



Review

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Extinction debt and colonization credit in conservation science

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Extinction debt and colonization credit describe the delayed impacts of environmental change on biodiversity, yet their significance largely remains unrecognized by those shaping conservation efforts. To address this gap, we conducted a systematic review of 127 empirical studies quantifying these biological lags across taxa, habitats and anthropogenic drivers. Our synthesis revealed geographic biases, with research concentrated in Northern Hemisphere terrestrial ecosystems, alongside taxonomic and habitat biases that continue to limit our understanding of these dynamics. Evaluation of anthropogenic drivers revealed a similarly skewed research effort, with habitat fragmentation dominating extinction debt studies and land-use change leading colonization credit research. By synthesizing proposed conservation strategies, we identified pathways for integrating time-lagged ecological responses into conservation frameworks. Despite the conceptual importance of these lags, most empirical efforts remain focused on isolated taxonomic groups, with limited consideration of how debts and credits propagate through communities or influence ecosystem services. This narrow focus restricts the utility of current findings for broad-scale conservation. We recommend that future research prioritizes the mechanisms driving lags across understudied ecosystems and environmental contexts. Crucially, conservation interventions must move beyond static biodiversity snapshots and explicitly account for extinction debt and colonization credit to ensure long-term ecosystem resilience.

1. Introduction

(a) Extinction debt and colonization credit: why do they matter?

The practice of conservation is often predicated on the need to balance ecological sustainability with human needs. Historically described as a crisis discipline [1], conservation management is often reactive, with resources being spent as rapidly as possible [2,3]. However, many ecological responses to environmental change unfold over long time scales, highlighting the need for sustained conservation commitments that account for delayed impacts.

Environmental change, such as habitat loss or fragmentation, may lead to immediate local extinctions [4]. However, for the remaining species, there is typically a lag between the perturbation and extinction [5,6]. There are, therefore, species existing in the new regime that are doomed to eventual loss, a phenomenon known as extinction debt [7], and the time taken for the system to stabilize is defined as the relaxation time (figure 1a) [8]. At the same time, there is a period between the creation of the new regime and the arrival of colonizers, described as the establishment lag [6]. The number of species able to colonize, but have yet to do so is referred to as the colonization credit (also termed immigration credit; for consistency, we use the term colonization

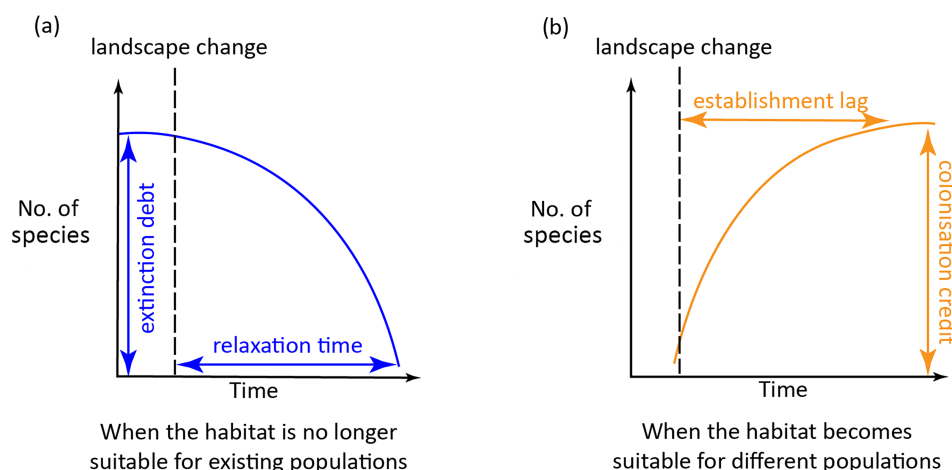


Figure 1. Conceptual framework illustrating how species may respond following a landscape or seascape change, showing (a) extinction debt, where species persist temporarily after a change in landscape, and (b) colonization credit, where populations or species gradually establish in a newly suitable habitat.

credit throughout; figure 1b) [9,10]. Extinction debt and colonization credit are therefore consequences of environmental change, leaving a period of disequilibrium while species assemblages restructure in response to the new conditions [11–13]. For example, in Mediterranean semi-natural grasslands undergoing forest encroachment, grassland species persist despite habitat change, representing an extinction debt, while forest specialist species have yet to fully colonize the new forest habitat, illustrating colonization credit [14]. This shifting balance is at the heart of extinction debt and colonization credit; species turnover is an ecological consequence of environmental change that unfolds over time. Once all debts have been resolved, and credits realized, the habitat is once again in dynamic equilibrium.

With the quantification of these concepts come both opportunities and challenges for conservation. The existence of extinction debt can lead to an overestimation of species richness [15,16], and decision makers may mistakenly assume that conservation efforts are unnecessary. Conversely, recognizing extinction debt can underscore the importance of habitat restoration, potentially preventing species loss and conserving populations [17,18]. In parallel, awareness of colonization credit, often driven by poor dispersal ability [19–21], can highlight the need for habitat corridors [9] or assisted colonization [22]. Together, species losses from extinction debt and species gains from colonization credit capture the delayed ecological effects of environmental change, emphasizing the complexity of measuring biodiversity responses over time and the challenges for conservation.

