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REVIEW ARTICLE

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A quantitative synthesis of approaches, biases, successes, and failures in marine forest restoration, with considerations for future work

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Abstract

1. Marine forests is a term commonly used for coastal marine habitats formed by dense stands of brown macroalgae, typically consisting of kelp and fucoids. These habitats are highly productive, offer habitat to numerous marine organisms, and support a range of invaluable ecosystem services. Despite their importance, marine forests are declining in many regions around the world as a result of interacting global, regional, and local-scale stressors. Consequently, interest in restoration as a tool to mitigate these declines and reinstate marine forests is growing.
2. Recent reviews have provided insights into marine forest restoration; however, for the most part, a synthesis of restoration success is lacking. A meta-analysis and quantitative review of published marine forest restoration efforts was conducted to examine: (i) how restoration affects the abundance and morphology of marine forest species; and (ii) trends in marine forest restoration success.
3. The meta-analysis of 25 studies revealed that restoration positively influences the abundance and morphology of marine forest species. The quantitative review of 63 studies demonstrated that taxa and restoration technique were important factors influencing restoration success, and revealed a bias towards the monitoring and reporting of abundance and morphological response variables. The review also highlighted a lack of monitoring and/or reporting of environmental variables at restoration sites, and limited comparative research across environmental contexts and restored species.
4. It is shown that successful marine forest restoration is possible at experimental scales, but that better monitoring and reporting of restoration efforts, alongside increased project durations, could improve our understanding of restoration success at the ecosystem level. Considerations for future marine forest restoration efforts are also provided. It is hoped that the review will advance marine forest restoration efforts, allowing the preservation of these valuable ecosystems and their associated services.

KEYWORDS
afforestation, canopy-forming macroalgae, Fucales, kelp, Laminariales, meta-analysis, repopulation, seaweed, sustainable management

1 | INTRODUCTION

'Marine forest' is a broad term increasingly used to describe coastal marine habitats dominated by stands of large brown macroalgae, most commonly of kelp and fucoids (Küpper et al., 2019; Wernberg et al., 2019; Tempera et al., 2021). Coupled with a high diversity of associated organisms, marine forests represent highly productive ecosystems that support a range of ecologically and socio-economically important ecosystem services (Smale et al., 2013; Bennett et al., 2016; Wernberg et al., 2019). Marine forests primarily occur in temperate and subpolar rocky reef environments and are estimated to occupy one-quarter to one-third of the world's coastlines (Wernberg et al., 2019; Jayathilakea & Costello, 2021).

The spatial extent and structure of marine forests in many regions has remained stable over time (Krumhansl et al., 2016; Smale et al., 2016; Bell et al., 2020; Friedlander et al., 2020). However, in recent decades, interacting global, regional, and local stressors have significantly impacted the distribution, abundance, and biomass of some marine forests. In the case of Laminarian (i.e. kelp) forests, although increases in kelp abundance may have occurred in 27% of ecoregions for which long-term data are available, significant declines are estimated in 38% of ecoregions (Krumhansl et al., 2016). Such declines can result in shifts from highly complex and productive marine forest habitats to simple low-complexity habitats (i.e. turf-dominated systems or urchin barrens) (Filbee-Dexter & Scheibling, 2014; Krumhansl et al., 2016; Piazzi & Ceccherelli, 2017; Filbee-Dexter & Wernberg, 2018). Positive feedbacks often stabilizes these less complex ecosystems and in turn inhibit marine forest recovery (Filbee-Dexter & Wernberg, 2018; O'Brien & Scheibling, 2018). Occasionally, alleviating the driver of decline has facilitated a degree of natural recovery of marine forests (Diez et al., 2013). However, environmental changes that favour the persistence of less complex ecosystems, coupled with the absence of reproductively mature source populations and the low dispersal capability of many marine forest species (Johnson & Brawley, 1998; Parada, Tellier & Martínez, 2016; Filbee-Dexter & Wernberg, 2018), has restricted recovery in some areas. Where natural recovery is limited, restoration, defined as *the process of initiating or accelerating the recovery of an ecosystem that has been degraded, damaged or destroyed* (Society for Ecological Restoration, 2020), may aid the re-establishment of marine forests (Verdura et al., 2018).

However, restoring marine forests is complex, and to be successful at ecologically meaningful scales requires: (i) research to identify the driver(s) of marine forest decline and/or loss (Layton et al., 2020; Morris et al., 2020); (ii) interventions that mitigate these drivers and promote recovery (Morris et al., 2020); and (iii) financial and institutional support (e.g. academic, governmental, industrial, as well as non-governmental organizations and community groups) (Eger et al., 2020b). In some cases, the primary driver of decline may be challenging to identify, either because it occurred prior to the degradation itself, because the degradation is historical and the driver is unknown (e.g. Coleman et al., 2008), or because the degradation is the result of multiple interacting stressors (e.g. Rogers-Bennett & Catton, 2019). Interventions designed to ameliorate the biotic or abiotic stresses that lead to forest decline, known as passive restoration or assisted recovery (Morrison & Lindell, 2011; Boström-Einarsson et al., 2020; Layton et al., 2020), include herbivore and competitor control, artificial habitat creation, nutrient enrichment, and pollution mitigation (Table 1). Techniques aiming to reintroduce or increase the number of forest individuals, known as active restoration (Morrison & Lindell, 2011; Boström-Einarsson et al., 2020), often involve transplantation and/or seeding (Table 1). The use of restoration interventions has primarily been academically motivated (Eger et al., 2020b) and has involved comparing techniques on single species or at a single site, with few studies comparing responses across a range of species (but see Falace, Zanelli & Bressan, 2006; Susini et al., 2007; Westermeier et al., 2016), regions (but see Falace, Zanelli & Bressan, 2006; Kautsky, Qvarfordt & Schagerström, 2019), environmental contexts, or seasons (but see Perkol-Finkel & Airoldi, 2010). Recent reviews have summarized marine forest restoration literature, with specific focuses on the Australian context (Layton et al., 2020), key principles and best practices (Morris et al., 2020), and future trajectories (Wood et al., 2019; Coleman et al., 2020; Eger et al., 2022b). However, for the most part, the success of marine forest restoration remains unknown and unquantified (but see Eger et al., 2022a for analyses using kelp survival as a metric of success).

