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Review

A synthesis of the prevalence and drivers of non-compliance in marine protected areas

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ABSTRACT

Non-compliance regularly negates the effectiveness of marine protected areas (MPAs) worldwide. Understanding and addressing non-compliance is critical given continued efforts to establish MPAs to meet international milestones (e.g., Aichi targets). We conducted a literature review and meta-analysis to address five key questions and research gaps for MPAs: 1) how is non-compliance best measured? 2) what are common drivers of non-compliance? 3) what is the overall prevalence of non-compliance? 4) how frequently is ecological failure of MPAs attributed to non-compliance? and 5) are there measurable management impacts on regulated fishing in MPAs (i.e., effective reduction of fishing)? We found 151 papers that had some focus on non-compliant resource extraction in MPAs and 96 that quantified it. Insufficient enforcement was the most cited driver of non-compliance, followed by several socio-economic drivers including lack of awareness, livelihood/economic gain, social norms, and ineffective governance. Prohibited fishing in MPAs was often reduced compared to outside areas, as shown by our meta-analysis. However, we found frequent reports and measures of non-compliance globally, and many cases of failed ecological performance attributed primarily to non-compliance (57% of 67 relevant studies). Overall, our synthesis demonstrates that non-compliance continues to be a prevalent issue for MPAs. Reducing non-compliance and ensuring effective MPAs will rely on continuous evaluation of non-compliance to inform adaptive management, as well as addressing the complex, interrelated drivers that arise throughout MPA planning, establishment, and management.

1. Introduction

Marine protected areas (MPAs) are key for ocean conservation, but their success can be undermined by non-compliance. MPAs are a tool for protecting biodiversity through regulation of maritime activities, usually applied to limit extractive impacts and in particular fishing. The IUCN definition of an MPA is 'a clearly defined geographical space, recognised, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values' (IUCN Definition, 2008). MPAs also provide co-benefits including improved catches outside of borders, alternative livelihood opportunities, and community cohesiveness (Ban et al., 2019). Stringent regulations or clear rules on extractive activities are a fundamental, and often raised, criterion for ecologically effective MPAs (Morgan et al., 2018; Sala et al., 2018). For instance, there were 902 fully or highly protected MPAs (no-take or only light extractive activities allowed) as of December 2020, whereas 12,262 allowed moderate to extensive extraction or had unknown protection (mpatlas.org). However, mitigating non-compliance of MPA regulations is a significant corollary that is relatively overlooked (Bergseth et al., 2015). We define non-compliance as a lack of adherence to fishing regulations or rules, which has negated positive outcomes of MPAs on marine biota in many cases worldwide (e.g., Graham et al., 2010; Martins et al., 2011; Venter and Mann, 2012; Rojas-Bracho and Reeves, 2013; Lysenko et al., 2018), alongside other causes of failure including ineffective protection levels or design strategies (Sala et al., 2018). Addressing the issue of non-compliance is critical for ongoing MPA management and in consideration of expanding MPAs, particularly as MPA numbers are rapidly increasing from international calls to protect 10% of the ocean by 2020 to 30% by 2030 (Woodley et al., 2019). The increased establishment of MPAs, combined with already limited management resources (Gill et al., 2017), necessitates well-informed marine spatial planning, governance

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strategies, and use of financial resources to combat non-compliance and ensure conservation goals are met.

Compliance by fishers can be influenced at all stages of MPA planning, implementation, and long-term management. Drivers of non-compliant fishing can stem from social and personal contexts that relate to self-interest, perceptions (including norms), beliefs, trust, and knowledge, and from external factors including surveillance effort and severity of fines (Arias et al., 2015; Thomas et al., 2016; Battista et al., 2018; Bergseth and Roscher, 2018). For instance, non-compliance related to social contexts can occur when local resource users perceive regulations as illegitimate, either from lack of consultation during MPA planning, exclusion in governance during implementation and management, or if governing bodies are not respected or effective (Thomas et al., 2016; Rohe et al., 2017; Battista et al., 2018; Oyanedel et al., 2020a). External factors including complicated MPA boundaries, zones, or gear restrictions can lead to involuntary non-compliance (Read et al., 2011; Cinner and Huchery, 2014), whereas large or remote MPAs are more difficult to patrol and may have more purposeful non-compliance from low perceived risk (Crawford and Sukmara, 2004; Rojo et al., 2019) or, conversely, may have less non-compliance from reduced accessibility (Advani et al., 2015; Kauano et al., 2017). There are often multiple, interacting drivers for non-compliance that are dependent on the socio-economic conditions of the resident communities and on the MPA itself (Rohe et al., 2017; Bergseth, 2018). Understanding drivers of compliance and non-compliance in MPAs can contribute to more effective spatial conservation planning and design, as well as best-practices for management and governance of MPAs.

Levels of non-compliance in MPAs are increasingly measured to assess ecological performance and management impacts on regulated fishing. A previous literature review by Bergseth et al. (2015) found that studies examining non-compliance were rare and most often provided qualitative or anecdotal, rather than quantitative, information to assess non-compliance levels. Quantitative measures have included use of questionnaires, law enforcement records, theoretical models, and direct and indirect observations (Bergseth et al., 2015). Here, we identify how much research on non-compliance in MPAs has progressed since the previous review and for the first time, begin to synthesize and analyze non-compliance measures across MPAs globally. Ongoing quantification of non-compliance in MPAs is important for understanding why an MPA may not be meeting ecological performance expectations and to guide adaptive management (Claudet, 2018; Dunham et al., 2020). However, the issue remains highly underrepresented in MPA research and monitoring, which to-date has been heavily focused on ecological performance (Dunham et al., 2020).

We conducted a literature review to present the current state of knowledge on non-compliant resource extraction in MPAs. We included all studies that measured or discussed non-compliance in MPAs, regardless of the MPA protection level, and that had some year-round fishing regulations or rules (i.e., we excluded seasonal fishing closures). We reviewed existing and novel methods used to measure non-compliance, compiled stated and measured drivers of non-compliance to identify their relative importance across MPAs, and determined the prevalence of MPAs with failed ecological performance attributed to non-compliance. We also compiled measured levels of non-compliance from commonly used metrics across MPAs, and conducted a meta-analysis of studies that compared regulated fishing inside MPAs (i.e., non-compliance) to fishing outside of MPAs to evaluate management impacts on regulated fishing. This latter measure does not determine whether an MPA is reaching its conservation goals as single non-compliance events can sometimes have large detrimental effects (e.g., Graham et al., 2010; Carr et al., 2013). However, it provides an indicator for whether or not regulated fishing is reduced and the extent of reduction relative to what it could be without protection. A large volume of theoretical literature exists on non-compliant resource extraction in fisheries and wildlife management (Boonstra et al., 2017; Kurland et al., 2017; Oyanedel et al., 2020b), and these diverse perspectives can contribute to understanding and mitigating non-compliance in MPAs (e.g., Weekers et al., 2020). The purpose of our review is to focus particularly on how non-compliance research in MPAs is advancing, to highlight the magnitude of non-compliance in MPAs globally, and to identify gaps and approaches for improving non-compliance research and monitoring in MPAs.