Although there is broad agreement that current extinction rates are greater than background rates [23], some argue that this difference is not significant [24]. Documented recent extinctions remain relatively rare in marine ecosystems [25,26], and terrestrial plants tend to experience lower rates of extinction than animals [27]. These low observed extinction rates may reflect a profound temporal mismatch between environmental disturbance and the biological response, where the full magnitude of biodiversity loss has yet to be realized [27,28]. This temporal lag underscores the relevance of both extinction debt and colonization credit for understanding and predicting transient dynamics.

Here, we synthesize and refine our understanding of extinction debt and colonization credit, identifying key knowledge clusters and gaps, while considering how these concepts can be applied to inform effective conservation strategies. Extinction debt, and to a lesser extent colonization credit, have been the subject of several previous reviews. Kuussaari *et al.* [11] provided an early synthesis of the methodological approaches used to detect extinction debt and discussed their relevance for conservation. More recently, Figueiredo *et al.* [12] examined the geographical distribution of extinction debt studies and highlighted persistent challenges in quantifying delayed extinctions, while Lira *et al.* [29] assessed patterns across habitats and taxa, revealing a strong bias towards plant studies in forest and grassland ecosystems. To date, only Jackson & Sax [10] have jointly reviewed both extinction debt and colonization credit, but their synthesis predates the growth of empirical studies in this field. Here, we provide a unified and timely assessment of both phenomena, aiming to address four key questions: (1) whether geographic biases in the distribution of research persist; (2) which taxa and habitats remain underrepresented and represent major gaps; (3) how the anthropogenic drivers studied influence the magnitude and detectability of extinction debt and colonization credit; and (4) what the existence of time-lagged ecological responses implies for conservation planning and management.

2. Material and methods

(a) Literature search

We systematically reviewed the literature to collate empirical studies of extinction debt or colonization credit following the Guidelines and Standards for Evidence Synthesis in Environmental Management [30]. Scope was defined using the PECO framework [31] to ensure a systematic and reproducible search strategy (supplementary material).

To refine the search strategy, we selected a pilot sample of 14 studies (supplementary material) [9,17,19,20,32–39] to identify key terms and establish search strings [40]. Preliminary screening revealed that extinction debt is frequently discussed alongside

broader time-lagged responses. Search strings therefore included 'time-lag*' using Boolean AND operators to ensure thematic relevance (supplementary material). Conversely, 'colonization credit' required more specific search terms. Using the wildcard search 'coloni* credit' retrieved numerous studies on the gastrointestinal tract, so searches using the full spellings were also included (supplementary material). The OR operator captured alternative phrasings of colonization credit, while NOT excluded studies related to financial credit. The pilot sample also highlighted the diversity of terminology describing colonization credit, requiring additional search terms to capture relevant literature.

We searched Web of Science, Scopus and Google Scholar on 15 July 2025, with alerts capturing additional publications until 30 November 2025. No publication date restrictions were applied. Although Google Scholar does not consistently reproduce identical search results, it is effective for identifying the grey literature [41] and was therefore included. We applied filters to the Web of Science and Scopus searches to retain only Ecology research areas. As Google Scholar does not support filtering and returned an unmanageable number of results ($n = 10\,300$ for extinction debt), searches were conducted using Publish or Perish software, which searches titles and keywords using the specified search strings (supplementary material) [42]. Results were capped at 1000, prioritizing the most relevant matches according to the search engine's ranking algorithm [43].

We exported the search results to EndNote 21 and removed duplicates, leaving $n = 1340$ for extinction debt and $n = 319$ for colonization credit for initial screening following PRISMA protocols (supplementary material) [40].

(b) Inclusion criteria

We developed decision trees to guide the initial screening and full-text screening. The remaining studies were screened and irrelevant studies excluded based on their titles, abstracts and keywords using the initial screening decision tree (supplementary material). The final stage used the full-text decision tree to screen the remaining studies. This resulted in $n = 92$ for extinction debt and $n = 35$ for colonization credit. We extracted the data required to answer the questions identified using the PECO protocol and placed the data in an Excel spreadsheet for further analysis. Full-text screening revealed one study that was identified in the colonization credit search, yet it also had data for extinction debt, so this was also included in the extinction debt metrics. The same occurred in the extinction debt full screening, and these data were included in the colonization credit metrics.

(c) Data analysis

We extracted information from the 127 studies to include bibliographic information, details of the subject being investigated, the methodological approach and the conclusions drawn by the authors. Details were collated in a Microsoft Excel spreadsheet (supplementary material), and all analyses were conducted using R 4.4.2 [44] and tidyverse [45]. To highlight the knowledge clusters and knowledge gaps, we summarized the data according to anthropogenic drivers under investigation, the taxa studied and the habitat type. To investigate the implications for conservation, we considered the recommendations provided by the authors.

3. Results

(a) Evolution of the field

MacArthur & Wilson [5] were among the first to quantify the time taken for a species to become extinct, which was further developed by Diamond [8], who coined the phrase 'relaxation time'. However, it wasn't until 1994 that Tilman *et al.* [7] proposed that extinctions occurring after a perturbation represented a 'debt', defined as the ecological cost of the disturbance quantified as the number of surplus species. To establish the existence of extinction debt, they developed a competitor-colonizer approach, using the assumption that good competitors are poor dispersers [46]. Subsequent studies tested the assumptions underlying relaxation time and extinction debt. McCarthy *et al.* [47] demonstrated that good competitors were not necessarily poor dispersers, and Stone *et al.* [48] found that in a marine model it was the weakest colonizers that were driven to extinction first, contrary to Tilman *et al.* [7]. Cowlshaw [34] took a different approach and used species-area relationships (SARs) to establish extinction debt in African primate species following habitat destruction, and this work represents the first empirical study that quantifies extinction debt. Following this seminal work, there was little research effort until 2004, when the mean rate of publication between 2004 and 2012 was two articles per year (figure 2). This increased to 6.25 articles per year from 2005 to 2025, with the highest number of empirical articles on extinction debt being published in 2017 (13%).

