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Does fishery management for groupers (Teleostei: Epinephelidae) protect them effectively? Context from the IUCN's Red list of threatened species

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ABSTRACT

Worldwide, groupers (Epinephelidae) are commercially valued fishes, which also play key ecological roles on tropical and subtropical reefs. In 2007 and 2016, the IUCN's Groupers and Wrasses Specialist Group assessed all 160+ grouper species, with 17 of these being identified as threatened in 2016 and the major threat factor being overexploitation. Our present study aimed to identify whether management measures (MMs) for previously assessed groupers were established, whether these measures aligned with IUCN's Red List categories, and whether they effectively protect grouper populations. Experts in grouper biology and management assigned scores per grouper species based on the extent to which MMs were in place and effective throughout these species' geographic ranges. Simple 4-level scores (0–3) were used to indicate the extent to which a MM was in place and how effective it was considered to be over the global distribution of each species. Of the 50 species scored, which included almost all threatened species, 97 % showed no/extremely limited/limited use of MMs, while only 3 % showed widespread/extensive use of MMs. Only 2 % of species showed highly/very effective scores for management, while 98 % showed limited/extremely limited/ineffective scores or no MMs in place. The

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MMs and their effectiveness were not commensurate with IUCN extinction risk levels. Overall, fishery management implemented for groupers by governments needs to be substantially improved, basic biological studies on many species are urgently required, fishing effort needs to be reduced, and regular biological and fishery monitoring conducted to evaluate the need for, and outcomes of, management. Although not all grouper species form spawning aggregations, recommendations are given to increase the protection of aggregating grouper species, in combination with well-placed Marine Protected Areas.

1. Introduction

Fisheries management should operate in such a way that exploited populations remain capable of sustaining the needs of fishers and communities (i.e. economic, socio-cultural or nutritional), while conserving wild populations at sufficient biological levels to remain healthy and reproductively viable (Cochrane, 2000). Fishery management measures employed include time- and area-based management, limited entry to a fishery, size-based restrictions, gear and catch restrictions, controls on fishing effort such as on numbers of fishers or boats and trade restrictions and sale controls (Melnychuck et al., 2021). As a measure of management effectiveness, the Food and Agriculture Organization (FAO) of the United Nations regularly reviews the status of global fisheries and reported that 64.5 % of global fished stocks were sustainably fished in 2021, down from 90 % since the mid-1970s, though proportions vary markedly depending on geographic area and species (Sharma et al., 2025).

Worldwide, groupers (Family Epinephelidae) are amongst the most valued reef-associated fishes but face high commercial exploitation and demand (Sadovy et al., 2007; Orth, 2023). Many species play key ecological roles, such as predation, on tropical and subtropical reefs (reviewed in Craig et al., 2011), where their populations are highly vulnerable to overexploitation. This is in part owing to their life history that, depending on the species, often includes slow growth, late maturity, residency, sex change and the formation of spatially and temporally predictable spawning aggregations (FSAs) (Abesamis et al., 2014; Robinson et al., 2015). As a result of both their biology and market demand, many species are now over-exploited and under varying levels of extinction risk according to assessments using the criteria and categories of the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species (Sadovy de Mitcheson et al., 2013; Sadovy de Mitcheson et al., 2020a,b; Rocklin et al., 2022; Coffill-Rivera, 2024; Sadovy de Mitcheson et al., 2024a).

Although total global landings for wild-caught grouper reported to FAO increase annually, from ca. 200 000 in 2000 to ca. 510 000 mt in 2022 (https://www.fao.org/fishery/statistics-query/en/capture/capture_quantity; accessed January 30, 2025), estimated actual grouper landings are almost certainly considerably lower and declining. Owing to the voluntary nature of reporting requirements to FAO, wild catches of groupers are poorly represented; a feature encountered by many fisheries in which actual catches deviate from those reported, as a consequence of, amongst others, omission of small-scale catches and non-reporting of bycatch (Pauly and Zeller, 2016). While these errors likely lead to underestimation of the true volume, the apparent inclusion of some aquaculture-raised groupers in China in wild-catch data is leading to inflation of reported landings, and likely explains the reported increases, even as these appear to be declining in many Asian countries (Sadovy de Mitcheson et al., 2020a,b).

The IUCN's Groupers and Wrasses Specialist Group assessed all grouper species worldwide using the IUCN's categories and criteria (www.iucnredlist.org), first in 2007 and then again in 2016, reaffirming the overexploited status of many species (Sadovy de Mitcheson et al., 2013, 2020b). Groupers have one of the highest proportions (>11 %) of threatened species among marine bony fish taxa (IUCN, 2025). Unfortunately, grouper fisheries management apparently did not improve in the decade between the two assessments above, despite concerns identified for multiple species (Sadovy de Mitcheson et al., 2020a,b). This scenario prompted the question as to whether the management situation for groupers could be qualitatively assessed in terms of management measures in place and the likely effectiveness of such measures. It is also of interest to identify whether grouper management measures and their effectiveness correlate with their assigned IUCN Red List categories. Thus, this study aimed to assess whether fishery management policy instruments and measures aligned with the threat status/categories assigned to grouper species based on the IUCN's Red List criteria and whether these instruments play a role in effectively protecting grouper populations.

2. Materials and methods

2.1. Scoring management measures by species

Seventeen IUCN Groupers and Wrasses Specialist Group (GWSG) members qualitatively assigned scores to management measures (MMs) for species which they were knowledgeable on; almost all of these members had undertaken Red List assessments for the species scored in the current study. The complete updated list of all groupers assessed by the GWSG is available in Sadovy de Mitcheson et al. (2020a,b) and the individual Red List Assessments (RLAs) are available at www.iucnredlist.org. A minimum of three scores (i.e. from three different scorers) was required for a species to be included in the analysis. Data Deficient (DD) species were excluded. The Red List (RL) categories used in the analysis, from most to least threatened, included Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT) and Least Concern (LC). The criteria used to assign threat categories can be found at www.iucnredlist.org. The Management Measure (MM) categories chosen for the analysis are those commonly used by various fishery management authorities (Table 1). Experts from the GWSG were also asked to give details regarding any species-specific MMs in place or if there were species-specific management recommendations - as opposed to general fisheries measures which were not particularly directed at groupers.

Experts were asked to assign qualitative scores based on their expert knowledge of species and management systems applied to each species i.e. an overall score per MM for each of their assigned species throughout

Table 1
Management Measure (MM) categories used by the GWSG experts to assess the 50 grouper species for which sufficient scores were received.