For other coastal marine habitats, systematic reviews and meta-analyses of restoration research have provided insights into the drivers of success, identified key knowledge gaps, and facilitated the development of best-practice guidelines (Crouzeilles et al., 2016; van Katwijk et al., 2016; Boström-Einarsson et al., 2020). For example, a meta-analysis of seagrass restoration demonstrated the importance of mitigating threats prior to commencing restoration, the positive influence of proximity to and recovery of donor sites, and the benefit of large-scale outplanting on the survival and growth of seagrass (van Katwijk et al., 2016). Similarly, a systematic review of coral restoration identified unachievable goals, weak project designs, and a lack of standardized surveying techniques and recording protocols as factors preventing the upscaling of coral restoration (Boström-Einarsson et al., 2020). In the case of marine forests, initial analyses have shown that restoration projects are often small in scale (<0.1 Ha), with the scalability and cost-effectiveness of different restoration methodologies explored by Eger et al. (2022a). Here, we build on this

TABLE 1 Restoration intervention definitions and examples of use

Restoration technique	Examples	References
Transplantation involves the installation of adult and/or juvenile individuals from a donor population, a laboratory culture, or opportunistic drift/beach cast individuals. Transplants can be installed at restoration sites using an array of techniques	Mesh devices bolted or tied/cable-tied to substrate	Correa et al., 2006; Marzinelli et al., 2009.
	Chains with tethers	North, 1976.
	Elastic/rubber bands to attach transplants to:	
	-natural substrates	Westermeier et al., 2014, 2016.
	-artificial substrates	Layton et al., 2021.
	-stumps of clear-cut macroalgae	Hernandez-Carmona et al., 2000.
	-longlines	Westermeier et al., 2013.
	-plastic grids	Westermeier et al., 2014.
	-buoys suspended above the substrate	Wilson, Haaker & Hanan, 1977.
	Adhesive glues	Serisawa et al., 2003; Westermeier et al., 2014, 2016.
	Epoxy putty to attach:	
	-transplants directly to the substrate	Vásquez & Tala, 1995; Susini et al., 2007; Tamburello et al., 2019.
	-exorcised rock fragments hosting naturally occurring individuals to the substrate	Whitaker, Smith & Murray, 2010; Sales et al., 2011; Gao et al., 2017.
	Cable ties to attach:	
	-transplants directly to pre-installed plastic mesh	Campbell et al., 2014.
	-substrates hosting individuals to pre-installed plastic mesh	Vásquez et al., 2014.
	Deployment of substrates hosting laboratory-reared individuals:	
	-bolted to the substrate	De La Fuente et al., 2019.
	-in pens or loose on the substrate	Fredriksen et al., 2020.
Seeding involves enhancing the recruitment potential at restoration sites through the installation of translocated reproductive tissues/bodies, and the dispersal of early-life-stage cultures	Installation of translocated reproductive tissues/bodies	Choi et al., 2000; Hernandez-Carmona et al., 2000; Collier & Machovina, 2005; Westermeier et al., 2014; Ford & Meux, 2010; Verdura et al., 2018.
	Installation of desiccated, translocated reproductive tissues/bodies	Vásquez & Tala, 1995.
	Distribution of laboratory spore culture	North, 1976; Vásquez & Tala, 1995; Yu et al., 2012.
Artificial habitat creation involves installing structures on the sea bed that mimic forest substrate. They are often used in conjunction with other interventions such as transplantation and/or seeding	Comprising natural rocks/boulders	Dean & Jung, 2001.
Competitor exclusion/removal refers to the removal of a species that would otherwise outcompete forest species for resources or inhibit their recruitment. It is often used in conjunction with other interventions such as transplantation and/or seeding	Clearing of turf algae	Sanderson, 2003; Fredriksen et al., 2020.
Herbivore exclusion/removal involves the installation of devices that exclude single or multiple herbivore species, or practices that remove specific herbivore species	Multiple species exclusion using cages	Bennett, Wernberg & de Bettignies, 2017; Tamburello et al., 2019.
	Multiple species exclusion using epoxy rings coated with anti-fouling paint	Whitaker, Smith & Murray, 2010.
	Herbivorous fish exclusion using bubble curtains	Bennett, Wernberg & de Bettignies, 2017.

(Continues)

TABLE 1 (Continued)

Restoration technique	Examples	References
	Urchin exclusion using plastic pseudo-kelp	Vásquez & McPeak, 1998.
	Urchin removal by:	
	-collection and relocation	Collier & Machovina, 2005; Ford & Meux, 2010.
	-crushing with iron pipes	Taino, 2010.
	-killing with quicklime (CaO)	Wilson, Haaker & Hanah, 1977.
Nutrient enrichment involves releasing nutrients to stimulate the growth of algae. It is often combined with other interventions in mixed-method experiments (e.g. Yu et al., 2012)	Bags of steelmaking slag plus compost (released iron humates)	Yamamoto et al., 2010.
Pollution mitigation involves the treatment of wastewater discharge. It is often somewhat overlooked as a restoration action	Removal of suspended solids and biological treatment (including nitrification–denitrification process) of sewage outflow	Diez et al., 2013.
Multiple techniques can be employed in restoration experiments and often involve a combination of active techniques to increase the number of individuals and passive techniques to provide a suitable environment for the individuals	Seeding and transplanting of individuals to artificial structures and pools	Dean & Jung, 2001; Terawaki et al., 2001; Yu et al., 2012.
	Seeding of substrates transplanted to elevated positions in the field to minimize sedimentation	Carney et al., 2005.
	Excluding/relocating herbivores from areas containing transplants or that have been seeded	North, 1976; Vásquez & McPeak, 1998; Collier & Machovina, 2005; Bellgrove et al., 2010.
	Installing additional materials to protect transplants from desiccation and wave action	Whitaker, Smith & Murray, 2010.
	Removal of competitors from areas with transplants	Hernandez-Carmona et al., 2000.

work by conducting a meta-analysis and quantitative review of marine forest restoration research to examine: (i) how restoration affects the abundance and morphology of marine forest species; and (ii) trends in marine forest restoration success.

2 | METHODS

2.1 | Literature review and data extraction

The literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol that provides an evidence-based minimum set of requirements for undertaking and reporting meta-analyses (Figure S1). Literature searches were conducted using Web of Science and Google Scholar, applying combinations of the keywords 'restor*', 'repopulat*', 'kelp', 'seaweed', 'macroalga*', 'marine forest*', 'Laminariales', 'Fucales', 'Desmarestiales', and 'Tilopteridales' to interrogate all literature available by April 2020. The searches yielded results from peer-reviewed articles and grey literature reports, both of which were included in the database. Potentially relevant studies were screened by their title and abstract, and if it was indicated that they were within the scope of the review, the full article was retrieved. Foreign language studies with English titles, abstracts, and figure legends were included in the retrieved studies. Studies were included in the review if they reported the outcome of a restoration technique or an experimental methodology that could be used for restoration on marine macroalgae of the orders Desmarestiales, Fucales, Laminariales, and/or Tilopteridales. In this way, restoration methodologies that may otherwise be overlooked because of the experimental framing of the research were incorporated. Reference lists of included studies were also screened for further relevant literature. Furthermore, one additional study, Layton et al. (2019), that was not identified in the literature search because of its experimental framing, was included in the database because the methodology could be considered a restoration technique and was later published as such (Layton et al., 2021).