Colonization credit has received much less empirical attention, with the first study being published by Cristofoli & Mahy in 2010 [9], using an SAR methodology to establish colonization credit in wet heathland butterfly communities. Research effort on this concept has been sporadic, with a mean publication rate of 2.3 articles per year between 2010 and 2025 (figure 2).

(b) Geographic research biases

The geographic distribution of studies (figure 3) highlights that the greatest research effort has been carried out in European countries (extinction debt $n = 41$; 44.5%, colonization credit $n = 23$; 65.7%), with Spain showing the greatest overall effort (total $n = 14$; 11.0%), a pattern that has changed little since 2019 [12]. While several studies have examined areas identified as biodiversity hotspots [49] ($n = 49$; 38.6%), critical gaps remain. Several hotspots, most notably the Caribbean Islands, the Malay Archipelago

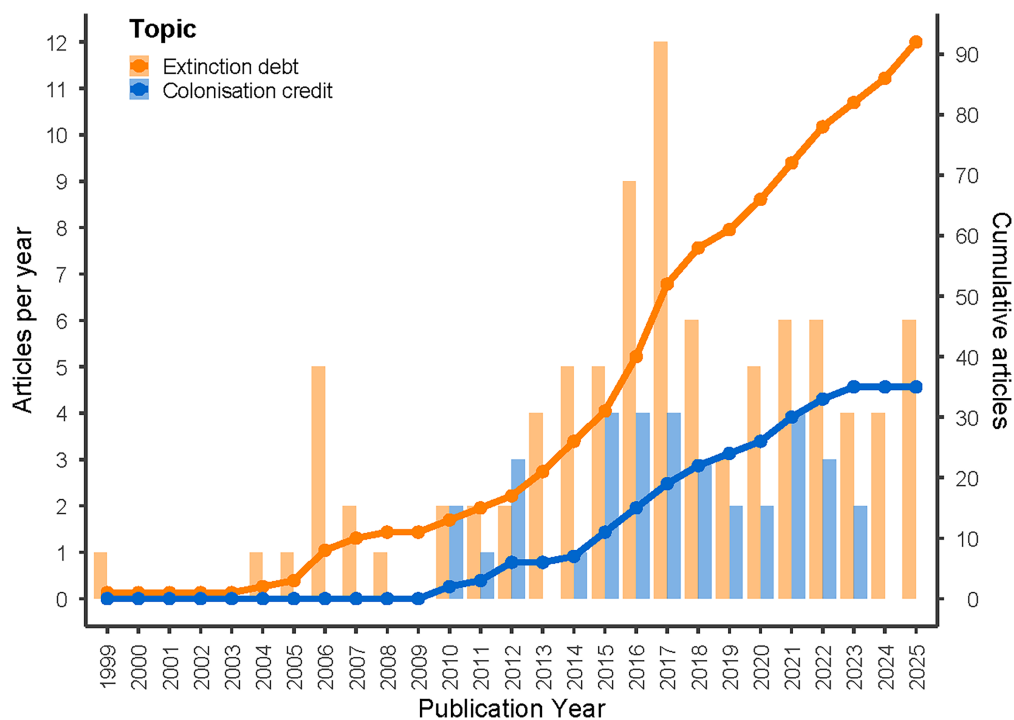


Figure 2. Cumulative number of published articles that empirically investigate extinction debt (orange line) and colonization credit (blue line), and the number of published articles per year (orange bars = extinction debt; blue bars = colonization credit).