Management Measure	Description
No-take MPAs	Includes permanent closures
Fishing bans	Includes bans on sale, catch, trade or possession for given species or groupers generally
Fishing quotas	Fleet quotas, as opposed to bag limits per boat/fisher
Licensing restrictions	Caps on numbers of fishing licenses
Bag limits	Overall catch limits per boat/fisher of which a species, or all groupers, or all fishes, are part
Species size limits	Can include maximum or minimum sizes and/or slot limits for given species
Seasonal closures	Can include temporary closed fishing periods during spawning seasons
Gear restrictions	Excluding general restrictions, e.g. use of explosives, poisons
Trade restrictions	Either species-specific or as part of a combined suite of species from several families

their respective ranges, as follows: MM Scores: 0 = No use of this MM for the species; 1 = Extremely limited use of this MM; 2 = Some/Partial/Limited use of this MM; 3 = Widespread/Extensive use of this MM. Experts were also asked to assign Management Effectiveness (ME) scores per each MM for each species, based on their expert knowledge and judgement but usually without empirical data because few grouper populations are assessed post-management interventions. Effectiveness was defined as the experts' perceptions of the extent to which a Management Measure achieved its intentions. These scores were generally based on the knowledge of (1) the appropriateness of the MM for the selected species based on its life history, distribution and exploitation; (2) levels of management enforcement/compliance; and (3) documented outcomes of ME, e.g. population increase, larger fish, increased catches. The ME Scores were: 0 = No use of this MM or Not effective for this species; 1 = Extremely limited effectiveness; 2 = Some/Partial/Limited effectiveness; 3 = Highly/Very effective.

2.2. Analysis

Various descriptive metrics were used to assess the relative extent to which MM were in place.

Per RL category:

$$\mu_r = \frac{1}{|E_r|} \sum_{e \in E_r} \left(\sum_{s \in S_r} M_{e,s} \right)$$

Where:

μ_r - mean of the summed MM scores per Expert for all Species in each RL category
r - RL category
e - Expert
S - Species
M - Management Measure
S_r - Set of Species per RL category
E_r - Set of Experts' scores per RL
$M_{e,s}$ - sum of MM score given by Expert (e) to Species (s)

Per management measure:

$$\overline{M}_{j,r} = \frac{1}{n_r} \sum_{s \in S_r} \sum_{e \in E_s} M_{j,e,s}$$

Where:

$M_{j,r}$ - mean of Experts' scores per MM category for all Species per RL category
n_r - no. of Experts' scores per RL category
$M_{j,e,s}$ - the score given by Expert (e) to Species (S) for MM category j

Per species:

$$P_{j,s} = \frac{\sum_{e \in E_s} M_{j,e,s}}{|E_s| \cdot M_j^{\max}} \times 100\%$$

Where:

$P_{j,s}$ - the sum of Experts' scores for each MM for each Species expressed as a percentage of the sum of the maximum possible scores per Management Measure
$M_j^{\max}$ - maximum possible score for MM_j per Expert
$|E_s|$ - number of experts who scored Species s

The same approach was used for ME scores to determine how effective each MM was per RL category, per species and per management category.

To test whether there were significant differences between RL categories in relation to MM, ME, or MM weighted by ME (i.e. MM x ME), univariate and multivariate permutational analyses of variance models were employed (PERMANOVA; Anderson, 2001). For multivariate models of MM and ME, a matrix of sample rows by variable column scores was used. For univariate models, a matrix of sample rows with a single total column score derived by summation across variable columns was used. To weight MM scores by ME for each management variable, MM scores were simply multiplied by the corresponding ME score before input to the multivariate model. For the univariate model, the matrix was subsequently summed across variable columns before input. The Euclidean distances between among samples were then computed. Variations in MM, ME, and MM x ME were analysed separately using two-factor PERMANOVA with type III sums of squares and 9999 Monte-Carlo permutations of the residuals under the reduced default model in which all terms except the one being tested at the time are included. RL status was considered a fixed effect with five levels, while species was treated as a random effect with 50 levels. These analyses were supplemented with permutational analyses of multivariate dispersion (PERMDISP) or its univariate analogue to test for significant dispersion or homogeneity of variance among the five RL categories, respectively (Anderson, 2006). The multivariate data were displayed using principal component analysis with vectors of each MM or ME overlaid on the RL category plot of the 50 grouper species. All analyses were conducted with the software program PERMANOVA + for PRIMER 7.0.21 (Anderson et al., 2008). A significance level of 95 % was used for all tests and routines.

3. Results

Of the grouper species, 50 received sufficient scores (3+) to be analysed. Of these, 37 received 3 scores and 13 received 4 scores (Table 2; Supplementary Table S1). Species scored per respondent ranged from 1 to 21. Half (25) of the species occur in the Western Pacific, while the other oceanic subregions were represented by between 5 and 16 species each (Table 2), indicating the wide geographic distribution of the species considered. Assessments included 26 LC species and 17 species in threatened categories (CR, EN, VU). The remainder (7) were Near Threatened (NT). All threatened species on the IUCN Red List received three or more scores, except for two VU species (*Plectropomus marisrubi* and *Epinephelus lanceolatus*).

3.1. Descriptive metrics of management measures

Analyses of the 50 species scored by three or more experts indicated that 41.3 % had no species-specific MMs (i.e. MM = 0) and 36.3 % had extremely limited use of MMs. Only 19.4 % had Some/Partial/Limited use of MMs and only 3 % had Widespread or Extensive use of species-specific MMs (MM = 3). Overall mean scores by IUCN category indicated that CR (10.7 ± 8) and VU (9.7 ± 5) species had the most Management Measures, followed by NT and LC species (Fig. 1). The three EN species had the lowest score (6.6 ± 4.3) and there was variation around the mean for all categories.

Broadly, no-take MPAs followed by Seasonal closures were the most common MMs (Fig. 2). No-take MPAs were applied irrespective of RL categories. Species bans and Seasonal closures were most often applied to CR species. Otherwise, VU species generally had more Management Measures applied to them relative to species assessed in other RL categories.

A wide range in variability (6–63 %) was found in per-species overall MM scores expressed as a percentage of the maximum possible total of all measure scores combined; scores ranged widely for VU (11–63 %) and LC (6–59 %) species (Table 3). The Sevenbar grouper, *Hyporthodus ergastularius* (NT) and *Epinephelus striatus* (CR) scored in the top 10 for MMs (Table 3). The 10 lowest-scoring species included 8 LC, 1 NT and 1

Table 2
List of 50 grouper species scored by at least three respondents, ordered by decreasing IUCN extinction risk. EA – Eastern Atlantic (including the Mediterranean Sea), WA – Western Atlantic, EP – Eastern Pacific, WP – Western Pacific, EI – Eastern Indian, WI – Western Indian. CR - Critically Endangered, EN - Endangered, VU – Vulnerable, NT - Near Threatened, LC - Least Concern.

