Conservation Letters

WILEY

Conservation Letters
A journal of the Society for Conservation Biology
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Permanence Risks to Biodiversity and Nature-Based Carbon Offsets

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Received: 25 November 2025 | **Revised:** 3 March 2026 | **Accepted:** 17 March 2026

Keywords: biodiversity offsets | carbon offsets | climate change | conservation policy | environmental governance | mitigation hierarchy | nature-based solutions | offset permanence | policy design | risk management

ABSTRACT

Biodiversity and nature-based carbon offsets are central to strategies addressing biodiversity loss and climate change. Their credibility depends on permanence—the expectation that biodiversity gains or sequestered carbon persist at least as long as the impacts they compensate for, or in perpetuity. Yet ecosystems are dynamic and increasingly exposed to disturbance, making perpetual outcomes difficult to guarantee. Despite this, many offset programs rely on fixed durations and static assumptions ill-suited to managing long-term risks, creating a structural misalignment between ecological permanence and the safeguards intended to secure it. To assess this misalignment, we reviewed three decades of literature to identify risks to long-term durability and strategies for managing them. We developed a typology spanning three domains. Non-physical risks, such as weak governance and limited data transparency, were most frequently reported, often co-occurred, and enabled other failures. Physical risks such as fire, storms, or flooding cause material damage and are intensifying with climate change. Methodological risks, including oversimplified metrics and flawed design, expose structural weaknesses in offset systems. Our typology provides a framework for assessing permanence risks and strengthening offset governance. Credible, enduring offsets are achievable, provided robust risk management and adaptive governance are aligned with ecological realities.

1 | Introduction

Biodiversity and nature-based carbon offsets are increasingly central to strategies addressing biodiversity loss and climate change. Target 19 of the Kunming-Montreal Global Biodiversity Framework calls for mobilizing $200 billion annually by 2030 and explicitly identifies biodiversity offsets as key instruments needed to close the biodiversity finance gap (Convention on Biological Diversity 2022). Similarly, Article 6.4 of the Paris Agreement enabled international carbon trading, positioning carbon offsets as tools for meeting decarbonization targets (United Nations Framework Convention on Climate Change 2015). As offsets become embedded in global conservation policy, ensuring they deliver real, measurable, and lasting outcomes is essential to advancing, rather than undermining, international climate and biodiversity goals (Maron et al. 2025; West et al. 2023; zu Ermgassen et al. 2026).

Central to offsetting is the concept of permanence: the expectation that an offset's ecological gains, from biodiversity supported by restored wetlands to carbon sequestered in forest biomass and soils, endure at least as long as the impacts it compensates for, or in perpetuity (BBOP 2009). Because many development impacts—new infrastructure replacing habitats, species extinction, greenhouse gas emissions—persist for extended periods and, in some cases, are effectively irreversible on human timescales (Arcusa and Lackner 2025), credible claims of *no net loss* or *net zero* require compensation that lasts for comparable durations. For carbon, this means storage lasting as long as emissions influence the climate (Arcusa and Lackner 2025). For irreversible biodiversity losses, offsetting is often in theory prohibited altogether, since meaningful compensation would need to endure indefinitely (Blackmore 2020; Damiens et al. 2021).

Perpetual ecological benefits, however, are rarely achievable in practice. Ecosystems are inherently dynamic and, under intensifying global change, increasingly vulnerable to disturbance, degradation, and loss (Dye et al. 2024). Even well-designed offsets may therefore deliver only temporary benefits (Balmford et al. 2023; Blackmore 2020). This creates a fundamental tension: offsetting relies on long-lived compensation delivered through ecological systems whose future condition cannot be guaranteed.

Permanence is thus better understood not as a literal guarantee of perpetual outcomes, but as the capacity to sustain additional ecological benefits over time—what we term durability (Balmford et al. 2023). Durability reframes permanence in practical terms as the ongoing management of ecological gains under disturbance and uncertainty.

Yet translating durability into policy has proven difficult. Rather than structuring safeguards to address long-term ecological and institutional risk, many offset programs instead treat permanence as a fixed duration requirement, often because land managers are reluctant to enroll in schemes that give away their property rights perpetually. Some programs set timeframes too short to compensate for irreversible harms; others mandate "long-term" protection without clear mechanisms for maintaining outcomes (Fischer et al. 2016; Li and Zhang 2024; McKenney and Kiesecker 2010). In the absence of a unified durability standard, offset programs have adopted divergent safeguards, leading to wide variation in form, duration, and stringency (see Table 1).

Consequently, current offset safeguards commonly rely on predefined temporal thresholds and static assumptions about ecological and institutional stability—features ill-suited to managing long-term risk (Buchholz et al. 2021; Damiens et al. 2021). As climate and ecological pressures intensify, such safeguards are increasingly inadequate (Anderegg et al. 2025; Badgley et al. 2022; Damiens et al. 2021; zu Ermgassen et al. 2019). The result is a structural misalignment between permanence from an ecological perspective, durability as the means of securing it, and the duration-based contracts and safeguards on which programs rely.

To address this gap, we reviewed the literature on biodiversity and nature-based carbon offsets (hereafter *offsets*) to identify key risks to durability and approaches to managing them. We develop a typology spanning biophysical threats (e.g., extreme weather, climate change, human disturbance), methodological challenges (e.g., poor design, implementation failures), and institutional vulnerabilities (e.g., funding gaps, weak governance, legal ambiguity). We then synthesize strategies to address these risks, offering a management framework to strengthen durability and support more credible permanence claims for offsets in a rapidly changing world.

2 | Methods

We conducted a rapid evidence assessment (Crawford et al. 2015) to identify peer-reviewed literature on permanence risks to biodiversity and nature-based carbon offsets. Searches were conducted in Web of Science and Scopus for English-language articles published from 1990 onwards, targeting titles, abstracts, and keywords. Grey literature was excluded. After removing duplicates, titles and abstracts were screened and categorized as "yes," "maybe," or "no," with full texts of "yes" and "maybe" studies reviewed for inclusion. Reference lists of included studies were screened for additional sources.

Screening and data analysis were conducted in R version 4.5.0 (R Core Team 2024) using the *metagear* package (Lajeunesse 2016) with standardized coding fields. Studies were included if they evaluated projects designated as offsets or functioning as compensatory mechanisms. Broader mitigation measures (e.g., Environmental Impact Assessments) and non-offset conservation programs (e.g., non-REDD+ Payments for Ecosystem Services or agri-environment schemes) were excluded. Studies on species conservation banking were included due to its functional similarity to formal offsets (White et al. 2021).

We applied broad inclusion criteria to capture varied discussions of risks. Studies were included if they (1) empirically assessed risks (e.g., through monitoring or evaluation), (2) modeled or projected risks, or (3) provided evidence-informed conceptual, legal, or policy analyses. We recorded study evidence type (empirical, modeling, review/discussion-based, or conceptual/legal/policy) to distinguish between observed, projected, and qualitatively reasoned risks.

For each study, we coded explicitly identified or implied risks and their rationales, along with contextual variables including offset type (biodiversity or carbon), ecosystem, geographic location, and program or policy context. Studies could be coded to multiple values across variables. Data was analyzed descriptively by calculating frequencies of reported risks across categories and studies. Geographic patterns were assessed by aggregating study locations and associated risks at the country and continental levels. Temporal trends were analyzed using publication-year frequencies. For selected summaries, we grouped closely related programs under shared regulatory frameworks (e.g., U.S. Section 404 permitting and wetland mitigation banking; UNFCCC Activities Implemented Jointly and the Clean Development Mechanism), with program-specific findings discussed separately where relevant.

To synthesize findings, we developed a hierarchical typology of risks with three levels: domain, category, and type. We grouped risks into three domains (physical, methodological, and non-physical) and further differentiated into categories and specific types. Where possible, we aligned the typology with existing frameworks (e.g., Dye et al. 2024; Galik and Jackson 2009); where none existed, we developed original categories.

TABLE 1 | Permanence requirements for a sample of 10 offset programs (5 biodiversity offset and 5 carbon offset programs).