2. Methods

We conducted a literature review of peer-reviewed publications on non-compliant resource extraction in MPAs following the PRISMA statement for standardized systematic reviews and meta-analyses (Moher et al., 2009) (Fig. 1). We searched Web of Science for peer-reviewed papers that included the terms “marine reserve*” or “marine protected area*” and “compliance”, “compliancy”, “compliable”, “comply*”, “complies”, “complied”, “poach*”, “illegal”, or “enforce*” from July 2012 through December 2019. The search returned 344 publications, and an additional 15 publications were identified through bibliography searches. This methodology matched that of Bergseth et al. (2015), which enabled us to also incorporate previously identified publications ($n = 122$; Bergseth et al., 2015). We then screened out all papers that were not on MPAs or did not meet the definition of MPAs, and further determined the eligibility of 267 (see Dryad Digital Repository for paper details). These papers were read in full to determine whether they had some focus on non-compliant resource extraction in MPAs (i.e., included measures of non-compliance or enforcement, or discussed non-compliance in detail; hereafter ‘non-compliance focused’). Those that did were selected for inclusion to build a comprehensive dataset of studies examining illegal fishing ($n = 149$) or coral harvesting ($n = 2$) in MPAs from 1996 onwards. From these 151 papers, we extracted information on 1) the study location, 2) whether the presentation of information on non-compliance was quantitative or qualitative (i.e., commentary), 3) the methodology used if quantitative, 4) whether the study presented on ecological, social, or both aspects of MPAs, 5) the drivers of non-compliance that were measured or discussed, and 6) the results of ecological performance, if measured, and their relation to non-compliance. Following Bergseth et al. (2015), quantitative methods were grouped into categories of direct observation, direct and indirect questioning, expert opinion, indirect observation, law enforcement records, modeling, and remote sensing.

We categorized drivers of non-compliance that were measured or discussed for the study MPA (i.e., broad, introductory statements about drivers of non-compliance were not compiled). Drivers were included if they pertained to why non-compliance was occurring or why non-compliance had decreased (or compliance improved); reasons for why compliance was high were relatively infrequent and not collected as these cannot inherently be reversed to explain non-compliant behaviour (Arias, 2015). We identified and defined driver categories based on commonly-cited issues found during our first reading of all papers and quality-checked our classifications during a second reading. Eight driver categories were identified (see Table 1 for full definitions), including lack of ‘awareness’ of the MPA and its benefits, better fishing ‘catch’ in MPAs or with illegal methods (refers specifically to fish abundance or catch), ‘dependence’ on MPA resources for food or livelihood, overly complex regulations or difficult to enforce MPA ‘design’ (e.g., size, remoteness), ‘economic’ incentives (refers specifically to financials or markets), insufficient ‘enforcement’, ineffective or non-inclusive ‘governance’, and ‘social’ norms or community conflicts; organized crime and apathy were also provided as drivers in the literature, but were mentioned infrequently and in some cases were difficult to distinguish from the others (e.g., apathy can be related to a lack of awareness or to social norms, and organized crime can be related to the black market, which we classified as an economic driver). We determined which driver categories were identified in a study based on the specific language used by the authors; for instance, if a study mentioned that regulations were hard to follow because they were overly complex,

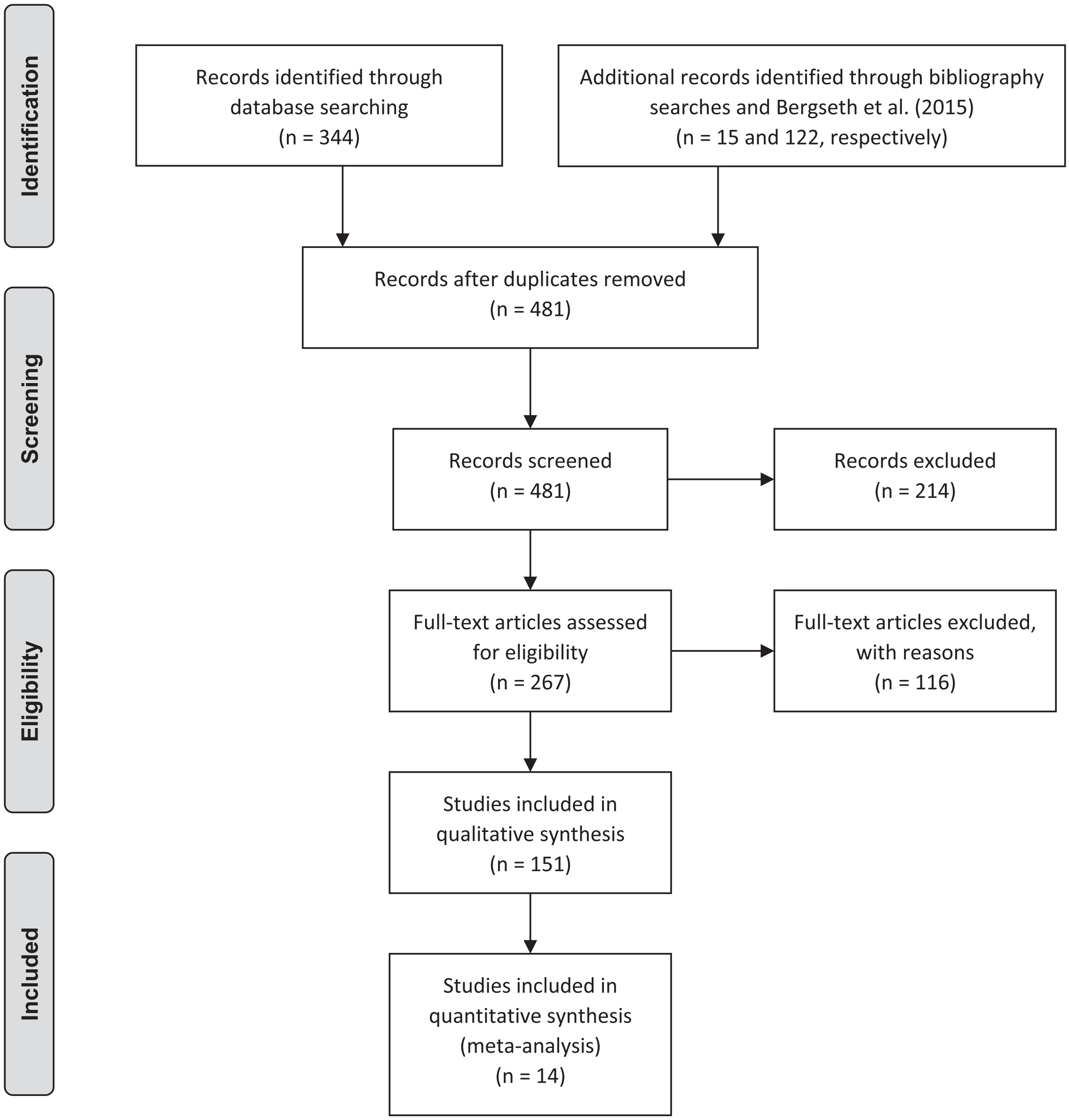

Fig. 1. Preferred reporting items for systematic reviews and meta-analysis (PRISMA) flowchart summarizing the sequence of paper selection in the literature review and meta-analysis on non-compliant resource extraction in MPAs.

we categorized that as a 'design' issue, not an 'awareness' issue, as the fishers may be fully aware of the regulations though they may be confusing. Conversely, cases where fishers did not know that the regulations existed were categorized as an 'awareness' issue as the MPA could be well-designed with simple regulations but lack public outreach.

