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Quantifying the Reporting, Coverage and Consistency of Key Indicators in Mangrove Restoration Projects

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Mangroves are often cleared for aquaculture, agriculture, and coastal development despite the range of benefits for people and nature that they provide. In response to these losses, there are multiple global, and regional efforts aimed at accelerating mangrove forest restoration, resulting in many restoration projects being implemented and managed by different groups with highly diverse objectives. The information reported from these restoration projects is extremely variable, limiting our ability to identify whether desired objectives have been met or key factors that determine effective and durable restoration have been applied. To address this problem, we developed a holistic monitoring framework that captures the key indicators of restoration, spanning project aims, intervention type, costs, and ecological and socioeconomic outcomes. Subsequently, using a systematic literature search, we examined 123 published case studies to identify the range and quality of reported information on restoration, relative to our framework. We found that there were many gaps in reporting, for multiple indicators. Sections related to site conditions prior to restoration (reported in only 32% of case studies) and socioeconomic outcomes (26%) were consistently missing from most project reporting. Conversely, information on the type of intervention was reported for all case studies, and the aims of the project (reported in 76% of case studies) and ecological monitoring (82%) were far more prevalent. Generally, the restoration literature did not follow any specific framework in terms of reporting which likely contributed to the gaps in the information recorded. These gaps hinder comparisons between case studies, inhibiting the ability to learn lessons from previous restoration attempts by identifying commonalities. The need for more structure and consistent reporting supports the development of a standard restoration tracking tool that can facilitate the comparison of restoration efforts, aiding the implementation of future projects.

Keywords: mangrove, restoration, framework, taxonomy, evidence-based practice, monitoring

INTRODUCTION

Mangroves support a wide variety of ecosystem processes, functions, and services (Dahdouh-Guebas et al., 2021). These range from local-scale benefits such as timber (Palacios and Cantera, 2017), fishery enhancement (Carrasquilla-Henao and Juanes, 2017), protection against storm events (Marois and Mitsch, 2015), and mangrove-associated tourism (Spalding and Parrett, 2019), to global-scale benefits such as carbon sequestration (Donato et al., 2011; Richards et al., 2020). Mangrove forests also support a wide variety of marine and terrestrial species, including plant species and marine megafauna of conservation concern (Polidoro et al., 2010; Sievers et al., 2019). Despite these benefits, between 1980 and 2005 an estimated 20% of global mangrove forests were lost (FAO, 2007). Mangrove forest loss has largely been attributed to conversion to aquaculture and agriculture (Richards and Friess, 2016; Thomas et al., 2017; Goldberg et al., 2020) and chronic overexploitation (Ilman et al., 2016). To combat these losses, there have been many recent efforts to restore mangrove forests (Lee et al., 2019); however, many of these have failed to establish natural functioning mangrove ecosystems (Barnuevo et al., 2017).

Mangrove restoration involves a range of interventions from restoring hydrological connectivity and increasing sediment capture, to natural regeneration, but the dominant strategy globally has been mangrove planting, often of a single species from a limited number of families (Kairo et al., 2001; López-Portillo et al., 2017; Lee et al., 2019). This approach has become widespread because of its relatively low costs and reporting indicators focused on number of seedlings planted (Bayraktarov et al., 2016). However, post-planting survival is typically low (Saenger and Siddiqi, 1993; Primavera and Esteban, 2008; Samson and Rollon, 2008), often due to the planting of incorrect species in locations that are unsuitable in terms of hydrology and salinity for mangrove forests to establish (Elster, 2000; Kodikara et al., 2017; Wodehouse and Rayment, 2019). Failures in mangrove restoration are also compounded by challenges associated with the socio-economic and political landscape of the area being restored (Gallup et al., 2020), with the inability of many restoration projects to adequately address governance issues often cited. Successful management of mangrove areas, which are complex socio-economic systems, requires a clear understanding of the needs of different stakeholders and the inclusion of local people in the decision making process (Hugé et al., 2016; Frank et al., 2017; Vande Velde et al., 2019; Martínez-Espinosa et al., 2020). However, practitioners are frequently working to short delivery timeframes from funding agencies, resulting in interventions occurring on land where land tenure is less contested, for example mudflats and seagrass meadows. These areas are usually unsuitable in terms of the physiological tolerances of the planted species (Lovelock and Brown, 2019) and can cause damage to these other coastal ecosystems. Despite these failures, there are also many examples of successful mangrove restoration projects (Saunders et al., 2020). For example, approaches have been implemented that involve local community participation and include a focus on non-planting restoration activities (Brown et al., 2014; Zaldívar-Jiménez et al., 2017). While planting is often cited as having low long term survival in some instances through altering local hydrodynamics and physicochemical conditions, mangrove planting may facilitate natural regeneration of other mangrove species (Bosire et al., 2003), encourage faunal recolonization (Bosire et al., 2004, 2008; Walton et al., 2006; Canales-Delgadillo et al., 2019), and provide the basis for the development toward a naturally functioning mangrove forest (Bosire et al., 2006, 2008; Tamooh et al., 2008).

The increase in mangrove restoration effort is underpinned by a number of global initiatives, such as the UN Decade of Restoration (Waltham et al., 2020), the Bonn Challenge,[1] country-level climate commitments (such as Nationally Determined Contributions as part of the Paris Agreement), and global conservation partnerships, such as the Global Mangrove Alliance.[2] Further encouragement for restoration is being given by both growing social and economic arguments for the benefits of mangrove restoration, and new work to help identify optional locations for restoration (Worthington and Spalding, 2018). Despite the large economic investments this will entail, it is still unclear whether global restoration targets can, or will, be met. Information on mangrove restoration efforts is disparate, with project outcomes often reported in gray literature (if documented at all), and project failures often underreported. Even where information is available, outcome indicators are inconsistent between projects, limiting our ability to learn from these projects to improve future restoration.

This study aims to improve our understanding of the problem of highly variable approaches and inconsistent outcomes from mangrove restoration efforts, and of a failure to disseminate and share lessons. While there have been a number of reviews looking at certain aspects of mangrove restoration project implementation such as costs (Bayraktarov et al., 2016), motivations and outcomes (Bayraktarov et al., 2020; Cadier et al., 2020; Su et al., 2021), here we develop a framework of key metrics and indicators that would enable a holistic description of any restoration attempt. The framework identifies the full range of factors that should be considered when planning, implementing and monitoring a mangrove restoration project and we apply this framework to peer-reviewed mangrove restoration literature to determine current reporting coverage. By identifying what is, and is not, being recorded, we can quantify knowledge gaps and highlight opportunities and benefits of more comprehensive and consistent reporting of indicators and outcomes.

METHODOLOGY

To determine the detail and consistency of reporting on mangrove restoration projects, their approaches, and outcomes, a review of the primary literature was undertaken. The work consisted of two broad approaches: the development of an idealized Candidate Indicator Set (CIS) of metrics and indicators that would be required to comprehensively report on a mangrove

[1] https://www.bonnchallenge.org/

[2] https://www.mangrovealliance.org

restoration project; and a comprehensive review of the primary literature describing restoration efforts world-wide.