Data were extracted from text, tables, and/or figures (using WebPlotDigitizer 4.2, https://automeris.io/WebPlotDigitizer), per restoration intervention, defined as a treatment aiming to enhance a marine forest macroalgal species (Table 1). Where possible, extracted data included: focal species, site coordinates (when not quoted these were estimated using Google Earth Pro, https://earth.google.com), reason for forest decline/loss in the region, depth, date and duration of experiment, and data (mean, variance, and sample size) for the intervention, and if available the control group per response variable assessed. For each intervention, success was quantified on a binary scale based on the authors' inference of success. In experiments where multiple restoration interventions were employed but the result was clearly attributed to a specific intervention, only the individual intervention was reported; however, if the result could not be attributed to one intervention alone, the intervention was reported as 'multiple'. Similarly, if an intervention involved several macroalgal species and the result per species could not be obtained, the species was reported as 'multiple'. Based on the type of data extracted, the review was divided into two sections: a meta-analysis (where information on the mean, variance, and sample size of an intervention and control group was available; Table S1) and a quantitative review (where such information was not available; Table S2). Percentage survival data (whereby the control was a natural forest or non-manipulated individuals) were included in the quantitative review, as estimates of variance were often not given.

2.2 | Meta-analysis

Control groups were defined as non-manipulated individuals, forests, or substrates, manipulated individuals within a forest (compared with manipulated individuals in a barren area), or rock/concrete substrates that received the same restoration treatment as novel substrates. As a result of a lack of data independence in repeated-measure experiments, only the final time point was included (Gurevitch et al., 1992). For the experiments that reported results for multiple response variables, data were extracted per response variable ($g_{individual}$). A conservative approach was taken if variance calculations were reported but undefined, and the value was assumed to be the standard deviation (Weibe et al., 2006), and where sample sizes were reported as a range of values, the smallest value was used.

Hedges g corrected for small sample sizes was used as the measure of effect size and was calculated per $g_{individual}$. Hedges g was selected over other measures of effect size because it allows zero-value responses to be included (Thomsen et al., 2009, 2012). Hedges g was calculated as $((R_{intervention} - R_{control})/SD_{pooled}) \times J$, where $R_{intervention}$ and $R_{control}$ represent the mean response variable for the restoration intervention and control, respectively, SD_{pooled} is the pooled standard deviation, and J is the small sample size correction (Borenstein et al., 2009) (Appendix S1). As in Smale et al. (2019), in cases where the outcome of multiple response variables was reported for the same intervention, autocorrelation was reduced by averaging effect sizes across response variables using equal weights for each variable, to give one 'independent' effect size per intervention ($g_{intervention}$).

Data analyses were conducted using the 'metafor' package (Viechtbauer, 2010) in R [v.1.2.1335] (R Core Team, 2021), and the 'ggplot2' package (Wickam, 2016) was used to plot the results. A weighted random-effects model was used to calculate an overall mean effect size, 95% bias-corrected confidence intervals, and the significance level. Weighted random-effects models assume that the studies included are similar enough to be synthesized together, but that they vary in some way (e.g. experimental conditions) and hence their effect sizes are similar, but not identical (Borenstein et al., 2010; Mengersen et al., 2013). The overall effect size is a weighted mean of study-specific effect sizes. Weights were calculated using the inverse variance method, which incorporates the variance within studies that results from sampling error, plus the variance between studies resulting from differences in their true effect sizes (Gurevitch & Hedges, 1999; Borenstein et al., 2009). More precise studies (i.e. with low variance and/or greater replication) are therefore more heavily weighted.

A positive effect size indicates that a restoration intervention was more successful than its control, whereas a negative effect size indicates that an intervention was less successful than its control. A significant effect of restoration ($P < 0.05$), either positive or negative, was found if the 95% confidence intervals of the effect size did not overlap with zero (Gurevitch et al., 1992). An insignificant result ($P > 0.05$), shown when the 95% confidence intervals of the effect size overlap with zero, indicated no significant difference between the restoration intervention and the control (i.e. a neutral effect of restoration). Depending on the type of experimental control, neutral effects can, at times, be interpreted as positive restoration outcomes with the intervention performing as well as the control. Seeding experiments whereby controls are represented by non-inoculated substrates as opposed to natural forests are an exception, as failed recruitment in both the intervention and control, resulting in an insignificant result, cannot be considered a positive restoration outcome.

Heterogeneity, or variation between studies that results from differences between the studies, as opposed to chance, was recognized in advance of the meta-analysis and thus a random-effects model was used (Mengersen et al., 2013). To minimize heterogeneity, the meta-analysis data were divided into two groups based on the reported responses (see Thomsen et al., 2009): abundance (i.e. density and biomass) and morphology (i.e. stipe length, holdfast diameter, etc.). We acknowledge that another method to reduce heterogeneity would be to analyse subgroups (i.e. restoration techniques or orders), separately; however, this would have resulted in small sample sizes and so conclusions may not have been robust (Brown & Sutton, 2010).

To determine the robustness of the findings, leave-one-out sensitivity analyses were conducted whereby the overall effect size was recalculated after omitting one experiment at a time. If the result remained similar as each experiment was omitted, the analysis was considered robust (Brown & Sutton, 2010; Viechtbauer & Cheung, 2010). Publication bias may also be present in meta-analyses and primarily occurs when results from experiments with non-significant findings go unpublished, but may also occur if studies with highly significant findings have been overlooked (Rosenthal, 1979). Publication bias was assessed by examining funnel-plot asymmetry using Egger's regression test (Egger et al., 1997) and the trim-and-fill method (Duval & Tweedie, 2000a, 2000b). Additionally, Rosenthal's fail-safe number (N) was calculated to estimate the number of studies with a mean effect of zero that would need to be added to the analysis to reduce the significance level of the overall effect size to $P > 0.05$ (Rosenthal, 1979). Fail-safe numbers are considered robust if larger than $5n + 10$, where n represents the number of studies in the meta-analysis (Rosenthal, 1979).

3 | RESULTS

3.1 | Meta-analysis

Twenty-five studies met the criteria for inclusion in the meta-analysis (Table S1). Twelve studies investigated the impact of restoration on marine forest abundance and contributed 36 $g_{intervention}$ values, whereas 18 studies investigated the impact of restoration on the morphology of marine forest individuals and contributed 54 $g_{intervention}$ values. Sensitivity and publication bias analyses found the results to be generally robust. Despite a degree of funnel-plot asymmetry shown by significant Egger's regression tests (abundance, $z = 3.53$, $P = 0.0004$; morphology, $z = 8.87$, $P < 0.0001$), adjusting for this bias using the trim-and-fill method did not alter the significance of the findings (Figure S2). Additionally, Rosenthal's fail-safe number remained greater than $5n + 10$ for both the abundance and morphology meta-analyses ($N = 963$ and $N = 1{,}537$, respectively).

