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REVIEW ARTICLE

Mapping the information landscape of the United Nations Decade on Ecosystem Restoration Strategy

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The strategy of the United Nations Decade on Ecosystem Restoration identifies three pathways for action for overcoming six global barriers thought to hamper upscaling. We evaluated 6,023 peer-reviewed and gray literature papers published over the last two decades to map the information landscape underlying the barriers and associated pathways for action across world regions, terrestrial ecosystem types, restorative interventions and their outcomes. Overall, the literature addressed more the financial and legislative barriers than the technical and research-related ones, supporting the view that social, economic and political factors hamper scaling up ecosystem restoration. Latin America, Africa, and North America were the most prominent regions in the literature, yet differed in the number of publications addressing each barrier. An overwhelming number of publications focused on forests (78%), while grasslands (6%), drylands (3%), and mangroves (2%) received less attention. Across the three pathways for action, the action lines on (1) promoting long-term ecosystem restoration actions and monitoring and (2) education on restoration were the most underrepresented in the literature. In general, restorative interventions assessed rendered positive outcomes except those of a political, legislative or financial nature which reported negative or inconclusive outcomes. Our indicative assessment reveals critical information gaps on barriers, pathways, and types of restorative interventions across world regions, particularly related to specific social issues such as education for ecosystem restoration. Finally, we call for refining "strength of evidence" assessment frameworks that can systematically appraise, synthesize and integrate information on traditional and practitioner knowledge as two essential components for improving decision-making in ecosystem restoration.

Key words: barriers, ecosystem restoration, evidence base, pathways, restorative interventions, systematic review, United Nations Decade on Ecosystem Restoration

Implications for Practice

- There is a need to intensify restoration research, policy and practice in grasslands, drylands, and mangrove ecosystems.
- Restoration-based education, monitoring, and long-term research require scaling up through long-term funding.
- Assessment frameworks that draw on qualitative evidence, such as traditional and practitioner knowledge, need further refinement and application to distill better the evidence base.

Introduction

The year 2021 marked the beginning of the United Nations Decade on Ecosystem Restoration (UNDER), a global campaign to catalyze efforts at "halting, preventing, and reversing degradation." The UNDER aims to engage actors from all spheres of society to overcome political, socioeconomic, and technical barriers to implementing ecosystem restoration at multiple scales. To this end, the strategy that guides the UNDER (UN 2020) conceives ecosystem restoration as a holistic approach to conserve native ecosystems and repair those that are degraded or damaged, thereby contributing to achieving the Sustainable Development Goals (SDGs). Ecosystem

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restoration directly addresses SDGs 14 (Life below water) and 15 (Life on land) via habitat recovery in natural and managed areas. In addition, ecosystem restoration contributes to adapting and mitigating climate change (SDG 13) while providing clean air and green spaces across rural and urban settings (SDGs 3 and 11). Ecosystem restoration can also improve the provision of clean water (SDG 6) and food (SDG 2) (IUCN 2019). Yet, despite the potential contributions of ecosystem restoration to sustainable development, its implementation at scale is inherently complex (Sutton et al. 2016; Cengiz et al. 2019; Mansourian & Parrotta 2019). The UNDER strategy aims at addressing such complexity by outlining six barriers and three related pathways for action (linked to "action lines") for overcoming the barriers (Table 1) with the overall goal of upscaling implementation. While we acknowledge that reviews on the biophysical (e.g. Jones & Schmitz 2009; Meli et al. 2014; Crouzeilles et al. 2017; Romanelli et al. 2020) and socioeconomic and human dimensions (e.g. Aronson et al. 2010; Wortley et al. 2013; Elias et al. 2021) of ecosystem restoration do exist, a thorough assessment of the information base underlying the multidimensional nature of the UNDER strategy, which can support catalyzing its implementation, remains unexplored.

The present work seeks to complement recent calls and proposals for action to fulfill the UNDER's aspirations. Aronson et al. (2020) suggested six strategies such as applying holistic measures at the appropriate scale, including traditional ecological knowledge, joining forces with relevant organizations and social movements, focusing on the soil dimension, and linking ecosystem health with human health. These actions will require, in turn, strong, long-lasting political will and positive behavioral changes from decision makers to rural communities and from social workers to scientists with support from both crowdfunding and institutional funding (Abhilash 2021). Furthermore, transdisciplinary research (Edrisi & Abhilash 2021; Farrell et al. 2022) will be needed, along with a "culture of innovation" that brings in policies and practices to support the recovery of ecosystem integrity (Jepson 2022). Others emphasize enhancing the scientific evidence base to inform the wide range of management decisions in the context of the UNDER (Cooke et al. 2019; Sutherland et al. 2021; Farrell et al. 2022). Ladouceur et al. (2022) further suggest refining knowledge and information-sharing approaches across scales to further strengthen evidence-based decision-making and improve the UNDER's outcomes.

That said above, our objective was to map the information landscape underlying the six barriers and associated pathways

Table 1. The six barriers and three pathways (along with action lines to overcome the barriers) outlined in the strategy of the United Nations Decade on Ecosystem Restoration (https://www.decadeonrestoration.org/strategy).

Barrier	*Description*
Legislative and policy environments	Relates to the prevalence of incentive mechanisms that promote degradation and, related to this, the lack or poor enforcement of enabling legislative environments and policies that incentivize the restoration of ecosystems.
Political will	Highlights the relatively small portion contribution of the national budget that governments currently assign to ecosystem restoration compared to the investments made in other areas, like energy and defense.
Financial streams	Highlights the reduced amount of private investments in restoration, given the perceived risk of the activities involved.
Technical capacity	Relates to the prevalence of limited capacities among organizations, governments, private companies, and communities in restoration initiatives.
Scientific research	Relates to the need for long-term scientific research devoted to understanding the restoration process, from its social and biophysical dimensions to improving and innovating methods and strategies.
Public awareness	Relates to the pervasive lack of public awareness of the threats that ecosystem degradation and climate change pose to our planet, and of the social, economic, and ecological benefits of restoring degraded ecosystems.
Pathway	**Action lines**
Global movement	(1) Raise awareness of the benefits of ecosystem restoration. (2) Increase the intent of societies worldwide to invest in restoration. (3) Shift behaviors to reduce ecosystem degradation. (4) Showcase economic returns from restoration in different ecosystems. (5) Support a decentralized global movement focused on restoration. (6) Embed restoration into education systems globally. (7) Promote a values-based imperative for restoration. (8) Develop and implement financing mechanisms for restoration.
Political will	(1) Assist societal leaders to champion ecosystem restoration. (2) Amend legislative and policy frameworks to promote restoration. (3) Facilitate cross-governmental and cross-sectoral dialogs and collaboration in restoration. (4) Redirect fossil fuel, agricultural, forestry, and fishing subsidies toward ecosystem conservation and restoration.
Technical capacities	(1) Designing, implementing, monitoring and sustaining ecosystem restoration initiatives. (2) Undertaking long-term scientific research on the implementation and benefits of ecosystems restoration. (3) Synthesizing lessons learned from existing ecosystem restoration initiatives. (4) Integrating Indigenous knowledge and traditional practices into ecosystem restoration initiatives. (5) Applying free, prior, and informed consent in ecosystem restoration initiatives.

for the action of the UNDER strategy across geographies, terrestrial ecosystem types, types of restorative interventions and their outcomes. We also evaluated a framework to assess the strength of the evidence of such outcomes. We expect our indicative results to assist those involved in implementing the UNDER strategy from the top-down and the bottom-up and to promote the use of well-informed, evidence- and knowledge-based tools and approaches as a major need identified by the Science Task Force for the UNDER (2021).