Offset program (Country)	Offset type	Permanence requirement	Safeguards (legal, financial, management)	Source(s)
Wetland and Stream Mitigation Banking (USA)	Biodiversity; compliance	Perpetual	**Legal**: Conservation easements or deed restrictions required **Financial**: Endowments, bonds, or escrow accounts mandatory **Management**: Long-term plan; credit release tied to ecological performance; 5+ years monitoring required	(U.S. Army Corps of Engineers and U.S. Environmental Protection Agency 2008)
Biodiversity Net Gain (England)	Biodiversity; compliance	30 years (minimum)	**Legal**: Section 106 agreement or conservation covenant mandatory **Financial**: Assurances encouraged but not required **Management**: Habitat management plan with reporting milestones over 30-year period required	(Ministry of Housing, Communities and Local Government and Department for Levelling Up, Housing and Communities 2024)
Fisheries Habitat Offsetting (Canada)	Biodiversity; compliance	Not explicitly defined; expected to last at minimum the duration of impact	**Legal**: Stewardship or tenure agreements typically used **Financial**: Assurances not mandated but may be required case-by-case **Management**: Offset management plan required; adaptive measures needed if targets unmet	(Fisheries and Oceans Canada 2025)
EPBC Act Environmental Offsets (Australia)	Biodiversity; compliance	Not explicitly defined; expected to last at minimum the duration of impact	**Legal**: Site protection via covenants or stewardship agreements mandatory **Financial**: No national standard; instruments may be required (e.g., bonds, trust funds) on a case-by-case basis **Management**: Offset plan detailing objectives and annual compliance reporting mandatory	(Department of Sustainability, Environment, Water, Population and Communities 2012)
EU Natura 2000 Directives (European Union)	Biodiversity; compliance	Not explicitly defined; expected to last at minimum the duration of impact and ideally in perpetuity	**Legal**: Variable based on member state law; conservation measures required under Article 6 of the Habitats Directive **Financial**: Developer-funded with possible endowments **Management**: Long-term site monitoring and adaptive management required	(European Commission 2018)
California Forest Carbon Offset Program (USA)	Carbon; compliance	100 years	**Legal**: Legally binding agreements enforced by California Air Resources Board **Financial**: Contributions to shared buffer pool (8%–20% of credits) **Management**: Annual monitoring, reporting, and third-party verification required	(California Air Resources Board 2015)
Australia ACCU Scheme (Australia)	Carbon; compliance	25 or 100 years (proponent choice)	**Legal**: Rights and obligations recorded on land title **Financial**: Permanence discount applied (5%–20% of credits); reversals trigger obligations **Management**: Long-term monitoring, reporting every 2–5 years; permanence plan required	(Clean Energy Regulator 2024)

(Continues)

TABLE 1 | (Continued)

Offset program (Country)	Offset type	Permanence requirement	Safeguards (legal, financial, management)	Source(s)
New Zealand ETS (New Zealand)	Carbon; compliance	50 years	**Legal**: 50-year no clearance obligation; land title may be restricted **Financial**: Direct liability for NZUs; penalties for non-compliance **Management**: Emissions returns required every 5 years; inspections by regulatory agency mandatory	(Ministry for the Environment and The Treasury 2007)
Plan Vivo Carbon Standard (International)	Carbon; voluntary	Variable; typically, 10–100 years	**Legal**: Land/user rights with binding agreements required **Financial**: 20% buffer contribution; replenishment required if exceeded **Management**: Annual reporting; third-party verification required every 5 years	(Plan Vivo Foundation 2024)
UK Peatland Carbon Code (UK)	Carbon; voluntary	30 years (minimum); extendable to 100 years	**Legal**: Binding land management agreement required; conservation covenants/burdens possible **Financial**: 15% buffer pool contribution required; projects must budget for monitoring and maintenance **Management**: Restoration and monitoring plan required; periodic third-party verification mandatory	(IUCN UK Peatland Programme 2023)

Domains reflect the primary level at which risks are framed and addressed in the literature. Physical risks capture proximate biophysical disturbances that directly degrade offset outcomes (e.g., natural disturbances or site-level pressures). Methodological risks reflect shortcomings in design, metrics, and accounting that shape how permanence is estimated or credited. Non-physical risks capture governance, legal, institutional, financial, and social conditions that influence how risks are anticipated, managed, and enforced. Further methodological detail is provided in the Supporting Information section.

3 | Results

3.1 | Overview of Included Studies

Our search yielded 17,089 articles; 335 underwent full-text review and 121 met our inclusion criteria. Sixteen additional studies were identified through reference screening, resulting in a final dataset of 137 studies published between 1992 and 2025 and spanning 35 countries (see Figure 1 for selected case studies; a full list is in the Supporting Information section).

Of these, 80 examined biodiversity offsets and 57 examined carbon offsets (Figure 2). The United States was the most frequently studied country ($n = 49$), followed by Australia (22), Canada (7), and the United Kingdom (7). Forests were the most examined ecosystem ($n = 61$), followed by wetlands (36) and coastal or marine ecosystems (16). The U.S. Compensatory Mitigation system was the most frequently examined biodiversity offset program ($n = 27$), while REDD+ ($n = 20$) and California's ARB Forest Carbon program ($n = 12$) were the most studied carbon offset programs.

3.2 | Risk Typology

Across these studies, we identified 33 risk types, organized into 10 categories within three domains (Table 2). Non-physical risks were most common, appearing in 106 studies (77%), followed by physical risks (47 studies; 34%) and methodological risks (43 studies; 31%). The most frequent risk types were non-physical: *limited data transparency* ($n = 30$), *policy non-compliance* ($n = 29$), and *poor management and monitoring* ($n = 27$).

3.3 | Biodiversity vs. Carbon Offset Risk Profiles

Risks were not evenly distributed between offset types (Figure 3). Biodiversity studies more frequently identified non-physical risks, with 57% referencing *compliance, legal, and governance risks* and 45% citing *data, transparency, and capacity issues*. Site-level methodological risks related to ecological design, implementation, and metrics were also concentrated in biodiversity studies.

Carbon offset studies, particularly those focused on REDD+, more often reported *socioeconomic and equity risks* (51%), including land tenure conflicts and community compensation gaps. Physical risks, such as fire, drought, extreme weather, climate change, and local human disturbances were likewise more common in carbon studies.

TABLE 2 | Risk typology: frequency of domains, categories, and types.

Risk domain (# Studies)	Risk category (# Studies)	Risk type (# Studies)	Risk type description
Non-physical **(106)**	Compliance, legal, and governance risks **(64)**	Policy non-compliance **(29)**	Offset proponents frequently fail to meet design, implementation, or maintenance obligations, jeopardizing long-term ecological outcomes
		Weak governance and enforcement **(19)**	Limited regulatory capacity and oversight prevent effective enforcement, allowing non-compliance and site degradation to persist
		Inadequate policy design **(15)**	Vague or non-binding policies introduce loopholes or ambiguities that reduce enforceability and enable avoidance of obligations
		Corruption and institutional capture **(9)**	Elite capture, bribery, or corruption can distort enforcement and undermine transparency, compromising accountability for permanence
		Lack of liability and accountability **(9)**	Ambiguous or absent legal liability provisions allow proponents to evade long-term responsibilities or shift risks to regulators or the public
		Insufficient legal protections **(5)**	Lack of protective legal instruments such as conservation easements or covenants leaves offset sites exposed to future conversion or conflicting land uses
	Data, transparency, and capacity issues **(45)**	Limited data transparency **(30)**	Offset data are inconsistently reported, poorly standardized, and often inaccessible, hindering evaluations of effectiveness
		Poor management and monitoring **(27)**	Monitoring is often infrequent, low-quality, or not conducted; when monitoring occurs, reports are not submitted, late, or lack sufficient documentation, obscuring outcome tracking
		Capacity, expertise, and resource gaps **(14)**	Shortages in staffing, funding, and ecological expertise constrain regulators' ability to enforce standards, review offset plans, or assess long-term performance
	Socioeconomic and equity risks **(33)**	Land tenure and access conflicts **(17)**	Disputes with local communities over land ownership, access, or customary rights disrupt offset management, fuel contestation and resentment, and increase the likelihood of offset failure

(Continues)

TABLE 2 | (Continued)

Risk domain (# Studies)	Risk category (# Studies)	Risk type (# Studies)	Risk type description
		Incentive misalignment, opportunity costs, and landowner behavior **(13)**	Short contract durations, high opportunity costs, and weak long-term incentives discourage landowners from committing to lasting offset management
		Community exclusion and compensation gaps **(12)**	Failure to engage local communities or provide adequate compensation fosters resentment, land-use conflict, and resistance
	Political risks **(18)**	Regime changes and policy reversal **(9)**	Political transitions dismantle or weaken offset policies, destabilizing commitments and disrupting long-term project continuity
		Regulatory inconsistency and institutional fragmentation **(6)**	Conflicting mandates and lack of coordination across institutions reduce regulatory coherence, increasing the risk of oversight gaps and policy contradictions
		Weak political will and enforcement **(3)**	Political disinterest, shifting agendas, or active opposition weaken long-term support for offset programs and reduce regulatory effectiveness
	Financial risks **(17)**	Inadequate financial planning **(9)**	Absence of long-term funding instruments or financial buffers leaves offset projects vulnerable to underfunding, cost overruns, and eventual collapse
		Market instability and volatility **(6)**	Fluctuating credit prices, demand uncertainty, and limited buyer confidence limit the financial viability of market-based offset schemes
		Financial mismanagement and failure **(4)**	Poor accounting, cost-shifting, or financial collapse (e.g., bankruptcy) compromise the funding needed for offset maintenance
Physical **(47)**	Climate and environmental disturbances **(37)**	Fire **(16)**	Wildfire and post-fire mortality destroy vegetation and release stored carbon; fire frequency and severity are intensified by climate change
		Invasive species, insects, and pathogens **(12)**	Invasive species, insect outbreaks, and pathogens impair vegetation success and increase offset failure risk
		Climate change **(10)**	Changing environmental conditions (e.g., temperature, precipitation) intensify other physical risks and negate the ecological assumptions of offset design