Species	EA	WA	EP	WP	EI	WI	No. scorers	IUCN Category
Epinephelus striatus		*					3	CR
Epinephelus akaara				*			3	EN
Mycteroperca jordani			*				3	EN
Mycteroperca olfax			*				3	EN
Epinephelus bruneus				*			3	VU
Epinephelus fuscoguttatus				*	*	*	3	VU
Epinephelus itajara	*	*					4	VU
Epinephelus morio		*					3	VU
Epinephelus polyphekadion				*	*	*	3	VU
Hyporthodus acanthistius			*				3	VU
Hyporthodus flavolimbatus		*					3	VU
Hyporthodus niveatus		*					4	VU
Mycteroperca fusca	*						3	VU
Mycteroperca interstitialis		*					3	VU
Mycteroperca marginatus	*	*				*	4	VU
Mycteroperca microlepis		*					4	VU
Plectropomus areolatus				*	*	*	3	VU
Epinephelus aeneus	*						3	NT
Epinephelus daemelii				*			3	NT
Hyporthodus ergastularius				*			4	NT
Hyporthodus nigritus		*					3	NT
Mycteroperca bonaci		*					3	NT
Mycteroperca goreensis	*						4	NT
Mycteroperca venenosa		*					3	NT
Cephalopholis argus	*			*	*	*	4	LC
Cephalopholis cruentata		*					3	LC
Cephalopholis fulva		*					3	LC
Cephalopholis furcifer	*	*					4	LC
Cephalopholis igarashiensis				*			3	LC
Cephalopholis nigripinnis				*	*	*	3	LC
Epinephelus adscensionis	*	*					3	LC
Epinephelus chlorostigma				*	*	*	3	LC
Epinephelus coioides				*	*	*	4	LC
Epinephelus fasciatus				*	*	*	3	LC
Epinephelus guttatus		*					3	LC
Epinephelus kupangensis				*			3	LC
Epinephelus malabaricus				*	*	*	3	LC
Epinephelus rivulatus				*	*	*	3	LC
Epinephelus stictus				*			3	LC
Epinephelus trimaculatus				*			3	LC
Epinephelus tukula				*	*	*	3	LC
Hyporthodus dermopterus				*			4	LC
Hyporthodus niphobles			*				3	LC
Hyporthodus octofasciatus				*	*	*	3	LC
Mycteroperca radiatus				*	*	*	3	LC
Mycteroperca rosacea			*				3	LC
Mycteroperca rubra	*						4	LC
Plectropomus laevis				*	*	*	3	LC
Plectropomus leopardus				*	*		4	LC
Plectropomus maculatus				*	*		4	LC

VU species. All three EN species (*E. akaara*, *Mycteroperca jordani*, *M. olfax*) received relatively low MM scores.

All nine MMs (i.e. all management categories identified in this study) were applied to the 50 grouper species with the following exceptions: 10 species did not have Trade restrictions; 4 species did not have Species bans or Size limits; and 1 species did not have Gear restrictions (Fig. 3). The Longtooth grouper, *E. bruneus* (VU), Oval grouper, *H. dermopterus*, Threespot grouper, *E. trimaculatus* and Leopard grouper, *Mycteroperca rosacea* (all LC) had the least Management Measures applied to them. Broadly, based on their slight visual prominence in Fig. 3, MPAs as well as Gear restrictions were the MMs most widely applied for the 50 species examined.

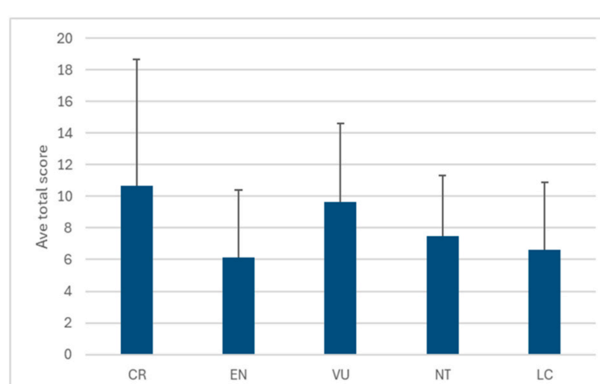

Fig. 1. Mean (±SD) overall Management Measures scores for 50 grouper species by IUCN Red List category. CR - Critically Endangered, EN - Endangered, VU – Vulnerable, NT - Near Threatened, LC - Least Concern.

3.2. Descriptive metrics of management measure effectiveness

Overall, only 1.6 % of scores indicated that MMs were Highly/Very effective (i.e. ME = 3), 15.5 % of scores were for Partially/Limited

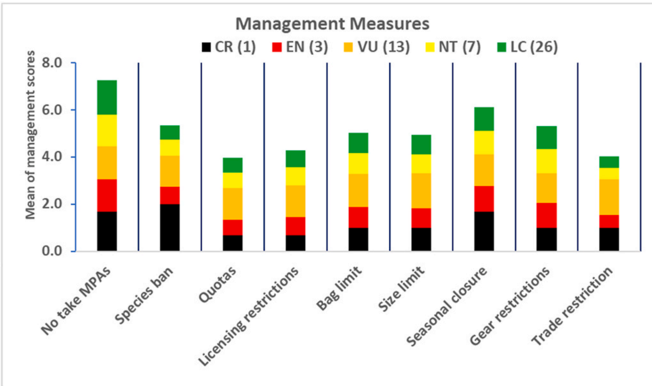

Fig. 2. Means of Management Measure scores for 50 grouper species per their IUCN Red List category, separated by Management Measure. CR - Critically Endangered, EN - Endangered, VU – Vulnerable, NT - Near Threatened, LC - Least Concern. Numbers in parentheses are numbers of species in each RL category.

Table 3
Overall Management Measure (MM) scores for 50 grouper species, expressed as a percentage (%) of the overall maximum possible score. IC = IUCN category.

Species	IC	%	Species	IC	%
Mycteroperca microlepis	VU	63	*Mycteroperca bonaci*	NT	27
Epinephelus coioides	LC	59	*Mycteroperca radiatus*	LC	26
Mycteroperca marginatus	VU	57	*Hyporthodus acanthistius*	VU	26
Plectropomus leopardus	LC	46	*Epinephelus stictus*	LC	25
Plectropomus areolatus	VU	46	*Hyporthodus octofasciatus*	LC	25
Epinephelus polyphekadion	VU	44	*Epinephelus adscensionis*	LC	23
Hyporthodus niveatus	VU	43	*Mycteroperca olfax*	EN	22
Hyporthodus ergastularius	NT	42	*Plectropomus laevis*	LC	22
Epinephelus striatus	CR	40	*Mycteroperca interstitialis*	VU	22
Mycteroperca rubra	LC	37	*Cephalopholis argus*	LC	21
Epinephelus morio	VU	36	*Cephalopholis igarashiensis*	LC	21
Epinephelus malabaricus	LC	36	*Epinephelus fasciatus*	LC	20
Hyporthodus niphobles	LC	36	*Cephalopholis fulva*	LC	19
Mycteroperca fusca	VU	36	*Mycteroperca venenosa*	NT	19
Epinephelus daemelii	NT	33	*Mycteroperca jordani*	EN	19
Epinephelus fuscoguttatus	VU	32	*Cephalopholis cruentata*	LC	19
Epinephelus tukula	LC	31	*Cephalopholis nigripinnis*	LC	19
Epinephelus itajara	VU	31	*Epinephelus chlorostigma*	LC	19
Epinephelus guttatus	LC	30	*Mycteroperca goreensis*	NT	19
Epinephelus rivulatus	LC	30	*Hyporthodus dermopterus*	LC	17
Epinephelus aeneus	NT	30	*Cephalopholis furcifer*	LC	16
Hyporthodus nigritus	NT	30	*Epinephelus kupangensis*	LC	12
Plectropomus maculatus	LC	28	*Epinephelus trimaculatus*	LC	11
Hyporthodus flavolimbatus	VU	28	*Epinephelus bruneus*	VU	11
Epinephelus akaara	EN	27	*Mycteroperca rosacea*	LC	6