Papers that provided results on ecological performance of MPAs included those that compared ecosystem metrics before and after implementation or enforcement, over time after implementation, inside and outside of an MPA, or presented metrics of ecosystem health (e.g., presence/abundance of high trophic level species, particularly sharks; high biodiversity values). We categorized the ecological performance results of these papers and whether they attributed failed ecological performance to non-compliance as 'success' (non-compliance may have been noted but did not deter ecological performance), 'fail, primary' (primary reason for failure was non-compliance), 'some fail, primary' (particular species, areas within an MPA, or some MPAs of multiple measured MPAs failed and the primary reason was non-compliance), 'fail, in part' (failure was attributed to multiple reasons including non-compliance), and 'fail, unrelated' (failure was attributed to reasons other than non-compliance). Ecological success or failure and the attributed reasons were taken from the authors' interpretation and discussion of their results; the terms 'success' and 'failure' were largely applied by the authors themselves. Success was generally concluded by the authors when the MPA had maintained or improved a high diversity of biota or high trophic level species, and failure was concluded when populations within the MPA had declined or the MPA had diminished populations representative of nearby fished sites or of poaching. Failed performance that was attributed to non-compliance was evidenced by direct measures or observations of non-compliance, observed effects of non-compliance (e.g., removal of large sized individuals; Avendano et al., 2017), referenced publications on non-compliance in the MPA, or local or anecdotal knowledge of lack of enforcement and non-compliance. We did not differentiate among levels of evidence; however, studies that made less substantiated claims about non-compliance gave other potential reasons for lack of success and were categorized as 'fail, in part'.

We extracted data from studies that provided quantitative measures of non-compliance in MPAs to depict the prevalence of non-compliance

Table 1
Descriptions of commonly presented drivers of non-compliance in MPAs.

Driver	Description. Fishers poach because:
Awareness	They are unaware of the MPA (i.e., no signage or markers), the zoning or gear restrictions, the benefits of the MPA, or the importance of environmental stewardship.
Catch	Catches are expected to be better in the MPA from improved fish abundances or illegal fishing methods are more efficient.
Dependence	They are dependent on MPA resources for food or livelihood.
Design	The boundaries, zoning, or gear restrictions are too complex, or the size, line of sight from shore, or remoteness of the MPA makes detection unlikely.
Economic	The financial gain outweighs the potential consequences, there is a tourism, jewelry, souvenir, or black market, or they are targeting notably high value species.
Enforcement	There is a perceived or actual lack of enforcement from surveillance efforts or prosecution rates.
Governance	The governance or management of the MPA is ineffective or corrupt, or they were not included in the planning, design, or management of the MPA.
Social	It is the social norm, they believe it is their right, or there is conflict within or between communities.

globally. We compiled rankings of non-compliance in MPAs (low, medium, high) from studies that made these categorizations based on interviews with experts, fishers, locals, researchers, and MPA staff, generally for the purpose of assessing them as an explanatory variable of ecological measures; authors either developed their own standards for classifying low, medium, and high non-compliance or applied previously published definitions. A common classification scheme was low non-compliance for MPAs with very occasional poaching, if any, along with active and continuous patrolling; medium when poaching occurred but was limited by infrequent surveillance; and high when there was common poaching and largely inexistent surveillance (Edgar et al., 2014; Giakoumi et al., 2017; Rojo et al., 2019). We also compiled reported numbers of fishing offenses from studies that used law enforcement records to measure non-compliance. However, we were unable to standardize these numbers because surveillance effort was often not reported in the studies. From studies that used questionnaires, we collected the percentage of respondents that admitted to non-compliance during direct or Random Response Technique questioning (Arias and Sutton, 2013), had observed non-compliance of others, or perceived non-compliance to occur within an MPA.

We conducted a meta-analysis on quantitative measures of regulated fishing in MPAs (i.e., non-compliance) compared to fishing outside MPAs to assess management impacts on regulated fishing. Calculation of effect sizes and variance for these measures indicated whether regulated fishing was significantly (i.e., negative confidence intervals that do not overlap 0) reduced in MPAs; more negative effect sizes indicated a greater reduction of fishing, whereas a non-significant effect indicated high non-compliance or overall minimal fishing activity in the area. Either of the latter cases signify the MPA is unlikely to yield marked changes in the ecosystem based on fishing regulations or rules. To calculate effect sizes, we extracted averages, standard deviations, and samples sizes from the 14 studies (representing 12 countries) that provided measurements of fishing activity inside and outside of no-take or gear restricted MPAs. We used WebPlotDigitizer (https://automeris.io/WebPlotDigitizer) to extract data and contacted authors for data when necessary. We calculated standardized mean difference effect sizes ($n = 60$) with unbiased sample size estimates (Hedges' g; Hedges, 1981) and tested random-effects meta-analytic models; all models included study ID as a random effect to account for multiple effect sizes within studies (i.e., measures in different locations within or outside of an MPA, measures during different years, or multiple MPAs or control sites) ("metafor" in R, Viechtbauer, 2010). We evaluated whether factors of measurement method, fisher group, and years since establishment mediated the measured impact of MPA management as a first step towards assessing global trends. Random-effects models were tested for the overall dataset and for each measurement method separately (direct observation, indirect observation, and remote sensing). Fixed factors of fisher group (commercial, recreational, subsistence) and number of years the survey took place after MPA implementation were tested with individual mixed-effects models. All analyses were conducted in R (R Development Core Team, 2018).

3. Results

We found 151 published papers in our literature review that were non-compliance focused with regard to illegal resource extraction in MPAs; this included 53 papers from Bergseth et al. (2018) and an additional 98 papers published since then. These studies were based on MPAs in Oceania ($n = 30$), Africa (26), Asia and South Asia (21), Central and South America (19), Europe (15), North America (14), and the Caribbean (5), or presented the issue in a global (19) or theoretical context (5) (some studies included more than one region). Publications with a non-compliance focus in MPAs started in 1996 and increased to 2019, with a peak in those that quantified non-compliance in 2015 and 2017 and those that qualitatively discussed the issue in 2018 (Fig. 2a). A total of 96 studies (64%) quantitatively measured non-compliance. Of these, the most commonly used method was direct and indirect questioning ($n = 33$). Remote sensing was a less common ($n = 7$), but emerging method as it began to appear in 2010 and was used in three papers in 2019 (Fig. 2b).

Non-compliance focused studies examined the social ($n = 60$) or ecological (41) aspects of MPAs, or included both (50), and many provided measured (i.e., through questionnaires), anecdotal, or posited drivers of non-compliance for their focal MPAs (56, 37, and 46, by focus respectively). The majority of these cited insufficient enforcement as a key driver of non-compliance – this was relatively consistent regardless of paper focus (Fig. 3). Studies that examined social aspects of MPAs also reported lack of awareness of the MPA and/or its benefits as a dominant reason for non-compliance (48% of 56), followed by social norms or community conflicts (41%), ineffective or non-inclusive governance (38%), and food or livelihood dependence on the MPA's resources (30%). Studies that focused on the ecology of MPAs also identified economic gain, particularly from tourism or black markets, as a reason for non-compliance (32% of 37), and rarely discussed social (5%), governance (0%), or dependence issues (3%) (Fig. 3).

Out of all studies that reported on ecological performance and had some focus on non-compliance ($n = 67$), 30% found overall success of MPAs, whereas 70% reported some degree of failure (Fig. 4a). For those that reported ecological failure, most found failure in some cases but not in others (e.g., relatively low abundance of target fishes, but high abundance of non-target fishes; failure of some MPAs or sites within MPAs, but success of others) and attributed these failures primarily to non-compliance (47% of 47; 'Some fail, primary'). Studies that reported overall failure attributed it most often to non-compliance (34% of 47; 'Fail, primary'), followed by non-compliance coupled with other issues (11%; 'Fail, in part') and issues other than non-compliance (9%; 'Fail, unrelated') (Fig. 4a). Insufficient enforcement was the primary driver cited by studies that found ecological failure related to non-compliance (79% of 43); the seven other non-compliance drivers were attributed by 14–26% of these studies (Fig. 4b).