The meta-analyses revealed that restoration intervention groups often out-performed control groups (i.e. significant positive effects were observed), both in terms of the abundance (i.e. density or biomass) and morphology (i.e. stipe length, holdfast diameter, etc.) of individuals within marine forests ($P = 0.0011$ and $P \leq 0.0001$, respectively; Figure 1a–d; Table S3). However, the nature of the effect varied across restoration techniques and taxonomic orders. Three of the five restoration techniques (competitor exclusion/removal, herbivore exclusion/removal, and transplanting) had significant positive effects on both the abundance and morphology of marine forest individuals (Figure 1(a, b)). Seeding had a significant positive effect on morphology and a neutral (i.e. insignificant) effect on abundance, although the latter may be considered a success because the corresponding controls constituted natural forests, meaning that abundance/recruitment in the seeded area was comparable with that of a natural marine forest (Figure 1(a, b)). Similarily, and despite a small sample size, the use of artificial habitats and multiple techniques had neutral effects on both the abundance and morphology of marine forest individuals, which can be interpereted as a positive restoration outcome (Figure 1(a, b)). Restoration was also found to have a significant positive effect on the abundance of Fucalean species and a neutral effect on their morphology, whereas the opposite pattern was observed for Laminarian species (Figure 1(c, d)). Based on a limited number of studies, restoration was also found to have a significant positive effect on multiple macroalgal species (Figure 1(d)).

3.2 | Quantitative review

Sixty-three studies comprising 387 marine forest restoration experiments were included in the quantitative review (Table S2). The frequency of restoration experiments was found to have increased significantly over the past two decades, with 290 experiments undertaken between 2000 and 2019, compared with only 18 between 1979 and 1999 (Figure S3). The reported drivers of marine forest degradation and/or loss were similar across taxonomic orders, with urbanization (e.g. coastal development, dredging, sewage outfalls, and pollution) the most commonly cited driver (34% of reports), followed by climate change/variability, which included the effects of ocean warming, extreme weather events, and climatic oscillations, such as El Niño (18%; Figure 2). Over exploitation of macroalgae and/or associated organisms and overgrazing by herbivores were also commonly cited causes of decline (18% and 21%, respectively; Figure 2). In a small proportion of cases, factors

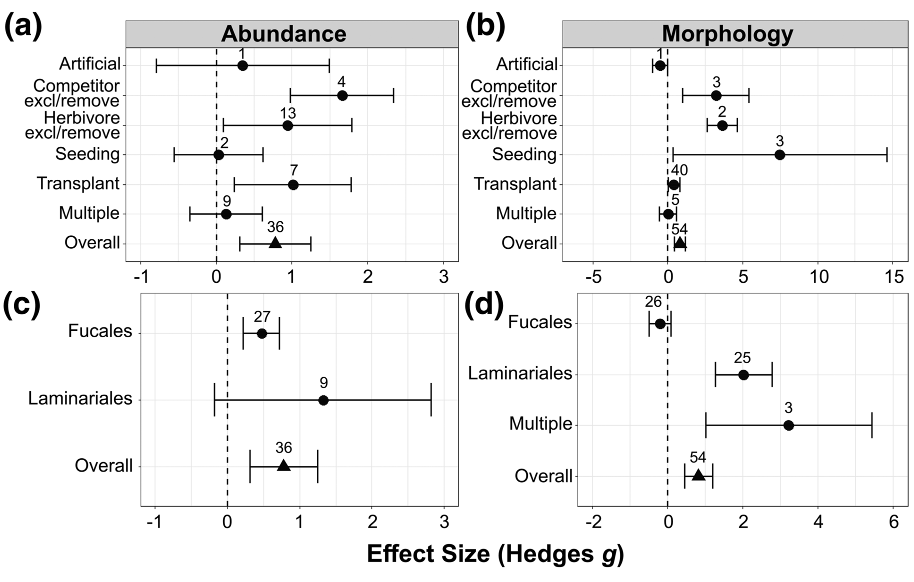

FIGURE 1 Meta-analysis. The effect of restoration on the abundance (a, c) and morphology (b, d) of individuals within marine forests per restoration technique (a, b) and taxonomic order (c, d). Circular values represent the effect size (Hedges g) ± 95% confidence intervals and triangular values represent the overall effect size (Hedges g) ± 95% confidence interval for the weighted random-effects model. Values adjacent to points indicate the sample size. The zero line indicates no effect, and non-significance of a result is indicated when the ±95% confidence interval overlaps zero. Note the difference in scales across the plots.

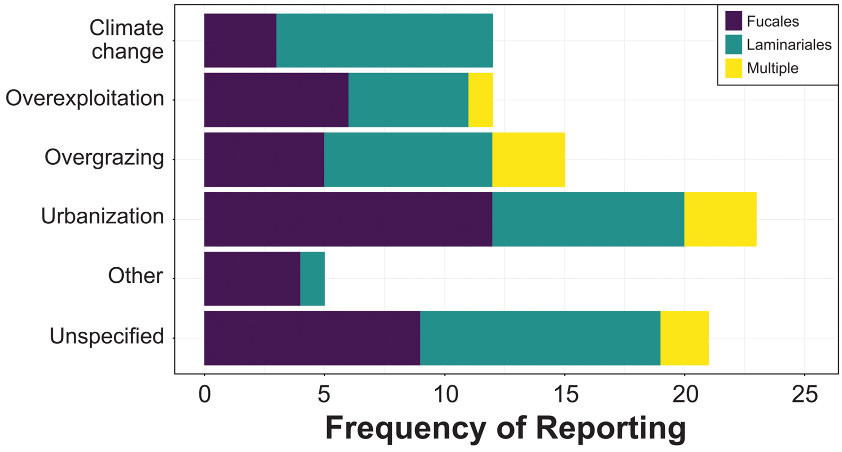

FIGURE 2 Quantitative review. Frequency of reporting of drivers of marine forest degradation/loss within study regions. For studies that reported multiple drivers, each reported driver was included individually. Studies that reported drivers of degradation/loss at the global scale only were combined with studies that did not report any drivers of degradation ('unspecified' category). The coloration of the bars demonstrates the taxonomic orders involved in the studies. Number of studies = 63, number of reports of drivers of decline/loss (excl. unspecified) = 67. Note: climate change grouping includes anthropogenic climate change and natural climatic variability, such as El Niño.

including recruitment failure, disease, and/or invasive species were responsible for degradation (collectively termed 'other', <8%; Figure 2). However, in a third of studies the driver of decline was not specified (Figure 2) because declines had not occurred in the area, the drivers were not known, or the drivers were inferred from regional to global scales.