Methods

Mapping the Information Landscape

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses framework extension for scoping reviews (Tricco et al. 2018), as we strived to gather all peer-reviewed literature as well as a subsample of gray literature concerning terrestrial ecosystem restoration published from 1990 to 2021 (Fig. 1). As entry points to the literature search, we used terms that related to each of the six barriers of the UNDER strategy (Table 1) and combined these with a series of terms about terrestrial ecosystem restoration interventions (Table S1); although we recognize that the UNDER includes ocean, coastal, and freshwater ecosystems.

We used Web of Science, Scopus, and SciELO databases to search for peer-reviewed publications, including opinion articles, case studies, primary research, and reviews. We also retrieved PDF articles found in the first five pages of gray literature "hits" in Google Scholar. In order to narrow our search for gray literature, we restricted our search to publications by organizations that partner with the UNDER (https://www.

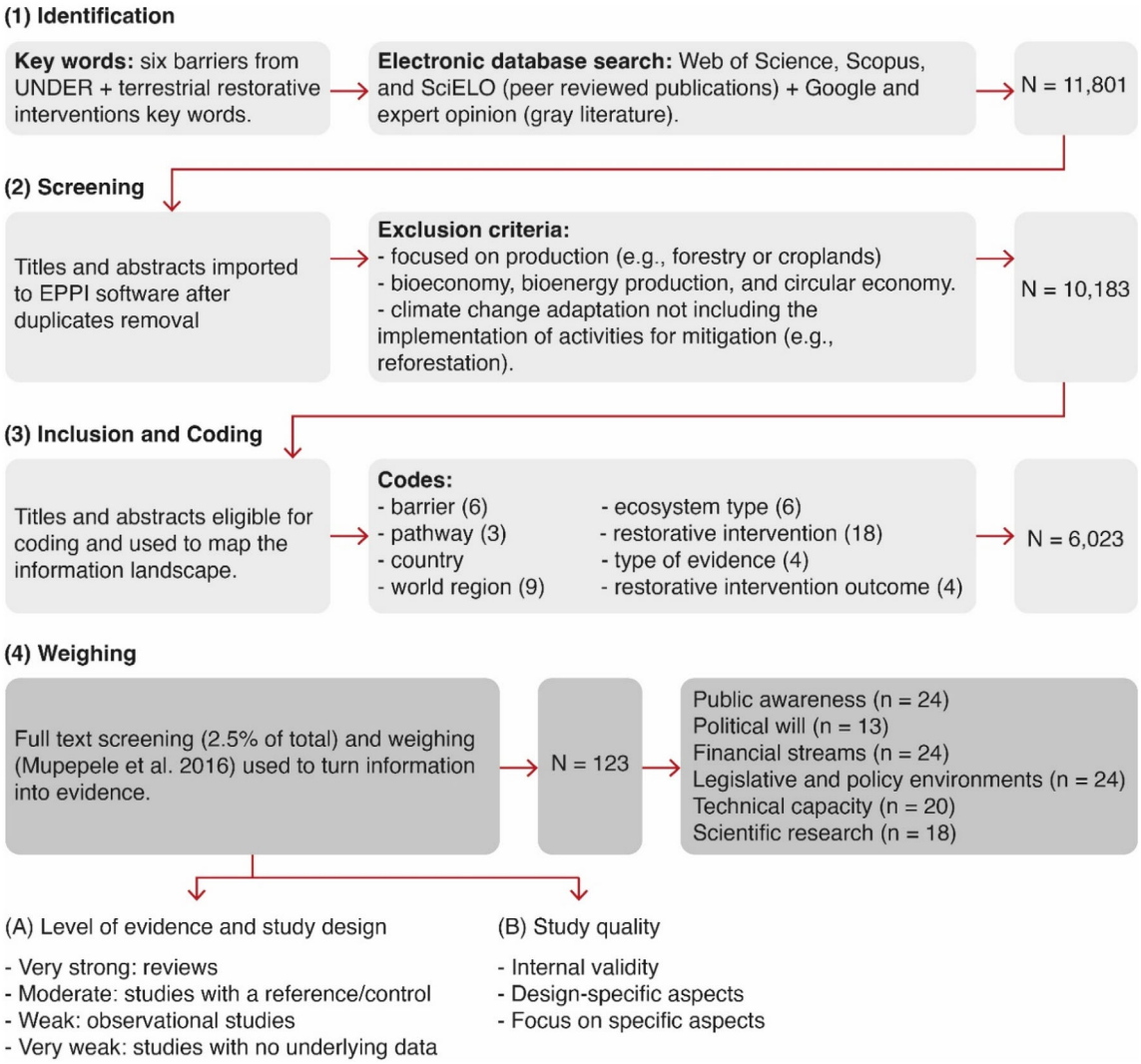

Figure 1. Methodological procedure to evaluate publications addressing the six barriers and three related pathways of the UNDER strategy. In (4) weighing, (A) corresponds to the literature hierarchy according to the design of the study, and sublevels within each design type, from very strong to weak evidence; while in (B), evidence is further weighed by study quality where the study design is combined with a quality score that supports decisions to downgrade (or not) from the original ranking based on a. modified from Mupepele et al. (2016). Note that this hierarchical approach applies only to peer-reviewed literature.

Table 2. Detailed description and explanations of the coding system.

