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Review

Ecological impacts and management strategies for recreational diving: A review

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ABSTRACT

Recreational diving is an expanding branch of ecotourism that when poorly managed, may cause considerable impacts to benthic organisms. Such impacts become a matter of concern in popular diving destinations. A systematic literature review was used to verify the characteristics of divers who cause damage to reefs, the effects on benthic organisms, and the range of management interventions available. We describe the knowledge gaps, addressed challenges and propose solutions hoping to reach successful management of diving tourism industry. We identified three main challenges on recreational diving management frameworks and discussed actions to overcome such challenges. The challenges are related to (1) the lack of baseline data and long-term monitoring; (2) integration of scientific research and management; and (3) adaptive management strategies and stakeholder involvement.

1. Introduction

Marine non-extractive wildlife tourism that involves recreational activities and interaction with diverse organisms in underwater ecosystems has grown globally over the last decades (Cisneros-Montemayor et al., 2013; O'Malley et al., 2013). Recreational diving is one of the fastest-growing types of marine wildlife tourism activities, with thousands of new practitioners trained in scuba diving each year (Garrod and Gössling, 2008; Spalding et al., 2017). Diving tourism usually generates financial benefits for coastal communities, mainly through income generated by visitors to marine protected areas – MPAs (Green and Donnelly, 2003; Emang et al., 2016). MPAs are known to harbor most of the diving destinations due to higher biodiversity attributes such as higher coral cover and fish biomass. Diving tourism may also contribute to, enhance public awareness of marine ecosystems and provide revenue for the maintenance of MPAs and conservation of biodiversity (De Brauwer et al., 2017). However, diving tourism must be effectively managed to ensure that any impacts caused to ecosystems do not outweigh its positive effects.

An increasing body of literature has demonstrated that diving activities, mainly on highly visited sites, can detrimentally affect marine life, particularly in sensitive benthic organisms such as corals, sponges, bryozoans and gorgonians (Barker and Roberts, 2004; Chung et al., 2013; Nuez-Hernández et al., 2014). Since the early 1990s, surveys have also revealed high levels of reef damage at destinations that receive intensive diver visitation (Riegl and Riegl, 1996; Zakai and Chadwick-Furman, 2002). The profile and behavior of divers are important to understanding diving impacts because they may directly influence the rates and types of damage caused to benthic reef organisms. Injury to reef benthos by divers occurs mainly through direct contact, which can fracture the rigid skeletal structures or abrade the soft tissues of benthic organisms (Chung et al., 2013; Au et al., 2014). This type of damage is especially problematic for scleractinian corals because of their role as foundational species on tropical reefs. Repeated direct or indirect damage can also increase the susceptibility of corals to predation (Guzner et al., 2010), disease (Lamb et al., 2014), growth impairment (Guzner et al., 2010), and eventual reduction in reef complexity (Lyons et al., 2015).

Comprehensive knowledge about the scope of reef degradation caused by recreational diving is crucial for the coastal economies that depend on reefs to sustain the expanding nature-based marine tourism industry. Divers use the quality and quantity of marine life on reefs as criteria for dive site selection (Uyarra et al., 2009; Giglio et al., 2015), and are willing to pay more to visit healthy rather than degraded reefs