effectiveness, 34.4 % of scores reflected Extremely Limited effectiveness and 48.5 % of showed there were no MM in place, or the MM was judged to be ineffective (ME = 0) (Fig. 4). Higher mean scores suggested that MM for VU (8.4 ± 4) and CR (8 ± 5) species were more effective, while NT and LC species scored lower and EN species the lowest (4.6 ± 3.4); there was wide variability in scoring within all management categories. Broadly, ME was highest for No-take MPAs and lowest for Trade restrictions (Fig. 5). Effectiveness of No-take MPAs was equivalent for all RL categories. The effectiveness of all nine MMs for VU species was similar and generally higher compared to other RL categories (Fig. 5).

There was species-specific variability in the ratios of actual to maximum possible ME scores (5–52 %) particularly for VU (11–48 %) and LC (5–52 %) species (Table 4). In contrast, less variability was observed for EN and NT species and generally VU species received the highest ME scores. Other species in the top 10 for management effectiveness included LC species (Orange-spotted grouper, *E. coioides* and Leopard coral grouper, *Plectropomus leopardus)* and *H. ergastularius* (NT). Eight of the 10 lowest scoring species were LC, in addition to *E. bruneus* (VU) and Dungat grouper, *Mycteroperca goreensis* (NT). Several VU species had higher effectiveness scores than the CR species and, except for *E. bruneus*, all VU species had higher scores than EN species, which had relatively low ME scores (Table 4). Broadly, effectiveness of MPAs appeared more visually prominent (Fig. 6).

Both univariate and multivariate models detected a significant difference among RL categories based on MMs ($p_{(Monte\text{-}Carlo)} < 0.05$). *Post hoc* pairwise comparisons only revealed significant differences between VU and LC for both the univariate ($p_{(Monte\text{-}Carlo)} = 0.0008$) and multivariate ($p_{(Monte\text{-}Carlo)} = 0.0023$) models (Supplementary Material Table S2). Similarly, both models based on ME indicated significant differences among RL categories ($p_{(Monte\text{-}Carlo)} < 0.01$). *Post hoc* comparisons indicated differences between VU and LC ($p_{(Monte\text{-}Carlo)} = 0.0002$), EN and VU ($P_{(Monte\text{-}Carlo)} = 0.0131$), and CR and EN ($p_{(Monte\text{-}Carlo)} = 0.0269$) for the univariate model, but only a difference between VU and LC ($p_{(Monte\text{-}Carlo)} = 0.0006$) for the multivariate model (Supplementary Material Table S3). When MMs were weighted by ME, differences among RL categories were again detected for both models ($p_{(Monte\text{-}Carlo)} < 0.05$; Table 5). Significant differences were detected between VU and LC for both univariate ($p = 0.0012$) and multivariate ($p_{(Monte\text{-}Carlo)} = 0.003$) models, and between EN and VU ($p_{(Monte\text{-}Carlo)} = 0.0322$) in the univariate model (Table 5). Permutational analyses of dispersion found no differences among RL categories for all test comparisons ($p_{(Monte\text{-}Carlo)} > 0.05$).

The PCA plot of Management Measures showed overlap among most RL categories with the first two axes accounting for 60 % of the cumulative variation (Supplementary Material Fig. S1). Management Measures 7 (Seasonal closures) and 1 (MPAs) had highest correlations with the first two axes. The PCA of Management Effectiveness similarly showed overlap among most RL categories, although there was more obvious separation between Least Concern and Vulnerable categories with the first two axes accounting for 56 % of the variation (Supplementary Material Fig. S2). Effectiveness of Management Measures 7 (for Seasonal closures) and 1 (for MPAs) again had the highest correlations with the first two axes. The PCA of Management Measures weighted by Management Effectiveness showed overlap among most RL categories, with some indication of separation between LC and VU; the first two axes accounted for 56 % of the variation (Fig. 7). Similarly to Management Measures and Management Effectiveness assessed separately, the weighted MM 7 (Seasonal closures) and MM 1 (MPAs) had the highest correlations with the first two axes.

4. Discussion

Information on the extent to which management measures for reef fishes are in place and effective is not readily available. For groupers there are no dedicated studies which assess management outcomes at broad regional scales and few (e.g. Halim et al., 2020; Kaplan et al., 2021) at the local level, even where management has been in place for many years. Assessment of management effectiveness is therefore challenging and was herein largely influenced by considering indications of recovery or cessation of population declines based on expert knowledge including available literature. Experts had to consider disparities in the application of management measures, and their likely effectiveness, throughout the ranges of species, and to reduce these to simple scores. Experts would also have encountered such challenges when assigning global Red List extinction risk categories to grouper species. These challenges stem from several factors: markedly variable population levels, very different exposure to fishing pressure, and varied management regimes across geographic ranges, together with limited population status assessments (Sadovy et al., 2007), and, as indicated above, even fewer evaluations of management outcomes. The responding experts emanate from a wide geographic range, with most having grouper experience from multiple oceans; however, it was not possible to ensure complete objectivity when scores were assigned.

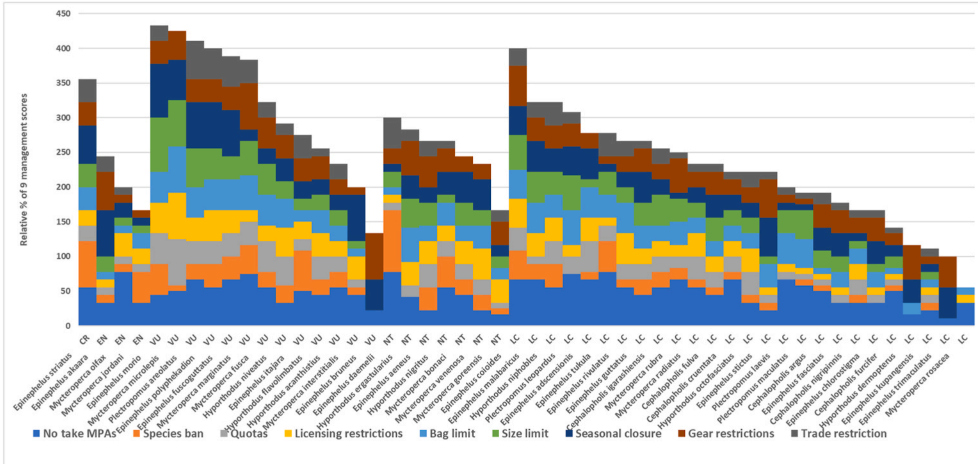

Fig. 3. Scores per Management Measure for the 50 grouper species, expressed as a relative percentage (%) of the maximum possible score for each Management Measure. The maximum possible score for a species is 900.

