Tshopo.

In parallel, the editorial landscape has undergone a significant transformation. From an initial focus on local publication outlets [26,29], Congolese landscape research has gained visibility in international indexed journals (Supplementary Material). This internationalization has been accompanied by increasing thematic and methodological specialization across publication venues. Among the most frequently cited sources, the journal Land leads with 15.7% of the studies, followed by Tropicultura (11.8%) and collective volumes published by the Presses Universitaires de Liège, particularly those focusing on forest anthropization. A clear trend is also emerging in recent publications (2020–2025), with journals such as *Land*, *Diversity*, and *Remote Sensing*—all published by MDPI—being increasingly favored by researchers in the field. Shifts in language practices also mirror the disciplinary evolution of landscape ecology in the DRC. Although French has traditionally been the dominant language, English now prevails in recent publications, particularly in international journals—accounting for 37 out of a total of 76 publications. This linguistic transition, while uneven across institutions and disciplines, reflects a growing effort to engage with global academic networks, while still maintaining functional bilingualism within the research community.

Methodological innovations have played a decisive role in advancing the analytical depth of landscape ecology in the DRC. Traditional techniques have been progressively complemented—and in some cases replaced—by advanced digital tools, including remote sensing, spatial modeling, and sophisticated statistical methods. These innovations have facilitated a transition from primarily descriptive studies to more nuanced analyses of landscape processes. The integration of field surveys, geospatial datasets, and participatory approaches reflects the emergence of a hybrid, operational analytical paradigm capable of capturing the multi-dimensional complexity of Congolese landscapes. In parallel, validation techniques have also evolved. Researchers increasingly rely on platforms such as Google Earth Engine, in combination with machine learning algorithms like Random Forest, to improve the accuracy of land cover classification and analysis [24,44]. Moreover, validation approaches based solely on stable land cover classes [31–33] are now being refined through the adoption of best practices [45], which emphasize the importance of considering both stable and changing land cover classes in accuracy assessment.

In the DRC, remote sensing has supported landscape ecology without forming its conceptual core, with sensor use evolving in response to shifting research needs and practical constraints. Early studies relied on very high-resolution imagery such as QuickBird to capture the fine-scale landscape structure, particularly in mining zones where artisanal activities disrupt forest patch connectivity—an essential concern in landscape ecology. However, due to high acquisition costs, QuickBird was soon abandoned in favor of more accessible platforms. From 2008 onward, Landsat emerged as the standard, offering free, multi-temporal data suitable for tracking long-term fragmentation dynamics, despite its limited capacity to detect sub-hectare disturbances. Since 2015, Sentinel-2 has provided improved spatial and temporal resolution, yet its adoption remains limited by barriers such as insufficient local processing capacity and technical training. Drones, while offering sub-meter precision for mapping microstructures and validating models, have seen only sporadic use, constrained by narrow spatial coverage and logistical challenges. These methodological choices reflect a pragmatic balancing act between resolution, temporal continuity, and resource availability. Importantly, the temporal depth of satellite archives has enabled the identification of non-linear, pulse-like landscape changes—often linked to conflict, displacement, or post-extraction recovery—highlighting the need for remote sensing approaches tailored to the socio-ecological volatility of the Congolese context.

Studies employing Landsat (30 m) and MODIS (1 km) imagery reported moderate classification accuracies (Kappa = 0.65–0.82); however, their coarse spatial resolution limited the detection of fine-scale disturbances, particularly in fragmented landscapes [18]. More recent approaches have utilized Random Forest classifiers with cross-validation, achieving overall accuracies above 90%. Nonetheless, confusion matrices revealed persistent omission errors in heterogeneous areas, consistent with findings by Mpanda et al. [24]. Participatory mapping methods introduced additional challenges, notably biases in the spatial translation of local knowledge, often due to the overrepresentation of accessible or familiar areas. Calibration with quantitative metrics—such as edge density—enhanced reliability but required larger sample sizes ($n > 100$) to reduce the influence of spatial autocorrelation and ensure statistical robustness [46].

The initial phase of landscape ecology research in the DRC (2005–2012) primarily employed GIS tools and basic landscape metrics (e.g., class area, patch number), but lacked standardized accuracy validation procedures, such as omission/commission error analysis. Later phases incorporated higher-resolution satellite data (e.g., Landsat 30 m), enhancing spatial detail but continuing to overlook methodological biases—particularly in participatory approaches, where the integration of local knowledge remained uneven and underreported. To advance methodological robustness, future research must address persistent gaps in validation practices, including the use of statistical accuracy assessments (e.g., Kappa coefficients, confusion matrices) and critically evaluate spatial resolution constraints to improve both reproducibility and contextual relevance.

5. Evolving Paradigms in Landscape Ecology in the DRC

Landscape ecology has undergone significant theoretical refinement over the past four decades, evolving through three major paradigms [47]. The foundational patch–corridor–matrix (PCM) model [5] offered a structuralist lens to describe landscape composition and configuration. Subsequently, the pattern–process–scale (PPS) paradigm introduced a functional dimension, emphasizing spatial heterogeneity, cross-scale interactions, and process-oriented modelling [6,7]. Most recently, the pattern–process–service–sustainability (PPSS) framework has emerged, embedding landscape ecology within the broader epistemological project of sustainability science by linking ecological patterns to ecosystem service provision and long-term socio-environmental resilience [48].