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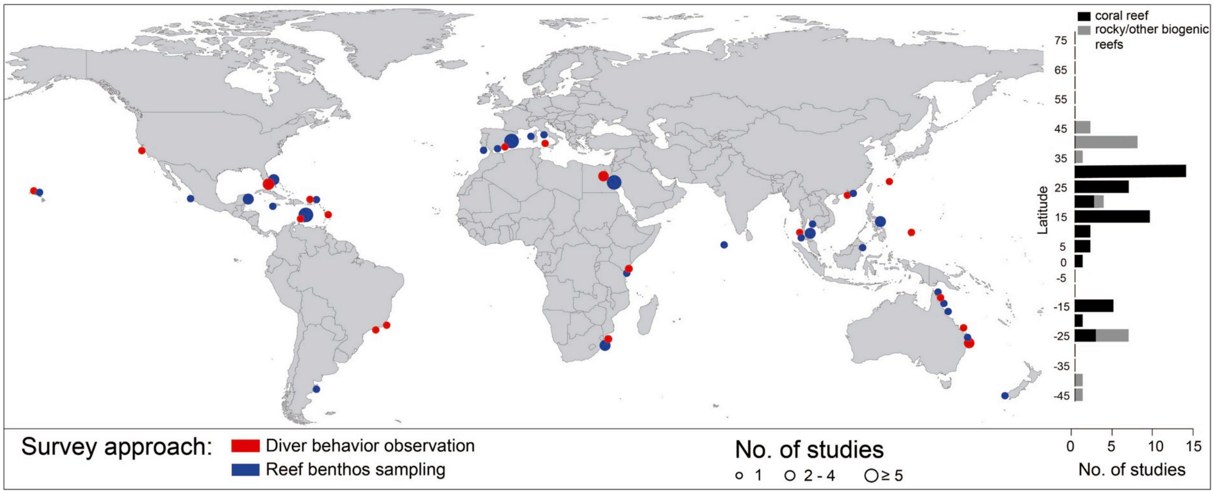

Fig. 1. Distribution of behavioral studies on diver-benthic organism interactions and the effects of recreational diving on benthic reef organisms.

(Wielgus et al., 2009). Understanding the effectiveness of different types of diving management initiatives to ensure reef biota conservation is also critical for designing targeted strategies that will work to address and manage diver impacts. In this review, we synthesize the current knowledge on negative ecological effects of recreational diving on benthic organisms and the management frameworks developed to mitigate such potential impacts. Despite that there is a range of management strategies available, many challenges to their implementation remains. Our aim is to provide a conceptual guidance to researchers and practitioners that may help to improve the effectiveness of these management strategies. We describe the knowledge gaps, challenges and propose solutions hoping to reach successful management of diving tourism industry. We also identified crucial factors that need to be taken into account for appropriate management of recreational diving.

To address the theme, this review was divided into three main sections. In Section 1 we seek to verify how divers interact with the reef, and what characteristics of diver profile are determinant to predict the increase of impacts to reefs. Identify how divers are more likely to make physical contacts with reef biota can assist in the development of best practice initiatives. In Section 2, we reviewed the effects of recreational diving on benthic organisms. Specifically, we verified the main effects and their potential to cause changes in reef systems functioning. Finally, in Section 3, we synthesized the current knowledge and applications of management strategies, verifying gaps, addressing challenges and