We compiled non-compliance rankings, offense records, and questionnaire responses for MPAs from all relevant studies. We found rankings of non-compliance levels for 185 MPAs from eleven studies (Fig. 5). The majority of MPAs had low non-compliance rankings (56%), followed by medium (32%) and high rankings (12%). Low non-compliance was most commonly reported for MPAs in North America (90% of 10), Oceania (74% of 50), and Europe (64% of 45), whereas MPAs were most commonly ranked as high non-compliance in Africa (52% of 29 MPAs) and Central and South America (45% of 22). Twelve studies reported on the number of offenses from enforcement records for 28 MPAs; notably, we were unable to find any reports on offenses in

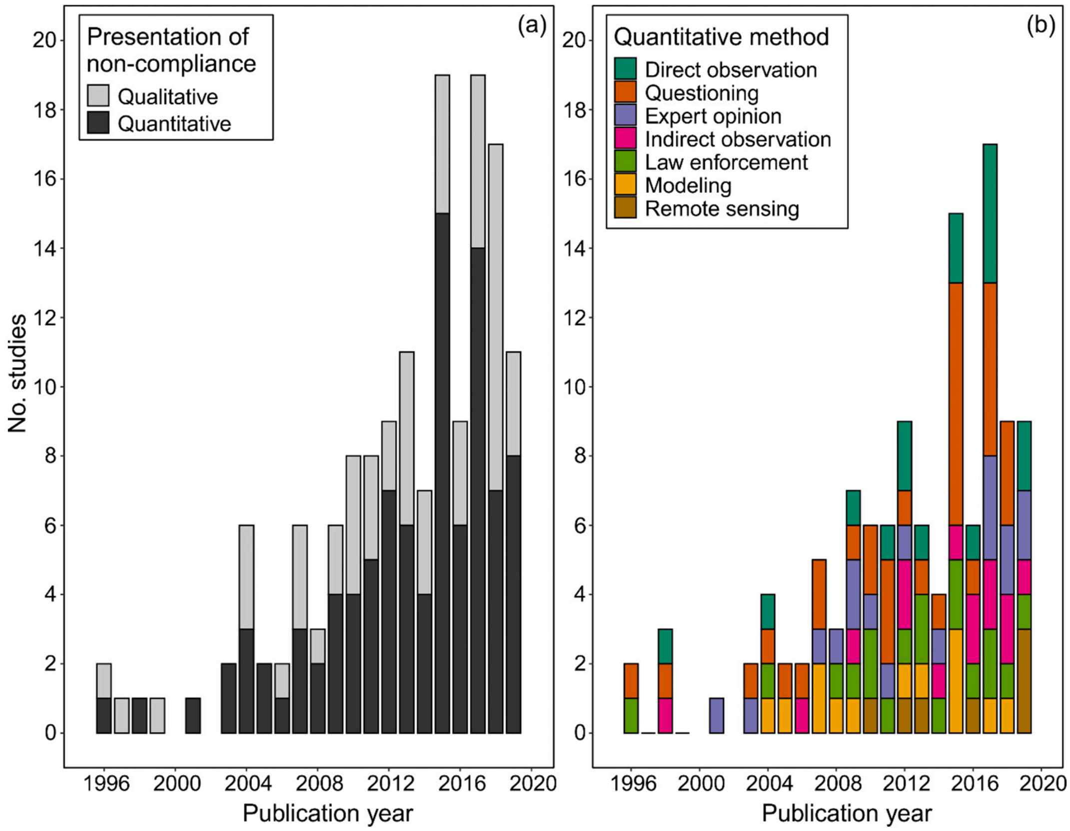

Fig. 2. Number of studies published from 1996 to 2019 that presented discussion ('qualitative') or measurements ('quantitative') of non-compliance in MPAs (i.e., non-compliance focused studies) (a) and methods used to quantify non-compliance (b). Note, studies were counted more than once in (b) if they presented multiple methods for quantifying non-compliance.

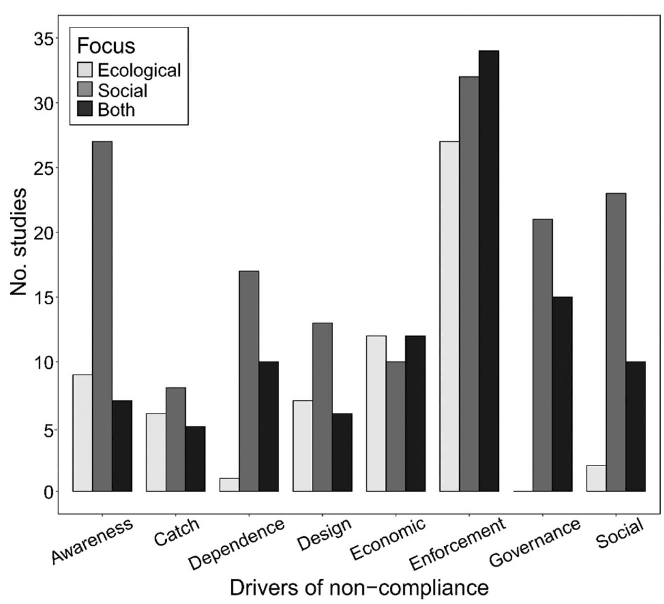

Fig. 3. Drivers of non-compliance as identified by studies with a measure or discussion of non-compliance and a focus on ecological, social, or both aspects of MPAs. See Table 1 for explanations of the drivers of non-compliance.

MPAs in North America or Europe (Fig. 6). The surveillance and enforcement effort within these MPAs varied and was often not reported, but recorded offenses were on the scale of hundreds per year. Sixteen studies reported on the presence of non-compliance in distinct MPAs or countries through questionnaires (Fig. 7). Respondents admitted to non-compliance much less on average (13%) than they confirmed the presence of non-compliance when not directly implicated. Over half of respondents had observed non-compliance of others (66%) or perceived non-compliance to occur within an MPA on average (52%).

We were able to examine the management impacts of no-take (and one gear restricted) MPAs from 14 studies that compared fishing or fishing-vessel detection measures inside and outside of MPAs (Fig. 8). Overall, MPAs were shown to significantly reduce regulated fishing ($z = -3.77$, $p < 0.001$). Direct observation studies used aerial, shore, and boat-based observations of fishers or vessels; indirect observation studies included dockside interviews and discarded gear or in-use trap detection; and remote sensing studies used vessel tracking data from Automatic Identification Systems and Vessel Monitoring Systems. Both direct observation ($z = -2.58$, $p = 0.01$) and remote sensing measures ($z = -2.28$, $p = 0.02$) showed significant effects of MPA management (reductions of regulated fishing inside vs. outside boundaries), whereas indirect observation did not ($z = -1.74$, $p = 0.08$). The non-compliant fisher group (i.e., commercial, recreational, subsistence) and number of years the survey took place after implementation did not influence MPA effect sizes ($p > 0.05$).