Code	*Categories*
World region (9)	(1) North America: English-speaking countries in North America (i.e. Alaska, Canada, United States) (2) Latin America: all Spanish- and Portuguese-speaking countries in America (3) Europe (4) Africa (5) Australia–New Zealand (6) Central Asia (i.e. Russia, Mongolia, China, Japan, North Korea, South Korea, Nepal, India) (7) East Asia (e.g. Emirates, Yemen, Iraq, Syria, Turkey, Pakistan) (8) Southeast Asia: includes the south peninsula (e.g. Vietnam, Laos, Cambodia, Malaysia, Thailand) (9) South Pacific Islands (e.g. Philippines, Indonesia, and smaller islands such as Timor Leste and Salomon Islands)
Ecosystem type (6) Ecosystems typology, modified from IUCN (IUCN Global Ecosystem Typology 2.0)	(1) Forest (includes woodlands and shrublands) (2) Grasslands (natural grasslands, as opposed to anthropogenic ones such as pastures); includes savannas (3) Mangroves (4) Drylands: arid and semiarid ecosystems (includes publications on karst ecosystems and combating desertification) (5) Anthropogenic ecosystems: ecosystems managed or heavily influenced by humans (i.e. agroforests, crops, silvopastoral systems, urban ecosystems, monoculture tree plantations, open soil habitats such as post-mining and quarries) (6) Generic: Other topics than land uses, such as biodiversity, endangered species, or landscapes, where several ecosystems or land uses converge
Restorative intervention (18)	(1) Vegetation reintroduction: any activity that implies actively reintroducing vegetation in an area that had been degraded, independent of the type of vegetation and the ecosystem; includes tree planting and grassland revegetation (2) Natural regeneration/resprouting: passive restoration, where human intervention is minimal or not present and the process of recovery of the vegetation occurs on its own (3) Assisted natural regeneration: a mix of active and passive restoration, where people intervene to help in the natural recovery of vegetation by eliminating barriers to the recovery or by enrichment planting activities that imply introducing a particular species into a naturally regenerating ecosystem (4) Agroforestry (under canopy): crops grown under a native canopy, such as coffee, cocoa, ornamental palms, and others; includes other nontimber forest products (5) Agroforestry (crops enrichment): tree planting activities in crops or other productive land targeting the improvement of a specific ecosystem service, such as soil fertility or providing food; also includes alley cropping systems (agro-silvopastoral) (6) Afforestation: includes any tree cultivation with commercial (e.g. pulp, wood) or ecological (e.g. carbon capture) goals in any ecosystem that was not originally a forest; does not include tree planting in crops (which is considered agroforestry) (7) Forestry/forest management: includes publications that did not explicitly address a passive or active restorative intervention or agroforestry but which generally addressed the sustainable management of standing forests, implicitly including a restorative action on a standing forest (8) Landscape restoration: a focus on the scale, not on the intervention type; includes studies addressing ecological restoration, ecosystems at landscape scales, or restoring landscapes (e.g. forest and landscape restoration) (9) Direct seeding: the introduction of seed to any ecosystem type; includes studies addressing practical issues on species propagation or collection (e.g. nurseries, seed collection) (10) Prescribed fire/control burn (11) Silvopastoral systems (12) Invasive species removal and control (13) Soil restoration (14) Urban restoration (15) Educative interventions: formal and nonformal education; includes degree programs, environmental education, participative public events (16) Financial interventions: financial instruments, such as forest certification systems (FSC and others), REDD+, PES and others (e.g. markets—carbon, biodiversity, nontimber forest products; taxes; incentives, subsidies) (17) Policy interventions: adoption of public strategies, national programs or policies (18) Social interventions: community-based forest management, governance enforcement, sustainable development (not targeted to a specific ecosystem), community empowerment, decentralization, social learning, collaborative processes, knowledge sharing, and gender issues

Table 3. Distribution of the 6,023 publications reviewed addressing barriers, pathways, ecosystem types, and world regions.

(A) Barrier	N°	%	(B) Pathway	N°	%
Financial streams	1822	30.3	Global movement	3,195	53.0
Legislative and policy environments	1,611	26.7	Political will	2,130	35.4
Scientific research	1,376	22.8	Technical capacities	3,403	56.5
Public awareness	1,348	22.4	(E) Restorative intervention		
Technical capacity	1,125	18.7	Forestry/forest management	1,677	27.8
Political will	662	11.0	Vegetation reintroduction	936	15.5
(C) World region			Agroforestry (crop enrichment)	779	12.9
Latin America	1,083	18.0	Financial intervention	742	12.3
Africa	957	15.9	Policy intervention	716	11.9
North America	870	14.4	Agroforestry (under canopy)	443	7.4
South Asia	696	11.6	Afforestation	421	7.0
Europe	689	11.4	Social intervention	407	6.8
South Pacific Islands	576	9.6	Natural regeneration	381	6.3
East Asia	435	7.2	Landscape restoration	374	6.2
Australia–New Zealand	251	4.2	Silvopastoral systems	219	3.6
Central Asia	22	0.4	Assisted natural regeneration	168	2.8
(D) Ecosystem type			Urban restoration	156	2.6
Forest	4,690	77.9	Prescribed fire/control burn	152	2.5
Anthropogenic ecosystems	672	11.2	Soil restoration	97	1.6
Generic	429	7.1	Invasive species removal/control	93	1.5
Grasslands	369	6.1	Educative interventions	91	1.5
Drylands	218	3.6	Direct seeding	49	0.8
Mangroves	96	1.6			

decadeonrestoration.org/partners, accessed on 24 November 2021). To further complement our literature search, we contacted 75 experts within our networks to solicit additional input on gray literature that merited inclusion (see Fig. 1, Identification). We searched publications and exported titles, abstracts, and the keywords of all citations selected from the databases using the bibliometric software EPPI (https://eppi.ioe.ac.uk). This allowed us to remove duplicates and screen publications by titles and abstracts to exclude publications unrelated to a restoration context (Fig. 1, Screening). We conducted the review in two phases: first, the coding of titles and abstracts, followed by a full review and weighing of a subset of the reviewed publications (see below).

As we aimed to map the information landscape for the UNDER strategy, we coded all publications (based on titles and abstracts) according to the barrier they addressed (Fig. 1, Inclusion and Coding), terrestrial ecosystem type, world region, the pathway for action, type of restorative intervention and the outcome of the intervention (Table 2). We selected publications for coding if the topic of the publication related to one or more of the barriers and restorative interventions used in the search terms. Furthermore, we matched these within a given pathway for action and action line whenever the literature examined documented actions to overcome the barriers, as in Table 1. We both included and coded a publication that addressed those topics either by providing evidence of an approach to resolve that barrier or by explicitly mentioning the topic as a barrier. For example, an article describing a case study on payment for environmental services and their recovery was coded to the "Financial streams" barrier and the "Develop and implement financing mechanisms for restoration" action line within the Global Movement pathway (Table 1). If a given publication addressed more than one barrier or pathway, it was coded under multiple categories. We acknowledge that coding and

Table 4. Key gaps found when mapping the information addressing the different barriers and pathways of the strategy of the United Nations Decade on Ecosystem Restoration. In pathways, we show gaps on specific action lines.