In the DRC, the empirical application of these paradigms reveals both convergence with and divergence from global trajectories. Between 2008 and 2015, research predominantly aligned with the PCM paradigm, focusing on quantifying landscape structure and deforestation dynamics, particularly in mining regions [26] and peri-urban areas [14,15]. While these studies advanced spatial characterization, they were limited in capturing the functional ecological implications of such transformations.

Between 2015 and 2020, methodological innovations—particularly in remote sensing, spatial statistics, and geospatial modelling—facilitated a gradual methodological shift toward PPS-aligned analytical frameworks. This transition, however, remained partial. It was limited by uneven spatial coverage, insufficient integration of socio-cultural drivers, and a lack of longitudinal ecological and governance datasets. Recent studies (2020–2025) demonstrate a tentative engagement with the more integrative PPSS paradigm, particularly in applied domains such as green infrastructure planning, urban ecology, and ecosystem restoration [22,31,36,49]. Despite these advancements, conceptual integration of the PPSS model remains fragile, revealing a persistent disjuncture between theoretical frameworks and the complex socio-ecological dynamics of Central African contexts [10].

A central limitation of the PPSS framework lies in its static assumptions regarding governance and institutional coherence. These assumptions are increasingly at odds with the spatially dynamic and politically contingent transitions documented in the GTS literature. For instance, mining corridors in southern DRC exhibit simultaneous ecological fragmentation and informal energy transitions—patterns that defy linear governance-development trajectories [25]. Incorporating the GST framework's emphasis on "urban transitions" could offer a valuable lens for reinterpreting Lubumbashi's rapid urban expansion. Rather than viewing it as unregulated sprawl, this perspective would frame Lubumbashi as a contested sustainability transition zone, in which landscape ecological metrics—such as connectivity, fragmentation, and land-use intensity—can inform more adaptive, place-based zoning strategies.

The application of landscape ecology paradigms in the DRC reveals fundamental mismatches between global models and local empirical realities. First, the widely used PPSS framework assumes the presence of functional governance structures that can translate ecological knowledge into sustainable land management [48]. However, the Congolese context—characterized by chronic institutional fragility and pervasive informal land-use systems, especially in mining zones, logging frontiers, and post-conflict areas—often undermines this assumption [24,50]. An alternative conceptual approach is needed, one that centers on "resilience through local self-organization," incorporating customary land tenure, informal resource governance, and community-led adaptive strategies [51].

Second, conventional fragmentation metrics (e.g., those derived from FRAGSTATS) tend to underestimate the ecological importance of sub-hectare disturbances caused by shifting cultivation, artisanal mining, and small-scale selective logging [52]. These disturbances are frequent, low-intensity, temporally dynamic, and spatially heterogeneous, often evading detection by standard spatial algorithms [53]. To address this, we propose developing "dynamic fragmentation indices" capable of capturing temporal variability and fine-scale disturbances within landscape-level analyses.

Third, the DRC provides a unique comparative vantage point. Unlike the post-deforestation landscapes of the Amazon [54] or conflict-affected regions in Colombia [55] and Angola [56], Congolese ecosystems are marked by hyper-fragmentation driven by the intersection of extractive pressures, anarchic urban expansion, and intermittent conflict [11,23,29,57]. This complex configuration serves as a natural laboratory to study ecological tipping points, spontaneous reforestation during conflict-induced land abandonment, and intricate feedback loops between socio-political instability and landscape dynamics [11,12,58,59].

Collectively, these divergences call for a critical re-examination of foundational assumptions in landscape ecological theory. Congolese landscapes—characterized by extreme fragmentation, institutional voids, and the coexistence of global extractive economies alongside traditional agroforestry systems—challenge dominant models of socio-ecological resilience. Addressing these challenges requires both theoretical flexibility and methodological innovation to develop a landscape science deeply grounded in the empirical pluralism and contextual realities of the Global South. Applying frameworks such as Kevin Lynch's theoretical model [20,60,61] or the evolutionary model of landscape anthropization [44] to southern Katanga offers a compelling illustration and promising pathway to advance landscape ecological research in this context.

In later research phases, metric selection became increasingly aligned with evolving conceptual frameworks. Structural metrics, such as patch size and edge density, were predominant during the PCM phase. In contrast, the adoption of the PPSS model facilitated the use of functional indices, including measures of ecological connectivity and resilience. For example, contagion metrics proved critical in characterizing landscape fragmentation in mining zones [18], while the Shannon diversity index was applied to assess forests resilience under anthropogenic pressure [9]. These developments underscore the growing methodological sophistication of landscape ecology in the DRC and the importance of aligning metric selection with theoretical orientation and landscape context.