Candidate Indicator Set

The CIS was developed to capture the key aspects of mangrove restoration projects. The initial structure of the CIS was based on a previous preliminary synthesis of mangrove restoration projects (Worthington and Spalding, 2018) and was further developed after reviewing key mangrove restoration literature and discussions amongst the authors. The framework was divided into 10 sections, with each section addressing a different aspect of a mangrove restoration project. Within each section there were several indicators for which data could be recorded. Where possible, the potential responses to an indicator were in the form of predefined categories, although freeform answers were allowed if the information did not fit with one of our pre-determined groupings (see **Supplementary Material 1**). For example, the type of project could be "Restoration," "Rehabilitation," "Protection," "Bioremediation" or a freeform "Other." The CIS attempts to capture all the salient information that would be required to comprehensively describe and monitor a mangrove restoration project (**Table 1**).

Searches

To assess coverage of the CIS we conducted a literature review of scientific articles that described mangrove restoration and/or rehabilitation case studies. The identification of relevant mangrove restoration case studies (**Figure 1**) followed the Reporting standards for Systematic Evidence Syntheses methodology (Haddaway et al., 2018). The searches were limited to abstracts, titles, author keywords and keywords plus in Web of Science (WoS) (coverage 1970—to date),[3] and abstract, titles, and keywords in Scopus (coverage 1788—to date).[4] The searches were limited to English language studies. To identify the literature the following search string was used: (mangrove OR mangal) and (restor* OR afforest OR rehab* or planting). Searches were run on 4th February 2020. It should be noted that our search string will not capture all mangrove restoration

[3] www.webofknowledge.com

[4] www.scopus.com

TABLE 1 | Overview of the mangrove restoration assessment framework.

Section	Description	Example information recorded
Project details	Background information on the restoration project including the type of project (e.g., restoration, afforestation, rehabilitation, bioremediation, or protection), its location and the land tenure and management status of the site.	Project title Type of project Site location Duration of project Management status Land tenure
Project cost	Whether the project had funding and its sources. The costs of the project are captured following Spurgeon (1999) and Iacona et al. (2018), where possible splitting the expenditure between capital, construction, and operational costs. The organizations participating and managing the project were also recorded.	Project funding Project initiated by Project lead Partner organizations Capital costs Operational costs Other costs
Project aims	The aim(s) of the restoration project.	Project aims
Causes of decline	The causes of the decline in the site's mangroves based on the IUCN Threats Classification Scheme (IUCN, 2021).	Causes of decline Consequences of decline
Site conditions	The pre-intervention activities and the underlying site conditions.	Site assessment Pilot study Expert consultation
Physical interventions	Type of restoration intervention applied, details on species and source of materials for planting projects.	Size of project area Methods used Species planted
Community	Awareness programs and community leadership or engagement. Post-restoration management and land tenure.	Awareness/involvement activities and training programs Volunteer/community participation Management of area Regulatory/protection Regime in place
Monitoring	Description of the post-intervention ecological monitoring including its duration and the organization involved.	Duration of monitoring Monitoring conducted by
Ecological outcomes	Metrics of ecological success, including the presence of natural recruitment and seedling survival.	Percentage seedling Survival Natural recruitment Goals of restoration met
Socioeconomic outcomes	Metrics of socioeconomic success assessed using the framework developed by McKinnon et al. (2016).	Socioeconomic outcomes

*See **Supplementary Material 1** for full framework.*

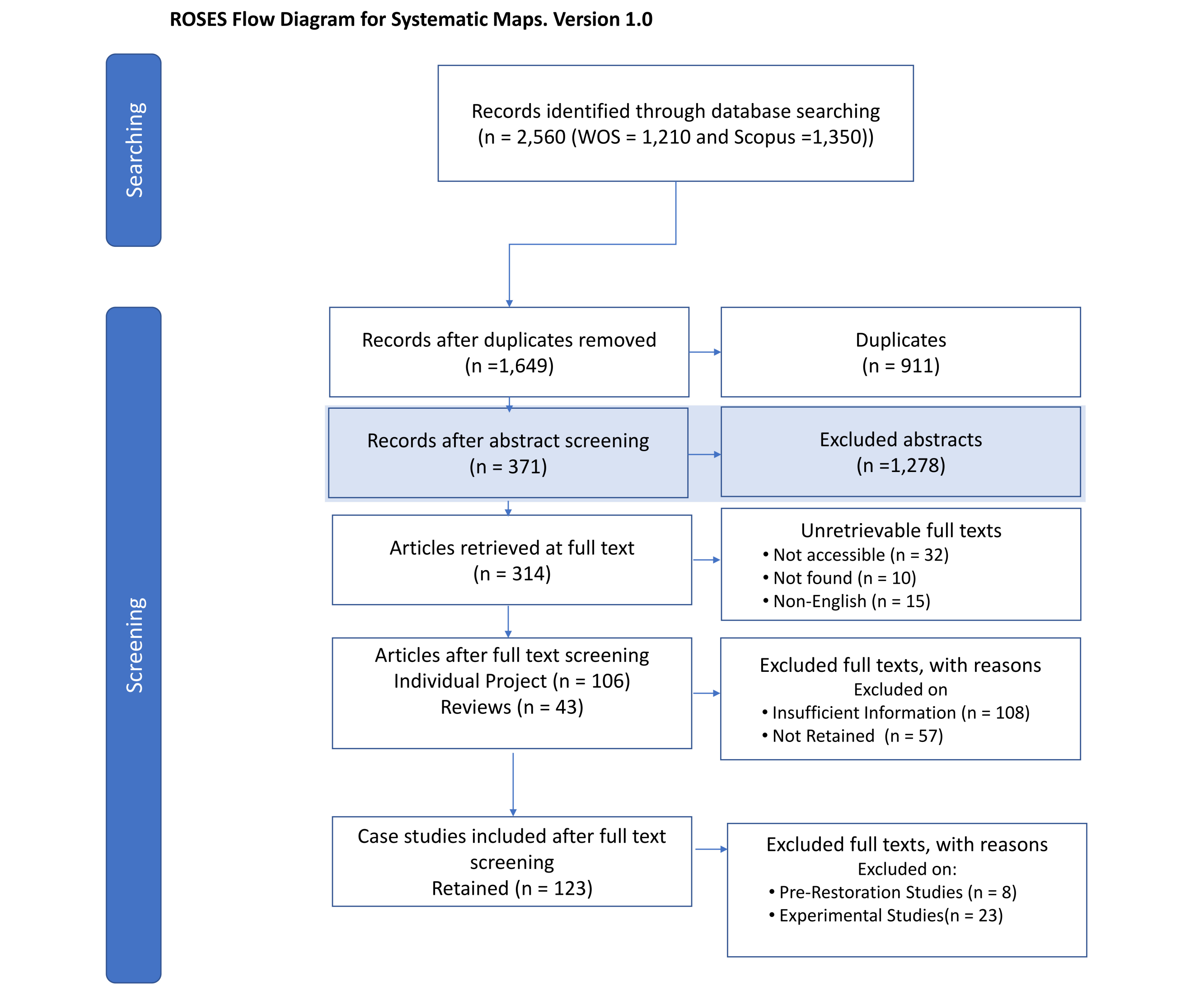

FIGURE 1 | ROSES flow diagram of the literature breakdown through screening.

case studies as such projects have been described using a variety of other terms including "replanting," "reafforestation" or "plantation" (López-Portillo et al., 2017). However, we believe our systematic approach results in a dataset indicative of the prevailing trends in restoration project reporting.