4. Discussion

Our literature review and meta-analysis highlight how non-compliance in MPAs is a fundamental and ongoing issue that needs to be addressed worldwide to achieve conservation goals. Both this paper and Bergseth et al. (2015) were originally conceived as meta-analyses of non-compliance levels and ecological outcomes in MPAs. However, a lack of sufficient comparative measures hindered the attempt to do so for the previous review, and data published since then enabled the

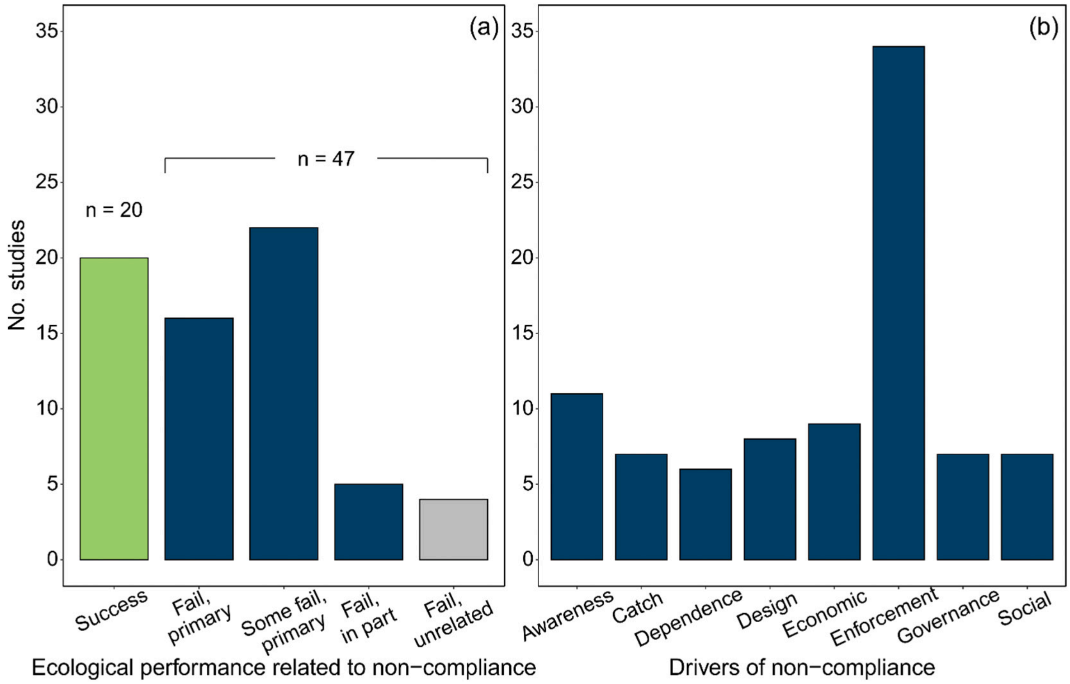

Fig. 4. Number of studies that measured ecological performance of MPAs and related it to non-compliance (a), and identified drivers for non-compliance for those that measured ecological failures (e.g., MPA biota were same or worse than reference, not improving, or declining) and included non-compliance measures or discussion ($n = 43$; more than one driver could be identified from a study) (b). Categories of ecological performance in (a) are "success" – MPA biota were better than reference, ecological metrics were improving, or high trophic level species were abundant (green bar); "fail, primary" – ecological failure resulted primarily from non-compliance; "some fail, primary" – some MPAs or species succeeded whereas others failed from non-compliance; "fail, in part" – ecological failure resulted from non-compliance and other issues (blue bars); "fail, unrelated" – primarily from factors other than non-compliance (grey bar). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

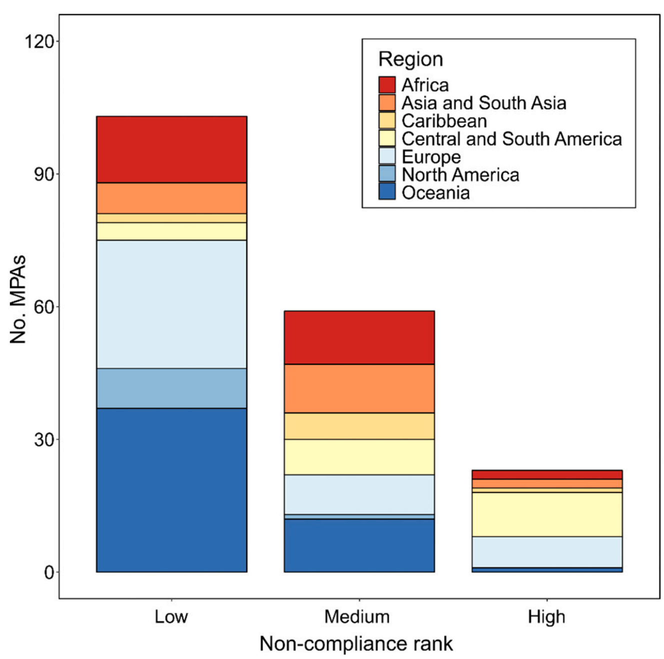

Fig. 5. Number of MPAs with low, medium, or high non-compliance rankings from eleven studies based on interviews with experts, fishers, locals, researchers, and MPA staff.

relatively small sample size meta-analysis presented here. Encouragingly, quantitative data on non-compliance levels have increased since Bergseth et al. (2015), to the point where we were able to synthesize and produce Figs. 3–8, but low data availability still impedes our ability to further unpack these quantitative relationships. Quantification of non-compliance is key for long-term monitoring of MPAs to understand ecological performance and determine management impacts on regulated fishing, two primary components of evaluating whether MPAs are achieving their goals (Dunham et al., 2020). We identified several prevalent drivers of non-compliance across MPAs globally, namely insufficient enforcement, and socio-economic drivers including lack of awareness, social norms, livelihood or economic benefits, and ineffective governance. Insufficient enforcement was also cited most commonly as the driver of non-compliance that led to failed ecological performance in over half of the studies that measured it. These results clearly identify insufficient enforcement as an important issue for MPAs, which likely stems from the global deficiency in staff and budget capacities (Gill et al., 2017). As such, many studies that measured non-compliance (e.g., direct or indirect observation, law enforcement records) or ecological performance (within our non-compliance focused search) found substantial poaching in MPAs or failed performance from non-compliance, respectively. Though most MPAs were ranked as having low non-compliance based on interviews, almost as many were considered to have either medium or high non-compliance. Our meta-analysis on studies that measured regulated fishing inside compared to fishing outside of MPAs indicated overall management impacts (i.e., levels of fishing inside MPAs were lower than those outside), however this varied greatly across methodologies and comparisons. These results emphasize that increased monitoring and understanding of non-compliance is imperative if the international focus on MPAs as a conservation strategy is to be successful.

4.1. Measurements and prevalence of non-compliance

Studies on non-compliance in MPAs, especially those that quantify non-compliance, have tripled in the seven years since the review by Bergseth et al. (2015). In particular, studies are more frequently using

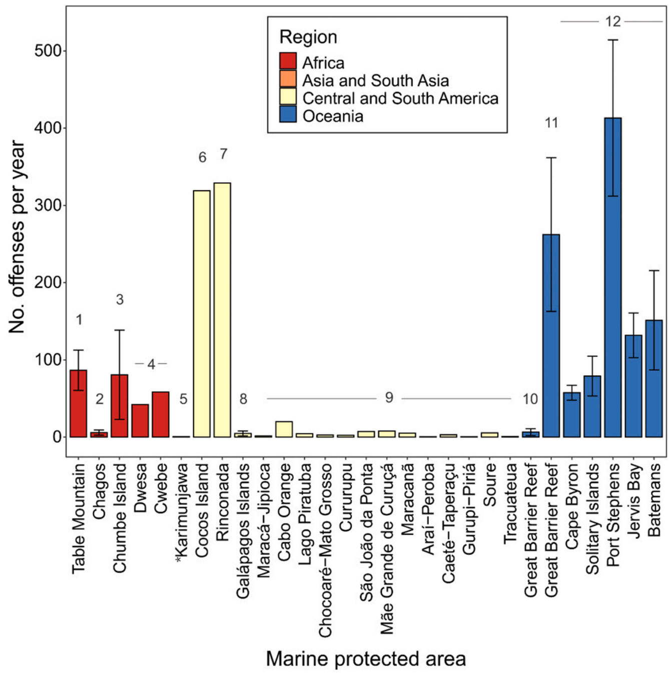

Fig. 6. Number of offenses reported in law enforcement records per year within MPAs across geographic regions (mean ± 1 SD). References are numbered above bars as follows [year range of offense records]: (1) Brill and Raemaekers (2013) ['00–'09], (2) Ferretti et al. (2018) ['02–'15], (3) Muthiga et al. (2000) ['93–'96], (4) Nakin and McQuaid (2014) ['02–'05], (5) Campbell et al. (2012) ['05–'09], (6) Arias et al. (2016) ['05–'10], (7) Avendano et al. (2017) ['01–'03], (8) Carr et al. (2013) ['01–'04], (9) Kauano et al. (2017) ['10–'15], (10) Alder (1996) ['85–'91], (11) McCook et al. (2010) ['99–'09], (12) Read et al. (2015) ['07–'12]. *Karimunjawa MPA (Central and South America) had notably low levels of enforcement (eight patrol days per year) resulting in a low number of offenses recorded.