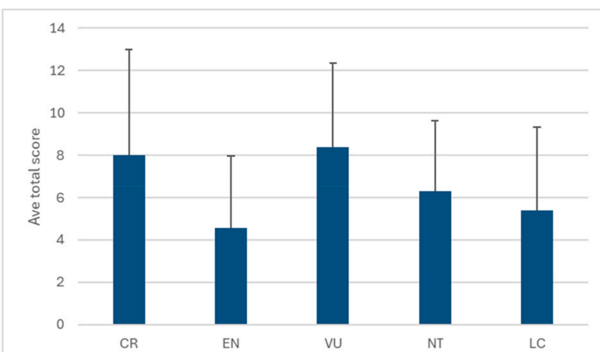

Fig. 4. Mean (±SD) overall Management Effectiveness scores for 50 grouper species by IUCN Red List category. CR - Critically Endangered, EN - Endangered, VU – Vulnerable, NT - Near Threatened, LC - Least Concern.

4.1. Management measures and their effectiveness in terms of the IUCN red list

The majority (77 %) of the raw MM scores were 0 or 1, suggesting that there was no/extremely limited use of management measures for the 50 grouper species examined. Similarly, a very large proportion (83 %) of experts' raw management effectiveness scores were also 0 or 1, indicating that there was also no/extremely limited perceived effectiveness of these measures. We predicted that more MMs would be applied, and more effectively, to species with greater risk of extinction (or at least a higher IUCN threat category). However, this was not the case, i.e. the extent and effectiveness of MMs were not commensurate with IUCN extinction risk levels. While MM and ME scores were consistently and significantly different between LC and VU species, including in combination (as the product of the MM and ME scores), there were no significant differences between any of the other category combinations, i.e. the application of MMs for CR, EN and NT species was considered to be no different to that for LC species. There was however some indication that ME differed among the RL categories in the univariate model.

The 15 VU species had the 2nd highest overall MM scores (after CR), i.e. the measures were generally thought to be more effective for these species, relative to most of the other RL categories. The 26 LC species

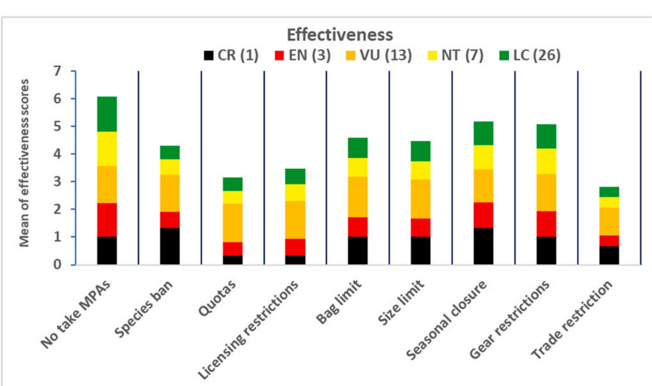

Fig. 5. Means of Management Effectiveness scores for 50 grouper species combined by Red List category. CR - Critically Endangered, EN - Endangered, VU – Vulnerable, NT - Near Threatened, LC - Least Concern. Numbers in parentheses are numbers of species.

Table 4
Overall Management Effectiveness (ME) scores for 50 grouper species, expressed as a percentage (%) of the maximum possible score. IC = IUCN category.

Species	IC	%	Species	IC	%
Epinephelus coioides	LC	52	*Epinephelus rivulatus*	LC	21
Mycteroperca marginatus	VU	48	*Hyporthodus nigritus*	NT	21
Plectropomus leopardus	LC	46	*Mycteroperca interstitialis*	VU	21
Mycteroperca microlepis	VU	44	*Plectropomus laevis*	LC	21
Hyporthodus ergastularius	NT	41	*Cephalopholis argus*	LC	20
Hyporthodus niveatus	VU	40	*Epinephelus adscensionis*	LC	20
Plectropomus areolatus	VU	38	*Mycteroperca venenosa*	NT	20
Epinephelus polyphekadion	VU	36	*Plectropomus maculatus*	LC	20
Mycteroperca fusca	VU	36	*Epinephelus akaara*	EN	19
Epinephelus morio	VU	34	*Cephalopholis fulva*	LC	18
Mycteroperca rubra	LC	31	*Cephalopholis nigripinnis*	LC	17
Epinephelus itajara	VU	30	*Mycteroperca olfax*	EN	17
Epinephelus malabaricus	LC	30	*Hyporthodus octofasciatus*	LC	16
Epinephelus striatus	CR	30	*Hyporthodus dermopterus*	LC	15
Epinephelus daemelii	NT	27	*Mycteroperca jordani*	EN	15
Epinephelus tukula	LC	27	*Cephalopholis furcifer*	LC	14
Epinephelus fuscoguttatus	VU	27	*Cephalopholis igarashiensis*	LC	14
Epinephelus aeneus	NT	26	*Epinephelus chlorostigma*	LC	12
Mycteroperca radiatus	LC	26	*Epinephelus bruneus*	VU	11
Epinephelus guttatus	LC	25	*Epinephelus fasciatus*	LC	11
Hyporthodus acanthistius	VU	25	*Epinephelus kupangensis*	LC	11
Hyporthodus niphobles	LC	25	*Mycteroperca goreensis*	NT	11
Epinephelus stictus	LC	22	*Epinephelus trimaculatus*	LC	10
Hyporthodus flavolimbatus	VU	22	*Cephalopholis cruentata*	LC	8
Mycteroperca bonaci	NT	22	*Mycteroperca rosacea*	LC	5

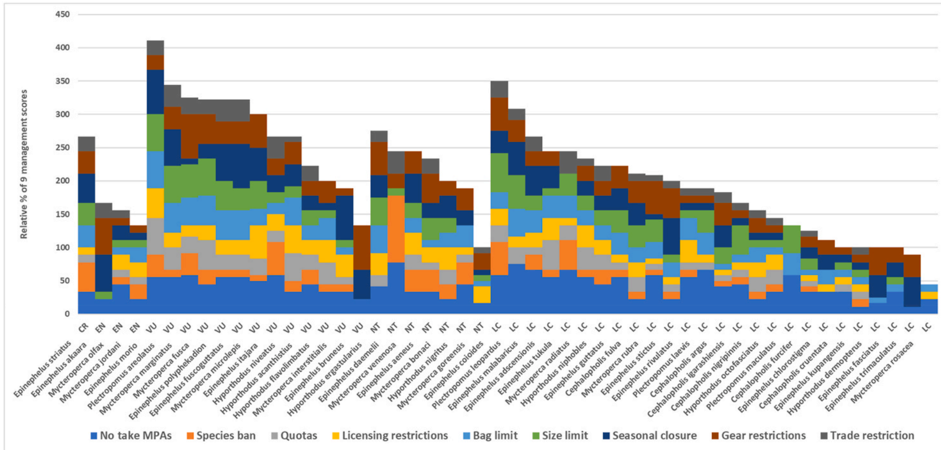

Fig. 6. Scores for Management Effectiveness for each of the 50 grouper species, expressed as a percentage (%) of the maximum possible score per Management type. The maximum possible score for a species is 900.