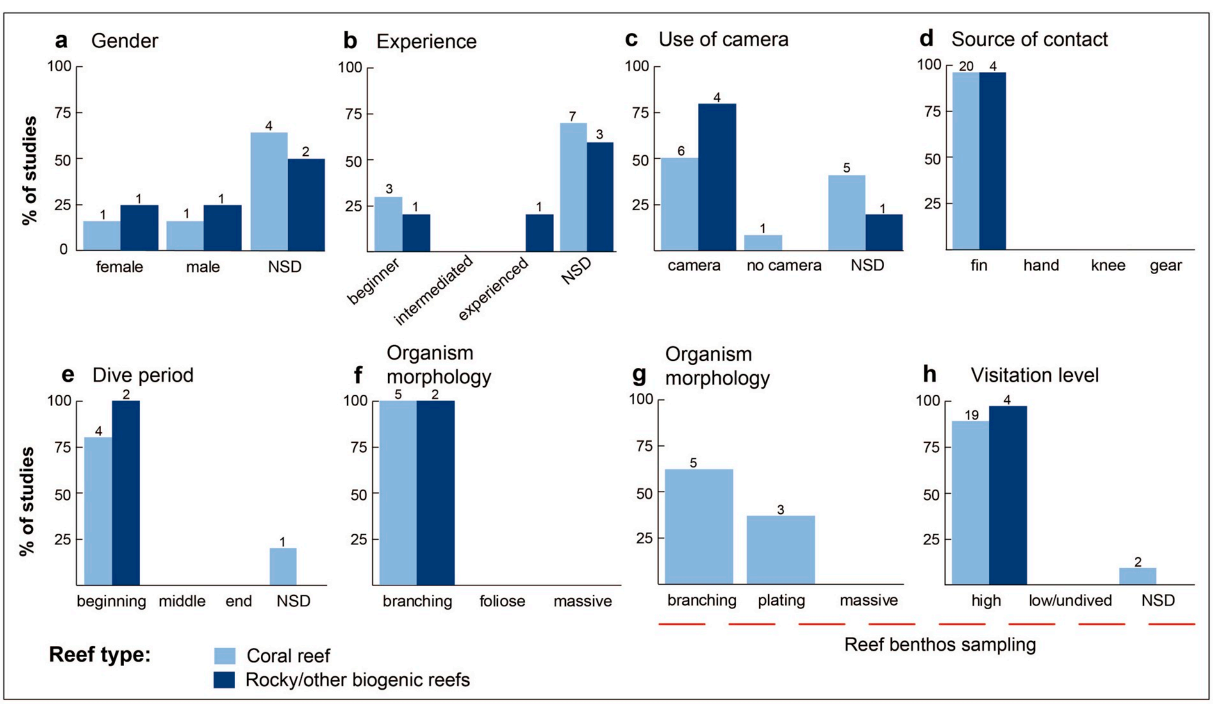

Fig. 2. Variation within eight types of diver (a–e) and reef characteristics (f–h) in the percent of studies that reported the most damage to benthic organisms, on both coral reefs (light blue) and non-tropical rocky or biogenic reefs (dark blue). Five types of diver characteristics are shown: (a) diver gender (b) diver level of experience, (c) diver status as a photographer, (d) area of the diver's body area contacting the reef, and (e) period during the dive; and three types of reef characteristics: (f) coral growth form more often damaged by divers. Red dashed line indicate results from reef sampling surveys (g) most damaged coral growth forms, and (h) level of diver visitation that caused more damage on the reef. NSD = No significant difference. Numbers above bars indicate the number of studies. The references used to this analysis are provided in Table S1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

discussing frameworks to management of recreational diving.

2. Methods

The scientific literature was systematically examined by conducting searches in the Scopus and Web of Science databases for peer-reviewed research articles published using a range of Boolean search terms in English. Searches were performed in December 2018 on the complete range of articles or reviews available at that time. Search terms were verified in the title, abstract and keyword as follows: (impact* OR behavio* OR effect* OR manag*) AND (scuba div* OR snorkel*). This initial search returned a total of 957 articles that potentially included information about impacts of recreational diving or behavior or divers on marine reef benthos. An article was retained if it met at least one of three major criteria: it described 1) characteristics of divers and their behavioral interactions with benthic reef organisms; 2) effects of scuba diving or snorkeling on benthic reef organisms; or 3) tested the effects of a management approach to reduce the potential impacts of recreational diving to benthic organisms. For each article, we verified the geographic location of the field study site; the type of reef environment and organisms examined; and types of management interventions tested or recommended.

As for the first criteria, we analyzed the following diver or diving characteristics in relation to rates of benthic contact by divers and their profile characteristics: 1) gender; 2) level of diving experience; 3) area of the diver's body that contacted benthic organisms (e.g., hands, fins, knees, etc.); 4) photographer status (i.e. observed to use an underwater camera); 5) period during each dive when interactions were observed to occur (i.e. beginning, middle, or end of the dive); and 6) growth forms of the benthic organisms contacted (i.e. branching, foliose, massive). For articles that surveyed reefs for impacts of diving on the benthos, we described adverse effects inflicted on the benthic organisms. We also examined any reported correlations between growth forms of benthic organisms and frequencies of diver damage and the extent to which rates of reef damage correlated with diver visitation rates.