6. Classification of Studies According to the Ten Principal Topics in Landscape Ecology

The ten priority research topics identified in landscape ecology encapsulate the core challenges and emerging opportunities within this interdisciplinary field [62]. These topics not only reflect the evolving scientific questions but also the practical needs for sustainable landscape management. Among these key subjects, we distinguish the following:

6.1. Ecological Flows in Landscape Mosaics

Ecological flows—the movement of organisms, genes, and resources—are strongly influenced by spatial heterogeneity and connectivity within landscape mosaics [63,64]. Studies in the Masako and Yoko Forest reserves in the DRC demonstrate how fragmentation and edge effects shape these dynamics [65–70]. Ref. [71] found that rodent communities in Masako exhibited high similarity (83%) between fallows and secondary forests, with demographics dominated by subadults, indicating structural homogenization alongside ecological instability. However, overall habitat connectivity remains low. Reference [72] reported only 3.9% inter-habitat mobility among rodents, with species such as *Deomys ferrugineus* and *Praomys* cf. *jacksoni* showing strong habitat specialization.

In the Yoko Reserve, Ref [73] observed that amphibian richness was highest in primary forests, while transitional zones supported edge specialists—illustrating how edges modulate biodiversity flows. Iyongo et al. [67] linked proximity to edges with skewed rodent sex ratios, suggesting demographic sensitivity to landscape structure. These findings collectively highlight edge effects and habitat isolation as key regulators of ecological flows in fragmented tropical systems. Maintaining functional connectivity and mitigating edge-driven pressures are essential for preserving biodiversity and ecosystem resilience [74].

6.2. Causes, Processes, and Consequences of Land Use and Land Cover Change

Land use and land cover change (LULCC) is a dominant force shaping landscape patterns and ecological processes in the DRC, generally supported by the application of the decision tree algorithm of Ref. [75]. Studies across diverse ecosystems show that anthropogenic pressures—particularly agricultural expansion, urbanization, and mining—drive significant land cover changes with cascading ecological consequences. In the Miombo woodlands near Lubumbashi, deforestation caused by charcoal production and farming resulted in a 50% loss of forest cover between 1990 and 2022, corresponding to an annual deforestation rate of 1.51% [44]. Similar patterns emerged in the Ituri-Epulu-Aru landscape, where deforestation accelerated from 0.05% to 0.14% (2003–2016) [76], and in the Katangese Copperbelt Area, where post-2002 mining catalyzed widespread forest attrition [77–79]. Consequences include declines in soil organic carbon (e.g., −26% following termite mound levelling) and biodiversity [80], along with increased fragmentation and habitat isolation [24], as well as fire sensitivity [81].

Urban sprawl compounds these effects. Lubumbashi's urban growth (8.7% annually, 1989–2014) significantly reduced per capita green space [32], while Kisangani lost 47% of mature forests between 1986–2021 due to peri-urban agriculture [22,82]. Diffusion-coalescence patterns typify these spatial changes, with dense urban cores and fragmented fringes [83]. Methodologies that combine Landsat imagery, landscape metrics (e.g., FRAGSTATS), and transition matrices have effectively characterized the scale and structure of land-use and land-cover change (LULCC). However, limitations such as coarse-resolution data and weak integration of socio-economic factors hinder robust causal inference. Emerging approaches—including high-resolution imagery, predictive modeling tools like DINAMICA EGO, and stakeholder-inclusive frameworks—offer more comprehensive insights. Projected scenarios indicate that, under sustainable governance, 81.4% of forests in the Ituri-Epulu-Aru region could be conserved by 2061 [65].

6.3. Nonlinear Dynamics and Landscape Complexity

Tropical landscapes in the DRC display complex, nonlinear dynamics shaped by ecological thresholds, feedback loops, and spatial heterogeneity. Understanding these processes is essential for assessing ecosystem resilience, degradation, and responses to anthropogenic pressures [83,84]. In Yoko Forest Reserve, spatial aggregation of tree species (*Gilbertiodendron dewevrei*, *Uapaca guineensis*) reveals small-scale dispersal limitations that generate broader biodiversity patterns [85]. These observations indicate the presence of scale-dependent processes, although further integration of abiotic data is necessary to identify critical thresholds driving shifts in forest composition [86]. The Virunga landscape exemplifies nonlinear land-cover trajectories, with protected zones maintaining relative stability while surrounding areas experience fluctuations influenced by socio-political factors. Periods of deforestation followed by unexpected regrowth during conflict highlight feedback linking human activity and ecosystem transitions [12,87,88].

In the Lubumbashi charcoal production basin, fire regimes are strongly linked to human land use [89]. Fires exhibit nonlinear spatial patterns, shaped by proximity to infrastructure and land cover type, with savanna areas being more susceptible to burning. These dynamics underscore fire-vegetation feedback critical for anticipating future landscape change [90]. The core forests of Lomami National Park demonstrate resilience despite fragmentation at the periphery caused by edge effects. Although forest cover remains high (92.75%), gradual losses in connectivity highlight the need for multi-scale conservation metrics and high-resolution monitoring [9]. The urban landscape of Lubumbashi exhibits ecological tipping points, where fragmentation of green spaces and the invasion of exotic species—such as *Tithonia diversifolia*—are transforming peri-urban biodiversity [90,91]. Collectively, these cases emphasize the value of nonlinear frameworks for predicting abrupt ecological shifts. Moving from descriptive to predictive science is vital for managing tropical landscapes amid escalating human and climatic pressures [92].