Table 5
Univariate and multivariate model results testing for differences in Management Measures weighted by Management Effectiveness between IUCN Red List categories. Bold signifies a significant difference $p < 0.05$.

IUCN Category	Univariate model		Multivariate model	
	T	$p_{(\text{Monte-Carlo})}$	T	$p_{(\text{Monte-Carlo})}$
CR vs EN	3.0376	0.0856	1.0649	0.4047
CR vs VU	0.18636	0.8523	0.7027	0.7852
CR vs NT	0.79083	0.4567	0.58475	0.877
CR vs LC	1.342	0.1872	1.1913	0.2176
EN vs VU	2.3164	**0.0322**	1.1712	0.2277
EN vs NT	0.93152	0.3841	0.69244	0.7884
EN vs LC	0.45191	0.6555	0.79006	0.6329
VU vs NT	1.5975	0.1255	1.3025	0.1334
VU vs LC	3.5222	**0.0012**	2.0693	**0.003**
NT vs LC	0.91434	0.3663	1.3678	0.1047

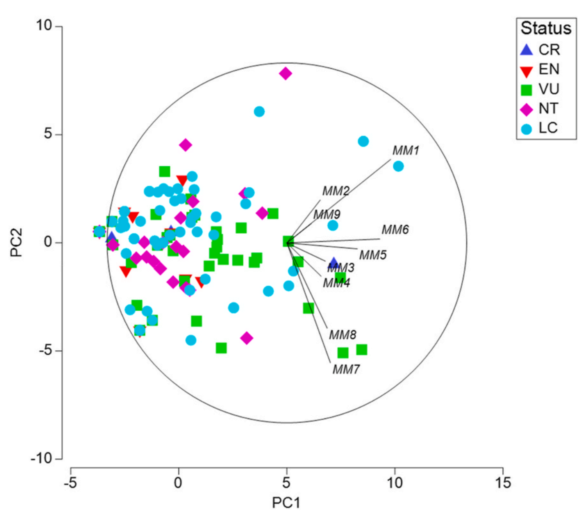

Fig. 7. Principal Component Analysis of the product of Management Measure x Management Effectiveness scores for 50 grouper species as a function of IUCN Red List category. Management Measures (MM) are: 1 - No-take MPAs; 2 - Species bans; 3 – Quotas; 4 - Licensing restrictions; 5 - Bag limits; 6 - Size limits; 7 - Seasonal closures; 8 - Gear restrictions; 9 - Trade restrictions.

had the 2nd lowest overall MM score, slightly higher than that for the three EN species. The VU and LC species showed the widest range in MM scores, although species' MM scores varied considerably within all RL categories, apart from NT species. The VU species generally had more MMs applied to them relative to the other RL categories, excepting for MPAs, Fishing bans and Seasonal closures, for which the Critically Endangered (CR) *E. striatus* scored higher. The VU category had the highest overall mean ME score, slightly higher than CR, while EN had the lowest. VU species scored highest for ME among all MMs, excepting for Seasonal closures. VU and LC species again had the widest ranges in scores. The single CR species, *E. striatus*, had only the 8th highest MM score, with an ME score that was even lower (14th). This species occurs in the wider Caribbean where it has been heavily exploited for decades and is particularly vulnerable owing to the formation and long-term exploitation of highly predictable fish spawning aggregations (FSAs) (Sadovy et al., 2018a). The use of MMs for *E. striatus* varies throughout its geographic range (Supplementary Table S4) though these measures are generally poorly or not enforced (Sadovy de Mitcheson et al., 2024b). However, it is noteworthy that, in the few places where enforcement is strong and monitoring is conducted, population increases have occurred (Craig et al., 2011; Sadovy et al. 2018a, 2018b; Waterhouse et al., 2020).

Among EN species, the Hong Kong grouper, *Epinephelus akaara*, Gulf grouper, *Mycteroperca jordani* and Sailfin grouper, *M. olfax* had lower MM and ME scores than most species in lower risk categories, as well as the lowest overall mean scores. None had species-specific management measures in place (Supplementary Table S4). *Epinephelus akaara* has experienced severe declines due to fishing and lack of regulation/management (e.g. Liu and Sadovy de Mitcheson, 2009) and it is caught throughout its limited geographic range between China and Japan, with extremely limited management. Although Japan introduced a restocking programme in one Prefecture, this has not demonstrably recovered the wild population despite increased capture levels of young fish (Yamamoto and Katayama, 2022). In California and Mexico in the Eastern Pacific, *M. jordani* is heavily targeted with poor enforcement over much of its limited geographic range (Erisman and Craig, 2018), while *M. olfax* has a very small geographic range, mainly populating eastern Pacific islands, and despite largely occurring within MPAs, management enforcement is ineffective (Craig et al., 2011, Erisman and Craig, 2018; Sadovy et al. 2018a, 2018b).

Among VU species, *E. bruneus* had the lowest MM and ME scores, with only three MMs in place (though no species-specific measures were listed by experts; Supplementary Table S4). This species was once common but is now generally rare throughout its small geographic range in the Western Pacific, where it is heavily fished across all size classes with a variety of fishing gears, and very little effective management is in place (Craig et al., 2011; To et al., 2018). Widely distributed in the Western Atlantic, *Mycteroperca interstitialis* (VU) also received low MM and ME scores and is experiencing substantial population declines due to overfishing and inadequate management (Craig et al., 2011; Padovani-Ferreira et al., 2018). Similarly, *M. goreensis* (NT) had particularly low MM and ME scores. While population data for *M. goreensis* are limited, what does exist exhibits marked declines. Like *M. interstitialis*, *M. goreensis* receives limited fisheries management which is of minimal perceived effectiveness across its range (literature reviewed in Craig et al., 2011; Pollard and Rocha, 2018).

Some species in the lowest extinction risk category (LC), scored high for management measures and their effectiveness. *Plectropomus leopardus*, *E. coioides* and Mottled grouper, *Mycteroperca rubra* (LC) all had MM scores in the top 10 (and amongst the highest ME scores for the first two species). The first two are overfished in some areas of their wide geographic distribution in the Indo-West Pacific but occur quite commonly. These species have differing MMs in place depending on their geographic location, and there is likely similar variability in effectiveness; their LC status may reflect higher perceived management effectiveness over their wide distribution. *Plectropomus leopardus* can possibly sustain somewhat higher levels of fishing pressure due to their relatively fast growth and early maturation (Samoilys, 1997). *Mycteroperca rubra* is widely distributed in the Eastern Atlantic and Mediterranean, but is naturally uncommon, with declines in areas with high fishing pressure (literature for these three species was reviewed in Craig et al., 2011; Amorim et al., 2018; Choat and Samoilys, 2018; Pollard and Francour, 2018).