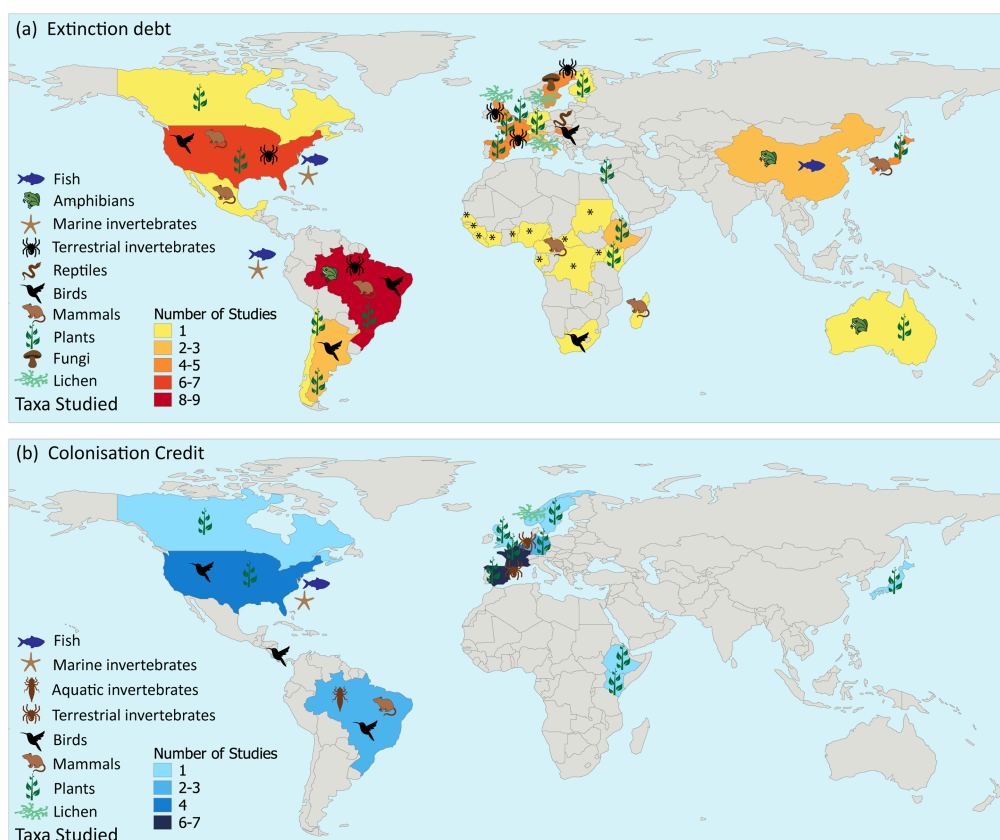


Figure 3. The range of geographic areas and taxa where (a) extinction debt and (b) colonization credit have been investigated. Data were extracted from 127 peer-reviewed papers that empirically investigated extinction debt (92 papers) and colonization credit (35 papers). The asterisks denote one paper that investigated mammals (specifically primates) across a range of African countries. Global and European studies (7 papers) were not included in this figure.

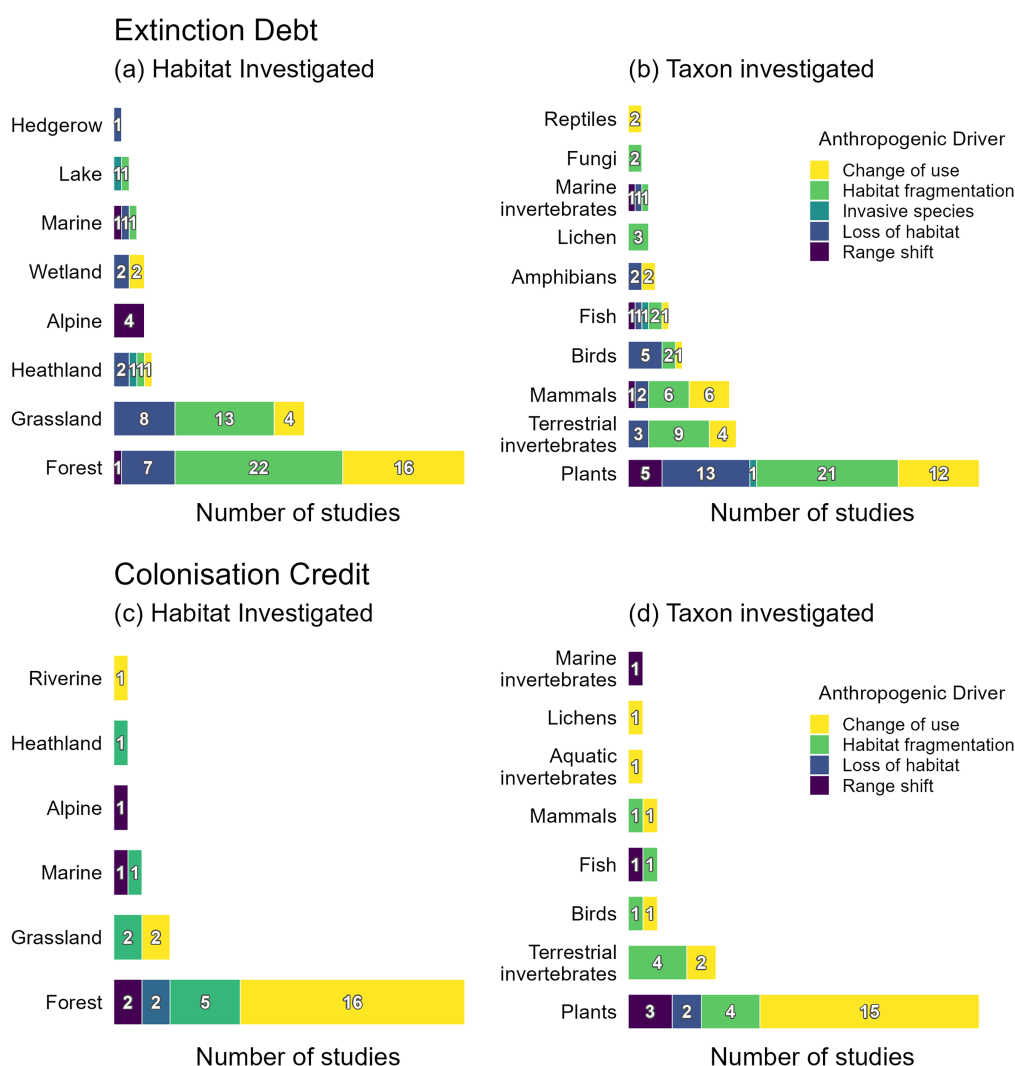


Figure 4. The range of ecosystems, taxa and types of environmental change where (a,b) extinction debt and (b,c) colonization credit have been investigated. Data were extracted from 127 peer-reviewed papers empirically investigating extinction debt ($n = 92$) and colonization credit ($n = 35$). Bar colours indicate the specific anthropogenic driver studied. Totals may exceed the number of individual papers because some publications studied multiple taxa and habitats. Studies describing habitat as 'mixed' were excluded ($n = 3$).

and New Zealand, show no empirical coverage to date. Our review also demonstrates that the majority of research has been conducted in terrestrial habitats ($n = 124$; 97.6%), leaving marine ecosystems underrepresented in the literature.