(Continues)

TABLE 2 | (Continued)

Risk domain (# Studies)	Risk category (# Studies)	Risk type (# Studies)	Risk type description
		Drought **(9)**	Reduced water availability leads to planting failures, vegetation stress, and lower carbon sequestration; climate change amplifies drought severity
		Extreme weather and force majeure events **(6)**	Hurricanes, storms, ice events, and other natural hazards destroy vegetation and release stored carbon, especially in forests
		Flooding **(5)**	Prolonged or extreme inundation hinders vegetation survival, particularly in wetland offsets
		Sea-level rise **(3)**	Sea-level rise and related hydrodynamic changes degrade coastal offset sites and drive habitat loss
	Direct anthropogenic disturbances **(15)**	Local-scale activities **(10)**	On-the-ground disturbances like encroachment, logging, agriculture, or grazing decrease habitat quality and ecological performance at offset sites
		Landscape-level pressures **(5)**	Urbanization, infrastructure, and other large-scale land-use changes near offset sites diminish ecological function and reduce long-term viability
Methodological **(43)**	Ecological design and implementation failures **(24)**	Poor ecological design **(18)**	Inadequate planning leads to poor species or habitat selection and neglect of ecological risks (e.g., disease, predation)
		Implementation failures **(7)**	Construction or operational errors during offset delivery lead to ecological dysfunction or permanent site degradation
	Misaligned metrics, standards, and performance criteria **(11)**	Oversimplified and ecologically misaligned metrics **(8)**	Use of generic or poorly tailored metrics ignores species needs, ecosystem complexity, and fails to meaningfully capture ecological performance
		Weak performance standards **(3)**	Standards used to define offset success omit key ecological indicators or fail to account for system variability, leading to superficial outcomes
	Systemic oversights and risk management gaps **(10)**	Buffer pool shortfalls **(6)**	Insurance mechanisms (e.g., buffer pools) are insufficient to absorb unexpected losses, leaving offsets under-protected against reversals
		Project risk oversight gaps **(4)**	Key physical, social, or institutional risks are overlooked during project planning and management, leading to unanticipated failures

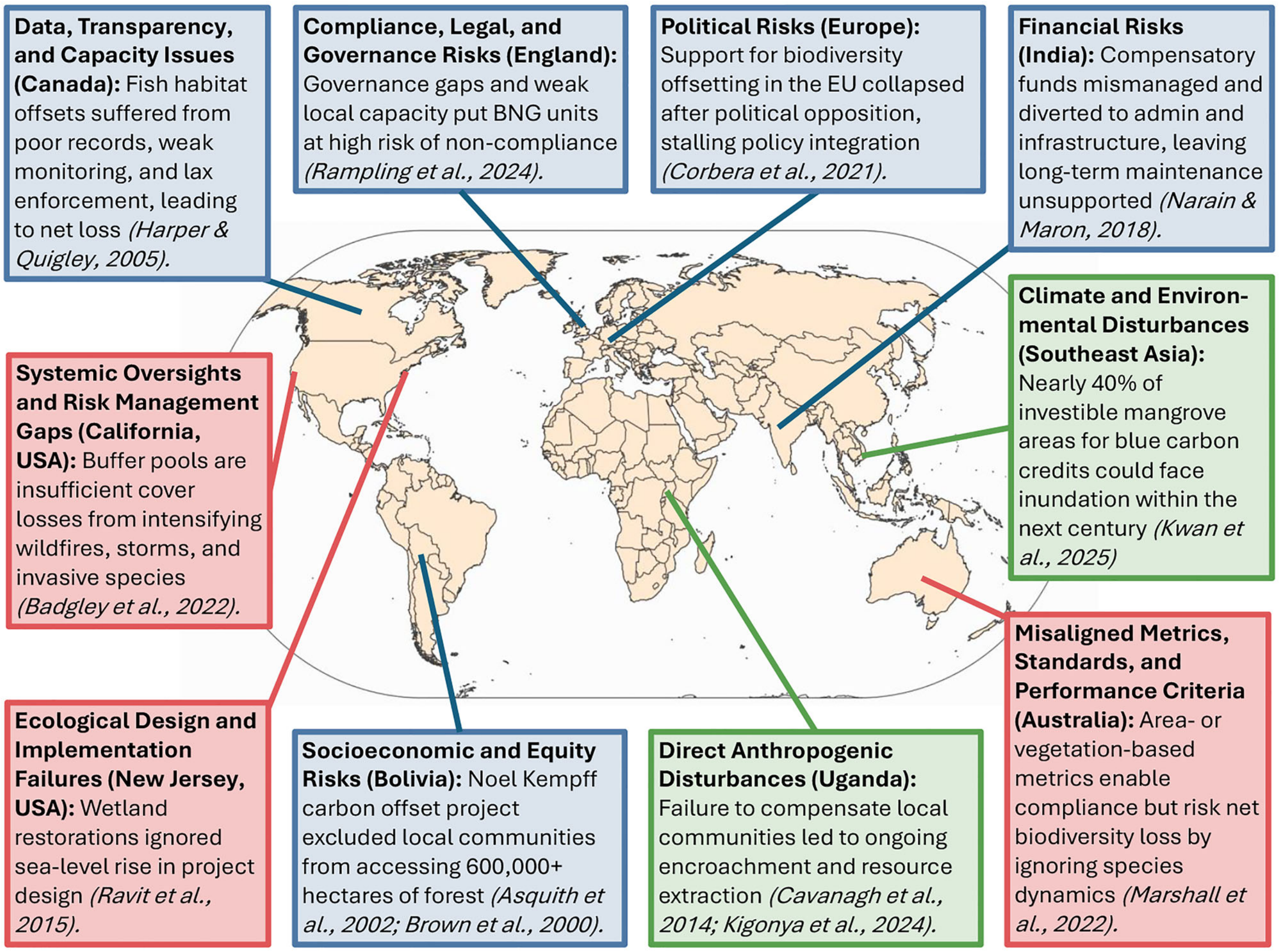

FIGURE 1 | Selected case studies describing recurrent risks to nature-based offsets. A subset ($n = 12$) of the total review ($n = 137$) is shown. Color-coding denotes risk domains: green (physical), red (methodological), blue (non-physical).

3.4 | Risk Co-Occurrence

Beyond differences in frequency, risks often co-occurred within studies (Figure 4). In biodiversity studies, the most frequent pairings were non-physical, particularly combinations involving *policy non-compliance*, *limited data transparency*, and *poor management and monitoring*. In contrast, carbon studies more often showed co-occurrence between socioeconomic and physical risks. Aside from *poor ecological design*, methodological risks rarely clustered with others.

3.5 | Geographic Patterns

Risk patterns also varied geographically (Figure 5). Studies on high-income countries, like the United States, Canada, and Australia, more often identified non-physical and methodological risks like *policy non-compliance*, *limited data transparency*, and *poor ecological design*. In contrast, studies on low- and middle-income countries, including Nigeria, Tanzania, Brazil, and Indonesia, highlighted socioeconomic and equity risks, as well as *corruption and institutional capture*. Physical risks were reported across all six continents, whereas methodological risks were rarely identified outside North America, Europe, and Oceania, where formal offset systems are more established.

3.6 | Program and Temporal Trends

Similar patterns appeared at the program level. Sixty-two percent of studies explicitly referenced a specific offset program, the most common being REDD+ and the US compensatory mitigation system (Section 404 permitting and mitigation banking). Risks to U.S. wetland programs included *policy non-compliance*, *limited data transparency*, and *poor management and monitoring*, whereas REDD+ studies more often highlighted *land tenure conflicts*, *corruption and institutional capture*, and *community exclusion* (Figure 6). Other carbon programs, like California's ARB Forest Carbon program and standards like Verra and Plan Vivo, were frequently associated with *incentive misalignment*, *fire*, and *buffer pool shortfalls*. Global mechanisms, including the Clean Development Mechanism and REDD+, were consistently associated with socioeconomic and equity risks.

Risk profiles also shifted over time. From 1990 to 2019, non-physical risks predominated; *policy non-compliance* was most cited between 2005 and 2014, followed by *limited data transparency* from 2015 to 2019. From 2020 to 2025, *fire* emerged as the most reported risk, suggesting rising concern over climate-driven threats.