The IUCN Red List criteria assess the threat status, which may help management decision-makers address threats to biodiversity (Betts et al., 2020; Marsh et al., 2022). However, when examining sustainability of wild species in terms of their Red List categorization, Marsh et al. (2022) noted that ca. 30 % of threatened or Near Threatened species were being exploited and about 33 % of the ca. 10 000 exploited species had no targeted management actions addressing exploitation. These authors also noted that aquatic exploited species often lack management, even though fisheries are the principal threat (Reynolds et al., 2005; Sadovy de Mitcheson et al., 2020a,b; Miranda et al., 2022). In our study, only 26 of the 50 species scored had species-specific management measures in place (Supplementary data, Table S4). Most species were covered by general (not species-specific) management measures, such as MPAs or general Bag limits in some areas, but the effectiveness of such measures for groupers is not always known. There were more species (36) for which management recommendations were provided, either in the RL assessments or during the scoring process (Supplementary Table S5), but these were often very general, such as "reduce fishing pressure". Sadovy de Mitcheson et al. (2020a,b) noted that management had improved for very few of the species originally assessed as threatened in 2007 (Sadovy de Mitcheson et al., 2013). Our findings support this latter observation – overall, experts considered there to be limited management measures in place for the 50 threatened groupers examined here, with management, if in place, largely ineffective or of unknown effectiveness, and mostly not species-specific.

4.2. Considerations for managers

Identifying grouper management measures and documented or inferred effectiveness across the geographic distributional range of species is complicated due to a lack of monitoring of most species whether managed or unmanaged. The number of species involved, combined with their variable life histories, fishing impacts, jurisdictional differences in management and effectiveness of implementation, result in management outcomes that vary enormously (Coffill-Rivera, 2024). Nonetheless, several examples of population recovery following management demonstrate that effective, long-term monitoring and management can protect and restore overfished grouper populations and enable adaptive management. Examples providing some hope include *Epinephelus guttatus* in Bermuda (Pitt et al., 2017) and the US Virgin Islands (Rosemond et al., 2022), *E. striatus* in the Cayman Islands (Waterhouse et al., 2020), Squaretail coral grouper *P. areolatus* in Palau (Sadovy de Mitcheson et al., 2020a,b) and Indonesia (Puspasari et al., 2023), Goliath grouper *E. itajara* in the U.S. (Coleman et al., 2023) and *Plectropomus* spp in Malaysia (Chung et al., 2017). However, cautionary tales exist even within recovering species, like *E. itajara* in the U.S., where increasing pressure from fishers to lift management measures as numbers increase, coupled with simultaneous effects of anthropogenic stressors and ignoring scientific advice, can lead to reversal of recovery (Coleman et al., 2023). Lack of success with management measures, and/or a lack of effectiveness, have recently been documented for Dusky grouper, *E. marginatus* in the Paraty Bay MPA, Brazil (Silvano et al., 2017), *E. itajara* in Cuba (Amargós et al., 2025), Saddletail grouper, *E. daemelii* in Australia (Harasti and Malcolm, 2024), Giant grouper, *E. lanceolatus* in the Western Indian Ocean (Samoilys et al., 2025) and Tomato hind, *Cephalopholis sonnerati* in Sri Lanka (Dalpathadu and Haputhantri, 2025).

Mariculture was not included as a MM herein because, despite claims and hopes to the contrary, and as currently practiced for groupers, its development does not take pressure off wild populations (Froehlich et al., 2023). Over the last few decades, global mariculture production has increased dramatically in response to increased demand for seafood and declines in wild capture fisheries (Ghazali et al., 2025). For groupers, mariculture production now equals or exceeds that from wild capture fisheries despite full cycle aquaculture only being developed for very few grouper species. In none of the grouper species we examined was mariculture development specifically part of a management plan to reduce either catch volumes or fishing effort. On the contrary, in some cases grouper mariculture increases exploitation pressure when juveniles are heavily targeted for grow-out operations; such juvenile fisheries are not managed or monitored (Mous et al., 2006; Sadovy de Mitcheson and Liu, 2022). There are also sustainability concerns with respect to safeguarding of wild grouper genetic stability (Ghazali et al., 2025).

A complicating factor for management is that groupers are mostly only one component of the catch, particularly in multi-species, small-scale fisheries (Babcock et al., 2018; Coronado et al., 2020; Sosa-Cordero et al., 2023). They are typically targets of reef fisheries and also valued by-catch in non-reef fisheries and their value depends greatly on size and condition as well as species. Fisheries which catch groupers frequently occur in complex socio-ecological settings and often in countries of low to moderate income levels (Amorim et al., 2019). Such fisheries tend to be data- and management resource-limited (Cope et al., 2023); but even well-resourced countries are compelled to apply management measures based on the life histories of only a few species, not necessarily groupers, which make the most contribution to catches in multi-species fisheries (e.g. Farmer et al., 2016).

Fisheries managers in countries which are less well-resourced could also adopt this approach of focussing on species which contribute the most to catches. There is also scope for geographically proximal countries to consider harmonising management for co-occurring species. Notwithstanding geopolitical tensions and differing priorities, it would make sense for countries with common biogeography to align their approaches to management. There are cases where this happens already, such as with National Oceanic and Atmospheric Administration Fisheries and the South Atlantic, Gulf and Caribbean Fishery Management Councils which manage the *E. morio* fishery, along with a suite of other reef fishes (Sadovy de Mitcheson et al., 2024a). Further afield, many of the reef fish management regulations in South Africa and neighbouring Mozambique, including for several grouper species, are closely aligned.

A common recommendation included in the RL assessments for aggregating species among the 50 groupers examined in our study is to increase the protection of their spawning aggregation sites and/or spawning aggregations. The best-known, and one of the most overfished aggregating groupers, is the Critically Endangered Nassau grouper, *E. striatus* from the Western Atlantic. Once numbering in the 10s–100s of thousands of fish aggregated in reefs of the Bahamas and Belize in the

1970s, many aggregations have either been fully extirpated or have declined to levels that make population recovery extremely difficult, even with management in place (reviewed in Sadovy et al., 2018a). Nonetheless, in the Cayman Islands in the Caribbean, some recovery was noted after more than two decades of careful governance and science-supported management, enforcement and monitoring (Waterhouse et al., 2020). Similarly, science-driven management of the aggregating *E. guttatus* in the US Virgin Islands over three decades has enabled the species to rebound from overfishing (Rosemond et al., 2022). These two examples highlight the need for effective management to protect both fish and fisheries, and of monitoring to detect the resulting changes (Khasanah et al., 2019).