(c) Drivers and ecological contexts

Our systematic review highlights an asymmetric research effort across taxa and habitats, with plants ($n = 76$; 59.8%) and forest habitats ($n = 71$; 55.9%) being particularly well represented (figure 4). In contrast, despite their status as the most threatened vertebrate group [50], amphibians represent only 3.1% of the research effort ($n = 4$). This represents a critical knowledge gap in our understanding of time-lagged vertebrate declines.

Anthropogenic drivers are defined as 'human actions that directly alter flows of ecosystem services' [51]. These can be direct (land/sea use change, climate change, biological invasions, pollution and resource extraction), or indirect (demographic, economic, scientific, socio-political and cultural) [52,53]. Indirect drivers were not considered in the literature reviewed, and of the direct drivers, only land/sea use change, climate change leading to range shifts and biological invasions were investigated. However, a nuanced approach to land/sea use change was taken, with some studies ($n = 55$; 43.3%) specifically referring to how use had changed, for example the impact of urbanization [54], while others investigated land conversion in terms of loss ($n = 29$; 22.8%) or fragmentation ($n = 58$; 45.7%).

Despite biological invasions being considered a significant contributor to community compositional change [55], very little invasion research is framed within the context of extinction debt and colonization credit ($n = 2$; 1.6%), representing a significant gap in our knowledge. Habitat fragmentation is the most extensively studied driver of extinction debt ($n = 39$; 42.4%; figure 4a,b), probably due to the strong theoretical foundations provided by island biogeography and the availability of long-term datasets collected in fragmented landscapes [5,56]. Conversely, colonization credit is most frequently examined in the context of land-use

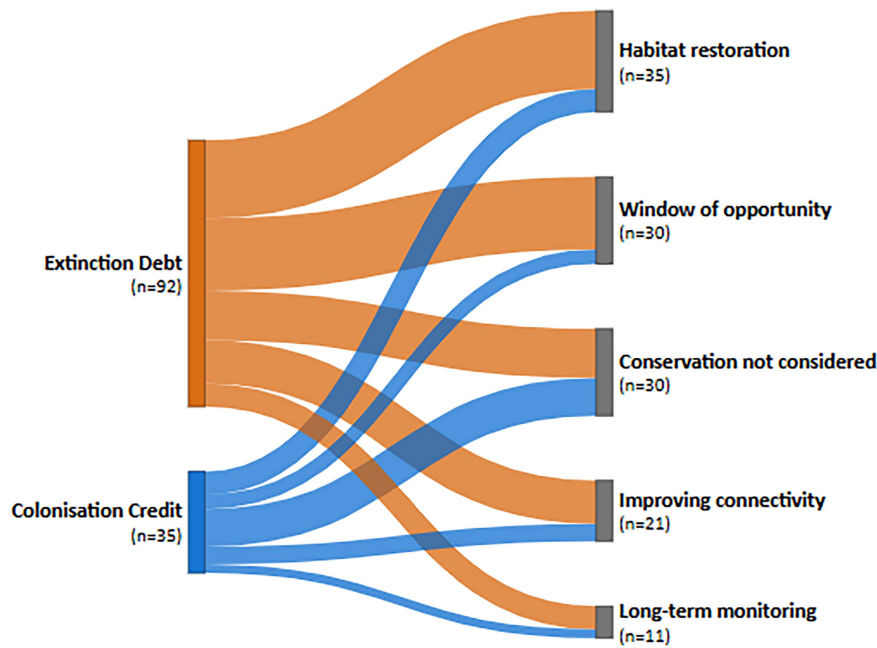


Figure 5. Distribution of conservation strategies suggested by the 127 peer reviewed papers empirically investigating extinction debt (orange) and colonization credit (blue). Ribbon width is proportional to the frequency of studies identifying each strategy.

change ($n = 20$; 57.1%; figure 4c,d), often involving the abandonment of agricultural land and allowing it to revert to its original habitat [38]. Notably, although climate-driven range shifts are primary drivers of community reshuffling [57,58], they remain a peripheral focus within debt and credit research ($n = 8$; 6.3%; figure 4), representing a significant untapped empirical frontier.

(d) From evidence to action

The delayed impacts of environmental change on biodiversity present a challenge and an opportunity for conservation efforts, particularly because management actions taken today may influence tomorrow's species losses or gains. Translating evidence of extinction debt or colonization credit into conservation practice, however, remains limited (figure 5).

While few studies state whether extinction debt or colonization credit have directly led to a change in conservation strategy in practice, potential strategies to mitigate these processes are nevertheless frequently suggested ($n = 97$; 76.4%). These strategies cluster into four broad categories: long-term monitoring ($n = 11$; 8.7%), windows of opportunity ($n = 30$; 23.6%), habitat restoration ($n = 35$; 27.6%) and enhancement of habitat connectivity ($n = 21$; 16.5%). In contrast, a substantial proportion of studies do not consider conservation implications at all ($n = 30$; 23.6%). It is equally notable that a higher proportion of colonization credit studies ($n = 13$; 37.1%) failed to address conservation relevance, compared to extinction debt studies ($n = 17$; 18.5%).