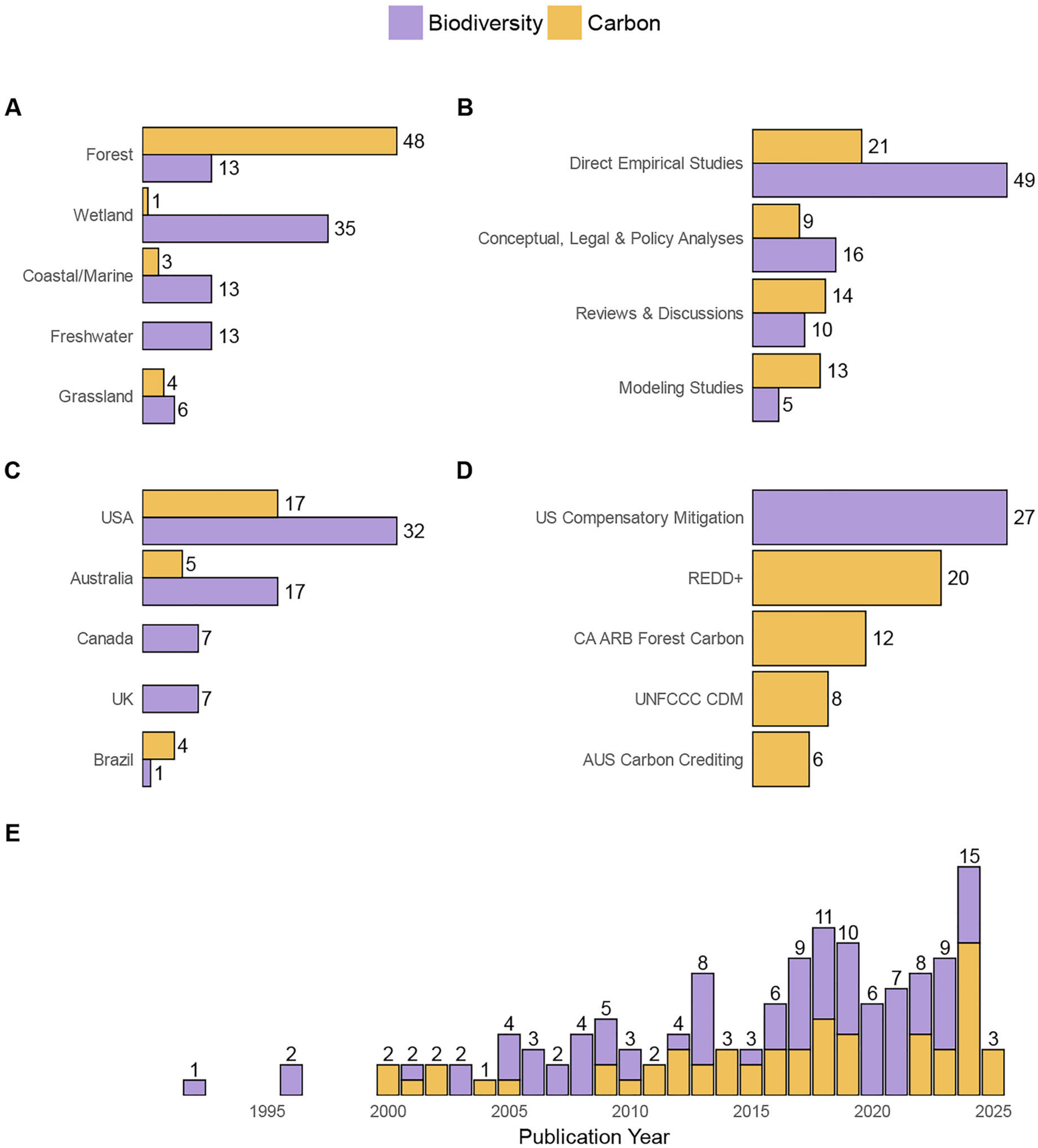

FIGURE 2 | Overview of study characteristics. Panels show the number of studies by (A) ecosystem, (B) study evidence type, (C), country, (D) offset program, and (E) publication year. Panels A, C, and D show the top five categories. Purple bars represent biodiversity offset studies ($n = 80$); yellow bars represent carbon offset studies ($n = 57$).

4 | Discussion

4.1 | Prevalence and Co-Occurrence of Non-Physical Risks

Non-physical risks appeared in over 75% of studies and persisted across three decades, indicating enduring challenges to permanence. Many co-occurred, making it difficult to cleanly separate risk types when developing the typology. Frequent pairings, like *limited data transparency*, *poor management and monitoring*, and *policy non-compliance*, highlight interacting institutional weaknesses. Their prevalence suggests non-physical risks are among the most pervasive threats to offset permanence.

Many non-physical risks function as enabling conditions for other risks. For example, insufficient policy requirements, such as REDD+ monitoring guidelines that omit key risks like fire, can result in ineffective management (Armenteras et al. 2017; Fischer et al. 2016). Limited data transparency likewise enables non-compliance and obscures ecological failures: absent national offset registers in South Africa (Brownlie et al. 2017) or Australia (Abdo et al. 2021), incomplete U.S. species conservation banking

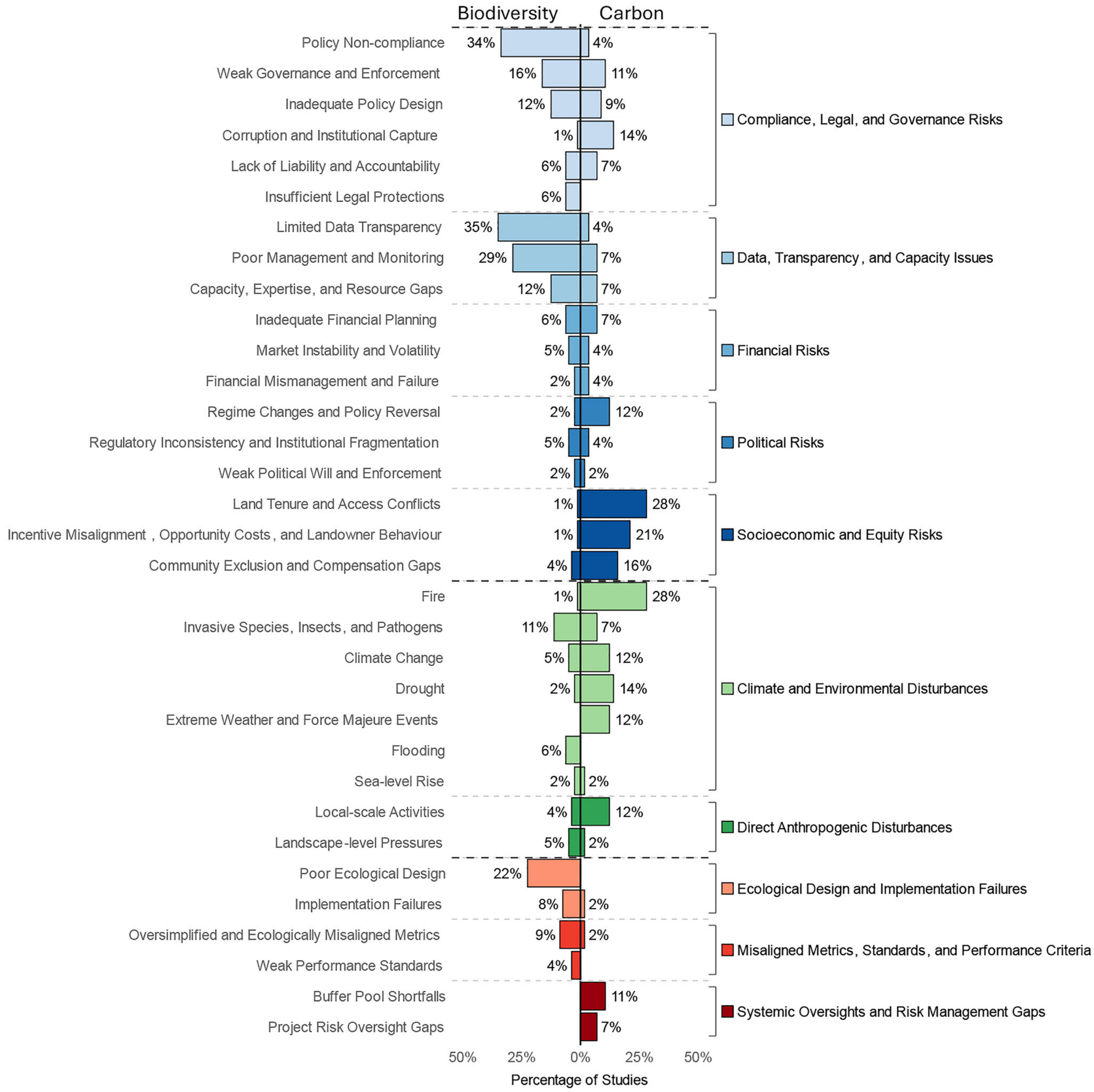

FIGURE 3 | Percentage of biodiversity and carbon offset studies identifying risk types. Bars extend left (biodiversity studies, $n = 80$) and right (carbon studies, $n = 57$). Individual risk types (left labels) are grouped into broader risk categories (right labels). Colors denote categories; grey dashed lines separate risk categories and dashed black lines separate risk domains.

records (Carreras Gamarra and Toombs 2017), and the lack of required outcome reporting in Australia's ACCU program (Macintosh et al. 2024) hinder long-term evaluation. Weak governance compounds these effects; in Michigan's wetland program, limited staff capacity and burdensome referral processes meant violations rarely triggered penalties and allowed degraded sites to persist (Hornyak and Halvorsen 2003).