6.4. Scaling

Scaling is crucial for understanding how localized ecological processes and disturbances propagate across broader spatial and temporal dimensions. In the DRC, forest edge degradation—typically occurring within 100 to 300 m zones—accounts for 25% of regional carbon emissions, a footprint three times larger than that of deforestation [93]. This illustrates how fine-scale changes cascade into large-scale impacts, necessitating integration of high-resolution data (e.g., LiDAR) with landscape-scale models to capture the true scope of the degradation.

Transboundary protected areas in Central Africa reveal spatial scaling mismatches in conservation. While some regions resist deforestation, others succumb to localized agricultural pressures, reflecting a disconnect between top-down governance and nested ecological threats [94]. This mismatch underscores the need for multilevel governance frameworks capable of adapting conservation strategies to both micro-scale land use patterns and macro-scale connectivity dynamics [95]. In Lualaba Province, 34 years of Miombo woodland degradation illustrate how temporal scaling can compound localized fragmentation into biome-level collapse. Deforestation driven by agricultural expansion and mining activities reveals a persistent lag in policy response and enforcement. Landscape metrics such as edge density and patch isolation demonstrate how localized anthropogenic pressures can escalate into large-scale, potentially irreversible ecological transformations [96].

Ecological processes such as biodiversity dynamics also defy linear extrapolation. In Katanga, tree density and understory diversity vary across patches, corridors, and watersheds, exposing the scale-dependence of hypotheses like intermediate disturbance [41]. This underscores the danger of applying local findings universally without scale-sensitive validation. Ultimately, scaling is both an analytical framework and a governance imperative [97]. Bridging spatial and temporal scales through remote sensing, hierarchical modeling, and the integration of socio-economic data is essential for anticipating ecosystem tipping points and promoting resilient, context-sensitive landscape management [98].

6.5. Methodological Development

Landscape ecology in the DRC has greatly benefited from methodological advancements that provide a more nuanced understanding of the complex interactions between landscape patterns and ecological processes. The sophisticated integration of remote sensing techniques—combining satellite imagery from platforms such as Landsat and MODIS with rigorous field validation—has significantly enhanced the accuracy of monitoring forest and urban dynamics [99]. For instance, the study by Khoji et al. [17] in Salonga National Park quantified a 10.8% deforestation rate between 2002 and 2020, highlighting the importance of radiometric corrections and the potential of LiDAR technology to enhance spatial resolution. Concurrently, analyses of urban heat islands in Kisangani by Ref. [36] underscored the critical role of spatial resolution in detecting thermal gradients. This study validated urban heat island (UHI) effects using MODIS LST data, cross-referenced with ground-based measurements under clear-sky conditions, and supported by morphological criteria (e.g., built-up areas, vegetation) from high-resolution Google Earth imagery and population density data.

Participatory approaches, such as the "Distance to Nature" method adapted by André et al. [100] in Lubumbashi, have revitalized the mapping of anthropization levels by combining field data with proximity-based rules. Bioindicator studies have been advanced through standardized protocols; Musubaho et al. [101] developed a rigorous nocturnal amphibian trapping method in the Yoko Reserve, enabling fine-scale quantification of diversity and endemism. Some studies stand out for their analysis of anthropogenic pressures, integrating landscape metrics with urban perception surveys. For example, Vranken et al. [20] identified a mining-related "pollution cone" in Lubumbashi. Despite these advances, limitations in spatial resolution (e.g., Landsat at 30 m, MODIS at 1 km) and sampling biases remain significant challenges. Furthermore, the sometimes-rigid dichotomy between qualitative and quantitative methods highlights the ongoing need for integrative approaches to achieve a more comprehensive landscape ecology [102].

6.6. Relating Landscape Metrics to Ecological Processes

The relationship between landscape patterns and ecological processes is profoundly shaped by anthropogenic activities such as agriculture, mining, and urbanization [75]. Land-use changes and fragmentation have significant effects on biodiversity, soil quality, and carbon cycling. For example, in the Luki Biosphere Reserve, fire disturbances account for 34% of land-cover changes. Primary forests in the reserve show relatively low stability (23–34%) compared to the more resilient savanna ecosystems (>73%) [103]. Similarly, studies in the Masako Forest Reserve reveal that primary and secondary forests share 53% species similarity, while young fallows differ markedly, illustrating an "inverse J" pattern of disturbed stands [104]. These findings underscore the importance of landscape configuration, including patch size and connectivity, for ecological resilience [105–109].

Anthropogenic pressures also degrade soil properties [110,111]. In Yangambi, Ferralsols subjected to shifting cultivation exhibit reduced clay content, increased bulk density, and decreased hydraulic conductivity, with edge effects extending up to 70 m into adjacent forest areas [112]. Mining in Lubumbashi produces spatial pollution patterns identifiable as "pollution cones" through high-resolution imagery [29], influenced by metrics like edge density and patch isolation.

Urban expansion alters habitat heterogeneity and species composition. *Acacia auriculiformis* plantations in Lubumbashi grew 30% from 2006 to 2021, with exotics comprising 51% of urban flora [42]. Domestic gardens in planned urban areas exhibit higher floristic richness, with anthropochory responsible for over 85% of seed dispersal. This highlights the important relationship between landscape diversity and urban ecosystem services [43].