Marine forest restoration experiments have been undertaken in 15 countries, with hotspots of restoration effort occurring in the north-east and north-west Pacific (20% and 19% of experiments, respectively), the south-east and south-west Pacific (12% and 29%, respectively), the Mediterranean Sea (13%), and the Baltic Sea (7%) (Figure 3). Despite variations in restoration success across countries, success rates (based on author inference) were always ≥50%, with the exception of the USA, where success rates were 46% (Figure 3), in part linked to the limited success of experiments involving *Nereocystis luetkeana* and *Silvetia compressa*. No restoration experiments were found for some forest-dominated regions, notably the UK, South Africa, and New Zealand (Figure 3).

Most marine forest restoration experiments have been conducted in subtidal areas (72% of those that specified depth), of which almost three-quarters were considered successful (Figure 4(a)). Subtidal experiments primarily involved Laminarian species, whereas Fucalean species were the main focus of intertidal experiments (Figure 4(a)). Intertidal experiments were less successful than their subtidal counterparts (with success rates of 45%; Figure 4(a)). Few studies conducted restoration experiments across a range of depths and almost a third of experiments did not specify the depth at which the experiment was conducted (Figure 4(a)). Furthermore, the majority provided limited information or quantification of other potentially important environmental variables (e.g. wave exposure or light environment).

Almost two-thirds of marine forest restoration experiments involved Laminarian species, and exhibited success rates of 69% (Figure 4(b)) and survival rates of 41% (Figure 5(a)), although the latter figure is based on a small sample with a high degree of variability between experiments. The majority of experiments on Laminarians comprised *Ecklonia* spp. and *Macrocystis* spp. (Figure 4(b)). Experiments involving Fucalean species appeared to be as successful as those involving Laminarians, despite lower survival rates (66% and −8.5%, respectively; Figures 4(b) and 5(a)). Of Fucalean species, *Cystoseira* spp. and *Sargassum* spp. were among the most common restoration targets (Figure 4(b)). For the six genera involved in >20 experiments, success rates were greatest for *Sargassum* spp. and *Macrocystis* spp. and were lowest for *Silvetia* spp. and *Lessonia* spp. (Figure 4(b)). Approximately one-quarter of studies assessed the impact of restoration on more than one macroalgal species.

Experiments involving multiple restoration techniques were common for both Fucalean and Laminarian species, with success rates of 66% and 74%, respectively (Figure 4(c)). However, most experiments employed individual techniques to restore marine forests (55%; Figure 4(c)), with active techniques used more widely than passive techniques (75% and 25%, respectively), despite passive techniques having a higher success rate (active, 65%; passive, 80%). Transplantation was the most common technique employed to restore both Laminarian and Fucalean species (Figure 4(c)) and was used as an individual technique in 10 of 15 countries where restoration experiments have taken place (Figure 3). Transplantation had a success rate of 63% despite an average survival rate of −10.4% (Figures 4(c) and 5(b)). Seeding accounted for 7% of experiments and was considered less successful for Fucalean species compared with Laminarian species (33% and 94%, respectively; Figure 4(c)). Herbivore exclusion/removal accounted for 10% of experiments and was employed in over one-third of the countries where restoration efforts have taken place (Figure 3), with success rates exceeding 80% for both Laminarian and Fucalean species (Figure 4(c)). Competitor exclusion, artificial habitats, and nutrient enrichment exhibited success rates of over 50% as sole techniques, but sample sizes were small as these techniques were often incorporated into multiple-method experiments (Figure 4(c)). Pollution mitigation was found to be a somewhat overlooked yet effective restoration technique, employed in only two experiments but with a success rate of 100%.

Restoration success has been assessed using a range of response variables as indicators, with the majority of experiments (62%) assessing two or more response variables (Figure 6(a)). Survival/recruitment was the most commonly investigated response variable, followed by growth (Figure 6(a)). Variables such as maturity, density/

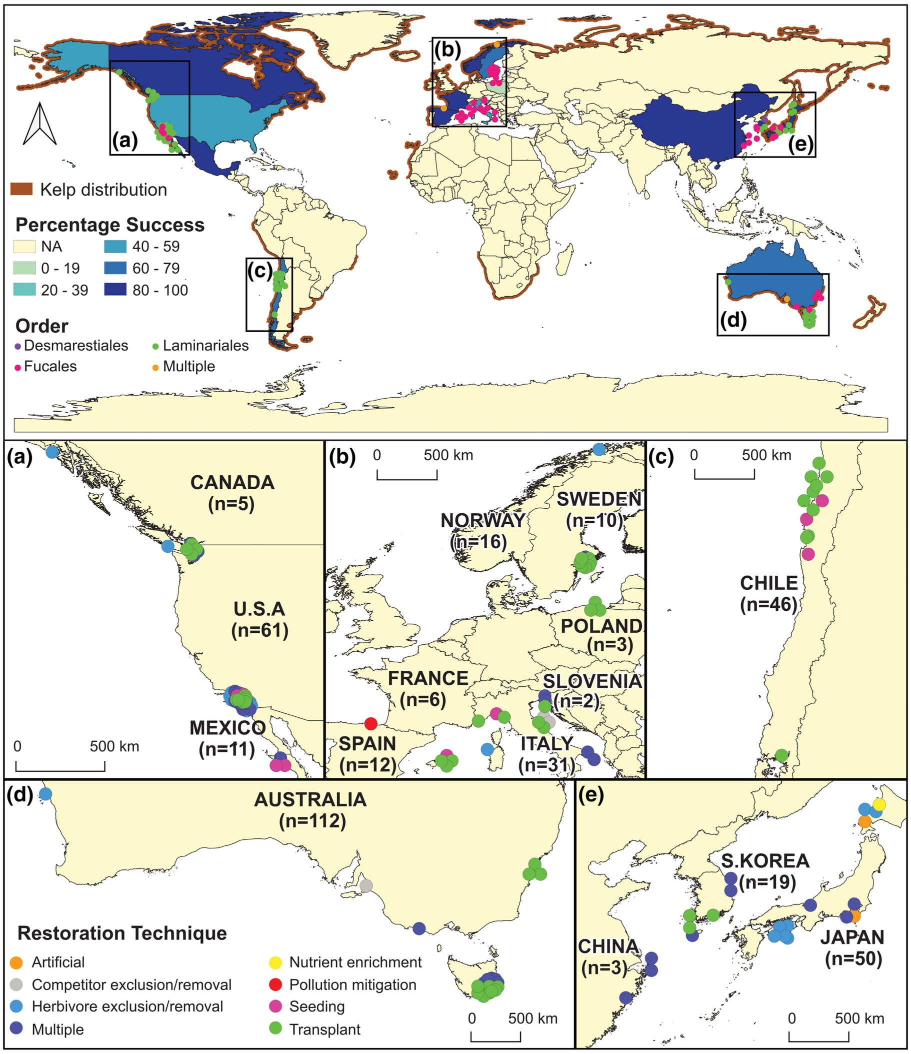

FIGURE 3 Quantitative review. World map showing the location and taxonomic order involved in restoration experiments ($n = 387$) and the restoration success rate (inferred by the authors) per country. The brown outlines indicate the approximate global distribution of marine forests (primarily Laminarian) (adapted from Filbee-Dexter & Wernberg, 2018 and Wernberg et al., 2019). Close-up maps (a–e) show the restoration techniques employed and the number of experiments per country.