Critically, the safeguards intended to secure permanence—legal protections, monitoring protocols, and financial assurances—can themselves create vulnerabilities when poorly designed or enforced. Missing conservation covenants in Michigan and Western Australia, for example, left offsets vulnerable to future land-use change (Kozich and Halvorsen 2012; May et al. 2017). Financial safeguards can similarly become risks. California's ARB forest carbon program allocates 9% of credits to a buffer pool to insure against bankruptcy and non-performance over 100 years, but projects are not evaluated for creditworthiness and commitments can be discharged in bankruptcy, exposing the program to liabilities beyond the buffer pool's capacity (Badgley et al. 2022).

	Biodiversity	Carbon
Limited Data Transparency & Poor Management and Monitoring	23.8%	0%
Limited Data Transparency & Policy Non-compliance	18.8%	1.8%
Policy Non-compliance & Poor Management and Monitoring	17.5%	0%
Limited Data Transparency & Weak Governance and Enforcement	12.5%	0%
Poor Management and Monitoring & Weak Governance and Enforcement	11.2%	1.8%
Policy Non-compliance & Weak Governance and Enforcement	10%	1.8%
Policy Non-compliance & Poor Ecological Design	7.5%	0%
Capacity, Expertise, and Resource Gaps & Limited Data Transparency	7.5%	1.8%
Poor Ecological Design & Poor Management and Monitoring	6.2%	0%
Limited Data Transparency & Poor Ecological Design	6.2%	0%
Community Exclusion and Compensation Gaps & Land Tenure and Access Conflicts	1.2%	12.3%
Land Tenure and Access Conflicts & Local-scale Activities	0%	10.5%
Drought & Fire	0%	10.5%
Corruption and Institutional Capture & Land Tenure and Access Conflicts	0%	10.5%
Climate Change & Fire	0%	10.5%
Climate Change & Drought	0%	10.5%
Community Exclusion and Compensation Gaps & Weak Governance and Enforcement	1.2%	8.8%
Community Exclusion and Compensation Gaps & Corruption and Institutional Capture	1.2%	8.8%
Climate Change & Extreme Weather and Force Majeure Events	0%	8.8%
Buffer Pool Shortfalls & Fire	0%	7%

FIGURE 4 | Co-occurrence of the ten most common risk type pairs in biodiversity ($n = 80$) and carbon ($n = 57$) offset studies. Each row represents a risk type pair; values indicate the percentage of studies within each offset type in which both risks were identified in the same study. Text color of the risk labels denotes risk domains: green (physical), red (methodological), blue (non-physical).

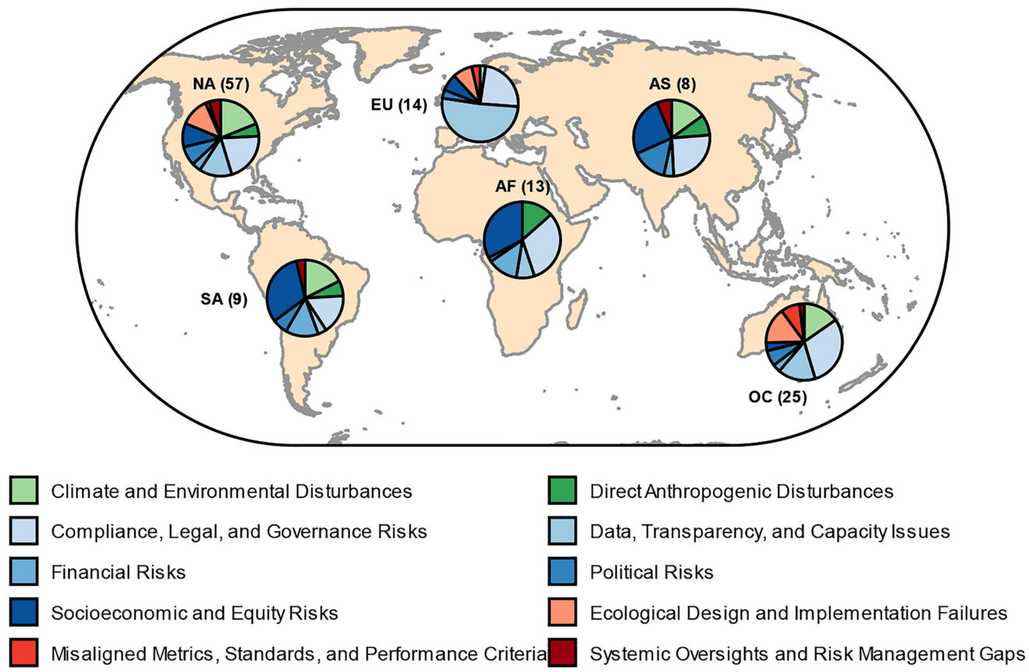

FIGURE 5 | Distribution of risk categories by continent. Studies could identify multiple risks; values are weighted so that each risk identified within a study–continent combination contributes equally. Colors denote risk domains: green (physical), red (methodological), blue (non-physical).

4.2 | Rising Prominence of Physical Risks With Climate Change

Climate-driven physical risks have become increasingly prominent. Fire was the most cited risk in studies from 2020 to 2025, reflecting heightened scientific attention and more frequent severe events. In California, escalating wildfires since 2015 have compromised forest carbon offsets (Badgley et al. 2022; Herbert et al. 2022), while in Australia, major bushfires have destroyed biodiversity offsets and threatened carbon market integrity (Mummery 2024; zu Ermgassen et al. 2023).

Physical risks often interact and compound. Drought reduces vegetation resilience and increases susceptibility to wildfires, pathogens, and insect outbreaks (Badgley et al. 2022; Dye et al. 2024; Galik and Jackson 2009). Invasive species, like the flammable grass *Andropogon gayanus*, have intensified fire regimes in Australian savanna offsets (Adams and Setterfield 2013). Coastal wetlands face sea-level rise, stronger storm surges, and prolonged flooding that accelerates vegetation loss and facilitates invasive colonization (Brown 2022; Ravit et al. 2015; Van den Bosch and Matthews 2017). Climate-driven species shifts may render sites ecologically unsuitable within project lifetimes (Souza et al. 2023; White et al. 2021).

Despite this evidence, many offset systems rely on static risk assumptions that underestimate dynamic ecological threats (Buchholz et al. 2021). California's ARB forest carbon buffer pool has already lost nearly one-fifth of its credits to wildfire, far exceeding contributions intended to insure permanence over 100 years (Badgley et al. 2022). A single hurricane or disease outbreak like sudden oak death could further exhaust credits reserved for "catastrophic" and "biological" risks (Badgley et al. 2022; Tumber-Dávila et al. 2024). Similar gaps exist in coastal and wetland offsets. In Southeast Asia, nearly 40% of mangrove areas suitable for carbon credits are projected to face inundation this century (Kwan et al. 2025), yet sea-level rise is often absent or outdated in offset design (Brown 2022; Ravit et al. 2015). Managing physical risks therefore requires better estimation of both individual stressors and their interactions.

4.3 | Methodological Risks as Structural Weaknesses

Although less frequently identified, methodological risks are potent because they are embedded in offset design. Ecosystems are inherently complex, shaped by interacting processes that cannot be fully represented by a single indicator. Yet offset systems translate this complexity into simplified metrics, such as habitat area, vegetation cover, or carbon stocks, because these are easier to standardize, regulate, and trade (Bull et al. 2013; Marshall et al. 2020).

This simplification creates a mismatch between what is measured and what sustains ecological function. Simple metrics overlook biodiversity's non-fungibility, permitting substitution of non-equivalent features and increasing the risk of net loss (Bull et al. 2013; Gibbons and Lindenmayer 2007; Walker et al. 2009). Habitat- or vegetation-based indicators also omit critical dimensions like population viability, reproductive success, disease susceptibility, and predation pressure, leading to long-term biodiversity decline despite meeting compliance thresholds (Beyer et al. 2018; Marshall et al. 2020, 2021, 2022).