direct observation, direct and indirect questioning, and remote sensing methods. Direct observations of non-compliance are likely to be the most accurate measures of non-compliance levels, assuming the observer is discrete and not deterring illegal fishing; this can be achieved, for instance, by using cameras aimed at known fishing grounds (Lancaster et al., 2017; Harasti et al., 2019), from aerial surveillance (Gribble and Robertson, 1998; Rojas-Bracho and Reeves, 2013; Smith et al., 2015), or by shore observation (Meyer, 2007; Smallwood and Beckley, 2012; Ferreira et al., 2015). Direct observations of non-compliance tended to reveal higher management impacts of MPAs (i.e., greater reduction of fishing inside vs. outside boundaries) than indirect observations, which largely measured discarded fishing gear (Fig. 8). Measurements of discarded fishing gear are a good indicator of fishing activity occurrence, but can be complicated by gear present prior to MPA enforcement or by drift. The former is often addressed by first removing gear and returning to count new accumulation (Williamson et al., 2014; Bergseth et al., 2017). This highlights the importance of using more than a single measure of non-compliance.

Direct and indirect questioning is another method commonly used to ascertain the prevalence of non-compliance and in some cases to understand drivers of non-compliance. Most questioning studies employ a number of specialised techniques to reduce untruthful responses about self-reported compliance (Arias et al., 2015; Lancaster et al., 2015; Bergseth et al., 2017; Mancha-Cisneros et al., 2018). The Random Response Technique is an indirect questioning approach designed to reduce biased responses by using a randomising device (e.g., a dice) to conceal the truthfulness of a respondent's answer from the interviewer (Arias and Sutton, 2013). However, admitted non-compliance levels and sample sizes must be sufficiently high to counteract the statistical noise introduced by the randomising device, which can be a significant challenge (Lancaster et al., 2015). Other indirect questioning approaches ask if the respondent has observed or perceives non-compliance of others in the MPA and are also effective indicators of the prevalence of non-compliance (Arias et al., 2015). These approaches were established at the time of Bergseth et al. (2015), but have been used more extensively since then. For instance, in the Great Barrier Reef Marine Park, the Random Response Technique yielded the highest estimate of non-compliance, followed by perceived non-compliance, whereas self-

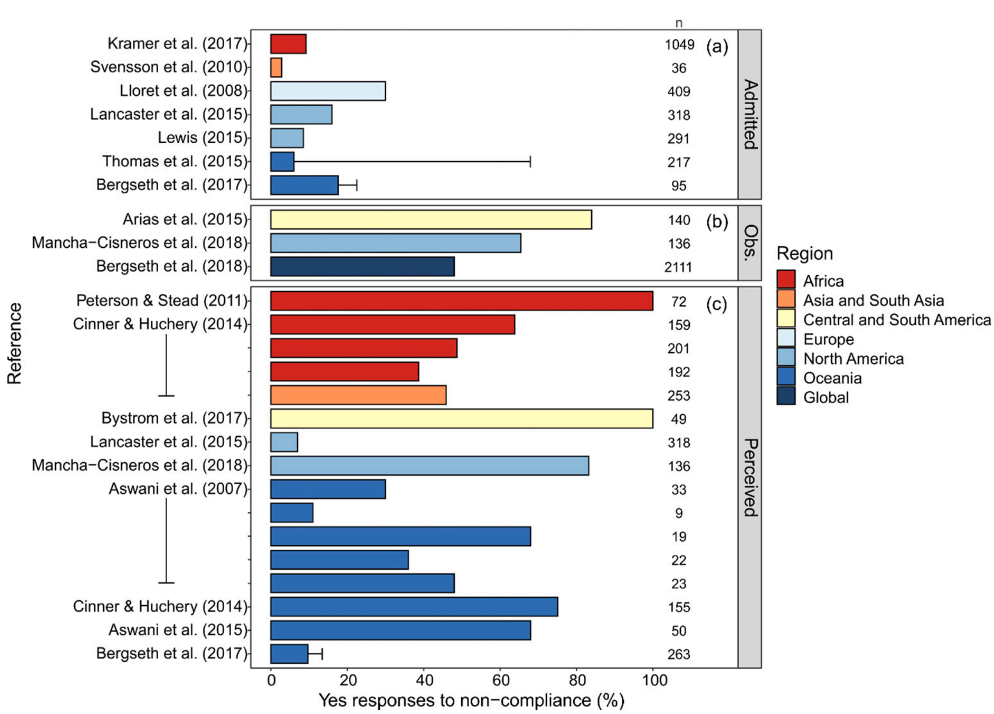

Fig. 7. Percent of questionnaire respondents who admitted to non-compliance (a), observed non-compliance (b), or perceived non-compliance in MPAs (c). The number of respondents for each study and location are provided in the right column. Studies with multiple bars surveyed more than one MPA or country; most recent or comprehensive survey results were presented in cases of MPA survey overlap (n = 3). Overall percentages were selected over results split among groups, and mean ± 1 SD is shown for studies that provided error estimates. Random response technique results were also selected over direct questioning results when multiple approaches were reported ('admitted' category). Note, the global extent of Bergseth et al. (2018) includes Africa, Asia and South Asia, Central and South America, and Oceania (Aswani et al., 2007, Aswani et al., 2015, Bystrom et al., 2017, Huang et al., 2017, Kramer et al., 2017, Lewis, 2015, Lloret et al., 2008, Renchen and Matthews, 2018, Svensson et al., 2010, Thomas et al., 2015).