Despite advances in remote sensing (Landsat, MODIS), spatial resolution and data gaps limit detection of fine-scale changes [99,113]. Future research should integrate higher-resolution tools, socio-economic data, and cross-scale modeling to better elucidate the mechanisms connecting landscape patterns with ecological processes. Such studies highlight the strong interdependence between human-driven landscape changes and ecological outcomes in the DRC, providing crucial guidance for sustainable land management [114].

6.7. Integrating Humans and Their Activities into Landscape Ecology

The relationship between landscape patterns and ecological processes represents a major concern in landscape ecology, particularly regarding the impact of land use on ecological dynamics [115,116]. Studies conducted in the Katanga region of the DRC clearly illustrate how human activities alter landscapes and influence vegetation [38,117], biodiversity [90], and ecosystem resilience [37,96].

Rapid urbanization in Lubumbashi and its surroundings has profoundly transformed landscape structures. Useni et al. [33] report a 32% increase in built-up areas between 2000 and 2008, accompanied by a concomitant 33% loss of forests and wetlands, exacerbating habitat fragmentation and disturbance. The expansion of the invasive species *Tithonia diversifolia* exemplifies the effects of anthropogenic disturbances on ecosystems. Useni et al. [37] also document forest loss of up to 80% in mining towns, where urban and agricultural activities predominate.

The links between land use history and ecological processes are evident. For example, Mujinya et al. [117] demonstrate that the distribution of termite mounds in degraded Miombo woodlands is more strongly correlated with anthropogenic pressures than with pedological characteristics. During the COVID-19 pandemic, deforestation in the Lubumbashi charcoal production basin temporarily slowed during lockdowns but accelerated thereafter [118], revealing the direct dependency of forest dynamics on human activity.

Finally, the resilience of Miombo forests is challenged by the proliferation of exotic species and floristic degradation, complicating restoration efforts [42]. These findings underscore the urgent need for sustainable management approaches that integrate the interactions between human land use and ecological processes [119].

6.8. Optimization of Landscape Pattern

The relationship between landscape pattern and ecological processes, particularly regarding deforestation dynamics, has garnered significant attention in landscape ecology. Recent studies demonstrate that the spatial configuration of protected areas critically influences deforestation risk. Strict protection zones, such as national parks, with large contiguous patches, significantly reduce deforestation [9,18], while less regulated areas, including hunting reserves, exhibit increased fragmentation [16,17,58]. Using Random Forest models, edge density and patch connectivity were identified as key predictors of deforestation, with agricultural encroachment leading to irregular patch shapes and a reduction in core forest areas. These findings emphasize the urgent need for optimized landscape planning that prioritizes contiguous protected area networks to preserve ecosystem functionality and enhance resilience.

In Lomami National Park, high forest aggregation within core zones (covering 92.75%) contrasts sharply with fragmentation observed at the periphery, driven by edge effects and human activities. Landscape metrics such as patch density and edge contrast highlight destabilizing influences on forest connectivity. These findings support the hypothesis that intact forest patches bolster ecosystem resilience, while fragmentation increases the risk of degradation [9]. Buffer zone management and corridor restoration are recommended strategies to mitigate peripheral fragmentation, with future research encouraged to incorporate high-resolution spatial monitoring for improved planning [120].

Urbanization-driven landscape fragmentation is pronounced in Lubumbashi, where green spaces are increasingly fragmented into smaller, isolated patches [31], and invasive species dominate peri-urban areas [121,122]. Patch size distribution and edge density metrics indicate declining connectivity of native vegetation due to unplanned expansion [32]. These results advocate for restoring green infrastructure using native species and strategic patch aggregation, with landscape metrics guiding urban planning to balance development and ecological preservation. Multi-scale interventions are vital for optimizing urban landscape patterns and sustaining ecosystem services [123].

6.9. Landscape Sustainability

Landscape sustainability science explores how spatial patterns interact with ecological processes to sustain ecosystem functions amid anthropogenic pressures [6]. In Lubumbashi, recent research sheds light on land-use change, vegetation dynamics, and biodiversity responses, offering insights for sustainable landscape management [41,42]. The expansion of *Acacia auriculiformis* plantations across the urban–rural gradient exemplifies a restoration-invasion trade-off. From 2006 to 2021, urban plantation coverage increased by 30%, accompanied by higher floristic diversity in urban zones. However, exotic species constitute 51% of the flora, half of which are invasive, posing long-term risks to native ecosystems. These findings highlight the need for afforestation practices favoring native species to prevent biodiversity loss [42].

Miombo woodland regeneration is strongly affected by land-use history [124]. Undisturbed and degraded miombo forests retain greater ecological resilience compared to post-cultural fallows, suggesting that degraded landscapes retain restoration potential and should be prioritized rather than abandoned [41]. While floristic and dendrometric indicators provide partial insights into vegetation responses, the underlying mechanisms driving species invasion and native community reassembly remain poorly understood. Addressing these knowledge gaps through cross-scale, integrative research is essential for understanding how landscape configuration influences restoration trajectories and for guiding adaptive management of sustainable urban landscapes.

6.10. Data Acquisition and Accuracy Assessment

Understanding the complex interactions between landscape patterns and ecological processes in Central African ecosystems demands robust data acquisition and rigorous accuracy assessment. Recent studies emphasize the critical role of spatial data quality and methodological rigor in evaluating land-use change impacts on soil and vegetation [125,126].