3. Overall patterns and locations of studies

The literature search yielded 67 peer-reviewed articles that examined impacts of recreational diving on benthic reef organisms, with the first article published in 1991. The majority of published studies investigated effects on reef benthos from scuba diving (79%), while a few (15%) focused on snorkeling, and only a handful (6%) studied the combined effects of both scuba diving and snorkeling (referred here collectively as diving). Nearly 50% of the studies surveyed characteristics of benthic reef organisms affected by divers, while 30% investigated the behaviors and profiles of divers interacting with the benthos, and the rest (15%) assessed both. Most studies (70%) were conducted on tropical reefs, particularly coral reefs on highly visited diving reefs as the Caribbean, Rea Sea, Florida, Southeastern Asia and Great Barrier reef (Fig. 1). The remaining studies examined temperate (18%) and subtropical reefs (12%). Marine protected areas represent most of the sites examined at both tropical (80%) and subtropical and temperate destinations (94%). Unsurprisingly, research is biased geographically to highly visited reefs, investigated mostly by researchers affiliated in institutions from nearby countries (Fig. S1).

4. How do divers interact with benthic reef organisms?

Studies that have quantified variation in damage rates with diver's gender have found no difference (66% and 50% of studies on coral reefs and rocky/other biogenic reefs, respectively; Fig. 2a). When a difference was found, studies reported mixed effects, so there does not yet appear to be a clear pattern in terms of gender effects on rates of reef damage. The level of diving experience also has not been found to be determinant for changes in levels of damage (Fig. 2b). Instead, frequencies of diver damage appear to vary among diving destinations based in part on reef and site characteristics and water conditions (Hammerton, 2017; Rouphael and Inglis, 1997) and diver profiles (e.g. specialization level, gender and motivation; Musa et al., 2011; Chung et al., 2013). Therefore, few broad generalizations can be made about how rates of benthic reef damage vary with diver characteristics. Instead, understanding aspects of diver profiles and behaviors at the site level appears to be essential for guiding local strategies to manage diving tourism.

Being an underwater photographer is the single diver's characteristic determinant to influence rates of reef damage. Most studies report that photographers cause more damage to benthic organisms than non-photographers (Fig. 2c). Photographers damage reefs by intentionally holding onto the reef surface to stabilize their bodies, and by unintentionally banging into the reef, both while attempting to take photographs (Hammerton, 2018). Photographers with different profiles may exhibit different behaviors and rates of reef damage (Giglio et al., 2016), and thus may require tailored management strategies.

In terms of the diver's body part that most often causes damage to reef organisms, fin kicks have been reported as the major culprit in all studies to date (Fig. 2d). Divers move their fins for propulsion and usually hang them lower than the rest of the body. As such, fins are the diver's body part most likely to contact the reef; the contact often is unintentional (Chung et al., 2013). This potential damage may be neglected because divers tended to underestimate their number of contacts and the potential impacts on benthic organisms (Hammerton, 2016). Scuba divers, especially introductory level ones, may exhibit poor buoyancy control and generally have not been trained to remain in the horizontal position while diving to avoid the risk of collision with the reef (Hammerton, 2016; Toyoshima and Nadaoka, 2015). Such diver-reef contacts are reported to occur mainly during the beginning of the dive (Fig. 2e). At this stage, divers are usually adjusting their buoyancy and their equipment, often causing them to move erratically and contacting the reef (Camp and Fraser, 2012). Throughout the dive, rates of diver contact with the reef tend to decrease, as divers further adjust their equipment and become more comfortable in the aquatic environment.

The benthic organisms with branching morphologies have been reported to receive high rates of damage than massive or foliose and plate-like ones. This pattern is consistent between studies examining diver-reef contacts (Fig. 2f), and benthic reef surveys (Fig. 2g). The susceptibility of branching organisms to diver damage likely occurs mainly due to their high abundance on many reefs and their upright structure in which the upper sections of the colony extend vertically into the water column. Such characteristics make branching corals vulnerable to fracture even when inflicted by gentle fin kicks.

The reef types reported as exhibiting the highest levels of observed damage were those that receive higher frequencies of visitation (Fig. 2h). Obviously, the increase in the number of divers was accompanied by an increase in damage to benthic organisms. However, there are few information on under what conditions damage increases regarding the size of dive groups and crowd in the dive site. We believe that large groups and crowded sites can be associated to the increase of damage because of group size influence the ability of guides to supervise visitors (Barker and Roberts, 2004; Roche et al., 2016) and small sites have space limitation to avoid contact with the reef. Further research is needed to understand in more details what conditions divers may cause more damage to benthic organisms.