4. Discussion

(a) Global patterns of debts and credits

Our review provides evidence that the geographical bias found in 2019 [12] persists, reflecting a broader, well-documented trend in ecological research favouring the Northern Hemisphere [59–62]. This bias potentially limits our ability to generalize temporal dynamics across different climatic and socio-economic contexts.

There have been five attempts to quantify extinction debt at a global level, all of which examine the resulting implications for conservation strategies [33,63–66]. For example, artificial islands formed in reservoirs harbour extinction debt despite their designation as protected areas [64]. The existence of extinction debt demonstrates that these islands are not effective biodiversity conservation areas and relevant legislators would need to reconsider their policy guidelines to avoid unintended extinction outcomes. Other global assessments have quantified extinction debt resulting from land use change in forested systems, showing that levels of extinction debt vary among taxa but are spatially concentrated in 'hotspots' [33,63]. Notably, these 'hotspots' do not align with areas of high extinction risk predicted by species distribution models under sustainable climate change scenarios [33,67]. For instance, Chen & Peng [33] identified regions of North America, southern Europe and southern Africa with high levels of extinction debt, whereas projected future extinction risk was highest in South America, Central Africa and Australia [67]. This mismatch highlights the importance of incorporating extinction debt into extinction risk assessments.

(b) Biotic patterns and anthropogenic drivers

Plants are the most commonly studied taxon (figure 4a,b), although findings from plant-dominated systems may not be directly transferable to other taxa [21,68]. With extinction debt increasingly invoked by conservation biologists [25,69,70], a broader taxonomic perspective is required. Multi-taxon studies suggest that species may persist in unfavourable areas because foundation species that structure habitats remain [71,72], yet few empirically test how biotic interactions influence extinction debt. The only study of corals as a foundation taxon found no difference in coral-associated species richness between dead and live coral over time, indicating no extinction debt during the limited timeframe investigated (July 2008 to February 2010) [73]. However, macrofaunal communities did shift significantly, with dead coral initially attracting an influx of opportunistic generalist species [73]. This suggests that locally extinct species were offset by colonizing species, resulting in the stable observed species richness. These findings emphasize the need to consider extinction debt and colonization credit in tandem, as species richness alone may obscure longer-term ecosystem change.

A similar taxonomic bias characterizes colonization credit research, which focuses largely on plants following land use change (figure 4c,d). Where colonization credit is observed, it is often attributed to a lack of connectivity or poor dispersal ability [19,32]. Orchids with specialized pollinators, for instance, exhibit greater colonization credit compared to those with a broader range of pollinators [74]. However, pollinator presence was not assessed, making it unclear whether a lack of specialized pollinators was responsible for the observed lag in orchid dispersal. This highlights a key limitation of single-taxon studies; without considering species interactions, the drivers of delayed responses remain unclear. Although most studies achieve high taxonomic resolution within a focal group, they typically interpret findings at broader taxonomic levels and rarely include multiple orders (supplementary material). Multi-taxon approaches are therefore needed to determine how biotic interactions shape extinction debt and colonization credit, and impact ecosystem functions.

The reviewed literature is dominated by studies of forest habitats (figure 4a,c), a trend that highlights a substantial gap in our understanding of other systems. This forest-centric approach has been widely recognized [75–77], and may contribute to legislation and management practices that inadvertently overlook other ecosystems [78]. Although forests are widely recognized for their high biodiversity and endemism [79], other ecosystems boast similar biotic complexity [80] and warrant equivalent attention. Our review also identified a pronounced gap in marine systems (figure 3 and figure 4a,c), with only three studies meeting the inclusion criteria [35,73,81]. This bias is not uncommon and is often attributed to limited funding and logistical challenges [21,82]. Such underrepresentation is of concern because marine ecosystems provide essential ecosystem services with the highest monetary value per hectare per year [83]. These works also highlight challenges in identifying extinction debt and colonization credit in marine ecosystems. Where extinction debt was identified, one study failed to untangle the impact of fragmentation due to bottom trawling, fishing activity and increasing sea surface temperature as the drivers of the debt [35]. Another study focused only on adult fish, leaving uncertainty as to whether the observed species represented reproducing populations or transient individuals [81]. This distinction is important given the role of fish productivity as an ecosystem service. Understanding the drivers of extinction debt and colonization credit, and distinguishing established from transient populations, is essential for effective fisheries management.

Habitat fragmentation remains a primary driver of extinction debt (figure 4a,b), highlighting the need to identify the mechanisms governing time-lagged species loss. Although traits such as longevity [84], clonality, and dormant life stages [85] are associated with persistence, no single characteristic consistently predicts debt across taxa. For example, despite their longevity, howler monkeys [86] in fragmented Mexican forests show no extinction debt, likely due to their dietary plasticity and ability to use regenerating habitats [87]. This suggests persistence depends on interactions among traits rather than isolated characteristics, motivating a shift towards community-level analyses focused on species' functional roles. Recent studies suggest that ecosystem functioning may depend less on total species richness and more on shifts in trait composition and functional diversity, as captured by concepts such as 'species trait debt' [88] and 'functional diversity extinction debt' [54]. These frameworks emphasize functional redundancy [89], where richness within functional groups may be more important than overall species richness because ecosystem functions are maintained despite the loss of individual species.