Variable	*Information gap*
Barriers	Political will
Pathways and action lines	Embedding restoration in education; modifying behavior; assisting restoration leaders; sustaining restoration; monitoring and long-term research; informed consent; traditional ecological knowledge
World regions	Africa: Legislative and policy environments; scientific research Latin America: Political will, public awareness North America: Legislative and policy environments; financial streams Europe: Political will; financial streams Australia and New Zealand: Legislative and policy environments; political will; financial streams Asia: Technical capacities; scientific research; public awareness; political will (only East Asia)
Ecosystems	Mangroves; grasslands; drylands
Restorative interventions	Social: educative interventions; social interventions Biophysical: direct seeding; invasive species removal and control; prescribed burns; urban restoration; assisted natural regeneration; silvopastoral systems

assigning articles to a given pathway for action imply a subjective valuation, as these were not explicitly mentioned in publications using the same language of the UNDER strategy.

We limited our selection to those publications addressing terrestrial ecosystems (sensu Keith et al. 2020): forests (including woodlands and shrublands), grasslands (native), mangroves, drylands (arid and semiarid), anthropogenic ecosystems (i.e. monoculture tree plantations, croplands, agroforests, urban, and silvopastoral systems). For instance, if a publication addressed forest restoration, the ecosystem was coded as "forest"; if it addressed a topic regarding ecological restoration of urban areas, it was coded under "anthropogenic ecosystems." We also included a "generic" category for those studies that either addressed a barrier at the global scale or did not mention a specific ecosystem. In addition, we coded "restorative interventions" into 16 categories, including 12 biophysical and four social categories (Table 2). Furthermore, we separated restorative intervention outcomes into qualitative, quantitative-based on field data (research papers), quantitative-based on mathematical models, and opinion-based. Finally, the outcome of a given restorative intervention was classified as positive, negative, mixed (i.e. the publication outlines both positive and negative outcomes), or inconclusive (no specific outcome mentioned).

In addition, we conducted chi-square tests to assess whether the number of publications across each coding category differed from that expected by chance ($p = 0.05$). For all statistically significant chi-square tests, we checked the Pearson residuals to explore the distribution of the information. All positive residuals exceeding 10% or greater of the value expected by chance were considered "concentration points" of information, while negative values exceeding the same percentage were considered "information

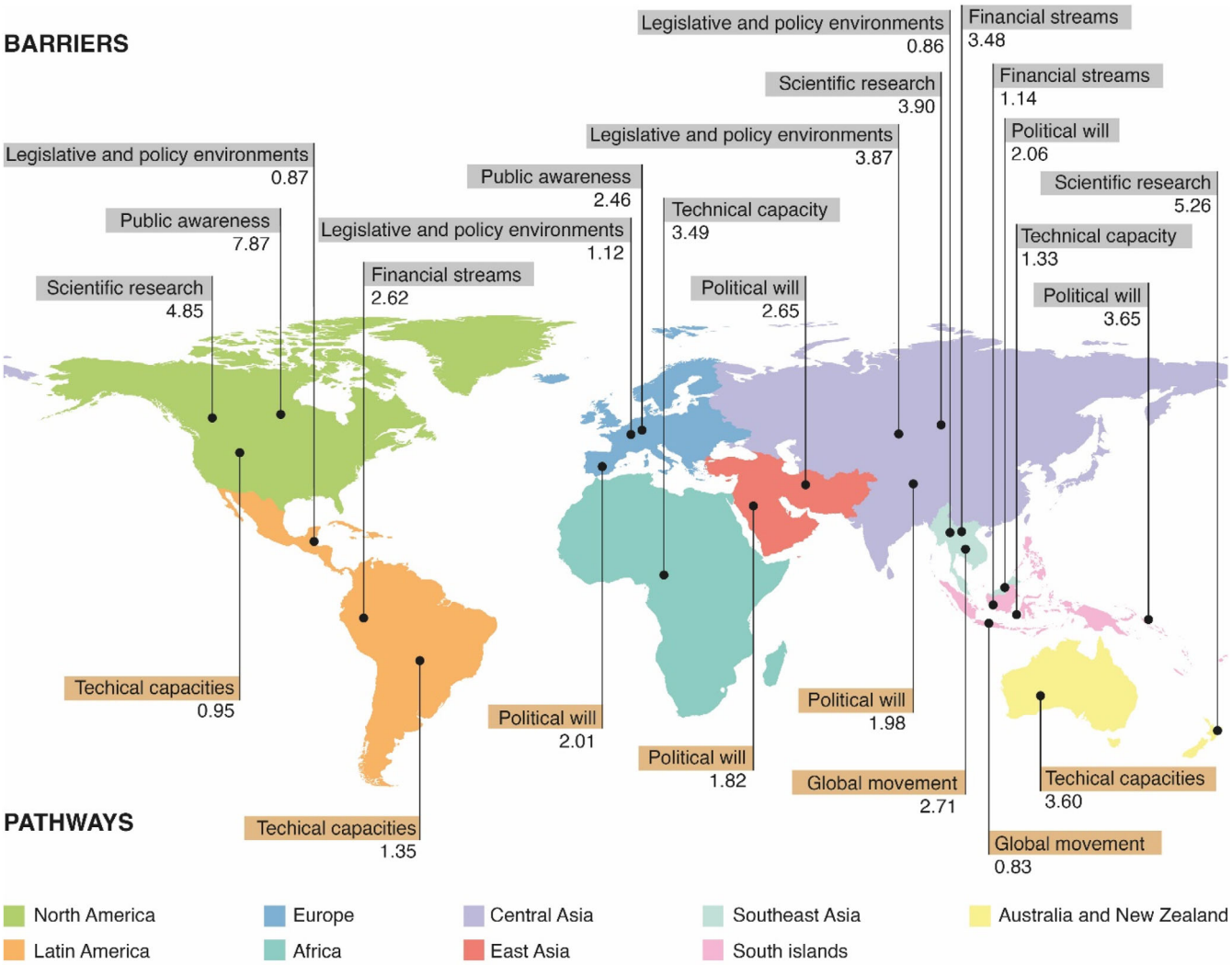

Figure 2. Global distribution of information addressing the six barriers and three pathways for the action of the UNDER strategy (see Table 1). Note that publications which mentioned more than one of the nine world regions assessed in this study were included. Barriers (gray-shaded) are shown in the upper half and pathways for action are shown in orange in the lower half. Dots only represent the world regions and not a specific location. Numbers represent the Pearson residuals from chi-square tests, which denote the deviation from an expected result in the number of publications. The higher the values, the higher the number of publications deviating from a random sample.

gaps." All figures in this manuscript show positive values considered as concentration points the values for all combinations in each test are included in Supporting Information figures (see below).