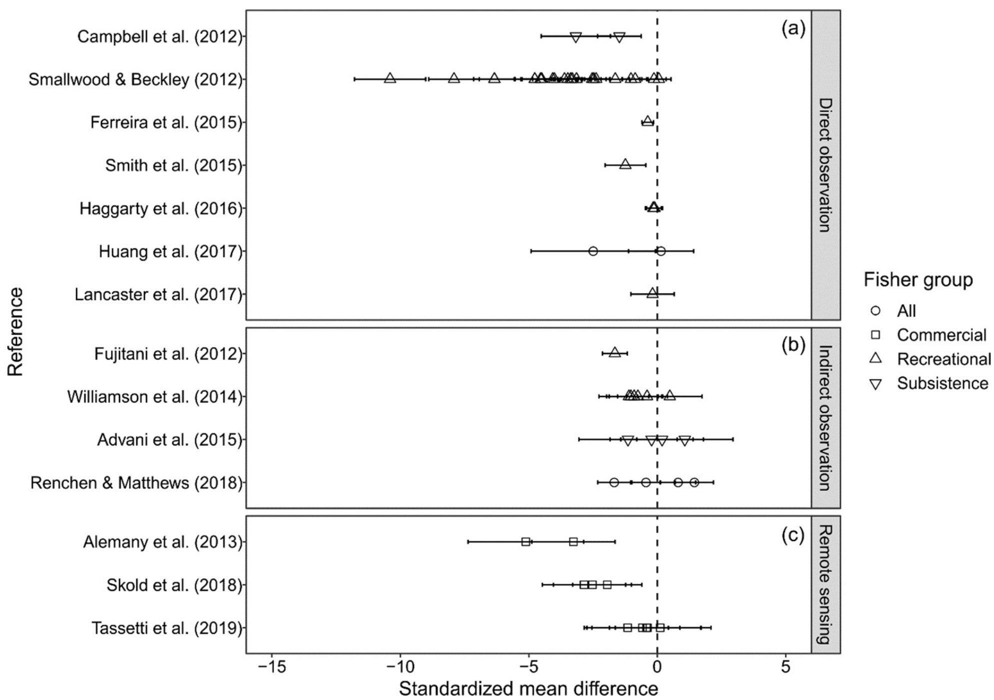

Fig. 8. Standardized mean difference (±95% CI) effect sizes of prohibited fishing activity inside MPAs versus outside from studies comparing fishers and vessels observed from aerial, shore, and boat-based surveillance ('direct observation') (a); dockside interviews (Fujitani et al., 2012) and discarded gear or in-use traps (remaining references, 'indirect observation') (b); and tracked vessels ('remote sensing') (c). Negative CIs that do not overlap zero indicate that regulated fishing activities were significantly reduced within the MPA. Multiple effect sizes for a single study represent comparisons made for different MPAs, locations within an MPA, control locations, or survey years (Aswani et al., 2007, Aswani et al., 2015, Bystrom et al., 2017, Huang et al., 2017, Kramer et al., 2017, Lewis, 2015, Lloret et al., 2008, Renchen and Matthews, 2018, Svensson et al., 2010, Thomas et al., 2015).

administered questions resulted in the lowest admitted levels of non-compliance (Bergseth et al., 2017). In this dataset, observed and perceived levels of non-compliance tended to be higher than admitted non-compliance levels, across both studies and regions (Fig. 7). There are numerous potential explanations for this discrepancy (Bergseth and Roscher, 2018), but the most parsimonious explanation is that non-compliance is prevalent and likely higher than what is admitted, further indicating that other methods are needed to estimate actual levels.

Remote sensing of vessel tracking devices is a promising method that is growing in utility as more vessels opt to carry tracking systems for navigational safety, satellite and terrestrial signal receiver coverage is expanding, and big data analytics are rapidly advancing (Iacarella et al., 2020). Remote sensing data includes transmissions from Automatic Identification Systems and Vessel Monitoring Systems; the six included papers that used these systems were all produced after the review by Bergseth et al. (2015). Automatic Identification Systems are required on large ships by the International Maritime Organization, and some countries have extended carriage requirements to fishing vessels (McCauley et al., 2016). Conversely, Vessel Monitoring Systems are used exclusively by fishing vessels and are mandated by national governments; these data are difficult to access by researchers given data privacy and use restrictions (Iacarella et al., 2020). However, both have been successfully used to detect non-compliance in MPAs (Bloomfield et al., 2012; Alemany et al., 2013; McCauley et al., 2016; Read et al., 2019; Rowlands et al., 2019; Tassetti et al., 2019), with particular advancement in the application of neural network analytics to determine fishing effort and gear types from vessel movement patterns (Kroodsma et al., 2018). This method is optimal for monitoring fishing activity over long timeframes and for large, remote MPAs (McCauley et al., 2016), but is currently less suited for MPAs that have large recreational or subsistence fishing populations, which only voluntarily use Automatic Identification Systems. For a comprehensive picture of non-compliance, remote sensing methods would ideally be paired with other observation or questioning methods given the less frequent use of vessel tracking devices on small vessels and the ability of vessels to mask signal transmission (Iacarella et al., 2020).

Law enforcement records have also been used over the years to estimate non-compliance levels, though this is highly dependent on active surveillance effort and successful prosecutions. For instance, a maximum of eight patrols per year were conducted across five years in an Indonesian MPA, and only three violations were recorded for fishers outside of the region; in this case, non-compliance of local fishers was not being enforced (Campbell et al., 2012). Thiault et al. (2020) recently used law enforcement records to model recreational poaching risk across the Great Barrier Reef Marine Park and compared this to patrol effort to identify areas with high poaching and minimal surveillance to guide future enforcement efforts. With extensive violations records across terrestrial protected areas and MPAs in Brazil, Kauano et al. (2017) found that illegal fishing was the second most prevalent natural resource use violation after suppression or degradation of vegetation, recording over 1000 fishing violations in MPAs across six years. They further found that population density was a strong predictor of illegal terrestrial and marine activities, whereas the age of the protected area had no effect (Kauano et al., 2017). Interestingly, none of the 18 studies that measured non-compliance using law enforcement records were on MPAs in North America or Europe (Fig. 6). Low numbers of violations in law enforcement records may reflect high compliance or minimal surveillance and enforcement levels; in the case of strong enforcement levels, violations can be an effective spatial and temporal measure of non-compliance.

4.2. Drivers and ecological effects of non-compliance

We found several common drivers of non-compliance across MPAs, though the ecological or social perspective of the studies influenced which drivers were emphasized. As can be expected, socially-focused papers were more likely to identify multiple social and personal drivers, often determined through questionnaires with local community members. For instance, in the Solomon Islands, interviews with locals identified non-compliance stemming from many interrelated and complex factors: distrust of leadership, reduced cooperation from community conflict, introduction of different customs into the community, perceptions of non-compliance of others, new economic opportunities, placement of the MPA, minimal perceived risk of sanctions, and reduced surveillance by local rangers from divisions and mistrust as well as from reduced funding (Rohe et al., 2017). These drivers of non-compliance are deeply entrenched in the social, personal, and economic experience within this community, but are a common theme for MPAs located nearby small, fishing-dependent communities (Aldon et al., 2011; Yang et al., 2013; Pomeroy et al., 2015; Chaigneau and Brown, 2016; Mancha-Cisneros et al., 2018). Similarly, terrestrial protected areas are experiencing increasing human pressures, which may reflect greater effectiveness of indigenous and community-managed reserves compared to formal protected areas that do not sufficiently include locals and stakeholders or their resource needs (Geldmann et al., 2019). Compliance in these contexts can be improved by increasing the legitimacy of the governing institution (often related to procedural and distributive justice; Levi et al., 2009), providing incentives (e.g., fuel for fishers to patrol the MPA or exclusive access zones for local fishers; Smallhorn-West et al., 2020), supporting alternative livelihoods (e.g., ecotourism, aquaculture), and through targeted enforcement efforts (Arias, 2015). Legitimacy-based issues are also prevalent in fisheries contexts (Battista et al., 2018; Oyanedel et al., 2020a) and can lead to resistance and rejection of rules, creativity in avoiding or breaking rules through loopholes, and reluctance to follow rules (Boonstra et al., 2017). Legitimacy is a concept that reflects individuals' perceptions of the right for a governing authority to rule (Turner et al., 2016). Perceptions of legitimacy can therefore be improved in a variety of ways, including increased participation in decision-making, using fair processes and making fair decisions (procedural justice), and ensuring resource users are treated equally or receive the same benefits (distributive justice) from MPAs (Levi et al., 2009; Turner et al., 2016). Insufficient enforcement was a top issue discussed across studies, particularly by ecologically-focused papers, but enforcement without consideration of socio-economic contexts is unlikely to succeed (Viteri and Chavez, 2007; Peterson and Stead, 2011; Pomeroy et al., 2015; Pieraccini et al., 2017).