In contrast, colonization credit following land-use change reflects the interaction between successional history and modern landscape connectivity. Although succession has long been recognized [90], colonization credit is typically assessed by comparing recovering sites with reference habitats. Such comparisons have highlighted limited dispersal as a key trait underlying colonization credit [19,32]. Species with poor dispersal ability struggle to colonize isolated post-arable forest patches, whereas those adjacent to ancient forest show reduced colonization credit [91]. These results show that connectivity and life history traits shape the magnitude and duration of colonization credit.

Climate-driven range shifts offer a unique empirical frontier where extinction debt and colonization credit can be observed concurrently, yet this potential remains largely untapped (figure 4). Unlike the discrete historical perturbations of land-use change, climate change acts as a continuous press disturbance, forcing species distributions to shift across latitudes, elevations and depths in real-time [20,92]. This persistent perturbation initially allows phenotypic plasticity, but continued change may exceed species' capacity to respond, leading to local extinction [93]. Prolonged environmental stress, often punctuated with climate-driven pulse disturbances such as heat waves, shifts population densities as some species become locally extinct and others colonize [93]. This community disequilibrium with the climate has recently been termed 'climatic debt' [94]. Although beyond the scope of this review, climatic debt considers species' ability to track suitable climates and may help explain the scarcity of empirical studies on extinction debt and colonization credit in range-shifting communities.

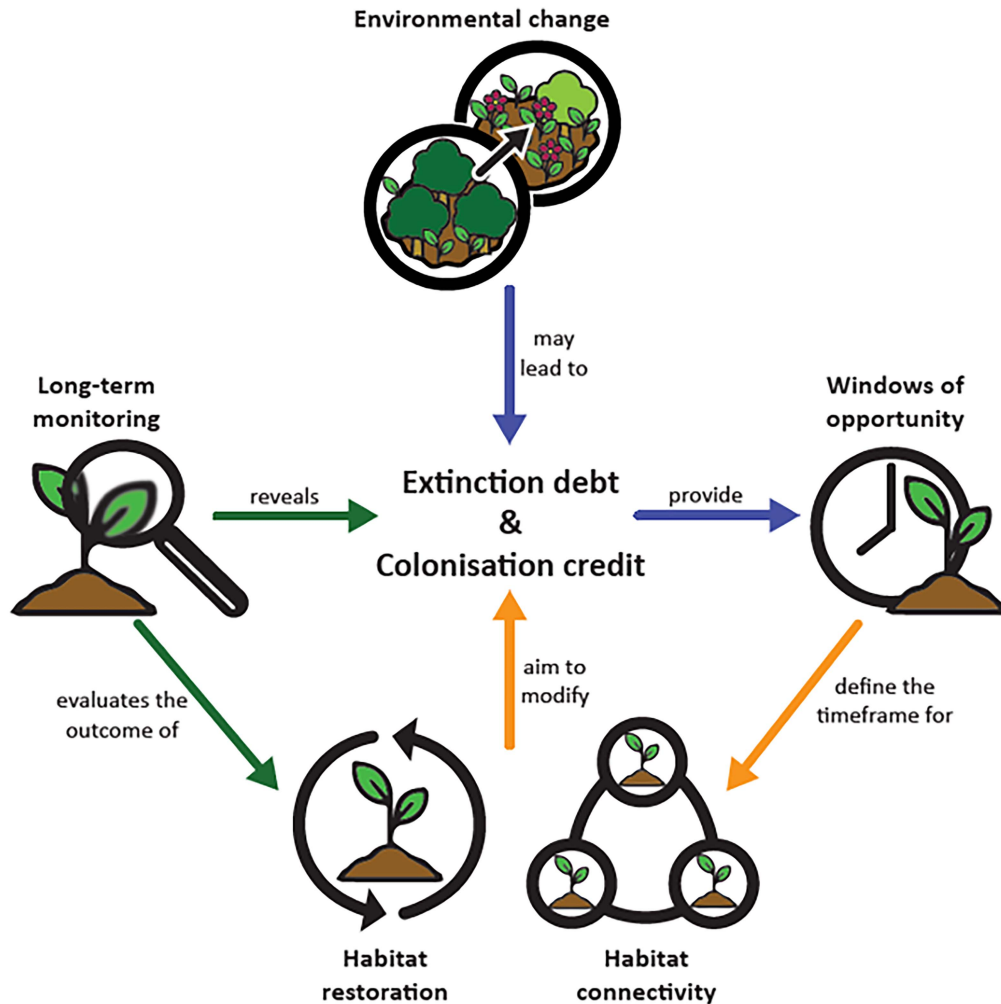


Figure 6. Conceptual framework for managing time-lagged biodiversity responses. Environmental change creates windows of opportunity (blue) where management strategies, such as habitat restoration and enhanced connectivity (orange), can be strategically deployed to resolve extinction debt and realize colonization credit. Long-term monitoring (green) is essential to detect these dynamics and evaluate the long-term efficacy of conservation actions.

(c) Conservation implications

The delayed impacts of environmental change on biodiversity present both a challenge and a strategic opportunity for conservation. Quantifying the magnitude of species debt and credit and the duration of associated lags (figure 1) is vital because these delays provide a window for proactive intervention. However, translating extinction debt and colonization credit into tangible conservation practice remains an under-used frontier. Although mitigation strategies, including long-term monitoring and enhanced habitat connectivity, are widely advocated [95,96], a substantial gap remains between identifying debts and credits and their integration into formal conservation policy. Nevertheless, models have demonstrated that incorporating extinction debt as a parameter can lead to nuanced conservation solutions that focus financial efforts and reduce trade-offs between land use change and conservation [97,98].