Evaluating a Framework to Turn the Information Into Evidence

For the ecosystem restoration literature, we explored the application of the evidence assessment tool proposed by Mupepele et al. (2016) for ecosystem services and conservation studies. To achieve this, we randomly selected a subsample of 2.5% of the total publications coded in each barrier, totaling 123 publications (the lower end of the range of 100–600 publications needed for a significant sample; Alreck & Settle 2003). We then assessed the evidence's weight by examining each publication's full text and assigning to it a "level of evidence" (Fig. 1, Weighing; Mupepele et al. 2016). Systematic reviews qualify as very strong evidence while, e.g. statements in a given publication without underlying data are categorized as weak evidence (i.e. usually individual expert opinions). However, a study with a sound experimental design could be poorly conducted, meaning that design alone is not always an adequate indicator of the strength of evidence (Rychetnik et al. 2002). To improve the assignment of a given weight of evidence, we evaluated research quality through a checklist (Mupepele et al. 2016) of 43 questions that apply to each type of study design (e.g. specific questions for reviews). All questions in the checklist answered with "yes" received one point for a maximum score of 43. The combination of the study design and the scoring of study quality allowed us to assess the evidence's strength and quality in a given publication. However, it should be noted that this categorization was initially conceived for natural sciences research (i.e. mostly quantitative) and not necessarily for social sciences (i.e. mostly qualitative). Therefore, our evidence-weighing results need to be cautiously interpreted since a "low evidence" weight for a given article with only qualitative results does not imply "low quality" but merely reflects the framework tested. We provide examples of this weighing procedure in Table S2.

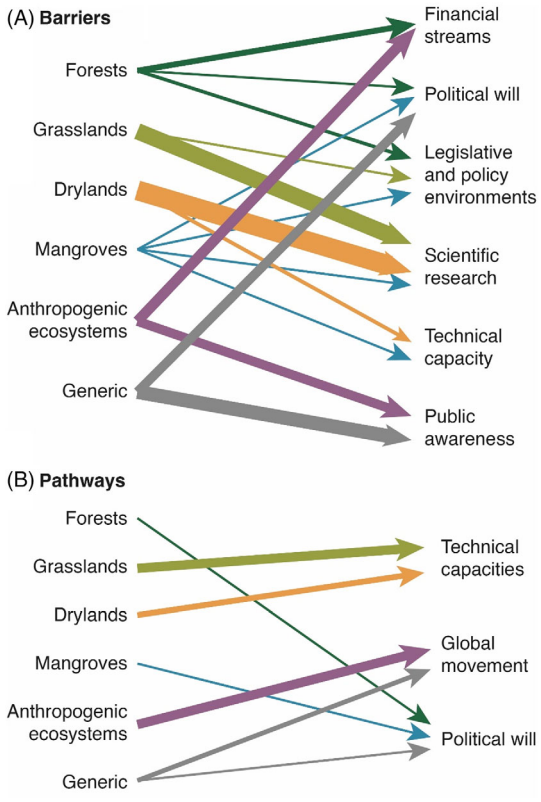

Figure 3. Links among the six barriers (A) and three pathways (B) for action of the UNDER strategy (Table 1) in the terrestrial ecosystem types studied. Arrows represent the links between ecosystems and given barriers and pathways; the width of the arrows represents the relative importance based on the number of publications, measured as the Pearson residuals from chi-square tests, which denote the deviation from expected and observed values.

Results

The different coding variables applied in our review allowed us to assess the distribution of information across the six barriers and three pathways for the action of the UNDER strategy while further disaggregating the information among specific action lines

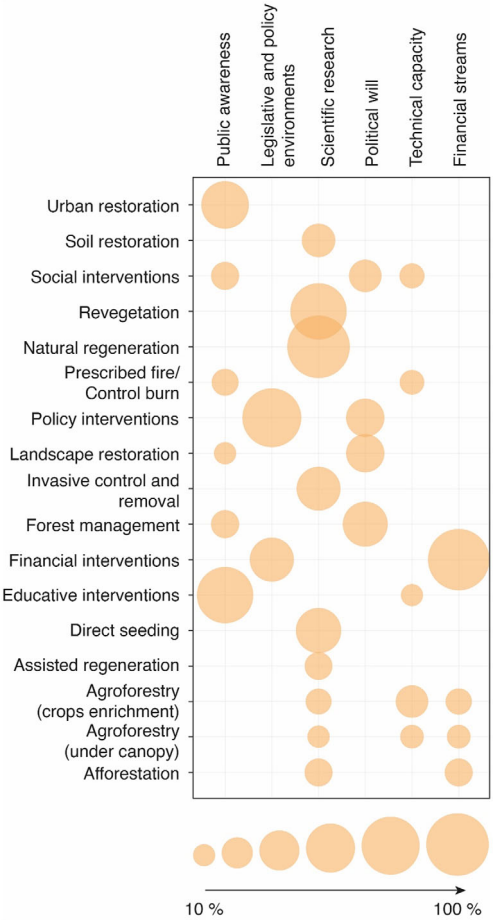

Figure 4. Pearson residuals (in percentage) relating barriers and restorative interventions as addressed in the literature assessed. Silvopastoral systems are not included in this figure as residuals did not differ from the expected results.

(within pathways) and across geographies, terrestrial ecosystem types, and types of restorative interventions. The initial search yielded a database of 11,801 publications, of which 6,023 were coded (Fig. 1). The database is stored in Meli et al. (2022).

Mapping the Information Landscape

Information Is Unevenly Distributed Across Barriers, Pathways for Action and Action Lines. The six barriers outlined in the UNDER strategy were documented during the coding process, although not uniformly (Table 3A). The two most common barriers mentioned were Financial streams (30% of publications) and Legislative environments (27%, legal and policy issues) as constraints hampering the scaling up of ecosystem restoration. Only 11% explicitly mentioned the barrier on Political will, thus denoting an information gap (Table 4).

The Technical capacities (56%) and Global movement (53%) pathways for action were addressed by more than half of reviewed publications, while the Political will pathway was addressed only by 35% (Table 3B). The most significant information gaps fell under the action lines of "behavior shift" and "embed restoration in education" (Global movement pathway), "assisting restoration leaders" (Political will pathway), "sustaining restoration," "monitoring restoration," "long-term research," and "informed consents" (Technical capacities pathway) (Fig. S1).

Most articles addressing a given barrier either mentioned or implemented a related action to overcome the barrier. For instance, articles coded under the barrier on Financial streams addressed actions such as "developing and implementing finances," "showcasing economic returns," and "increasing the intent of societies to invest" (Global movement pathway, Fig. S1A), and "redirecting subsidies" (Political will, Fig. S1B). Similarly, publications addressing the barrier on Public awareness mentioned the action lines "awareness-raising" and "embedding restoration topics in education curricula" (Fig. S1A). Furthermore, "assisting restoration leaders," "amending legislation" (Fig. S1B), and including "traditional ecological knowledge" informed the pathway for action on Technical capacities (Fig. S1C). The action line on "traditional ecological knowledge" (TEK; within the Technical capacities pathway for action), was prominently addressed as a strategy to overcome the barriers of Public awareness, Scientific research, and Legislative and policy environments.