Screening

In total 2,560 articles (WoS = 1,210 and Scopus = 1,350) (**Figure 1**) were identified by the search string. Duplicates between the two databases were manually removed, resulting in 1,649 articles. A benchmark test was conducted to quantify how well our search string captured the published literature on mangrove restoration projects. The database of mangrove restoration project literature used in the benchmark test was obtained from a previous coastal restoration synthesis (Bayraktarov et al., 2016). Out of the 54 mangrove publications cited in Bayraktarov et al. (2016), 26 were journal articles that should have been captured by our search of WoS and Scopus (the remaining entries were webpages, book chapters, and reports that are less likely to be within the WoS and Scopus databases). Of these 26 journal articles, our search found 22, with the four missing articles comprising two articles from journals not indexed in WoS or Scopus, one from a newsletter not indexed in WoS or Scopus, and one article that, while indexed, did not include any of our search string terms in the abstract or title.

Given that the benchmark test suggested our search gave good coverage of the literature, we screened the 1,649 search results for restoration projects, using both titles, and abstracts for initial inclusion/exclusion decisions. We developed an inclusion/exclusion criterion for reviewing titles and abstracts following the SPIDER (Sample, Phenomenon of Interest, Design, Evaluation, Research type) protocol to ensure consistency in decisions (Cooke et al., 2012). To test the accuracy and repeatability of our inclusion procedure a kappa test was undertaken, 10% of the abstracts were chosen randomly and labeled by two reviewers (YMG; TAW) as either being a restoration project or not. The kappa statistic for this 10% of abstracts was 0.26 suggesting only a "fair" level of agreement between the two reviewers (Landis and Koch, 1977). Therefore, the inclusion criteria were revisited, with the aim of being more inclusive when determining whether to retain a study for the database based on the title and abstract (**Table 2**). As such, in the revised criteria a paper was retained if the abstract or title only briefly mentioned a restoration project, the restoration case study itself did not have to be the focus of the abstract. A second random 10% sample of the articles was chosen and assessed by the same two reviewers. The more inclusive criteria resulted in a "substantial agreement" (kappa statistic = 0.77) (Landis and Koch, 1977).

After obtaining a high kappa value the remaining 80% of the abstracts were screened by a single reviewer (YMG) using the new inclusion criteria. In total, 371 abstracts were found that potentially contained restoration projects (**Figure 1**). Full texts were sought for the 371 articles; however, 10 were not found, 32 were not accessible and 15 were not in English. The full texts of the remaining 314 journal articles were reviewed to determine whether they contained information on a single or multiple mangrove restoration project(s) (relevant information, $n = 257$), or not (no relevant information, $n = 57$). These 257 papers were then placed into one of three categories based on the amount of information on restoration projects they contained: "individual project," "review," or "insufficient information." For a paper to be labeled as an "individual project" ($n = 106$), it required at least three of the following key pieces of information: the project location, the duration of the physical restoration activities (project duration), the restoration method used, the duration of post-restoration monitoring and results that encompassed any form of monitoring data that was recorded post restoration (**Table 3**). We chose these key pieces of information as indicators as to whether to retain a study as we assumed them to be the most regularly recorded types of information for mangrove restoration projects. By targeting papers that had a minimum amount information, we aimed to ensure that sufficient data could be extracted from the paper to contribute to the review. Reviews ($n = 43$) were individual articles that contained data from multiple projects meeting the individual project criteria. Many papers reviewed at the full text stage cited a restoration project had been undertaken but contained little information except its approximate location, these were labeled as insufficient information papers ($n = 108$). Given that the focus of these papers was generally not to describe in detail a restoration project but rather provide it as an example of restoration in the context of a scientific piece of research, we deemed that they would not contribute sufficient data to the review, and they were therefore not retained. Papers marked as an "individual project," or a "review" were retained ($n = 149$). A random 10% of the full text papers were chosen and labeled by two reviewers (YMG; TAW) as either not relevant or relevant with the kappa statistic between the two reviewers 0.83 considered as "substantial" in terms of strength of agreement (Landis and Koch, 1977). The same 10% of papers were also labeled by the two reviewers as: individual projects, reviews and insufficient information. The kappa statistic was 0.71, subsequently the remaining 90% of papers were screened by one reviewer.

A final assessment of the 149 "individual project" and "review" papers was undertaken to identify case studies for which data could be extracted. Case studies are defined as a unique individual restoration project that have data available sourced from both the "individual project" and "review" papers. At this stage, the 106 "individual project" papers were further subdivided into three groups: "pre-restoration studies", "experimental studies" and "case studies". Pre-restoration studies ($n = 8$) outlined initial intervention assessments but did not contain information on an actual restoration effort. Experimental studies ($n = 23$) were methodological papers on specific aspects of mangrove restoration (e.g., statistical comparisons on different planting approaches) but lacked wider framing of mangrove restoration as a conservation intervention (e.g., absence of non-research project aims, socio-economic setting or outcomes of the restoration effort). Once the "pre-restoration studies" and "experimental studies" were removed, this resulted in 75 "case studies" for data extraction.

The "review" papers were then assessed to identify additional "case studies." As the review journal articles contained multiple projects, each project was identified and any in-text references describing the project were collated. If, for a project, the information in the review and the associated references contained at least three key pieces of information (see above) it was retained for data extraction. As "review" papers often contained information on the same restoration projects, only 48 "case studies" were identified from the 43 papers. The final dataset comprised 123 restoration case studies (see **Supplementary Material 2**).

TABLE 2 | Spider protocol applied for abstract inclusion/exclusion (Cooke et al., 2012).

S	PI	D	E	R
Sample	**Phenomenon of interest**	**Design**	**Evaluation**	**Research type**
1,649 Journal abstracts and titles	Mangrove restoration field studies	Abstracts reviewed and retained or rejected	Abstracts retained at any mention of a restoration case study	Mixed

Recording the Data

The CIS framework was then used to extract data from the 123 case studies. An initial consistency assessment was carried out using five randomly selected case studies, which were reviewed by two reviewers (YMG; TAW). The results from the two reviewers were compared, with similar responses for the majority of categories. Where there were disparities in what was recorded between the reviewers, this was discussed and the remaining 118 case studies were screened by a single reviewer. The case study papers occasionally had in-text references to papers that held more information about the restoration case study under

TABLE 3 | SPIDER protocol applied for inclusion/exclusion based on article full text (Cooke et al., 2012).