Methodological risks arise across all stages of offset design, implementation, and management. At the design stage, projects can misalign with ecological realities. Nest boxes may go unused

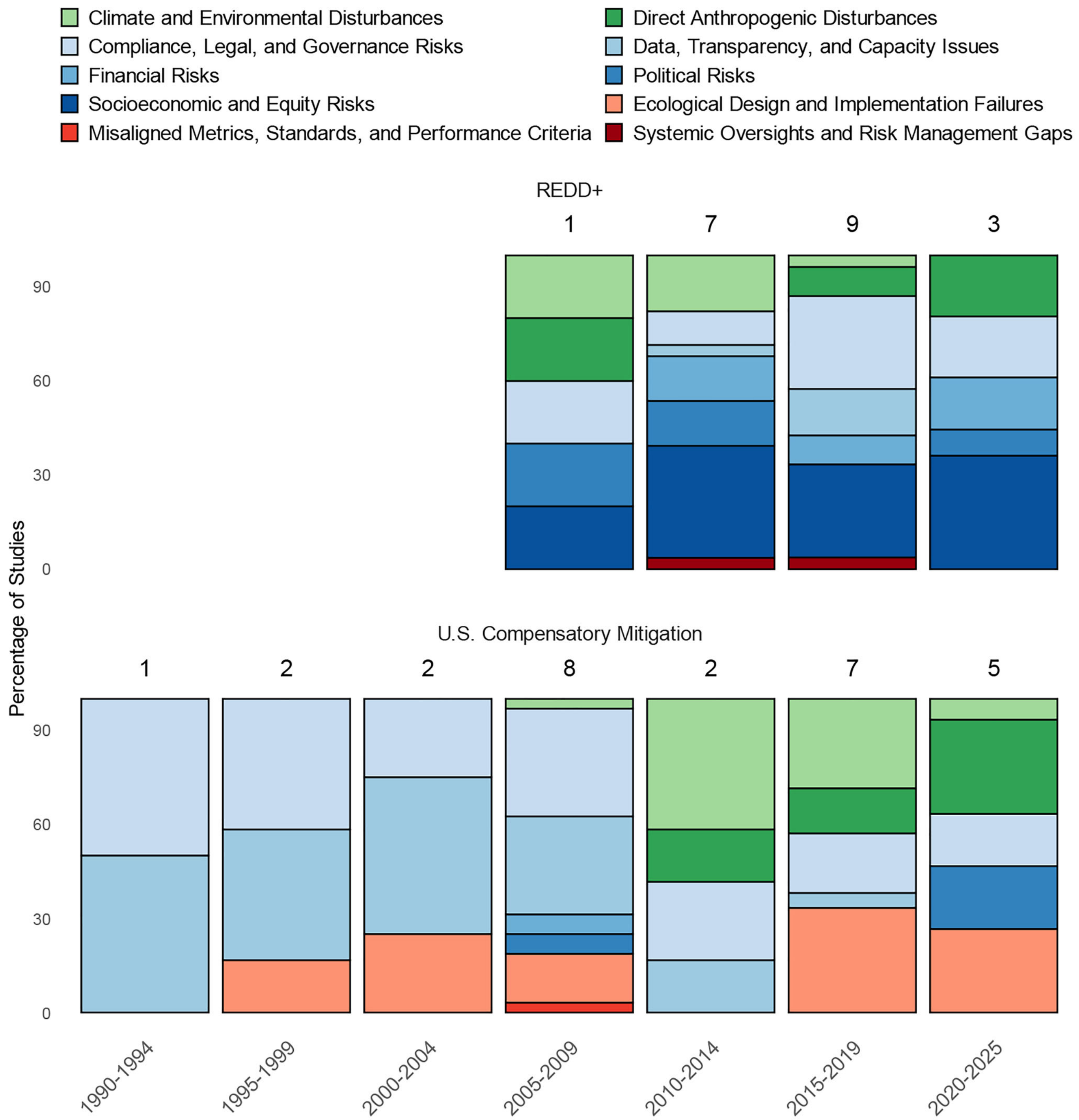

FIGURE 6 | Temporal distribution of risk categories in studies on REDD+ (top) and the U.S. Compensatory Mitigation system (Section 404 permitting and mitigation banking; bottom), grouped into 5-year intervals from 1990 to 2025. Bars show the percentage of studies identifying each risk category in each period, with numbers above bars indicating the total number of studies. Colors denote risk domains: green (physical), red (methodological), blue (non-physical).

(Lindenmayer et al. 2017), constructed pools may fail due to vegetation mismatches or predation (Kolozsvary and Holgerson 2016), time lags in vegetation development can create resource bottlenecks (Maron et al. 2010), and overlooking metapopulation dynamics may result in colonization failure or extinction (Drechsler 2024). Implementation failures can similarly occur. Several Natural Channel Design offset projects, for instance, saw fish species richness revert to pre-restoration levels within 7 years (Stowe et al. 2023). At the management stage, misaligned incentives can heighten reversal risk. In California, several Improved Forest Management projects incentivized maximizing carbon stocks at the expense of fuel reduction practices like prescribed burning and thinning, thereby increasing fire risk (Herbert et al. 2022).

4.4 | Divergent Risk Profiles Across High- to Low-Income Countries

Regional contrasts reflect differences in institutional capacity and political economy. In high-income countries like the United States, Canada, Australia, and the United Kingdom, risks are primarily legal, technical, or governance related. With mature regulatory systems and long-standing programs (e.g., US wetland permitting since the 1980s), risks arise less from the absence of rules and more from loopholes, weak enforcement, or limited capacity. Australia's EPBC Act offset policy, for example, relies on non-statutory guidelines that allow developers to modify or weaken commitments post-approval (Bell-James et al. 2024; Evans 2023; Reynolds 2023). In England, more than a quarter of proposed Biodiversity Net Gain units were found to be at a high risk of non-compliance due to under-resourced planning authorities and governance gaps (Rampling et al. 2024). In high-income contexts, non-physical and methodological risks arise from under-enforcement and under-resourcing rather than complete regulatory absence.

In contrast, studies from low- and middle-income countries frequently emphasized socioeconomic and equity risks—land tenure disputes, community exclusion, inequitable benefit-sharing—alongside corruption, elite capture, and capacity and enforcement constraints. These are potent threats to permanence. When projects displace, exclude, and inadequately compensate local communities, as documented in Uganda (Cavanagh and Benjaminsen 2014; Kigonya et al. 2024), India (Narain and Maron 2018) or Bolivia (Asquith et al. 2002), community resentment and mistrust can erode stewardship by those best placed to manage and safeguard offsets. Governance and enforcement failures intensify these tensions. In Nigeria, REDD+ procedures were manipulated to benefit elites while enforcement bodies diverted revenues, further weakening local trust in the program (Asiyanbi 2016; Asiyanbi et al. 2017). Across many low- and middle-income countries, structural inequalities, contested tenure, and weak institutions create fragile foundations for permanence.

4.5 | Managing Risks: Definitions, Approaches, and Solutions

Permanence risks are diverse, interacting, and often insufficiently addressed in existing offset systems. Programs have responded with a range of strategies that reflect contrasting assumptions about how long-term compensation should be defined, credited, and secured (FAO 2024). These strategies differ in where they intervene within the offset system and how they conceptualize permanence. We synthesize these into three levels: (1) definitional approaches that alter the permanence obligation itself, (2) crediting and instrument design approaches that retain a physical target but adjust issuance and accounting for risk, and (3) governance and operational approaches that reduce failure risk and sustain outcomes over time. These approaches are summarized in Table 3 and discussed below.

4.5.1 | Definitional Approaches

Debates over permanence begin with how it is defined. In most carbon and biodiversity offset programs, permanence is framed in physical terms: specified carbon stocks or ecological gains must be maintained for a defined duration (e.g., 100 years or in perpetuity; see Table 1), and premature loss constitutes non-compliance. Under this framing, permanence means maintaining a biophysical stock over time, and a reversal represents a failure to do so.

Alternative approaches define permanence in time-integrated or economic terms. Tonne-year accounting, for instance, integrates stored carbon over the period it remains in place, treating climate benefit as proportional to the cumulative "tonne-years" delivered (Brander and Broekhoff 2023). Temporal discounting applies economic discount rates to future emissions or climate impacts to derive equivalence between temporary and permanent mitigation (Parisa et al. 2022). In both cases, mitigation is valued as a time-weighted or discounted flow of benefit rather than as the continued maintenance of a physical stock.

Under these approaches, permanence no longer requires maintaining a stock for a fixed period; temporary storage can be treated as equivalent to permanent mitigation once sufficient cumulative benefit has been delivered. However, because long-term temperature change depends on cumulative CO_2 emissions, equating temporary storage with permanent mitigation can misstate alignment with carbon budgets (Brander and Broekhoff 2023). Definitional approaches are therefore analytically distinct from crediting or governance strategies that retain a physical permanence requirement and seek to secure durability.