5. Effects of diving on benthic organisms

5.1. Tropical coral reefs

Eleven types of impacts caused by recreational diving have been described for benthic organisms on coral reefs. Increase in skeletal breakage of corals is the most frequently-documented impact (Table 1 and Table S2), being used as a major indicator of the level of diving

Table 1
Effects on benthic organisms caused by recreational diving. References are provided in Table S2.

Type of diver damage	Type of effect	Frequency of studies (%)
Coral reefs (no. of studies = 53)		
Increase in skeletal breakage of corals	Short-term	40
Decrease in coral percent cover	Cumulative	13
Shift in benthic assemblage composition	Cumulative	11
Increase in coral tissue loss	Short-term	8
Increase in coral disease prevalence	Cumulative	8
Increase in algal overgrowth of corals	Cumulative	6
Increase in sedimentation on corals	Short-term	6
Increase in predation on corals	Cumulative	4
Decrease in coral colony size	Cumulative	2
Decrease in reef structural complexity	Cumulative	2
Decrease in coral growth	Cumulative	2
Rocky reefs or other biogenic reefs (no. of studies = 18)		
Decrease in abundance or percent cover of benthic organisms	Cumulative	28
Decrease in sizes of individuals or colonies of benthic organisms	Cumulative	22
Change in distributional patterns to more cryptic reef habitats	Cumulative	22
Shift in benthic assemblage composition	Cumulative	11
Increase in skeletal breakage of stony corals	Short-term	11
Detachment of coral colonies	Short-term	6

pressure, in part because is an impact detectable at short-term, easily visible and can be recorded quickly and unambiguously (Jameson et al., 1999; Au et al., 2014). The second most frequently-reported diver damage include the loss of live stony coral cover, which is suggested to be a cumulative effect of diver visitation due to coral mortality (Hawkins et al., 2005; Hasler and Ott, 2008), and shifts in benthic assemblage composition to species resilient to frequent damage (Table 1). The following effects described include other cumulative damage at assemblage and organism level, such as an increase in coral diseases and algal overgrowth of corals. Cumulative consequences of diving disturbance include a reduction in the structural complexity of reefs, which have implications for reef dynamic and resilience (Lyons et al., 2015; Fig. 3). There is a gap in the literature regarding studies evaluating diver damage effects at the level of the coral microbiome. These changes are likely to occur because corals may shift their microbial assemblage composition in response to stressors, impairing coral resistance to microbial infection or increasing pathogen virulence (Webster et al., 2011; Morrow et al., 2012). Diving related damage to corals have been linked to higher levels of disease prevalence (Lamb et al., 2014). Understand the threshold between coral health and diver visitation is essential to subside zoning and ecological carrying capacity. Coral microbiome aspects must be considered in long-term reef monitoring initiatives to understand how microbiome composition and function changes at different levels of diver visitation.

Corals with structurally complex morphologies such as branching and plating have been described as the most frequently fractured by divers (Worachananant et al., 2008; Au et al., 2014; Giglio et al., 2018a). However, such corals may exhibit more rapid recovery to disturbances and growth than do massive corals and thus may be able to better withstand with cumulative diving impacts over the long term (Lirman, 2000). On Caribbean reefs, branching corals dominated areas that had been covered mostly by slower-growing massive corals before extensive visitation by divers (Hawkins et al., 1999). Branching corals appear to be opportunists which may gain advantage in space use at disturbed sites (Fig. 3). Massive corals constitute the major reef-builders on many reefs (Dornelas et al., 2017), so their relatively slower ability to recover from diver damage is a cause for concern.