S	PI	D	E	R
Sample	**Phenomenon of interest**	**Design**	**Evaluation**	**Research type**
314 Journal articles	Mangrove restoration projects	Papers defined as: (1) Relevant or not relevant (2) Retained or not retained	Papers categorzed as: (1a) Not relevant—no information on a mangrove restoration project (1b) Relevant—information on a mangrove restoration project (2a) Retained—when an article contained three or more key pieces of information for an "individual project" or "review" (2b) Not retained—contained fewer than three of the key pieces of information labeled as "insufficient information"	Mixed

consideration. In these cases, we searched for the referenced papers and, if found, relevant information was also extracted from this source. The final 123 case studies are not an exhaustive list of mangrove restoration projects referred to in the published literature. For instance we did not capture all the projects identified in Bayraktarov et al. (2016) and López-Portillo et al. (2017). This is due to several factors (1) our search string did not capture all the terms that have been used to describe mangrove restoration (see above) (2) our searches were confined to English language studies biasing against regions where English is less widely used (3) we only included studies from the published literature which is unlikely to be the medium of publication for many organizations and (4) our inclusion criteria removed studies that only provided a very limited description of a restoration project. However, our approach to surveying the literature was systematic and we believe the results are indicative of the overall trends in reporting, coverage, and consistency of key indicators in mangrove restoration projects.

RESULTS AND DISCUSSION

Articles with case study information were published between 1990 and 2019, with restoration interventions commencing between 1957 and 2015. No case studies contained information for all the 10 CIS sections. Pre-restoration activities and socioeconomic outcomes were particularly data deficient with only 15% of case studies covering both of these categories (**Figure 2**). Conversely, information on the intervention itself and the cause of mangrove decline were recorded for 68% of case studies (**Figure 2**). Whilst our analysis suggests that 80% of the case studies had information on costs, it should be noted that these papers mainly referred to the funding source rather than providing a breakdown of the costs of the restoration itself.

Project Details

Restoration case studies were recorded in 24 countries with over three quarters carried out in Asia (**Figure 3**). This is unsurprising given that this region contains a large proportion of the global mangrove extent and has exhibited the greatest recent losses in mangrove area (Hamilton and Casey, 2016). However, this number is skewed by 23 case studies being recorded in Sri Lanka in a single review (Kodikara et al., 2017).

Only 12% of the case studies were recorded from Africa, the Middle East, the Caribbean or Central America, mirroring the broad scale patterns identified in a synthesis of marine and coastal restoration research (Bayraktarov et al., 2020). West and Central Africa only had 2% of the recorded case studies, despite the region supporting 14.5% of the global mangrove area. This could indicate that either few restoration attempts have been undertaken, that restoration has been undertaken but has not been recorded in the primary literature, or that limiting our search to English articles and removing non-English full-texts resulted in bias against regions where English is less

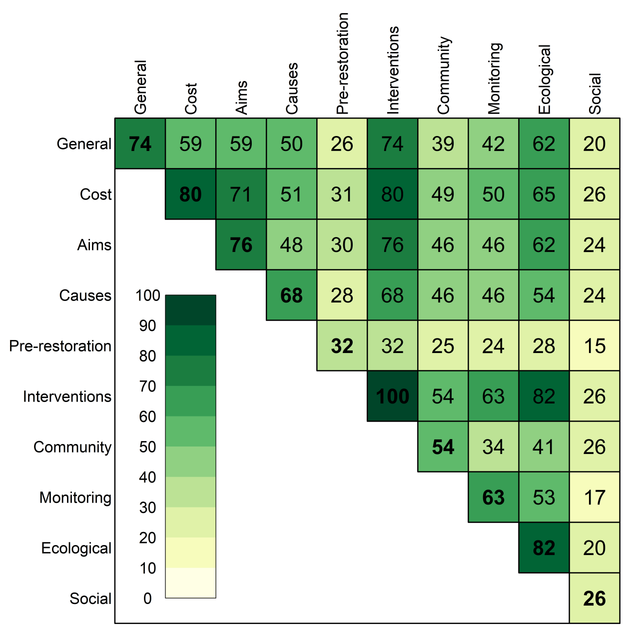

FIGURE 2 | Frequency of reporting across the different sections of our Candidate Indicator Set (CIS). A case study is considered to report on a section of the CIS if it contains any information addressing one or more indicators within the respective section, with the exception of the general section where only information for the indicators start and end dates, management status, and land tenure were used. The diagonal boxes (bold numbers) identify the percentage of case studies that record information for each single section of the CIS. The off-diagonal boxes represent the percentage of case studies that record information for the two interacting sections of the CIS.

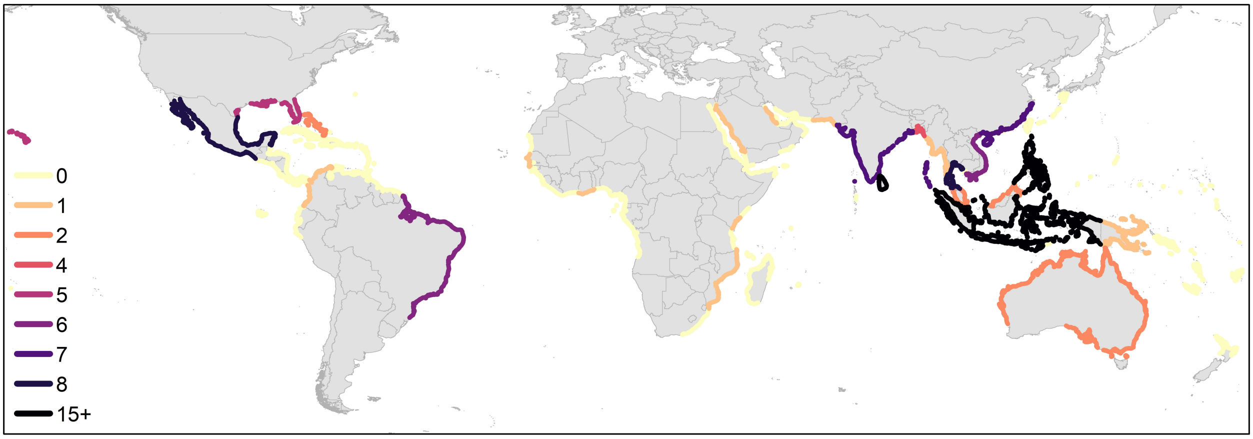

FIGURE 3 | Global map showing the location of countries that have mangroves and the number of restoration case studies recorded from each country.

widely used. Individuals in certain countries encounter barriers such as wealth, language biases, and security and geographical location challenges that reduce opportunities to collect or publish scientific data (Amano and Sutherland, 2013). These barriers are underscored by the observation that in terrestrial ecology and conservation studies Africa is highly underrepresented (Martin et al., 2012; Christie et al., 2020, 2021).

For the remaining project details' questions, very little information was available from our case studies. Management status, which recorded whether the site was protected as defined by the International Union for Conservation of Nature or Other Effective Area-Based Conservation Measure categories (Dudley, 2013; IUCN-WCPA Task Force on OECMs, 2019), was only recorded for 13% of case studies, with these few locations distributed across a range of management status designations. In addition, only 11% of case studies provide details on land tenure. Of the 13 studies that did record land tenure, six stated that the restoration sites were on land owned by the national government, with three each on communal and private lands. Given that the failure to understand and address potential challenges associated with land tenure has been highlighted as a key driver of restoration failure, because it influences the choice of restoration site and the continued resource use of an area (Mukherjee et al., 2015; Asante et al., 2017; Lovelock and Brown, 2019), this shortfall in reporting is a particular concern.