A major challenge lies in accurately detecting ecologically significant features such as termite mounds in Miombo woodlands. These mounds strongly influence soil nutrient distribution and hydrological functioning but exhibit complex spatial arrangements—clustered in savannas and dispersed in woodlands [80]. Vranken et al. [125] highlight that high-resolution remote sensing is essential for reliable mapping, as standard satellite imagery, especially in dry seasons, risks false positives due to low spectral contrast. Ground-truth validation remains indispensable for refining classification accuracy.

In urban landscapes like Lubumbashi, long-term land-use monitoring relies on time-series satellite data. Seasonal NDVI analyses reveal combined climatic and anthropogenic effects, yet their accuracy hinges on the temporal resolution and correction of urban spectral noise [126,127]. NDVI accuracy was validated using GPS ground-truth data from field surveys, high-resolution satellite imagery, and cross-checked land cover datasets. Integrating field surveys with socio-economic data strengthens the assessment of vegetation and green infrastructure by reducing spatial uncertainties related to fragmentation.

In Salonga National Park, deforestation analyses couple accessibility modelling with remote sensing to delineate forest degradation gradients linked to proximity to infrastructure. Fine-scale fragmentation detection and edge effect assessment require high spatial–temporal resolution data and rigorous validation through ecological field sampling to confirm remote sensing interpretations [18].

7. Challenges Limiting Landscape Ecology Research

Landscape ecology research in the DRC currently faces several significant challenges that constrain its scientific scope and operational impact. These technical, methodological, and conceptual limitations affect the quality of analyses and the ability to produce relevant results for sustainable territorial management.

From a technical standpoint, limitations in spatial data resolution remain a persistent obstacle to accurately characterizing landscape dynamics in the DRC. While satellite imagery from platforms such as Landsat and MODIS offer extensive temporal and geographic coverage, their moderate spatial resolution is often inadequate for capturing the fine-scale ecological and anthropogenic processes that define Congolese landscapes. This is particularly evident in highly fragmented environments, including the urban peripheries of Lubumbashi and artisanal mining zones in the Katanga region [44].

The anthropogenic transformation of Katanga's miombo woodlands exemplifies the socio-ecological complexity of such landscapes. These transformations parallel the 'agri-food transitions' identified in the GST literature, where extractive pressures and biomass-based livelihoods (e.g., charcoal production) intersect with reforestation efforts. Yet, existing transition models lack a spatially explicit framework to assess these trade-offs. Landscape ecology, with its emphasis on spatial heterogeneity and pattern-process relationships, could fill this gap by mapping and quantifying trade-offs between charcoal-driven deforestation and restoration potential—an approach currently underutilized in transition theory [25].

Additionally, persistent cloud cover—common in tropical regions—further constrains the availability of cloud-free optical imagery, thereby limiting the temporal continuity of observational data [18]. This technical limitation significantly affects the accuracy and reliability of landscape monitoring efforts, especially when attempting to detect short-term changes or seasonal variations [128]. The absence of consistent, high-resolution, cloud-free datasets reduces the ability to monitor fragmentation dynamics, quantify land-use change, and evaluate the effectiveness of conservation interventions over time.

A major limitation in vegetation mapping remains the lack of systematic field validation. Numerous studies rely predominantly on satellite-derived data, often without sufficient ground-truthing, which contributes to classification inaccuracies and hampers the precise differentiation of vegetation types and levels of ecological degradation [129]. Additionally, floristic and faunistic inventories are frequently conducted in a sporadic and heterogeneous manner, limiting their utility for robust spatial and temporal analyses. Recent findings by Ramalason et al. [130] further demonstrate that global vegetation maps inadequately represent dryland ecosystems; however, integrating tree and shrub cover into a unified woody cover metric significantly enhances mapping accuracy, underscoring the need for improved remote sensing strategies tailored to specific landscapes.

Methodologically, the absence of standardized protocols hinders the coherence of results across different studies. Land-use classifications vary, as do the landscape metrics employed, limiting the synthesis of knowledge at the national scale (i.e., [39,76]). Furthermore, most research focuses on relatively short timeframes (ten to twenty years), which are insufficient to capture long-term dynamics typical of tropical ecosystems that require robust and often unavailable historical datasets [13].

Conceptually, landscape ecology research in the DRC tends to emphasize biophysical factors while underrepresenting socio-economic and cultural dimensions that are crucial for understanding territorial dynamics [131]. Human drivers such as agricultural practices, land tenure issues, and local governance systems are often inadequately integrated, reducing the explanatory power of ecological models [44]. Additionally, the challenge of linking spatial and temporal scales—from local to global—prevents a systemic understanding of complex interactions between human activities and ecological processes [58].

Finally, practical applications of research findings remain limited. The weak dialogue between scientists, policymakers, and local communities hampers the effective translation of knowledge into conservation policies and sustainable land-use planning. As a result, research has yet to become a strategic driver for the management of Congolese landscapes [132].