5.2. Non-tropical rocky and other biogenic reefs

Benthic assemblages on non-tropical reefs consist mainly of macroalgae and encrusting, low-relief or soft-bodied colonial invertebrates, such as ascidians, gorgonians, zoanthids, and bryozoans (Gibson et al., 2006; Aued et al., 2018). Studies addressing the impacts of recreational diving have focused mainly on the coralligenous reefs of the Mediterranean Sea (Fig. 1, see other studied sites in Table S1). Most of studies have examined bioindicator species of diving impacts such as bryozoans (Garrabou et al., 1998; Sala et al., 1996; Nuez-Hernández et al., 2014), corals (Terrón-Sigler et al., 2016) and ascidians (Luna-Pérez et al., 2010). The focus on bioindicator species has allowed data collection with reduced cost and time. The most frequently reported types of diver damage are cumulative effects related to reduction in organismal abundance, body size and colony size, as well as distributional patterns altered from occurrence on exposed reef surfaces to persistence only in cryptic, shaded habitats (Table 1 and S2). Similar to tropical coral reefs, the most susceptible and affected organisms on non-tropical reefs appear to be the structurally complex and fragile ascidians, bryozoans, corals and gorgonians (Garrabou et al., 1998; Linares et al., 2010; Terrón-Sigler et al., 2016).

The exposure to intensive diving may cause non-tropical reefs to shift to an alternate community state, in which the reef is dominated by erosion-resistant encrusting and massive organisms (Garrabou et al., 1998). Diving-susceptible species are absent from this alternate state (or occur only in cryptic habitats) (Casoli et al., 2017; Nuez-Hernández

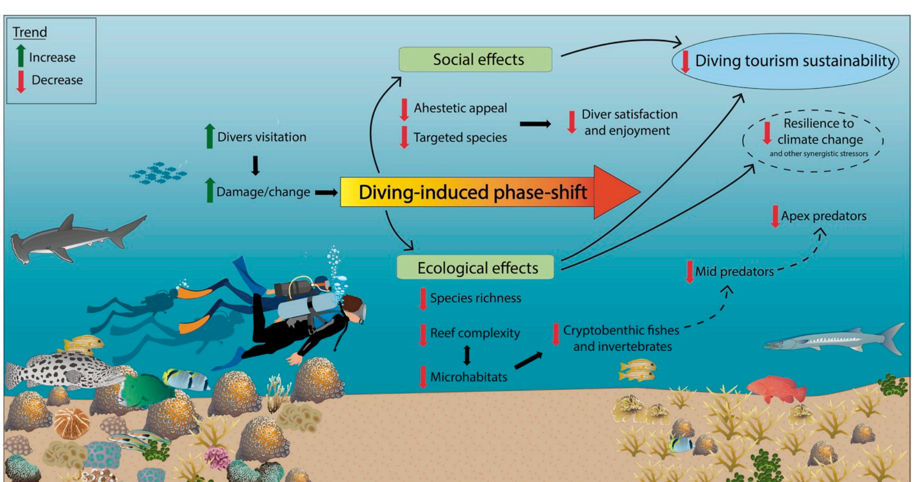

Fig. 3. Ecological and social effects of diving tourism on coral reefs. Symbols courtesy of the Integration and Application Network (http://ian.umces.edu/symbols/).