biomass, and 'others' (e.g. percentage bleaching) were assessed to a lesser extent (Figure 6(a)). Less than a quarter of studies (23.8%) commented on or assessed the impact of restoration on associated flora and fauna. As with assessments of macroalgal maturity, assessments of associated flora/fauna require time and/or exhibit a degree of seasonality, so monitoring these parameters is often not feasible within the limited time frame of most experiments, with 85% of experiments found to be ≤12 months in duration (Figure 6(b)).

4 | DISCUSSION

This review explored the success of published marine forest restoration efforts conducted over the last 70 years. The meta-analysis revealed that restoration interventions often outperformed control groups and positively influenced the abundance and morphology of marine forest species. The quantitative review demonstrated that taxa and restoration technique were important factors influencing restoration success, but that gaps and inconsistencies between studies in the way restoration experiments are conducted, monitored, and reported, limits comparative assessment across studies. Collectively the results demonstrate that marine forest restoration is feasible, although challenges need to be overcome to succeed beyond experimental scales. These challenges include identifying and mitigating the original driver(s) of forest decline, determining where and how restoration should be conducted, deciding how to monitor success, and gaining stakeholder support (Lake, 2001; Wood et al., 2019; Boström-Einarsson et al., 2020). The ways in which enhancing monitoring and improving reporting could increase our understanding of restoration success are discussed, before considerations for future marine forest restoration efforts are provided.

4.1 | Evaluating restoration success

Diversity in the aims, design, and reporting of restoration experiments/projects makes evaluating restoration success and comparing success across experiments or projects challenging (Ruiz-Jaen & Aide, 2005; Wortley, Hero & Howes, 2013; Christie

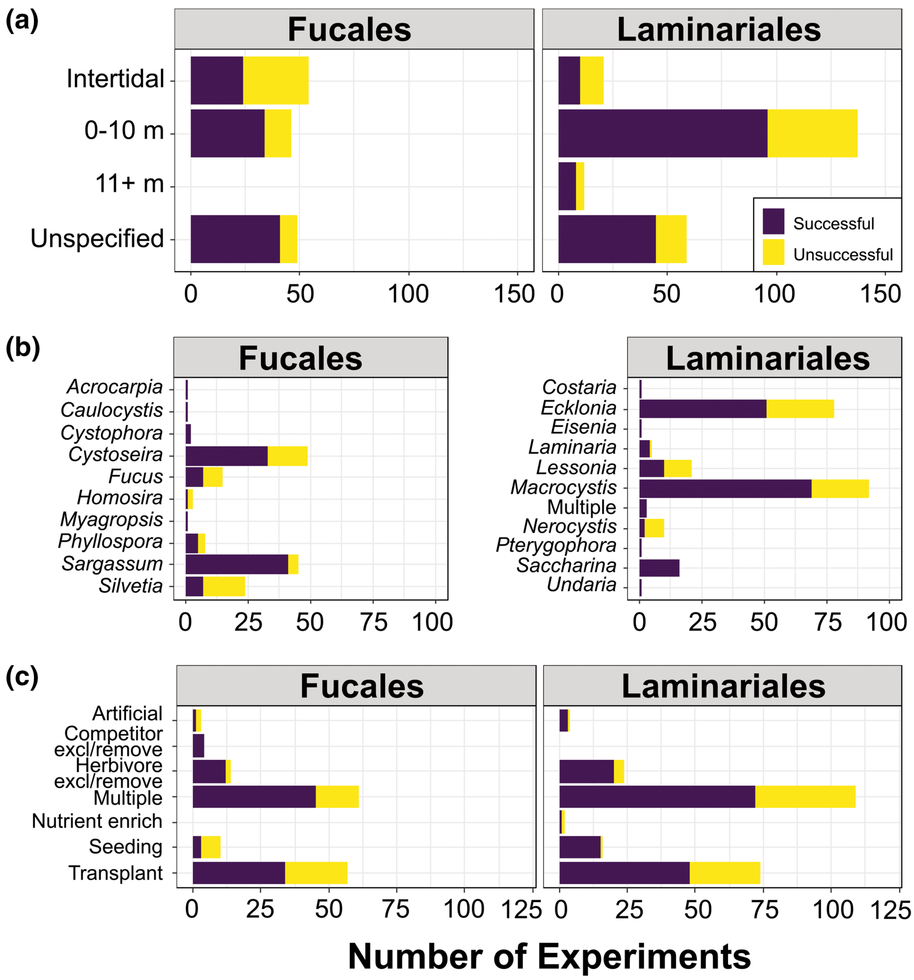

FIGURE 4 Quantitative review. Number of restoration experiments per depth (meters) (a), genus (b), and restoration technique (c), divided by taxonomic order. Bar coloration indicates experimental success (inferred by the authors). Number of experiments = 378 (Fucales, $n = 149$; Laminariales, $n = 229$). As a result of their low sample size, experiments involving Desmarestiales ($n = 2$), multiple orders ($n = 4$), or where no inference of success was given ($n = 3$) were excluded from the graphs.