Over half of the studies that measured ecological performance and had some focus on non-compliance found overall or partial failure of MPAs to improve population or ecosystem metrics. Twenty-two of these studies determined that cases of overall failure were caused by illegal fishing, and cited insufficient enforcement as the primary driver (Fig. 4). For instance, poorly performing MPAs in the Gulf of California, Mexico experienced intensive illegal fishing in no-take zones and an estimated 50% of fishers were without permits (Rife et al., 2013). In another example, an endangered limpet was predicted to go locally extinct from ongoing poaching within an Italian MPA; no fines had been issued for illegal intertidal harvesting during the 16 years of this MPA (Coppa et al., 2016). Sharks and rays, including those with small home ranges, have also been declining in one of the world's oldest MPAs, Cocos Island National Park, from illegal fishing over the past 20 years (White et al., 2015). Even single illegal fishing events can be highly destructive to populations, particularly in the case of some shark poaching operations (Graham et al., 2010; Carr et al., 2013). Meta-analyses have also shown a direct negative relationship between fish biomass and estimated non-compliance across more than 50 reserves (Pollnac et al., 2010; Bergseth et al., 2015). These collective findings of MPAs failing to meet expected conservation goals owing to non-compliance are a major concern that needs to be given greater priority as expansion of MPAs continues to be the focus for conserving biodiversity worldwide.

4.3. Gaps and advances in non-compliance research and monitoring

The rise in published studies using quantitative methods to understand and track non-compliant resource extraction in MPAs is encouraging, though still greatly insufficient given the magnitude and importance of this issue. The focus on ecological effectiveness of MPAs has far outweighed that of management effectiveness (i.e., the reduction of extractive activities and other impacts) to-date, despite the difficulty in interpreting failing ecological performance without understanding the underlying context of human stressors (Claudet, 2018; Dunham et al., 2020). Measures of the levels and drivers of non-compliance are a necessity for MPA monitoring programs, and essential for adaptive management of existing MPAs and improvement of future conservation planning efforts.

The current state of the literature describing non-compliance levels in MPAs continues to inhibit global evaluations of management impacts on regulated fishing and patterns in non-compliance. This is in part owing to a lack of standardized measures, as was also observed and advocated for by the previous review on this topic (Bergseth et al., 2015). Few measured comparisons of regulated fishing inside and outside of MPAs exist ($n = 20$ studies). Even fewer studies quantified levels of non-compliance before and after interventions such as MPA establishment, increased enforcement, or public awareness efforts ($n = 8$), many of which did not present data that could be readily extracted for meta-analysis. In particular, remote sensing studies that provide maps of fishing effort inside and outside of MPAs would increase their contribution by including summary statistics. Reporting surveillance effort would also enable standardization and comparison of values across spatial and temporal scales (Haggarty et al., 2016; Thiault et al., 2020). The direct and indirect questioning method is further along in enabling comparisons across studies with the development of a clear suite of recommended interview techniques (Arias et al., 2015). Provided enough quantitative and comparative measures (inside/outside or before/after enactment, increased enforcement, or education events), a suite of study-design and MPA characteristics could be tested to determine what influences management impacts on regulated fishing across MPAs. Measured changes in fishing activity further provide an indicator for the degree of population or ecosystem improvement that can be expected from protection, i.e., if a minimal or substantial amount of fishing was reduced by the MPA regulations or rules. Continued improvement and standardization for quantifying and reporting non-compliance will enable future meta-analytic approaches to address non-compliance in a global context and benefit adaptive management of individual MPAs.

It is important to note that our results reflect only what has been reported in peer-reviewed literature and therefore should not be interpreted as a globally representative sample of all MPAs. For instance, some ecological studies may focus on MPAs with low non-compliance to understand ecological performance in a well-managed scenario (Cinner et al., 2018), whereas suspected non-compliance in MPAs may incite a study on the issue (Graham et al., 2010). It is difficult to determine how representative these studies are of worldwide MPAs, though most geographic regions were represented in the relevant literature and a few studies spanned multiple regions (Cinner et al., 2012; Edgar et al., 2014; Bergseth et al., 2018). Our focus on non-compliance related papers also greatly limited the extent of MPA literature reviewed. Non-compliance is a much less prevalent topic for MPAs relative to ecological performance (Dunham et al., 2020); however, this does not inherently reflect the importance of the issue, particularly as has been established in fisheries and wildlife realms (Kurland et al., 2017; Battista et al., 2018; Oyanedel et al., 2020b).

A growing avenue of research examines the normative influences on compliance-related behaviours in MPAs, which can reinforce, encourage, or discourage non-compliance. For instance, the false consensus effect may lead non-compliant individuals to mistakenly believe that non-compliance levels are higher than they actually are, thereby allowing them to justify continued non-compliance (Bergseth and Roscher, 2018). Similarly, perceived social norms can influence whether people choose to report non-compliance (Bergseth et al., 2018), which is critically important given most MPAs have insufficient resources for management and enforcement (Gill et al., 2017). Studies have found great variation in how, and whether, locals respond to observed non-compliance. For instance, a recent comparative study found that locals in Papua New Guinea and Indonesia often confronted or reported poachers, whereas inaction was common in Australia and Costa Rica (Bergseth et al., 2018). Mancha-Cisneros et al. (2018) found that locals in the Gulf of California, Mexico were most likely to discuss observations of non-compliance with other fishers or do nothing, followed by talking to or reporting poachers, respectively. Many people who did nothing cited a fear of conflict or a belief that it was not their responsibility (Bergseth et al., 2018), whereas fishers in the Philippines took action because they perceived an economic benefit of the MPA (Chaigneau and Brown, 2016). Such results aid in understanding how to engage locals in voluntary surveillance, which can also create a sense of ownership and commitment to the MPA. Finally, very few studies address why compliance occurs (Pollnac et al., 2010; Bergseth et al., 2015), which may differ from reasons for non-compliance. Understanding drivers of compliance may provide more direct guidance on how to achieve the desired result through coercive (i.e., focus on enforcement) and voluntary approaches (i.e., focus on legitimacy, incentives, alternatives, and communication) (Arias, 2015).

Another emerging research frontier is the application of theoretical frameworks adapted from criminological disciplines to understand and measure non-compliance in MPAs. These have been reviewed in the context of fisheries and wildlife poaching (Kurland et al., 2017; Oyanedel et al., 2020b) and more recently applied to MPAs (Thiault et al., 2020; Weekers et al., 2020). For instance, the environmental criminology concept that illegal activities are structured and non-random was used to evaluate spatial and temporal concentrations of recreational poaching in the Great Barrier Reef Marine Park to guide enforcement efforts (Thiault et al., 2020; Weekers et al., 2020). Research on law enforcement strategies, particularly strengthening surveillance and making poaching more difficult, is also growing for wildlife protected areas (Kurland et al., 2017) and can be similarly applied to MPAs.

The various avenues of research discussed in this review are imperative to ensuring and bolstering effective development and management of MPAs. Quantitative measures of non-compliance in MPAs have increased substantially since 2012 (Bergseth et al., 2015), though challenges remain with lack of standardized measures, inconsistent reporting, and relatively few comparative approaches. However, our synthesis revealed the consistent importance of enforcement, socioeconomic, and governance related drivers of non-compliance across MPAs, and the relatively high occurrence of ecologically failing MPAs (within our non-compliance focused search) attributed primarily or in part to non-compliance. Advancement of quantitative non-compliance measures and reporting will enable more in-depth syntheses for future global evaluations of non-compliance as an issue for MPA effectiveness. Understanding non-compliance at this broader scale, as well as applying lessons from other regulatory contexts, can guide monitoring and adaptive management of individual MPAs.

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.

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