We suggest that incorporating extinction debt and colonization credit into strategic planning requires a holistic framework integrating environmental change, delayed community responses and targeted management (figure 6). Environmental change leads to transient dynamics that create a window of opportunity. For example, modelled extinction debt in Brazilian Amazon vertebrates predicted that debts would not be paid until 2050, providing time to develop policies [17]. Moreover, declines in deforestation rates were shown to extend this period of conservation opportunity. These windows provide the period during which restoration and enhanced connectivity can alter species trajectories. Identifying actions that resolve debts and realize credits during these windows is therefore critical [91,99]. Colonization credit, for example, is likely when suitable species are present nearby but have not yet colonized the newly suitable habitat [19,32]. However, successful colonization depends on both the presence of a source population and the availability of viable dispersal routes to the area. Increasing habitat connectivity through wildlife corridors, a common conservation strategy [95,96,100], is increasingly recognized as a means of reducing extinction debt and realizing colonization credit [101,102]. Finally, the framework emphasizes that long-term monitoring is not merely a data-collection exercise, but a diagnostic tool that provides the necessary feedback to evaluate whether interventions are succeeding over ecologically relevant time scales.

Beyond these broad recommendations, the conservation relevance of debts and credits is increasingly evident when applied to specific management and assessment contexts. Both metrics have been repeatedly linked to the conservation status of habitats and species [36,98,103,104]. For example, colonization credit offers a more nuanced restoration metric than simple occupancy counts [37,74]. In cases where forests or grasslands had been restored, several species remained in colonization credit despite the habitat now being suitable for recolonization. This raised questions about the true success of the restoration programmes, with active species introductions being suggested to enhance biodiversity [19,20,37].

Extinction debt has been used to assess the capacity of protected areas to sustain populations of carnivores [104], and to evaluate the validity of IUCN Red List categories [34]. An early African study reported that 50% of forest primate taxa were committed to extinction due to historic habitat loss [34]. Although these findings aligned with Red List classifications, they highlight an underused opportunity within the assessment framework. The IUCN Red List includes a criterion for species facing a high predicted risk of extinction (Criterion E) [105], yet it is rarely used [106,107] and has even been proposed for removal to simplify assessments [107]. While simplification may have a practical appeal, failing to account for extinction debt risks systematically underestimating future losses, particularly for species experiencing delayed responses to past environmental change. Integrating extinction debt into Criterion E assessments could improve the Red List's ability to identify species already committed to extinction and prompt timely conservation intervention [108].

Extinction debt and colonization credit also impose strict temporal constraints on management actions. Extinction debt limits the window for effective intervention before species losses become irreversible [17,72,88]. This window depends on the relaxation time, defined as the period between habitat change and a species's extinction. However, only one study reviewed here quantified relaxation time alongside extinction debt [109]. This study found that sensitive bird species exhibited extinction debt with a relaxation time of 25 years, estimated by reconstructing the historical landscape capable of supporting current species richness. These findings imply a finite window of opportunity within which habitat restoration could prevent local extinction of the sensitive bird species [109]. Accounting for both extinction debt and relaxation time enables conservation efforts to prioritize areas where restoration is most likely to prevent biodiversity loss.

Despite the growing implementation of restoration and connectivity as conservation solutions, little evidence suggests interventions are evaluated over the time scales needed to detect extinction debt and colonization credit. This gap is significant because extinction debt, for example, can overestimate long-term species richness and underestimate extinction risk [33,34,39], creating the false impression that conservation strategies are unnecessary. Long-term monitoring following restoration or improved connectivity could indicate whether debts and credits are resolved, or inadvertently created by conservation actions.

Paradoxically, despite investigating community restructuring following environmental disturbance, a substantial number of the empirical studies reviewed make no reference to conservation strategies. This disconnect is particularly evident in research on colonization credit, which frequently fails to articulate how delayed species arrival could inform conservation action. This may stem from a focus on passive recovery; notably, proactive interventions such as assisted migration or species reintroductions were proposed by only two of the reviewed studies [19,20], probably reflecting their limited application to date [110] and the potential for unintended ecological consequences [111]. If colonization credit is to be resolved rather than merely documented, there is a clear need to bridge the gap between quantifying delayed responses and identifying the specific actions required to address them.

5. Conclusion

Understanding the role of extinction debt and colonization credit in ecosystems undergoing environmental change is important for conservation biologists to incorporate into their strategic planning. To date, most studies have concentrated on plants in terrestrial ecosystems and have focused on the impact of habitat loss and habitat fragmentation. Marine ecosystems are under-represented in this field of study, and empirical data on the dual dynamics of extinction debt and colonization credit in range-shifting communities are notably scarce.

The time-delayed impact of environmental change means that the observed species richness may not represent the long-term trajectory of an ecosystem, with some species on a path to local extinction, while others have yet to colonize. Shifting focus toward long-term monitoring, coupled with an understanding of the species traits driving extinction debt and colonization credit, will allow for a more nuanced understanding of the transient dynamics. Ultimately, the capacity to anticipate these delayed responses provides a vital window of opportunity. By accounting for the debts and credits already embedded in a landscape, practitioners can implement more proactive strategies to safeguard ecosystem services before critical thresholds are breached.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. Data from the systematic review can be found in the supplementary material files [112].

Declaration of AI use. AI was used on occasion to improve readability.

Authors' contributions. K.L.R.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing; S.S.: supervision, validation, writing—review and editing; M.B.: project administration, supervision, validation, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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