There Is a Geographical Imbalance of Information Across Barriers and Pathways for Action. Although Latin America, Africa, and North America comprised 48% of the reviewed information (Table 3C), there was significant variation among world regions in the number of publications related to a given barrier ($\chi^2 = 388.27$; $df = 40$; $p < 0.0001$; Table 4; Figs. 2 & S2A). For example, Africa showed a large number of articles addressing the barrier on Technical capacity but very few addressing the barriers on Legislative and Policy environments and Scientific research. The barrier of Financial streams was prominent in the literature from Latin America but mentioned significantly less in Europe. Similarly, world regions differed in the number of publications across the three pathways for action ($\chi^2 = 62.48$; $df = 16$; $p < 0.0001$). On the one hand, in Australia, most publications addressed the pathway on Technical capacities, but significantly less addressed the pathways of Global movement and Political will. On the other hand, South Asia had significantly more publications addressing the Global movement pathway for action, and Central and East Asia had more on Political will (which was also more prominent in Europe; Figs. 2 & S2B).

Most of the Information Focuses on Forest Ecosystems at the Expense of Grassland, Dryland, and Mangrove Ecosystems. Among the six barriers of the UNDER strategy, an overwhelming number of publications focused on forests (78%), followed by anthropogenic ecosystems (11%). Few addressed grasslands (6%), drylands (4%) or mangroves (2%) (Tables 3D and 4). We found significant differences in the number of publications addressing a given barrier and pathway within ecosystem types ($\chi^2 = 306$; $df = 25$; $p < 0.0001$). Notably, the literature referring to drylands and grasslands primarily addressed the barrier of Scientific research and the pathway on Technical capacities (Figs. 3A, 3B, & S3A), highlighting the

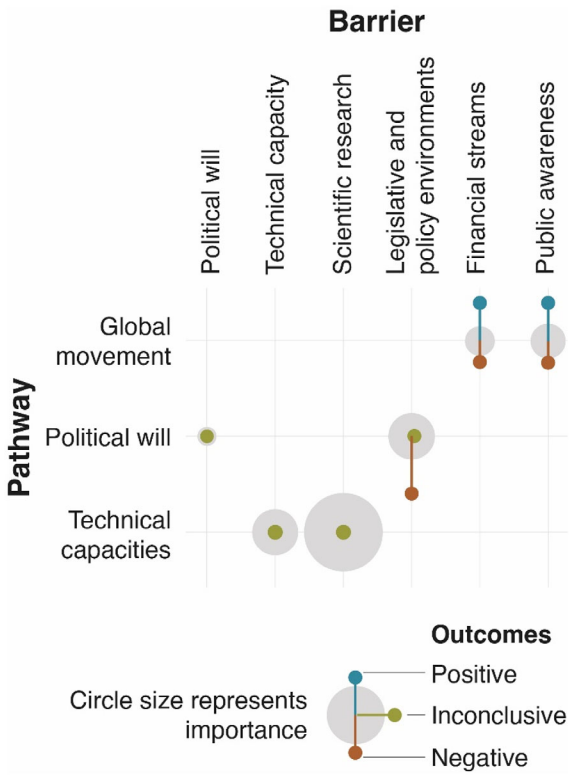

Figure 5. Relationship between the three pathways for action and the six barriers of the UNDER strategy (Table 1). The importance of the relationship is depicted by the size of the gray circle and was measured as the Pearson residuals from chi-square tests, which denotes the deviation from an expected and observed number of publications. Colors of the small dots and lines represent the direction of reported outcomes from an intervention implemented to overcome the barrier, and the length of the colored line represents the importance of the outcome (also measured as Pearson residuals from chi-square tests).

need to increase research and action to restore these ecosystem types. However, the barriers of Public awareness, Legislative environments, Political will and Financial streams, all relevant for upscaling restoration efforts in these two ecosystems, were notably missing in our review (Fig. S3). As mentioned above, anthropogenic ecosystems comprised the second-highest number of publications. In particular, urban ecosystems were prominent in our assessment.

Types of Restorative Interventions Are Unevenly Addressed While Most Showcase Positive Outcomes. Of the various restorative interventions in the reviewed literature, none showed a disproportionally high number of citations (Table 3E). For example, forest management was mentioned in 28% of the articles coded, followed by revegetation (15%), agroforestry (13%), and interventions of a financial (12%) or political nature (12%). Other restorative interventions such as soil restoration, control and removal of invasive species, and direct seeding were found in less than 2% of the articles coded. There was also a large imbalance in the number of publications on educative interventions compared to other social interventions, such as those related to policy and finance.

Overall, publications addressing types of restorative interventions differed across all six barriers ($\chi^2 = 2{,}808.5$; $df = 90$; $p < 0.0001$). Publications addressing the Scientific research barrier related to vegetation reintroductions, natural regeneration, direct seeding, or invasive species removal/control more so than other interventions of biophysical nature (Figs. 4 & S4A). Not surprisingly, publications addressing socially-oriented barriers such as Public awareness and Political will (Table 1) either applied or recommended policy or financial interventions. We also noted that agroforestry interventions, addressed in over 1,000 publications, mentioned Technical, Research and Financial barriers.

Most interventions addressed in the reviewed literature rendered positive outcomes, except those concerning political, legislative and financial topics, which were either negative or inconclusive (Fig. S4B). In particular, social interventions, such as education campaigns or financing programs, were prominent in the review and claimed positive outcomes underscoring their importance. Furthermore, the direction of the outcome of implementing a given restorative intervention (Table 2) varied significantly within pathways for action (Fig. 5; $\chi^2 = 193.87$; $df = 6$; $p < 0.0001$). The pathway on Global movement, related mainly to financial and awareness-raising interventions, showed more positive than negative outcomes (Fig. 5). Publications under the Technical capacities pathway, addressing research on various technical dimensions of ecosystem restoration, largely yielded inconclusive outcomes.

Evaluating a Framework to Turn the Information Into Evidence

The evidence-weighing framework from Mupepele et al. (2016) evaluated a subsample of 123 publications and categorized the

Figure 6. Weighted evidence on the most common drivers behind the six barriers outlined in the UNDER strategy, the common approaches linked to the UNDER strategy pathways to overcome the barriers, and cited outcomes of these approaches.

evidence mainly as moderate and weak (Figs. 1 & 6). However, the full review of the subset of articles allowed identifying factors underlying the barriers identified by the UNDER strategy, the most common approaches to overcoming these barriers, and outcomes stemming from these approaches (Fig. 6 provides an indicative road map for action). In particular, the key underlying factors identified for each barrier are (1) poor inclusion of social context and processes (Legislative and policy environments barrier); (2) limited information flows from local to national levels (Political will barrier); (3) financial streams competing against ecosystem restoration (Financial streams barrier); (4) insufficient mobilization of financial resources and limited stakeholder dialog (Financial streams and Technical capacity barriers); (5) information gaps on ecosystems other than forests (Scientific research barrier); and (6) lack of empowerment and education and power asymmetries (Public awareness barrier).