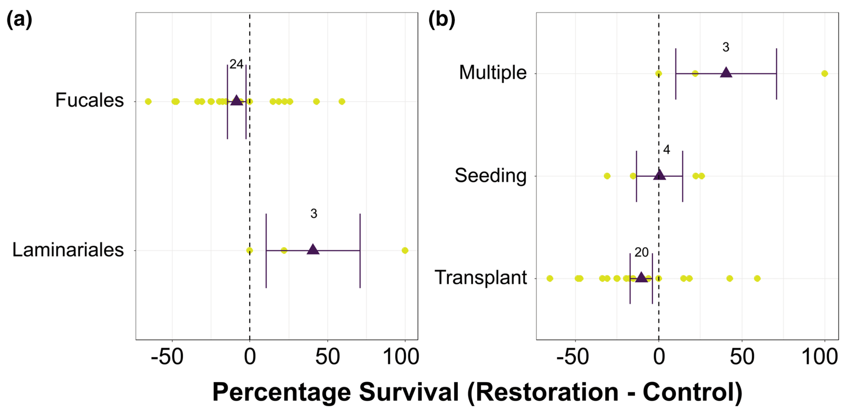

FIGURE 5 Quantitative review. The percentage survival of macroalgae in restoration experiments per taxonomic order (a) and restoration technique (b). Yellow circular points indicate the values per restoration experiment ($n = 27$), purple triangular points indicate the mean ± 1 standard error, values adjacent to points indicate the sample size.

et al., 2020). Meta-analyses represent a valuable statistical means of combining and synthesizing comparable data from multiple experiments or projects to evaluate restoration success. However, bias can be introduced from the limited reporting of restoration 'failures' despite the valuable nature of this information. At the same time, a lack of experimental controls or failure to report the sample size and/or an estimation of variance can result in relevant studies being excluded from meta-analyses. The lack of such information resulted in the exclusion of 38 studies from the meta-analysis, meaning it was unable to incorporate the full body of marine forest restoration research. However, a lack of publication bias confirms that the results presented are robust indicators that can be used by practitioners to understand the potential impacts of restoration on the abundance and morphology of individuals within marine forests.

Given that not all restoration data can be included in meta-analyses, a suite of quantitative metrics have been employed to compare restoration success across studies, including survival scores

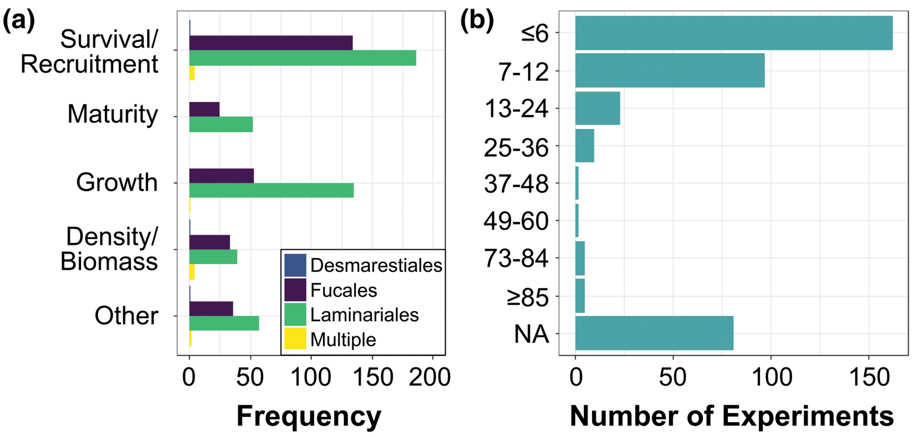

FIGURE 6 Quantitative review. Frequency of response variables investigated in restoration experiments ($n = 387$) per taxonomic order (indicated by bar coloration) (a). Note: experiments could investigate more than one response variable, thus the number of response variable assessments was 764. Duration of restoration experiments (months) (b). $n = 387$, NA represents experiments where no information on duration was found. *Note*: there were no experiments between 61-72 months in duration and thus this category was excluded from the graph.

(Eger et al., 2022b) and novel success scores (van Katwijk et al., 2016). However, such metrics are often challenged to capture variation amongst projects in terms of their aims, the size of the restoration area, or the duration of the monitoring period. Furthermore, the metric threshold may give an incorrect indication of success: for example, the survival of one individual could be considered a success using some metrics, but as one individual is unlikely to develop into a self-sustaining population, the action would be better described as a failure. Although it was not possible to overcome all of these challenges in the analyses presented here, by using the authors' inference of success it was possible to better assess restoration success relative to experiment-specific aims and designs. Although we acknowledge that at times there may be a degree of subjectivity involved in deducing the authors' inference of success, by combining the quantitative review with a meta-analysis it was possible to provide a valuable insight into the state of the art of marine forest restoration and a point of comparison for similar works (see Eger et al., 2022b; Morris et al., 2020).

Nonetheless, to better understand restoration success at the ecological scale and to enhance comparisons across studies, we urge for a more holistic, yet standardized approach to future restoration monitoring and reporting, particularly in terms of the experimental design (i.e. controls and sample size) and the variables assessed (e.g. biological metrics regarding both kelp and associated species and environmental conditions at the restoration site), alongside increased monitoring durations. Such data are invaluable for large-scale syntheses and online databases (e.g. www.kelpforestalliance.com) that are likely to inform future experiments and decision making.

4.2 | Enhancing monitoring and reporting to better determine restoration success

The meta-analysis and quantitative review revealed a bias towards the assessment of abundance and morphological traits as indicators of restoration success. Although such variables are often selected because they are simple and time effective to monitor, key attributes of successfully restored ecosystems identified by the Society for Ecological Restoration include self-sustainability and the diversity of the community relative to a reference system (Ruiz-Jaen & Aide, 2005). Both these attributes were largely overlooked by the studies included in this review, despite being more indicative of restoration success at the community or ecosystem level. We suggest that future works consider simple evaluations of self-sustainability and diversity within their monitoring protocols: for example, the presence/absence of reproductive tissue (i.e. sorus tissue or receptacles) (Correa et al., 2006) and the abundance of ecologically important fish and invertebrate species. Where resources permit, monitoring protocols could be scaled-up further to include factors such as associated macroflora and macrofaunal communities.

The quantitative review also found that reporting on the driver(s) of local marine forest degradation was absent in one-third of studies. Their identification represents an important step towards successful restoration, allowing the most appropriate and cost-effective restoration techniques to be identified (Morris et al., 2020). It was also noted that the environmental conditions experienced at restoration sites are often overlooked in restoration monitoring and/or reporting, making comparisons between studies challenging, but more importantly making it impossible for practitioners to determine which techniques are best suited to the environmental context they are operating in. Most studies quantified only depth, but often failed to include other important variables such as temperature, light, wave exposure, and nutrient availability (Engelen et al., 2005; Mabin et al., 2013; Coppin et al., 2020). It would be advantageous for future studies to provide environmental information for restoration sites by measuring factors *in situ* or by using remotely sensed data and models (for remotely sensed data, see www.bio-oracle.org/index.php; for wave fetch models, see Burrows, Harvey & Robb, 2008). Information on the driver of decline and the environmental conditions at the restoration site may also help practitioners to time restoration actions to ensure maximum success: for example, transplant survival may be enhanced during periods of reduced wave action to minimize dislodgement, or when climate conditions favour growth, whereas herbivore reduction techniques may be viable all year round.