4.5.2 | Crediting and Instrument Design

Where permanence is defined in physical terms, programs can adjust crediting and instrument design to align credit issuance with durability. Unlike definitional approaches, these mechanisms retain the physical permanence requirement but calibrate the number and timing of credits to anticipated or observed reversal risk.

For example, ex post issuance models, like the Permanent Additional Carbon Tonne (PACT) model, issue credits based on observed additionality and conservatively anticipate future releases through dynamic release schedules and Equivalent Permanence adjustments (Balmford et al. 2023; Rau et al. 2024). Probability-weighted accounting approaches incorporate modeled disturbance risk directly into credit quantification (Buchholz et al. 2021). Digital monitoring, reporting, and verification approaches similarly link credit generation to observed ecological performance (Van Dam et al. 2024).

In each case, the permanence requirement itself remains unchanged. Instead, credit volumes are adjusted to reflect risk, which reduces over-crediting and improves transparency. However, these approaches depend on robust data, credible modeling, and sustained institutional oversight. They improve how permanence is reflected in crediting, but they do not directly reduce ecological exposure or institutional vulnerability.

TABLE 3 | Summary of permanence risk management approaches.

Primary risk management function	Approaches	Benefits	Limitations
Redefine permanence obligation *(definitional)*	Tonne-year accounting, temporal discounting, and other time-integrated equivalency methods	Reframes permanence as cumulative climate benefit, reducing reliance on long-term stock maintenance	Redefines the obligation rather than managing reversal risk under a fixed physical target; may weaken equivalence claims; generally not applicable to biodiversity offsets
Internalize reversal risk in credit design *(crediting and instrument design)*	Ex-post crediting and probability-weighted accounting	Incorporates modeled reversal risk into credit issuance, reducing over-crediting and aligning claims with realized or risk-adjusted outcomes	Requires robust data and institutional oversight; less applicable in biodiversity contexts; does not directly reduce ecological risk
	Digital MRV and performance-linked issuance	Links credit issuance to observed ecological performance, improving transparency and reducing premature crediting	High data and technical demands; dependent on institutional capacity and monitoring integrity
Define and detect reversals and performance failures *(governance and operational)*	Improved ecological metrics and performance standards	Clarifies failure thresholds and enables earlier detection through species- and site-relevant indicators	High data and technical demands; limited availability across taxa and regions
	Strengthened monitoring, reporting, and transparency systems	Provides standardized, long-term evidence to detect reversals, verify compliance, and trigger liability	Monitoring often truncated; costly; requires institutional capacity and enforceable mandates
Enforce and compensate for failure *(governance and operational)*	Legal and policy reforms (e.g., statutory mandates, liability clarity, enforcement mechanisms)	Defines enforceable obligations, clarifies liability, and enables corrective action when failures occur	Dependent on political continuity, staffing, and consistent enforcement
	Financial safeguards (e.g., endowments, bonds, pooled reserves, insurance)	Provides dedicated resources for corrective action and buffers against economic shocks	Vulnerable to weak oversight, mismanagement, market volatility, and policy misalignment
Reduce probability and severity of ecological failure *(governance and operational)*	Physical risk management (e.g., prescribed burning, invasive species control, hydrological engineering)	Directly manages site-level threats, reducing exposure to ecological risk	Risks are stochastic; interventions insufficient in isolation; dependent on stable funding and expertise
	Robust ecological planning and climate-informed offset design	Improves long-term viability through appropriate site selection and alignment with species, climate, and landscape context	Requires detailed ecological data, technical expertise, and sustained oversight; vulnerable to external pressures and governance weaknesses
	Integrated local partnerships, tenure security, and community stewardship	Strengthens local incentives for sustained management and reduces risks of abandonment or conflict	Requires secure tenure systems, equitable institutional design, and sustained political and financial investment; insufficient on their own
Sustain institutional durability *(governance and operational)*	Long-term legal instruments, endowments, tenure security	Anchors monitoring, liability, and management obligations across political and economic cycles	Dependent on political continuity and stable governance

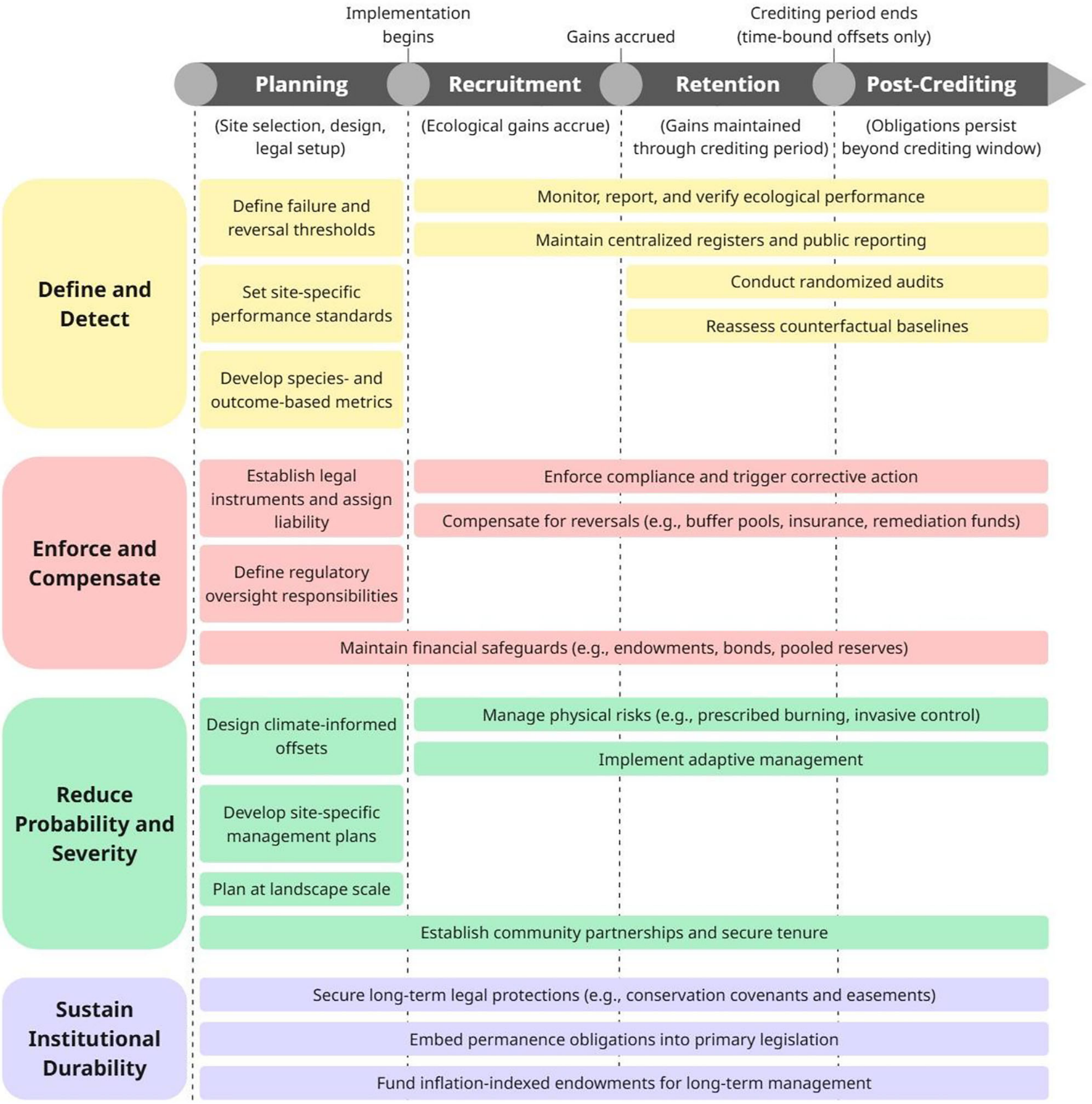

FIGURE 7 | Conceptual governance framework for managing permanence risk across the offset lifecycle. Interdependent functions (definition and detection, enforcement and compensation, risk reduction, and institutional durability; left) span successive phases from planning through to post-crediting (top).

4.5.3 | Governing Permanence in Practice

Permanence is fundamentally a governance challenge rather than a purely biophysical or accounting problem. While definitional and crediting reforms reshape how permanence is defined or reflected in credit issuance, they do not by themselves secure long-term outcomes. Rather, sustaining durability requires a coordinated and interdependent set of institutional functions—defining failure, detecting reversals, assigning and enforcing liability, reducing risk exposure, and sustaining oversight across decades—that operate across the full offset life cycle, from planning and implementation through post-crediting (Figure 7). Together, these functions constitute a systemic approach to permanence risk management (FAO 2024). Without this governance architecture, technical instruments alone cannot secure durable outcomes.

4.5.3.1 | Defining and Detecting Failures. Effective risk management begins with clear definitions of failure and explicit performance thresholds. Liability cannot be assigned, nor corrective action triggered, unless standards for reversals and breaches are clearly specified in advance.