8. Perspectives for Integrated and Sustainable Landscape Ecology

Landscape ecology in the DRC must move beyond broad conceptual approaches toward innovative, operational frameworks that directly engage with the region's unique socio-environmental complexities. To facilitate this transition, we propose three strategic priorities:

8.1. Development of a Human–Fragmentation–Ecosystem Interactions Index (HFEI)

Conventional fragmentation metrics primarily capture structural land cover changes but fall short in reflecting the complex socio-political drivers of landscape transformation in the DRC—such as artisanal mining, informal settlements [41], and fluctuating governance regimes [11]. To address this gap, the proposed Human–Fragmentation–Ecosystem Interactions (HFEI) index would integrate multi-source remote sensing data—including high-resolution satellite imagery, LiDAR, and drone-based observations—with socio-political indicators such as mining concessions and population migration patterns. By combining ecological and human dimensions, the HFEI would quantify fragmentation more holistically, incorporating temporal dynamics to reflect both episodic disturbances and gradual transformations [133].

Technically, the HFEI should integrate LiDAR-derived canopy height models with high-accuracy land cover classifications (e.g., confusion matrices with global accuracy > 0.8) to detect sub-hectare disturbances, particularly in degraded or regenerating zones. Furthermore, it should be embedded within hybrid governance frameworks, supported by sensitivity analyses to evaluate the relative weight of scientific data versus local knowledge inputs. Such an index would significantly enhance the precision and relevance of landscape monitoring and management in socio-ecologically complex contexts like the DRC.

8.2. Experimentation with Hybrid Governance Models

In contexts marked by governance fragility and informal socio-political structures, like the DRC, conventional top-down conservation and land management approaches often fail. Innovative governance frameworks co-designed with local communities, scientists, and policy actors can facilitate adaptive management of landscapes [132] and protected areas [9]. These hybrid models would recognize and formalize the role of informal actors (e.g., artisanal miners, traditional agroforestry practitioners) as legitimate stakeholders, fostering resilience through local self-organization, knowledge exchange, and shared stewardship [134]. Pilot projects testing these governance hybrids could provide replicable models for other fragile states.

8.3. Adaptation of Remote Sensing Tools to Capture Fine-Scale Dynamics

Large-scale satellite data often overlook sub-hectare disturbances typical of shifting cultivation, artisanal mining, or spontaneous reforestation during post-conflict recovery. Integrating low-cost drone technologies with ground-based sensor networks can offer detailed, near-real-time data on these fine-scale processes [135]. This granular monitoring capability would improve understanding of landscape dynamics, enhance early detection of degradation or recovery trends, and support timely interventions [136].

Collectively, these priorities seek to create a contextualized, interdisciplinary landscape ecology in the DRC that bridges ecological science, socio-political realities, and technological innovation—ultimately supporting sustainable land-use planning and biodiversity conservation in one of the world's most ecologically and socially complex regions.

9. Toward a Contextualized Conceptual Framework for Landscape Ecology in the DRC

Despite two decades of empirical research in the DRC, most landscape ecological studies continue to rely on imported theoretical models that do not fully capture the country's unique socio-ecological contexts. The DRC presents a rare convergence of interacting drivers—armed conflict, extractive industry expansion, institutional vacuums, and traditional ecological knowledge—that together reshape landscape structure, function, and governance. This complexity calls for the development of a situated conceptual model capable of addressing these multiscalar dynamics and guiding both research and policy-making.

We propose a framework tentatively titled "Socio-political fragmentation model: when informal governance redefines ecological connectivity." This model integrates three core dimensions:

- Feedback loops between extractive pressures and demographic shifts, e.g., industrial and artisanal mining triggering rural exodus and peri-urban settlement, which in turn increases pressure on secondary forests and agroforestry mosaics [37].
- Non-linear temporal regimes, driven by the recurrence of political crises, economic shocks, and post-conflict reconfigurations. These cycles create pulsed disturbances (e.g., spontaneous reforestation during conflict, abrupt deforestation during reconstruction) that challenge linear degradation models and classical successional assumptions [9,58].
- The centrality of informal actors and governance regimes—including artisanal miners (creuseurs), customary chiefs, local conservation networks, and informal markets—which mediate land-use decisions and ecological outcomes outside formal institutions [24,131].

This conceptual framework departs from dominant paradigms in landscape ecology by challenging assumptions of institutional stability, data continuity, and static land-use drivers. Instead, it foregrounds adaptive socio-ecological assemblages, territorial fluidity, and fragmentation as processes that are simultaneously spatial and political. By formalizing this approach, we aim to encourage comparative research across crisis-affected geographies—such as post-conflict Colombia and resource frontiers in the Amazon—and to contribute to the development of a globally relevant, yet locally grounded, theory of landscape dynamics under conditions of institutional fragility.

10. Broader Implications for Global Landscape Ecology and Sustainability Science

The Congolese case, though contextually specific, offers critical theoretical and operational insights with broader relevance for global landscape ecology and conservation science. Most notably, the extreme socio-political volatility and institutional fragility observed in the DRC challenge the foundational assumption of governance stability embedded in many resilience and conservation frameworks. The ecological behavior of Congolese landscapes illustrates that resilience cannot be fully understood without systematically accounting for political instability, institutional discontinuity, and socio-economic fragmentation—variables that are equally salient in other fragile and conflict-affected states, including Madagascar, South Sudan, and Haiti.