Discussion

Mapping the Information Landscape

Key Information Gaps Across Barriers, Pathways for Action, and Action Lines of the UNDER Strategy. Although our mapping exercise revealed that the information in a given publication often informed multiple barriers, pathways for action and action lines of the UNDER strategy, a few distinct information gaps were identified, specifically related to three action lines within the Technical Capacity Pathway: (1) long-term research, (2) monitoring, and (3) sustaining restoration. Collectively, these gaps reflect previous findings highlighting that long-term monitoring is notably missing from ecosystem restoration projects and that most ecosystem restoration research is biased toward small-scale and short-lived projects, thus hampering long-term sustainability and social learning (Wortley et al. 2013; Cooke et al. 2019; Christmann & Menor 2021). This is a fundamental challenge that needs to be addressed in the context of the UNDER. Only by increasing the amount of evidence on what has, and has not worked in ecosystem restoration can we improve future actions, expand the scale of interventions with a reasonable probability of achieving desired outcomes, and thus enhance the potential of ecosystem restoration to improve human well-being, mitigate climate change and reduce biodiversity loss. To this end, the recently created Global Restoration Observatory (globalrestorationobservatory.com) may help address knowledge and data gaps hindering comprehensive ecosystem restoration monitoring globally and is expected to positively contribute to augment and refine the evidence base in the context of the UNDER.

Our mapping exercise also revealed information gaps related to the barrier on Political will. Such gaps could be related to the complexity and multidimensional nature of the term, which may lead to different definitions. That said, Brinkerhoff (2016), although working in the human health realm, identified helpful indicators of political will such as (1) government initiatives, (2) policies and programs based on solid scientific and technical feasibility, (3) stakeholder engagement processes, (4) public commitment and resource allocation, (5) design and application of credible incentives, and (6) continuity, learning, and adaption. Had we used these indicators, it could have helped to dissect further the Political will barrier of the UNDER strategy in our mapping. In other words, institutional factors and governance structures may determine the extent of political will in a given country to implement policy changes around specific agendas such as climate change and ecosystem restoration (Post et al. 2010; Fox et al. 2011), issues that were not possible to capture in our review fully.

Another notable finding was that most of the publications reviewed addressed barriers related to finance, legislation and policies, largely reflecting current discourses on scaling up ecosystem restoration through sustained financial and political support (Chazdon et al. 2017; Löfqvist & Ghazoul 2019) and underscores the need to link restoration finance for implementing ecosystem restoration including nature-based solutions (Demirci & Öztürk 2015; Rooney & Paul 2017; Jo et al. 2020; Nonini & Fiala 2021). To this end, innovative financial instruments, such as green bonds and impact investment, are raising the hope of a transition to economies focused on sustainable development and not on eternal growth (Löfqvist & Ghazoul 2019). Other options, such as more equitable benefit sharing and the revision of investments into military spending, are perhaps more contentious but are being discussed in an ecosystem restoration context (Naidoo & Fisher 2020). In order to scale up the implementation of ecosystem restoration, the will to remove major financial, legal, and political barriers needs to be in place.

We also found information gaps for the action lines of embedding restoration in education, assisting restoration leaders, and modifying behavior; all under both the Global movement and Political will pathways for action. Closing these gaps are reflected in recent calls to embrace the social dimension of ecosystem restoration (e.g. Pérez & Ceccon 2017) and, collectively, provide entry points to emerging socioecological approaches (Cross et al. 2019; Fischer et al. 2021) that incorporate public health and education in policy and regulatory frameworks to create a "restorative culture" (Cross et al. 2019; Aronson et al. 2020). The ontological uncertainty when groups of disparate people try to work together on wicked problems, such as ecosystem restoration, needs education policies and programs designed to interconnect fields and disciplines and to involve a wide variety of actors from scientists to politicians and economists (Blignaut & Aronson 2020).

Finally, the information gaps found in action lines, such as achieving "informed consent" and "traditional ecological knowledge" may require further focus in the context of the UNDER. The more a given restorative intervention engages all relevant stakeholders in planning, implementation and monitoring, the higher the likelihood of success and long-term sustainability (Mansourian & Vallauri 2022). This underscores the critical role of TEK in advancing the planning, managing and monitoring of ecological restoration actions (Uprety et al. 2012) and the importance of including and respecting all ways of knowing as well as devolving or else recognizing land rights to Indigenous populations (Herrmann & Torri 2009; Velazquez-Rosas et al. 2018; Singh et al. 2020). Although governance is not explicitly stated in the UNDER strategy, neither as a barrier nor as a pathway for action, publications coded for the barriers of Public awareness, Political will or Legislative

environments all addressed governance issues. In this sense, they provide critical information about governance structures needed to the success of ecosystem restoration actions (Sapkota et al. 2018; Chazdon et al. 2021; Larson et al. 2021).

Imbalances Across Geographies and Ecosystem Types. The geographical imbalance of the reviewed information is not surprising as different world regions respond to particular histories and hence may apply different pathways to implement ecosystem restoration. For example, countries with strong government institutions often experience rapid change due to awareness-raising campaigns (Vigmostad et al. 2005; Cortina-Segarra et al. 2021). Notably, Africa was overrepresented in publications addressing the barrier of Technical capacity, reflecting efforts toward sustainable land use management in the face of weak governments, poverty and depletion of natural resources (Mansourian & Berrahmouni 2021). However, there are still major knowledge gaps across Sub-Saharan countries on the key drivers of environmental and socioeconomic outcomes of farmer-managed natural regeneration (Chomba et al. 2020) and tree planting programs (Boissière et al. 2021).

Another important finding in our assessment was the large number of publications focused on forest ecosystems at the expense of grassland, dryland and mangrove ecosystems, underscoring the need for enhanced focus on restoring these as suggested elsewhere (Buisson et al. 2020; Dudley et al. 2020; Farrar et al. 2020). A recent bibliometric analysis by Guan et al. (2019) on ecosystem restoration also showed that forests are overrepresented, while a review on tropical montane restoration reported that grasslands were disproportionally underrepresented in comparison to forest ecosystems (Christmann & Menor 2021). Although tree planting is perceived as an effective strategy to mitigate atmospheric climate change (Bastin et al. 2019; Busch et al. 2019), native grasslands and mangrove ecosystems are also significant carbon sinks. Mangroves also play a fundamental role in protecting coastal environments from storm surges and sea-level rise (Seddon et al. 2019; Dudley et al. 2020). Notably, only 8% of Nationally Determined Contributions for climate actions encompass the global restoration or protection of natural grasslands (Seddon et al. 2019).