Project Costs

From the 123 case studies, 47 recorded their source of funding, 73 did not record if the project was funded, while just three cases stated that they were not funded. Over a third of case studies reporting a funding source had more than one (two funding sources $n = 11$, three $n = 5$ and six $n = 1$). For those case studies that explicitly stated the source of funding, there was an approximate 50:50 split between domestic and foreign funding sources. The most commonly cited source of funding was from the government or its agencies in the country where the restoration took place ($n = 22$), with foreign and international development banks ($n = 11$) and foreign governments and development agencies ($n = 9$; **Figure 4A**) also identified regularly. This is in line with a previous synthesis of marine and coastal restoration which highlighted government funding as the predominate source of mangrove, and other coastal ecosystem, funding (Bayraktarov et al., 2016).

While the source of funding was recorded for almost 40% of the 123 case studies, the total monetary value of that funding was only recorded in 14. Further, only eight case studies documented a breakdown of the costs enabling finer details of the expenditure, with the cost recorded varying hugely between case studies. The lack of reporting on project costs is an issue across conservation (Cook et al., 2017) and has stimulated a number of attempts to unify cost reporting frameworks (Iacona et al., 2018), such as those used here. This issue has been highlighted for mangrove restoration previously, with only 11% of the papers from a synthesis of marine restoration projects reporting project costs and a breakdown of expenditure (Bayraktarov et al., 2016). Due to this ongoing poor cost reporting, the ability to compare studies and evaluate the factors that modify costs and benefits is seriously hindered (Cook et al., 2017).

Project Aims

Across the 123 case studies, the majority (76%) stated at least one aim for the restoration, with many case studies having more than one (two aims, $n = 17$; three aims, $n = 6$ and four aims = 1). The most frequently recorded aims were related to coastal defense ($n = 33$), and biodiversity enhancement ($n = 31$, **Figure 4B**), which included a variety of different goals associated with increasing the area or functioning of the mangrove forests themselves. The prevalence of case studies whose aim was coastal defense was driven by the review of Kodikara et al. (2017) who examined mangrove planting following the 2004 Indian Ocean Tsunami. In addition, employment and income generation ($n = 9$), and enhancing shoreline stability and climate change resilience ($n = 12$) were frequently cited. It is notable that the stated aims across case studies were diverse, likely driven by the multitude of ecosystem services that mangroves provide (Brander et al., 2012).

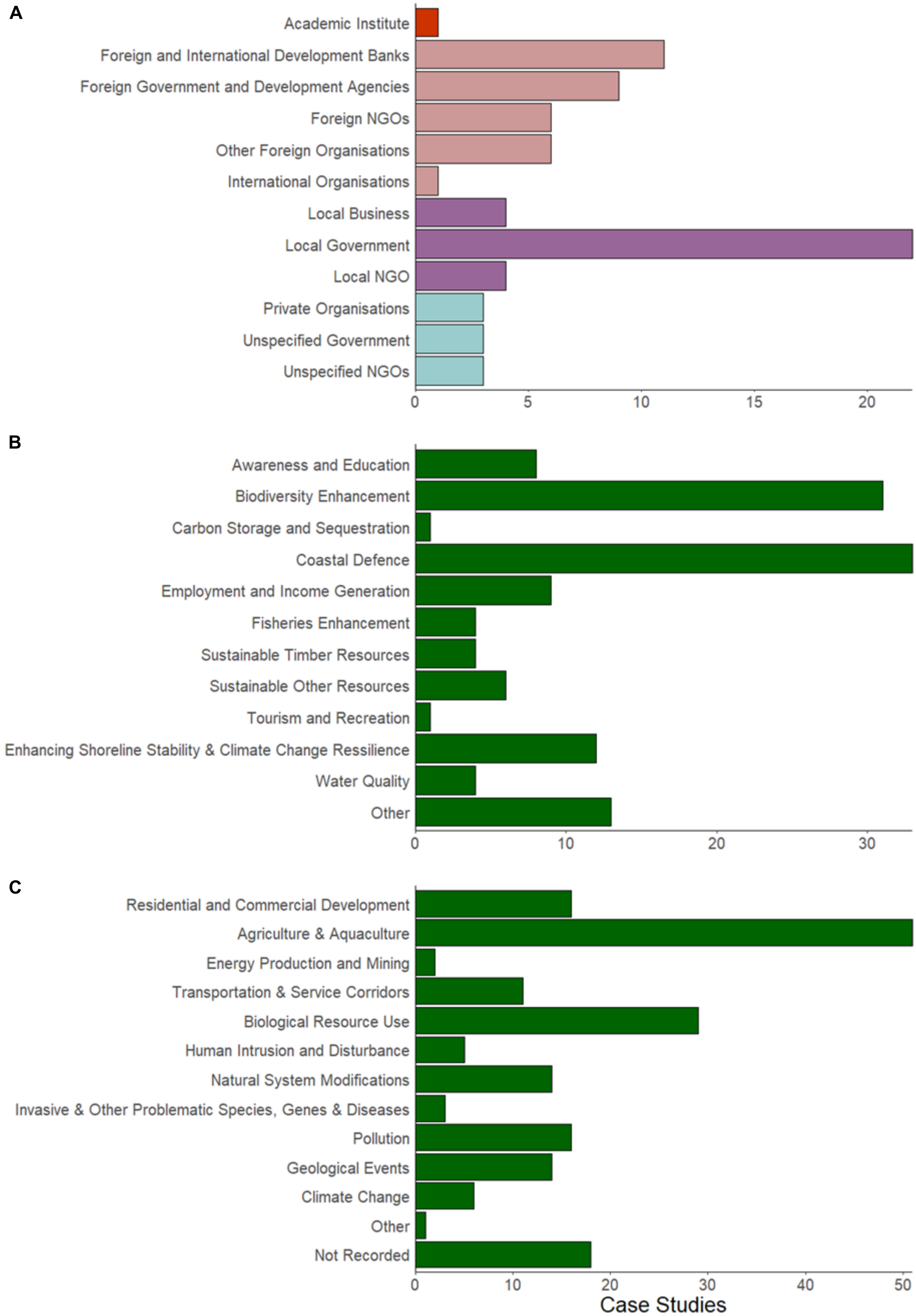

FIGURE 4 | (A) Source of funding recorded from the restoration case studies. The orange bar indicates funding from academic institutes, pink bars indicate funding from a foreign entity, purple bars indicate funding from local entities, light green bars indicate funding from unnamed governments NGOs and organizations. A case study could report multiple sources of funding. **(B)** Different project aims recorded in the restoration case studies. If a restoration project had more than one aim, all were recorded. **(C)** Causes of decline recorded in the restoration case studies. A case study could record multiple causes of decline.

Cause of Decline

The cause of the decline was recorded for the majority (67%) of the 123 case studies, with anthropogenic impacts rather than natural factors (e.g., erosion) predominantly identified. Over half of the 82 case studies that stated the cause of decline identified more than one (two causes of decline, n = 18, three, n = 20, four, n = 4 or five, n = 4), suggesting that mangroves are often subject to multifaceted human impacts. Within the IUCN Threats Classification Scheme (IUCN, 2021) the Level 1 categories "agriculture and aquaculture" and "biological resource use" (**Figure 4C**) were most frequently identified. Within "agriculture and aquaculture," aquaculture was the most regularly cited cause of mangrove decline and loss (Level 2 categories: aquaculture n = 40; agricultural expansion n = 11). After aquaculture, the second most common Level 2 cause of decline was wood harvesting (n = 27).