In addition, monitoring or providing information on environmental variables allows for the comparison of restoration techniques both across environmental contexts and across a range of species, thus improving the understanding of factors influencing success, methodological limitations, and points of failure. Although comparative marine forest restoration research remains limited, projects such as the Green Gravel Action Group (www.greengravel.org) are testing the applicability of a novel and cost-effective restoration technique across an array of environmental contexts and species. Similar work is also underway as part of the World Harbour Project (www.worldharbourproject.org/bivalve-restoration) to understand global variation in eco-engineering techniques for enhancing bivalve assemblages. Both projects demonstrate the increasing importance of comparative restoration experiments.

Over three-quarters of restoration experiments were monitored for less than 12 months. Although short-term experiments can be beneficial in demonstrating methodological efficacy, limited monitoring durations may lead to misrepresentation and/or misinterpretation of the findings. For example, monitoring growth and survival for less than 6 months will not account for seasonal variation in growth and dislodgement/erosion rates (Brown et al., 1997; Hernandez-Carmona et al., 2000; de Bettignies et al., 2013; Graham et al., 2021). Furthermore, short-term experiments often cannot account for the impact of stochastic events that can be detrimental to restoration efforts (e.g. storm surge, experienced by De La Fuente et al., 2019), or the restoration of associated communities and ecosystem-level structure and functioning that can take considerably longer to re-establish (Christie, Fredriksen & Rinde, 1998). Consequently, we encourage future studies to consider the benefits of long-term monitoring when designing and or/seeking funding for restoration efforts.

Statistical outputs are a common means of interpreting and reporting restoration success, yet information on the explanatory power of such outputs is often absent. Power analyses can promote confidence in restoration results/conclusions, and they can be undertaken prior to and upon completion of a project using open-source software such as G*Power (Faul et al., 2007). Statistical power is positively correlated with sample size, meaning prior to commencing a restoration project practitioners could use information from pilot/similar studies to determine the minimum sample size required to detect a true effect based on the desired power and significance levels. Alternatively, upon completion of a project, power analyses can determine whether non-significant findings represent a true lack of relationship between groups or a lack of statistical power. Of the studies examined in this review, none used power analysis to help contextualize their results.

4.3 | Scaling up restoration and future directions

To date, marine forest restoration has generally been conducted on small to medium scales (Eger et al., 2020b; Layton et al., 2020; Morris et al., 2020). Consequently, there is often little to no upscaling from restoration 'experiments' to large-scale restoration 'interventions'. Although small-scale restoration may be effective in the short term, particularly to conserve genetic diversity and locally adapted populations in areas where stressors are being mitigated (Boström-Einarsson et al., 2020), there are several potential benefits to conducting larger-scale restoration that are often overlooked. Increasing the scale and density of mature transplants can provide a favourable environment for the settlement, growth, and survival of recruits (Layton et al., 2019; Eger et al., 2020b). Greater transplant densities may also enhance chemical communication amongst individuals: for example, those impacted by herbivory may release chemical cues that induce the production of defensive compounds in proximal individuals, thus reducing the impact of herbivorous grazing (Toth & Pavia, 2000; Rohde, Molis & Wahl, 2004). Similarly, installing greater numbers of transplants or successfully seeding multiple areas is likely to enhance survival in regions with intact herbivore populations, as the relative impact of herbivory on the overall macroalgal population is diluted (Hambäck & Englund, 2005; Morris et al., 2020). However, for current and future restoration to expand and be successful beyond experimental scales, it is important to consider the lessons learned from previous works, the scalability of the methodology (for suggestions, see Eger et al., 2022b), and potential collaborations with stakeholders. For example, collaborating with the aquaculture industry could provide insights into technological advancements for effective rearing, or a greater source of propagules, whereas involving citizen scientists could be a cost-effective means of increasing the scale of implementation and monitoring of restoration initiatives.

Despite the aim of restoration most commonly being to restore species-rich habitats that support multiple ecosystem functions and services, a somewhat monospecific or species-centric approach to marine forest restoration is often employed. Although passive restoration techniques were found to restore multiple marine forest species, the active restoration of mixed species has yet to be employed (Morris et al., 2020). Mixed-species restoration has yielded positive results for other systems, including corals (Cabaitan, Yap & Gomez, 2015) and seagrass (Williams et al., 2017). Doing so in marine forest restoration could facilitate positive interspecific interactions and enhance the restoration success (Eger et al., 2020a). Furthermore, microbiome manipulation (Wood et al., 2019; Eger et al., 2020a) and co-restoration, involving the restoration of marine forest species alongside organisms that positively influence their survival (e.g. herbivory-controlling lobsters and otters) could promote favourable ecological interactions and, in turn, resilience. These approaches, however, require further investigation into their feasibility at scale (Eger et al., 2020a).

There is also a need to develop restoration beyond simply recovering what has been lost, to building marine forests tolerant to changing environmental conditions. For the most part, active restoration has involved seeding and/or transplanting individuals sourced from local donor populations. This process minimizes the swamping of local gene pools with foreign alleles that may result in outbreeding depressions and the loss of rare but locally adapted alleles. However, in the face of a changing climate, there is a growing need to investigate the restoration of areas using specially adapted foreign genotypes that can be identified through experiments (Coleman et al., 2020; Institure for Marine & Antarctic Studies, 2020) or environmentally adapted/tolerant species with similar ecological functions (Wood et al., 2019; Coleman et al., 2020). It is noteworthy, however, that there are ethical concerns surrounding the use of these techniques (Filbee-Dexter & Smajdor, 2019; Coleman et al., 2020) and, alongside genetic techniques, they may be costly and inaccessible to some restoration practitioners.

4.4 | Conclusions

The evidence reviewed here demonstrates that restoration can positively influence marine forests and is an important tool for reversing declines and protecting these ecosystems and their associated services. This review represents the first meta-analysis of marine forest restoration and provides a baseline for comparisons with future research (that should incorporate non-English language reports and projects in which the aims may not involve publication). To date, marine forest restoration has mainly occurred at experimental scales, primarily involving one species in one area, with monitoring often limited in scope and duration. Although there is no single formula for the successful restoration of marine forests, there is a need to streamline restoration efforts to facilitate comparisons across environments, species, and techniques to discern factors influencing success and inform best practices. In addition, a more holistic approach to restoration is required, including understanding the roles of genetic variability, local adaptation, and interactions among individuals and/or species. Similarly, determining whether the restoration of macroalgal species alone is sufficient to restore associated communities and ecosystem services is crucial. Future restoration efforts must be driven by innovative, multidisciplinary solutions, and have sustained financial and societal support to minimize further degradation, enhance restoration success, and ultimately promote marine forests that are resilient to changing environmental conditions.

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CONFLICT OF INTEREST

The authors have no conflicts of interest associated with this work.

DATA AVAILABILITY STATEMENT

The data used in this study are available from the corresponding author upon reasonable request.

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