In addition to forests, anthropogenic and generic ecosystems accounted for a significant proportion of reviewed publications which largely addressed the barrier on Public awareness by either highlighting lack of awareness on the need for restoration actions or documenting perceptions about the negative effects of climate change and degradation. Enhancing awareness of the importance of anthropogenic ecosystems for the provision of certain ecosystem services (Agrawal et al. 2014) may help to overcome the awareness barrier as productive ecosystems, in particular, cover the largest percent of the global land surface (Ellis & Ramankutty 2008).

Types of Restorative Interventions and Their Outcomes. Biophysical-type interventions such as direct seeding, invasive species management and natural regeneration outnumbered those referring to prescribed burning and silvopastoral systems in the literature assessed. Further, planting trees in croplands as a forest enrichment strategy and on degraded lands was highlighted as an intervention that balanced biodiversity, carbon sequestration and livelihood gains. However, although tree planting initiatives, spearheaded by corporate offsetting, promote the establishment of billions of trees across rural areas worldwide, researchers warn that planting trees is more complex than it seems and therefore warrants scrutiny (Holl & Brancalion 2020). It should also be noted that natural forest regeneration is usually seen as a cost-effective tool for scaling up forest restoration (Chazdon & Guariguata 2016), yet it is highly context-dependent (Meli et al. 2017).

Reflecting its widespread application as a land use system globally (Nair et al. 2021), agroforests were addressed in over 1,000 publications in our review. Nevertheless, despite being often perceived as win–win solutions for biodiversity recovery, carbon sequestration and livelihood improvement (van Noordwijk et al. 2020; Zinngrebe et al. 2020; Nunez et al. 2021), much is still needed on extension and research programs for upscaling adoption (Rodrigues et al. 2016). Similarly, urban restoration gathered a significant number of publications, denoting the attention given to improving well-being and conservation outcomes in cities, with the realization that more than 50% of the global human population lives in urban areas (Elmqvist et al. 2015; Ko 2018). Social interventions, particularly of policy or financial nature, were prominent in our review yet mainly related to payment for environmental services or REDD+ (reducing emissions from deforestation and forest degradation and enhancement of forest carbon stocks) initiatives. Although low in number, publications mentioning educative interventions such as public-private incentive schemes and education programs, claimed positive outcomes and thus should be considered as a fundamental component for successful ecosystem restoration as emphasized recently by the Science Task Force for the UNDER (2021).

Most restorative interventions assessed in our review showed positive outcomes, except those concerning political, legislative, and financial issues, which were either negative or inconclusive. Publications coded under the Political will pathway for action largely documented negative outcomes related to lack of political will or corruption, elite capture or insufficient consideration of local norms and rules—issues that are pervasive in ecosystem restoration (Boissière et al. 2021; Sayer et al. 2021). This reinforces the need for views that consider bottom-up, people-centered approaches (Elias et al. 2021). In contrast, the pathway for action on Global movement through financial and awareness-raising interventions showed more positive than negative outcomes. Publications under the Technical capacities pathway addressed research on various dimensions of ecosystem restoration and largely yielded inconclusive outcomes, which can also be related to insufficient monitoring from both a technical and social perspective (Hohl et al. 2020; Mansourian & Vallauri 2022) while emphasizing compliance—instead of performance monitoring (Ota et al. 2020).

Evaluating a Framework to Turn the Information Into Evidence

Most evidence fell within the moderate and weak level of strength. We posit that this result largely stems from the application of the evaluation framework, as it places more weight on quantitative than on qualitative information, which in turn is insufficiently appraised in evaluation frameworks aimed at

environmental management (Macura et al. 2019). Rooted in the medical sciences, the importance of developing frameworks for qualitative evidence synthesis is clear (Hannes et al. 2013) yet not traditionally integrated into environmental evidence synthesis (Pullin & Stewart 2007). Therefore, a "strength of evidence" framework that can systematically appraise, synthesize, and integrate information from different knowledge domains, including traditional ecological knowledge, may provide a broader understanding of the complex socioecological nature of environmental challenges that include the science, policy, and practice of ecological restoration (Adams & Sandbrook 2013). That said, standards are being developed to increase the transparency and reliability of qualitative evidence synthesis methods, such as the RAMESES standard for realist synthesis (Wong et al. 2013) and the eMERGe project for meta-ethnographies (France et al. 2019). These novel frameworks could be helpful for future evidence-based work on ecosystem restoration in the context of the UNDER.

Concluding Remarks

We have presented a preliminary overview of how published information addressing the barriers, pathways for action and action lines of the UNDER strategy is distributed across its various dimensions. We highlight critical information gaps and suggest priority areas where information for the UNDER strategy is missing or else incomplete. We found that published information related to either the Political will barrier or pathway for action was seldom addressed. Although this dimension may be indirectly referred to in publications related to legislation and policy barriers, we believe there is a need for further work that explicitly documents the political will aimed at scaling up restorative interventions. Other areas that may need further attention relate to promoting long-term ecosystem restoration actions and monitoring. Furthermore, while the need for scientific research and capacity-building activities in Africa and Asia became clear, our results suggest that legislative and financial barriers should be further considered. There is also a need to intensify the information on restoring grassland, dryland and mangrove ecosystems, not only around the technical know-how but on awareness-raising, legislative and financial aspects.

Finally, our results suggest that improved frameworks for weighting the strength of qualitative evidence are needed to understand better both the socioeconomic impacts and catalysts of ecosystem restoration for enhanced decision-making. Thus we support recent calls to share knowledge and consolidate fine-scale restoration data to improve evidence-based decision-making (Ladouceur et al. 2022). Given the breadth of the information assessed in our review and the framework that weighted qualitative evidence somewhat poorly, the causality between a given social action and the outcomes for ecosystem restoration was challenging to assess. In addition, our review largely missed information and evidence stemming from local experiences and local knowledge (Adams & Sandbrook 2013). Thus, the much-needed bridge between scientific and practitioner knowledge remains insufficient in ecosystem restoration (and conservation; see Kadykalo et al. 2021). We recommend creating an overarching framework that includes quantitative and qualitative information and different knowledge types to guide both programs and project-based activities embraced by the UNDER in the near future.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Pearson residuals from chi-square test evaluating differences across barriers and pathways.
Figure S2. Pearson residuals from chi-square test evaluating differences in barriers and pathways across world regions.
Figure S3. Pearson residuals from chi-square test evaluating differences in barriers and pathways across ecosystem types.
Figure S4. Pearson residuals from chi-square test evaluating differences in restorative interventions across barriers and their outcomes.
Table S1. List of search terms used for primary search data.
Table S2. Examples of the weighing procedure.

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