These results reflect the fact that the major driver of mangrove losses at a global scale is conversion to aquaculture and agriculture (Goldberg et al., 2020). The role of aquaculture has been particularly apparent in Southeast Asia (Richards and Friess, 2016; Thomas et al., 2017), where there was an industrial shrimp aquaculture boom in the 1980s and 1990s (Hall, 2003). Regarding wood harvesting, mangrove wood can provide important fuel and timber resource and as such chronic overharvesting has been identified as an issue in some areas (Iftekhar and Islam, 2004). Our results also identified 32 cases studies that identified urbanization or development (under the Level 1 categories "residential and commercial development," "transportation and service corridors" and "human intrusion and disturbance") as a major source of decline—in line with the findings of Dale et al. (2014).

Site Conditions Prior to Restoration

Twenty percent of the 123 case studies stated that some form of pre-intervention monitoring was carried out, with a further five specifying it hadn't been undertaken; however, for the majority (n = 93) this information was not recorded. Of the pre-restoration data available the most commonly recorded metrics were those related to the species present (n = 9 case studies), the geomorphic typology of the restoration area (n = 8) and the water or soil salinity (n = 7). In addition, six case studies specifically stated that they conducted a pilot restoration study. It is unknown whether these data are being collected for a greater proportion of restoration efforts and this information is just not presented in the published literature. However, this lack of information provides challenges for future restoration efforts as (1) the absence of details of initial conditions means before-and-after comparisons assessing intervention effectiveness are not possible and (2) knowledge of the pre-restoration biophysical setting may aid practitioners in identifying the most appropriate intervention.

Physical Interventions

The intervention method was stated in all except one of the case studies, with the most commonly used intervention being mangrove planting (n = 108), followed by hydrological restoration (n = 27; **Figure 5**). Approaches aimed at restoring hydraulic conditions (for example interventions such as fences to trap sediment and reduce erosion, n = 7) or altering site topography (such as restabilising the original site elevation, n = 4) were much less frequently recorded. There were also relatively few case studies that combined multiple restoration approaches, with only a combination of planting and hydrological restoration (n = 14) recorded in more than five case studies (**Figure 5A**). Hydrological restoration is more expensive than planting (Lewis, 2005) due to the need for heavy machinery and different countries have vastly different funding potentials (Bayraktarov et al., 2016). In addition, costs vary with location. For example, the median costs of mangrove restoration in the United States were recorded at US$100,861 ha^{-1} y^{-1}, compared to US$989 ha^{-1} y^{-1} for southeast Asian countries (Taillardat et al., 2020). Given that the majority of the case studies we reviewed occurred in Southeast Asia this may partly explain the high number of planting-based restoration methods observed. The timing of when the different intervention types were applied showed some variation. Within our case studies, pre-1990 only planting based restoration projects were recorded (**Figure 5B**). However, toward the end of the twentieth century there was a growing recognition that large-scale planting efforts had had very limited success in terms of establishing viable mangrove forests (Primavera and Esteban, 2008). There was an emphasis within the scientific literature that mangrove restoration should be centered on restoring an area's ecological functions, such as re-establishing hydrological connectivity (Ellison, 2000; Lewis, 2005). Within our data, post-1990, planting based interventions continue at the same rate; however, case studies that incorporate particularly hydrologic and to a lesser extent hydraulic restoration started to be recorded (**Figure 5B**).

Of the 108 case studies where mangrove planting was the focus, there was almost an even split between those that used propagules (n = 23) compared to tree seedlings (n = 26). For 23 case studies the stage of planting material was not differentiated between propagules and seedlings and for the remaining 36 case studies that planted material was not reported. The most frequently planted species were those from the genera *Rhizophora*, *Avicennia* and *Bruguiera*, with *Rhizophora mucronata* Poir., *Avicennia marina* (Forssk.) Vierh. and *Rhizophora apiculata* Blume recorded in 17, 16, and 14 case studies, respectively. Ideally, the species planted should be driven by the location of the restoration site within the tidal frame and exposure and the aims of the project. For example, colonizing species such as *A. marina, A. alba* Blume and *Sonneratia alba* Sm. in the Indo West Pacific or *R. mangle* L. in the Atlantic East Pacific region may be used where restoration of fringing mangrove is aimed at providing storm protection (Primavera et al., 2011). While preferences on the species used were apparent and are supported by the published literature (see below), the variation between genera is also a function of their abundance. For instance, the families Caesalpinaceae, and Bignoniaceae, and the genus *Pelliciera* were not recorded in our case studies, which is likely a combination of their relatively restricted distribution in Central and South America (Spalding et al., 2010) and the few case studies identified from that region (**Figure 3**).

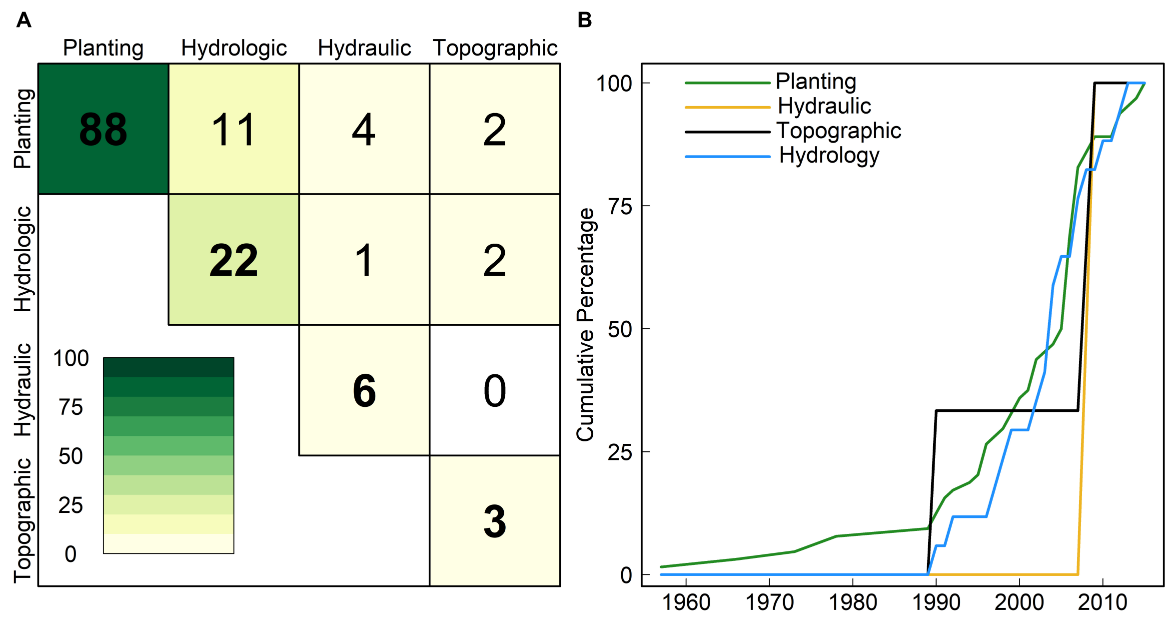

FIGURE 5 | (A) Frequency of different restoration methods used in the case studies. The diagonal boxes (bold numbers) identify the percentage of the different restorative methods used overall. The off-diagonal boxes represent the percentage of case studies that record information for the two interacting restorative methods. **(B)** The cumulative percentage of cases studies within each of the four intervention types vs. the start year of the intervention.