The recurrent failure of top-down conservation models in the DRC—particularly in areas where protected zones overlap with industrial mining concessions or artisanal extraction sites [16,18]—raises substantive concerns regarding the universal applicability of global biodiversity targets such as the "30 × 30" agenda. These findings call for a reconceptualization of spatial conservation goals. Rather than relying solely on cartographic coverage or legal designation, spatial targets must be grounded in functional ecological connectivity, social legitimacy, and multi-actor governance arrangements. In highly contested and institutionally fragmented landscapes, formal protection does not necessarily equate to ecological or social effectiveness.

From a policy perspective, this study underscores the need for a more integrated interpretation of the SDGs. While SDG 15 ("Life on Land") remains central to biodiversity protection, its achievement in contexts such as the DRC is contingent upon progress toward SDG 16 ("Peace, Justice, and Strong Institutions"). Environmental sustainability in fragile states cannot be decoupled from the dynamics of armed conflict, informal governance systems, and state fragility.

Emerging research in the GST further suggests that sustainability pathways in resource frontiers require spatial intermediation—a function that landscape ecology is uniquely positioned to fulfill. Through tools such as conflict-sensitive spatial mapping and multi-scalar connectivity analysis, landscape ecology can help identify viable corridors for agroforestry, artisanal mining, or biodiversity restoration, calibrated to local governance regimes and socio-political realities [25]. This approach resonates with GST's emphasis on prioritizing regional agency and place-based transitions, rather than imposing externally derived conservation or development targets. The DRC's hybrid land governance landscape—comprising overlapping formal, informal, and customary systems—exemplifies the urgent need for flexible, integrative frameworks that reconcile ecological priorities with local institutional complexity.

Finally, we argue for the development of new sustainability indicators that reflect not only ecological metrics but also conflict intensity, governance quality, and the resilience of local knowledge systems [137,138]. These composite indicators could better guide international funding, conservation planning, and post-crisis reconstruction in ecologically critical but politically unstable regions.

11. Conclusions

A retrospective assessment of landscape ecology research in the DRC over the past two decades reveals a field in active transformation—from largely descriptive studies to disruptive theoretical innovation. Initially lagging global trends, research in the DRC has progressively adopted a transdisciplinary approach, integrating spatial analysis, ecological theory, and social science to address its complex socio-ecological realities.

The DRC's landscapes—shaped by mining, armed conflict, and unregulated urban expansion—exhibit extreme fragmentation that challenges conventional frameworks like the PPD model and standard fragmentation metrics. These traditional paradigms assume governance stability and linear degradation-recovery cycles, assumptions at odds with the non-linear feedback mechanisms (such as conflict-induced reforestation) and governance vacuums observed in the Congo Basin. In contrast, the proposed "socio-political fragmentation model" integrates informal actors, pulsed disturbances, and adaptive socio-ecological assemblages. Structurally, it foregrounds political instability and local self-organization, dimensions notably absent from the PPD approach.

In response, this article proposes new conceptual tools, including the Human–Fragmentation–Ecosystem Interactions Index (HFEI) model, which can explicitly incorporate political instability and informal institutions. These innovations challenge the universality of dominant landscape ecology theories and emphasize the need to treat governance fragility as a core ecological variable.

Comparative insights from other fragile or post-conflict regions (e.g., the Colombian Andes or post-deforestation Amazonia) suggest the relevance of these lessons beyond the DRC. Future research must systematically integrate conflict dynamics (aligned with SDG

16) alongside biodiversity objectives (SDG 15) and foster hybrid governance models that engage local communities as active agents in sustainability transitions.

Despite its contributions, landscape ecology in the DRC continues to face three key gaps:

1. Limited integration of spatial transition frameworks from the GST literature.
2. Insufficient testing of landscape metrics as negotiation tools in land-use transitions (e.g., charcoal production zones);
3. Persistent Northern bias in participatory methods, often overlooking local spatial knowledge.

Rather than merely applying global models, DRC-based research is actively reshaping the theoretical foundations of landscape ecology. By positioning Congolese landscapes as boundary objects—where ecological, governance, and local knowledge systems intersect—landscape ecology emerges as a translational science. This boundary role enables it to (1) quantify spatial trade-offs (e.g., between mining concessions and community forests), and (2) visualize contested transition pathways through participatory, place-based mapping approaches.

In fragile contexts, landscape-scale analyses uncover hidden socio-ecological linkages—from artisanal mining corridors that double as economic lifelines and degradation hotspots, to conflict-affected forests experiencing unexpected regeneration. Leveraging this boundary role requires co-producing landscape metrics with local communities and informing polycentric governance models that reflect the DRC's institutional complexity.

To realize this potential, the field must address three persistent constraints: fragmented socio-ecological data, untested governance innovations, and top-down metric design. Prioritizing longitudinal, community-based monitoring and experimental governance in mining corridors would directly respond to these challenges and strengthen landscape ecology's role in advancing sustainability transitions under crisis conditions. Future research must prioritize transparent reporting of accuracy metrics (e.g., OA, Kappa), scale-sensitive validation, and participatory method calibration to align Congolese landscape ecology with global standards while addressing local complexities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/earth6030097/s1, Table S1: Distribution of Published Landscape Ecology Studies by Journal in DRC (*n* = 76, Excluding Master's Thesis) from 2008 to 30 June 2025.

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