In our study, MPAs and Seasonal closures were the management measures most widely applied and sometimes considered effective for some of the 50 grouper species examined. However, studies have shown that, despite their appeal for conservation, the capabilities of spatial/seasonal protection measures, such as MPAs, be they for aggregations or otherwise, is heavily dependent on their extent, duration, location, species' life history, migration, larval dispersal, and enforcement effectiveness (Biggs et al., 2021; Coffill-Rivera, 2024; Sadovy de Mitcheson et al., 2024b). While MPAs are generally important for sedentary species, these MPAs need to be large enough for wider-ranging groupers and, for those that migrate to spawn, multiple management measures, including seasonal protection of spawning aggregations, are probably needed. One advantage of MPAs is that they can be planned to simultaneously protect the spawning aggregation sites and the nursery areas for multiple fishery resources. Ultimately, a two-pronged approach of seasonal closures inclusive of both fishing and sales/possession bans during spawning times together with judiciously placed MPAs could prove successful for species which aggregate to spawn.

Notwithstanding the lower management effectiveness scores we recorded for Trade restrictions, Fishing quotas and Licensing restrictions, these measures do have a potential role in management. Trade control following a CITES Appendix II listing in 2004 substantially reduced international trade in Napoleon wrasse *Cheilinus undulatus*, both through reduced export quotas by the major exporter, Indonesia (but see Sadovy et al., 2007; Hau and Sadovy de Mitcheson, 2023), and because several countries opted to ban exports following the listing (Vincent et al., 2022). Reduction in international trade has also occurred in other CITES-listed marine species, such as some elasmobranchs (Bond et al., 2025). Hence, a CITES II listing could be a management option for highly threatened species, such as *E. striatus*, for which the major threat is international trade.

While fleet catch quotas and effort control are often not appropriate for informal (unlicensed) small-scale fisheries, which are frequently open-access (Arthur, 2020) and may be employers of last resort (Cross, 2015), these measures are successfully used in more formal small-scale commercial fisheries which target groupers, such as in Australia (Harrison et al., 2023). Here, the Leopard coral grouper, *P. leopardus* is protected by temporal and spatial closures for the main spawning aggregation periods on the Great Barrier Reef, Queensland, which closures also apply to other coral reef fish species in this area (Frisch et al., 2016), making compliance with these closures simpler to manage. This has resulted in a well-managed and sustainable grouper fishery for *P. leopardus* (Campbell et al., 2019), though a relatively fast growth rate also helps (Samoilys, 1997).

While minimum size limits are often applied to groupers (Table S4), their effectiveness as a harvest control measure has seldom been demonstrated, one positive example being for coral grouper (*P. maculatus*) in Australia (Lavin et al., 2021). However, survival of sublegal-sized groupers caught at depth and returned to the water may be compromised by barotrauma (Sauls, 2013; Foster et al., 2017); survival can be improved, though, by rapidly recompressing such fish by returning them to deeper water (Stallings et al., 2023). An alternative approach via regulating hook size to reduce the catch rates of small groupers has demonstrated some utility (Yulianto et al., 2023).

The effectiveness of any management measure, including MPAs, is generally proportionate to the levels of monitoring, enforcement effectiveness and compliance, but the latter also depends on the levels of stakeholder education and communication and of government engagement, especially in relation to management. Many tropical locations where groupers occur have poor monitoring and compliance, partly a function of high fisheries species diversity, difficulties with identification leading to lumping of species in catches, numerous and dispersed landing sites, limited enforcement capacity, and socioeconomic pressures. So even when management measures are in place, they may often remain ineffective and are rarely assessed for outcomes (Williams and Corral, 1999). Finally, there are instances in which even highly protective management has not succeeded – such as for *E. daemelii* in Australia, which has been severely depleted for over a century, followed by almost total protection for the past ca. 40 years, yet with no convincing signs of population recovery (Harasti and Malcolm, 2024).

Bearing in mind the fundamental premise of fisheries management is that wild populations can be exploited at sustainable levels, and that the most benefits can be gained from fishing at close to maximum productivity, it is evident that species particularly susceptible to overfishing need to be managed carefully and effectively to achieve such a goal. Establishing which species are at risk requires fundamental knowledge on their taxonomic identity, life history, ecology and behaviour, which is lacking for many groupers that are fished. Finally, management agencies would do well to be more cognizant of IUCN RL threat status assessments in pursuit of improving management and its outcomes for groupers; while recognizing the realities of difficulties with species identification and the tendencies of fishers and traders to aggregate similar-looking/similar-value species together.

5. Conclusion

We recognize that we have only considered management effectiveness in terms of implications for grouper populations and acknowledge that there is considerable scope to also consider management outcomes and implications for fishers and communities, such as potential loss of income, or increased food insecurity. However, these were beyond the scope of this study. We explored the use and effectiveness of fishery management measures for 50 groupers worldwide, including almost all threatened species, and found that species-specific fisheries management is typically absent. Where measures do exist, their effectiveness is frequently limited, unknown or inadequate. Further, although the Critically Endangered *E. striatus* is subject to multiple management measures, Endangered species are receiving less management than species assessed at lower risk levels i.e. Vulnerable (VU), Near Threatened and Least Concern (LC) and there was little difference in the management measures among the Red List categories, other than between VU and LC species.

While a few species in some countries or regions have effective management, overall grouper management clearly needs to be improved. This is challenging, as many grouper fisheries are small-scale and multi-species operations. Notwithstanding their value, groupers are often a bycatch or are not the major catch component of fisheries, which complicates the implementation or prioritization of management measures and imposes limits on their effectiveness. These features, together with difficulties in identification, further hinder efforts to monitor catches, which partly explains the high number of Data Deficient groupers identified during the IUCN RL assessments. In some contexts, a combination of management measures may be necessary but for many species basic biological data are lacking, making it difficult to determine which approaches would be most effective and what the species' responses might be. Nevertheless, cohesive efforts by decision-makers and conservation officials to enact and enforce appropriate management plans, together with compliance by fishers, can lead to improved outcomes for grouper fisheries.

CRediT authorship contribution statement

Sean T. Fennessy: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christi Linardich:** Writing – review & editing, Data curation. **Kevin Rhodes:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Joao P. Barreiros:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **David Pollard:** Writing – review & editing, Writing – original draft, Investigation. **Eloy Sosa-Cordero:** Writing – review & editing, Writing – original draft, Investigation. **Felicia Coleman:** Writing – review & editing, Investigation. **Alfonso Aguilar-Perera:** Writing – review & editing, Writing – original draft, Investigation. **Christopher R. Malinowski:** Writing – review & editing, Writing – original draft, Investigation. **Thierry Brulé:** Writing – review & editing, Writing – original draft, Investigation. **Pedro Afonso:** Writing – review & editing, Investigation. **Kayan Ma:** Writing – review & editing, Writing – original draft, Investigation. **Min Liu:** Writing – review & editing, Writing – original draft, Investigation. **Muktha Menon:** Writing – review & editing, Writing – original draft, Investigation. **Colin Wen:** Writing – review & editing, Writing – original draft, Investigation. **Stanley K.H. Shea:** Writing – review & editing, Writing – original draft, Investigation. **Sean N. Porter:** Visualization, Methodology, Investigation, Conceptualization. **Matthew Craig:** Writing – review & editing, Writing – original draft, Investigation. **Yvonne Sadovy de Mitcheson:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.108065.

Data availability

Data will be made available on request.

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