Mangrove planting efforts have been plagued by poor site/species matching, with species planted outside their physiological tolerances (Wodehouse and Rayment, 2019). Mangrove planting has generally been limited to the use of a restricted group of species, often from the genus *Rhizophora* (Friess et al., 2019). These species are preferred as they produce large propagules that are both easy to collect and are easily planted, and they exhibit fast growth (Samson and Rollon, 2008; Lee et al., 2019). *Rhizophora* species are also the most viable species for charcoal and firewood (Bandaranayake, 1998) so the establishment of a production forest may be seen as a co-benefit. It should be noted that the native species pool available to a restoration project varies hugely with location, with mangrove species richness highest (>25 native species) in the Indo-Malay Philippine Archipelago contrasting with communities limited to a single native species (Polidoro et al., 2010).

As well as relying on a small number of species, the majority of the mangrove replanting projects only use one or two mangrove species per site (Alongi, 2002; Wodehouse and Rayment, 2019). Out of the 108 case studies where planting occurred, 42 reported using a single species or species from a single genus, with a further 12 using two species or genera in the restoration. The remaining 48 case studies recorded between three and seven mangrove species or genera being planted. The use of monospecific planting has been questioned as it has been hypothesized that multispecies communities result in niche complementarity, and are needed to fully provide ecosystem services and functions (Kirui et al., 2008; Su et al., 2021). For example, it has been suggested that monospecific plantations of *Rhizophora* were more impacted following Typhoon Haiyan in the Philippines than other taxa (e.g., *Sonneratia*, *Avicennia*, and *Aegiceras*) as defoliated and damaged trees with broken stems were unable to regenerate new shoots resulting in high mortalities compared to the other taxa which had the potential to resprout epicormic buds (Villamayor et al., 2016). Monospecific restoration also often results in lower diversity of macrofauna and reduced habitat heterogeneity (Macintosh et al., 2002); however, outcomes of monospecific vs. mixed species restoration varies across species and ecosystem functions (Su et al., 2021).

Community Involvement

Out of the 123 case studies, 51 stated that local communities were involved during the restoration process. A large proportion of mangroves are found near rural communities (Aye et al., 2019) and mangroves support local livelihoods, through the provision of timber, fuelwood and food (Himes-Cornell et al., 2018). As such, community involvement in mangrove restoration is seen as a key determinant of restoration success—resulting in the development of concepts such as community-based mangrove management (CBMM). The CBMM approach has mainly been applied in countries where there was a wide scale adoption of decentralized governance policies, allowing local communities to take the initiative (Datta et al., 2012). Community led mangrove restoration projects generally have lower costs (Primavera and Esteban, 2008; Bayraktarov et al., 2016), with communities making decisions and conducting key tasks such as post intervention monitoring and governance (Brown et al., 2014; Mukherjee et al., 2015; Wylie et al., 2016).

Monitoring

Nearly two-thirds (n = 72) of the 123 case studies reported that some form of monitoring took place; however, only 19 case studies recorded the duration of that monitoring. The median length of post-restoration monitoring was 16 months, with the longest period recorded 9 years and 7 months, in line with the findings of Cadier et al. (2020).

The relatively short duration reported in the literature highlights a potential problem in that the time taken for an area to fully re-establish is often considerably longer than the monitoring timeframe. For example, in southwest Florida, 18 years after restoration, it was observed that the mangroves had similar measures to natural forests for certain factors such as species richness and vegetation cover, but were not yet comparable in terms of tree size and stem density (Proffitt and Devlin, 2005). Similarly, certain aspects of biodiversity and ecosystem function can take time to approach natural levels (Bosire et al., 2008). For example, 5–8 years after planting, sediment-infauna density and litter degradation in the mangroves of Gazi Bay, Kenya had not reached that of reference sites (Bosire et al., 2004, 2005).

The challenge of supporting longer-term monitoring was highlighted in a study from three states in India. Only 24% of the projects carried out monitoring of the restored area for 3 or more years (Mukherjee et al., 2015). Further, the majority of the projects that were carried out by foreign NGOs often did not include a monitoring section in the project design, resulting in the local communities banding together to monitor the area (Mukherjee et al., 2015). This issue is underpinned by the cost of long-term monitoring, with annual monitoring costs of 20% of the initial restoration budget observed in the Philippines (Primavera et al., 2012) and Vietnam (Tuan and Tinh, 2013). If accurate information on the location of the restoration site is available, there is the potential to remotely monitor mangrove extent change at regular intervals and lower cost using satellite imagery (Alexandris et al., 2013). However, there are challenges in detecting change in very small restoration areas without very high-resolution imagery.

Ecological Project Outcomes

Measures of vegetation structure are often recorded following restoration, as they are easy and rapid to quantify and there is assumption that vegetation recovers at a faster rate than an area's fauna or ecological functions (Ruiz-Jaen and Aide, 2005). In a review of indicators for coastal wetland restoration success, Cadier et al. (2020) identified metrics related to structural diversity as being the most frequently recorded, which for mangroves most commonly related to measures of mangrove density, height, diameter at breast height and basal area. However, even these simple structural metrics were infrequently recorded in our case studies. Less than 30% ($n = 36$) of the 123 case studies identified that natural recruitment had occurred at the restoration site, and despite the preponderance of mangrove planting ($n = 108$) within our case studies, only 47 recorded the percentage seedling survival. Future monitoring of coastal restoration should incorporate a greater use of metrics related to ecosystem functions (Bayraktarov et al., 2016; Cadier et al., 2020).

Socioeconomic Project Outcomes

To assess the socioeconomic outcomes recorded in a case study we used the typology of McKinnon et al. (2016). Socioeconomic outcomes were recorded from 31 case studies, with over half of these ($n = 18$) identifying more than one outcome (range: 1–5). The two most commonly cited outcomes were those related to material living standards and the economic living standards (**Figure 6**). In comparison, culture and spirituality, and freedom of choice and action were not recorded. Non-material values are hard to quantify and identify, and it is particularly difficult to quantify the link between changes in the non-material value of restoration interventions (Chan et al., 2012). Compared to other coastal ecosystems, mangrove restoration projects more frequently report socioeconomic outcomes (Bayraktarov et al., 2020). However, in the papers reviewed here that recorded socioeconomic outcomes, few attempted to quantify these. The value of mangroves to local communities has long been identified; however, quantifying the socioeconomic benefits of restoration is challenging. Understanding socioeconomic outcomes is key to improving the sustainable management of mangrove areas; for example, Satyanarayana et al. (2021) quantified the flows of money between charcoal and pole producers in the managed Matang Mangrove Forest Reserve.

Overall Trends

From our analysis several key trends were observed, which have the potential to impact our understanding of the magnitude and success of restoration within mangrove ecosystems. From our synthesis of the literature there was a clear spatial dominance in terms of the location with three quarters of the restoration taking place in Asia. This is perhaps unsurprising given the region's extensive mangrove forests (Spalding et al., 2010) and the multitude of human pressures impacting mangroves in this region (Richards and Friess, 2016). However, a significant finding was the general lack of case studies from large parts of Africa and Central and South America, limiting our ability to understand the drivers of restoration success and failure in those regions. The major causes of decline of mangroves in our restoration sites were linked to anthropogenic impacts, with losses due to agriculture and aquaculture particularly prevalent. The role of aquaculture in the decline of mangroves in Southeast Asia is well established (Richards and Friess, 2016), with these losses potentially explaining why so many restoration projects are occurring in this area.