Strengthening ecological metrics and performance standards improves the ability to identify failure. Species-specific indicators such as habitat suitability, metapopulation viability, or reproductive success (Beyer et al. 2018; Marshall et al. 2020, 2021, 2022), along with ecosystem- or outcome-based targets (May et al. 2017; Theis et al. 2020), provide more ecologically meaningful indicators than area-based metrics alone. Site-specific standards grounded in local baselines, rather than generic benchmarks, further improve ecological relevance (Matthews and Endress 2008; Tillman and Matthews 2024).

Detection ultimately depends on long-term monitoring and transparent reporting systems. Many biodiversity offset programs monitor for only 5 years, too short to capture delayed failures or long-term ecological trajectories (Robertson et al. 2018; Tillman and Matthews 2024; van den Bosch and Matthews 2017). Extending monitoring periods across the full permanence period, developing ecosystem-specific protocols, implementing outcome-based standards, maintaining centralized registers, and requiring publicly accessible data can strengthen detection ability (Abdo et al. 2021; Brownlie et al. 2017; Robertson et al. 2018; Tillman and Matthews 2024; van den Bosch and Matthews 2017). Randomized audits and clear data standards further support verification (Macintosh et al. 2024). However, extended monitoring is costly and creates obligations that few stakeholders are willing to assume. Yet without monitoring that spans the full permanence period, assigning and enforcing liability is practically impossible.

4.5.3.2 | Enforcing Liability and Compensation. Detection must be paired with enforceable corrective mechanisms. Embedding clear permanence obligations in legislation and clarifying long-term liability—whether borne by developers, buyers, registries, or governments—reduces risks of non-compliance and policy reversal (Bell-James et al. 2024; Elton and Fitzsimons 2023; Wilkinson 2009). Clearly defined oversight hierarchies further reduce regulatory fragmentation and improve accountability (Brownlie et al. 2017; Robertson and Hayden 2008).

Governance reform is both possible and effective. Australia's 2016 *Biodiversity Conservation Act* introduced statutory mandates, in-perpetuity agreements, diversified funding mechanisms (e.g., fixed-price offers, tenders, revolving funds), and inflation-indexed endowment funds to support long-term conservation delivery (Elton and Fitzsimons 2023). The 2008 US *Compensatory Mitigation Rule* required legally binding instruments, full-cost accounting, watershed-based planning, and financial assurances overseen by the US Army Corps of Engineers (Wilkinson 2009). Clear allocation of long-term liability is essential to ensure management and remedial obligations are enforceable throughout the commitment period.

Financial safeguards, like endowments, trust funds, insurance bonds, and pooled reserves, provide resources for remediation and buffer against economic shocks (Elton and Fitzsimons 2023; Wilkinson 2009). However, without strong oversight, these instruments are vulnerable to mismanagement and market volatility (Carreras Gamarra and Toombs 2017; Narain and Maron 2018). Financial tools alone cannot substitute for effective governance.

4.5.3.3 | Reducing the Probability and Severity of Ecological Failure. Operational strategies can reduce ecological risk exposure before liability is triggered. Physical risk management, such as prescribed burning and fuel reduction in forests (Buchholz et al. 2021; Herbert et al. 2022) as well as invasive control or hydrological management in wetlands (Ravit et al. 2015; Tillman and Matthews 2024), reduces disturbance likelihood and severity.

Robust ecological planning and climate-informed design align offsets with long-term species and habitat requirements and anticipate stressors like sea-level rise and climate change (Maron et al. 2010; Ravit et al. 2015). Landscape-level planning, such as prioritizing high-connectivity forest patches or co-locating wetland offsets near high-quality reference sites, enhances ecological function and persistence (Souza et al. 2023; Tillman et al. 2022; van den Bosch and Matthews 2017). Evidence-based, site-specific implementation plans improve restoration outcomes relative to generic templates (Stowe et al. 2023).

Integrated local partnerships, tenure security, and community stewardship reduce risks of abandonment, neglect, and conflict. Clarifying tenure (Fischer et al. 2016), devolving management authority to local institutions (Rochmayanto et al. 2019), establishing equitable revenue-sharing (Mabhuye et al. 2023), and supporting alternative livelihoods (Fischer et al. 2016; Mabhuye et al. 2023) strengthen local stewardship incentives. These measures, however, depend on secure tenure, institutional capacity, and political stability; poorly designed benefit-sharing can reinforce inequities or enable elite capture (Asiyanbi et al. 2017; Mabhuye et al. 2023).

4.5.3.4 | Sustaining Institutional Durability. Permanence ultimately depends on the persistence of institutions themselves. Long-term legal instruments, such as conservation covenants, as well as clearly defined permanence periods anchor obligations beyond short crediting windows (Elton and Fitzsimons 2023; Wilkinson 2009). Inflation-indexed endowment funds and mandated financial assurances help sustain monitoring and management over time (Elton and Fitzsimons 2023). Yet institutional durability is not guaranteed; even robust institutions are vulnerable to political discontinuity, administrative turnover, and shifting policy priorities (Damiens et al. 2021).

4.5.3.5 | Interdependence and System Constraints. Taken together, these functions form an interdependent governance system rather than a set of independent safeguards. Clear performance standards define when a failure has occurred; monitoring detects it; enforceable liability triggers corrective action; risk reduction lowers the likelihood of failure; and institutional durability sustains these processes over time.

Each function also relies on broader enabling conditions. Monitoring requires sustained funding and legal mandates; enforcement depends on clearly assigned responsibility and regulatory authority; financial safeguards require competent oversight; and community stewardship depends on secure tenure and institutional trust. Weakness in any one of these areas, such as unclear standards, inadequate monitoring, unstable financing, or political retrenchment, can undermine the effectiveness of the entire system. Securing permanence therefore depends on a coordinated institutional architecture that addresses the interacting physical, methodological, and non-physical risks identified in our typology.

4.6 | Limitations and Future Directions

Despite growing attention to permanence and durability, considerable uncertainty remains about how existing risk management strategies will perform under real-world ecological, institutional, climatic, and economic pressures. Policy reversals, weak enforcement, underperforming financial safeguards, and shifting ecological baselines under climate change may all undermine long-term outcomes. How these risks are prioritized, and who ultimately bears responsibility for failure, remain unresolved.

Project-scale assessments of biodiversity or carbon persistence, like many in our review, also risk overlooking system-level dynamics that shape long-term effectiveness. For example, biogeophysical feedbacks associated with some nature-based solutions, such as albedo or land-atmosphere interactions, can alter climate outcomes even where carbon stocks remain intact (Kristensen et al. 2024; Riley et al. 2025; Zickfeld et al. 2023). Similarly, long-run development pathways, shifting land demand, and broader ecological or economic regime shifts shape the structural pressures facing offset sites (Crépin et al. 2012; Marques et al. 2019; Müller et al. 2014). These Earth-system and political-economic dynamics influence permanence but are not fully captured within our typology.

Greater alignment is also needed between permanence and additionality. Additionality is assessed relative to a counterfactual baseline, whereas permanence is typically evaluated only in terms of remaining on-site biodiversity or carbon stocks. As a result, loss events may be interpreted as declines in absolute stock rather than as failures to sustain the credited incremental benefit. If permanence is intended to safeguard those incremental gains, counterfactual baselines must be carried forward beyond credit issuance.

Finally, greater consistency in how permanence is defined is essential. Across offset programs, permanence is framed variously in terms of fixed time horizons, perpetual protection, or economic and risk-adjusted equivalence, often without explicit justification. Such variation complicates comparability, influences how reversals are interpreted, and may allow permanence to be resolved through accounting conventions rather than substantive risk management. Cohesive, transparent definitions and explicit evaluation of trade-offs among them are therefore needed to ensure that safeguards are genuinely durable, scalable, and equitable.

Acknowledgments

Alexander Dhond was supported by the Centre for Ecologically Relevant Multiple Stressor Effects on Wetland Wildscapes (ECO-WILD), in partnership with AstraZeneca (NERC reference: NE/Y006445/1). Sophus zu Ermgassen and Joseph William Bull were supported by the EU Horizon 2020 project SUPERB (Systemic solutions for upscaling of urgent ecosystem restoration for forest-related biodiversity and ecosystem services; Ref.: GA-101036849). Andreas Heinemeyer received funding as part of the Peatland-ES-UK project and from the Natural Environmental Research Council (NE/X005143/1). We thank two anonymous reviewers for their feedback in shaping the final draft of the article.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The author has provided the required Data Availability Statement, and if applicable, included functional and accurate links to said data therein. The dataset compiled during the review process is available in the Supplementary Material. All code used to conduct the literature search, standardize and analyze the dataset, and generate figures is available at: https://github.com/alexdhond/offset-permanence-review. An interactive, web-based database is available at: https://alexdhond.shinyapps.io/offset-permanence-database/.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Information Supplementary Information