Across our case studies, very few recorded a detailed breakdown of the project costs, and this coupled with limitations on the monitoring of outcomes from restoration, reduces our capacity to determine cost effectiveness of different interventions. This issue is not unique to mangrove restoration (Pienkowski et al., 2021), but without the greater implementation of standardized reporting frameworks (Spurgeon, 1999; Iacona et al., 2018) our ability to maximize the impact from limited conservation funding is diminished. One area where our synthesis suggests mangrove restoration has started to tackle more effectively is the integration of local communities within mangrove restoration. Over 40% of the case studies stated there was local community involvement to some extent. This progress may in part be driven by the more recent promotion of "community based ecological mangrove rehabilitation" (Brown et al., 2014) and the recognition

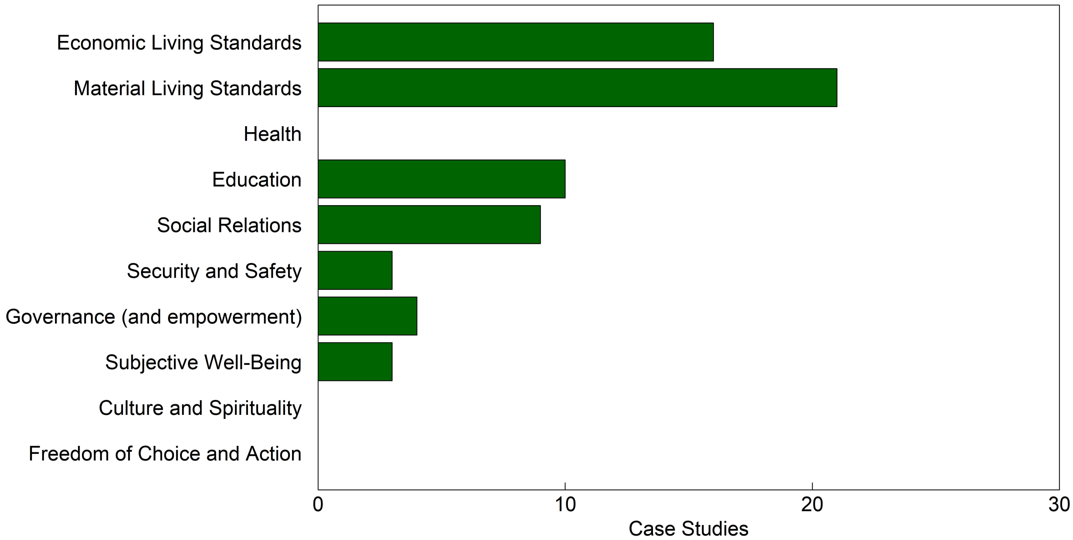

FIGURE 6 | The socioeconomic outcomes recorded in the restoration cases studies.

that mangrove restoration can have both ecological and socioeconomic outcomes (Bayraktarov et al., 2020). By adjusting mangrove restoration activities based on the needs and desires of local communities, and adequately supporting local community-led mangrove restoration it is likely that mangrove restoration will be more durable (Lovelock and Brown, 2019).

Our synthesis reaffirms challenges on several topics that have been repeatedly highlighted as limitations in mangrove restoration approaches. Firstly, the land tenure of a project location is often either unknown or not reported in nearly 90% of our case studies. This land tenure issue can often drive inappropriate restoration approaches that focus on planting mangroves in ecologically unsuitable locations (Lovelock and Brown, 2019). Secondly, for the majority of our case studies mangrove planting was still the intervention of choice. Large-scale, often monospecific planting of *Rhizophora* species, has been driven by unsuitable performance metrics and short-term measures of project success (Lee et al., 2019), and when coupled with land tenure issues and poor site/species matching this has resulted in limited mangrove survival and damage to other coastal habitats such as mudflats and seagrasses (Primavera and Esteban, 2008). Finally, the range of outcome metrics reported for restoration projects is large (Cadier et al., 2020), with the indicators recorded often not following a standardized methodology or without suitable comparison sites either in space or time. A more standardized reporting and monitoring framework would allow us to make inferences across restoration projects and different types of intervention, providing an understanding of the nuances of when and why restoration does or does not work, allowing organizations to adjust direct project implementation to improve outcomes and increasing our ability to determine cost-effectiveness. One area of promise is the integration of multiple types of outcome (e.g., economic, social, and ecological) with in the mangrove restoration literature, a trend not as apparent in other coastal, and marine ecosystems (Bayraktarov et al., 2020).

Overall, for certain sections of our framework, information in the published literature is reasonably well recorded (e.g., physical interventions and causes of decline), while several of the others lack all but the basic metrics. However, viewing all the sections through a single lens shows that there is lack of cohesion throughout. Unsurprisingly given journal styles and differences in paper focus, no paper follows the same reporting style and only reports a subset of the information. This results in information being of variable quality and consistency.

CONCLUSION

There has been a marked increase in marine restoration efforts over recent decades (Duarte et al., 2020), a trend which is likely to increase in response to multiple international, national and local policies associated with climate change mitigation and wider calls for "nature based solutions." For such restoration to have the maximum impact, both for biodiversity and for people, it is critical that we are able comprehensively and accurately to track restoration efforts. However, data collection in mangrove restoration projects has often been *ad hoc* and incomplete (Worthington and Spalding, 2018). Our analysis identified major knowledge gaps relating to the reporting of restoration costs and socioeconomic outcomes. We also found biases in location of restoration projects reported in the published literature, which have the potential to undermine restoration efforts in areas that are understudied.

Reporting key metrics and indicators on mangrove forest restoration, using standardized approaches, could provide a critical tool for restoration practitioners, both in evaluating their own efforts, and in providing a valuable baseline for future restoration. Given the increase in efforts there have been attempts to standardize the reporting and monitoring of restoration outcomes (e.g., FAO and WRI, 2019; Gann et al., 2019; Yando et al., 2021); however, challenges remain in implementing these global frameworks at the site level. There are also difficulties in applying generic frameworks to specific ecosystems given differences in project aims, restoration approaches, and potential outcomes. The review and synthesis of systematic reporting would also greatly facilitate current efforts to "scale up" mangrove restoration to the levels being targeted, including a likely reduction in failures, and considerable savings in terms of both reducing costs and optimizing benefits. A holistic approach capturing a broader set of measurements would facilitate an understanding of the environmental, socioeconomic and political setting, to inform what might be driving outcomes. Our findings show that there is a need for a framework which practitioners can use to report the process of their restoration studies and their outcomes. Such a framework would make it easier to compare across regions, approaches and outcomes allowing lessons to be learnt from previous restoration attempts.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

TAW, YMG, and MS conceived the idea. YMG undertook the literature review with input from TAW, DA-B, and PM. YMG wrote the manuscript with input from all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2022.720394/full#supplementary-material

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