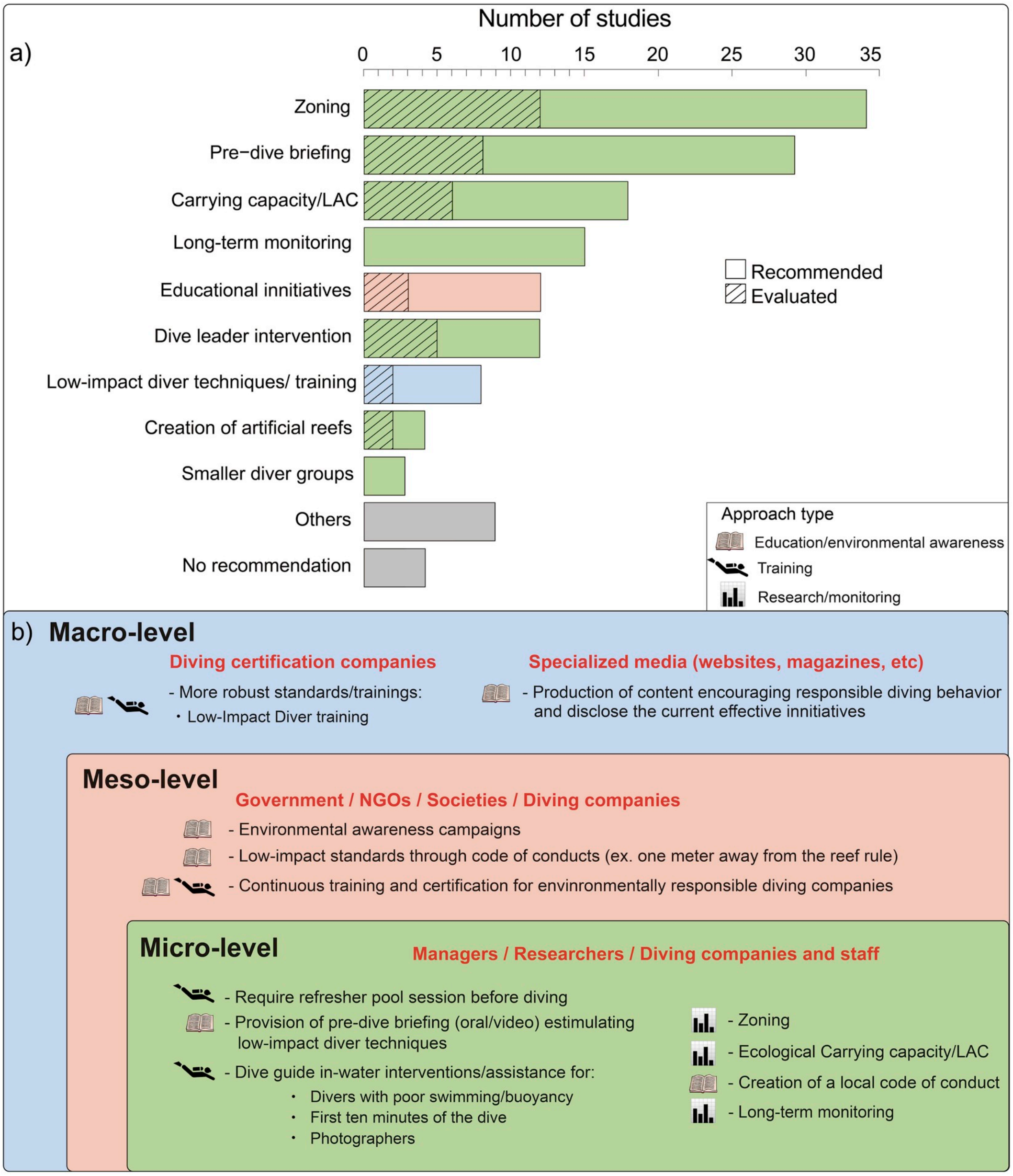

Fig. 4. a: Number of studies which tested or recommended management strategies to mitigate the potential impacts of recreational diving on marine reefs. References to each recommendation are provided in Table S3 **b.** Management strategies organized into a multiscale framework. To the analysis of tested management recommendations, we consider long-term monitoring if a study has temporal data over ten years or more. The colors in the bar plot (a) matches the scale colors in (b). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

et al., 2014). In the same way from tropical reefs, such shift to an altered reef state reduces the structural complexity of the reef, which may in turn cause flow-on effects to reef systems by altering their predator-prey interactions and influencing competition (Kovalenko et al., 2012).

6. Management strategies for recreational diving: current use, gaps and challenges

Most studies analyzed have focused on described potential impacts of diving tourism, while research on the development of management strategies to deal with these impacts have been verified in 40% of studies. Those articles usually recommend specific management interventions, but few actually tested or evaluated their effectiveness. Fifteen distinct types of management interventions are proposed in the literature, with an average of two intervention types per study. The number of intervention types per study did not vary with the type of reef examined (Kruskal-Wallis test: $H = 3.7$, $p = 0.5$). Studies proposed mainly site-level management interventions, particularly limiting the visitation spatially and numerically and strategies to improve the low-impact diver (LID) behavior through diver-level information and assistance underwater (Fig. 4a). The different management initiatives verified in the literature may act synergistically through different spectra, from broader (macro-level) to local (micro-level; Fig. 4b) as well as have different complexity and feasibility of implementation and continuous execution. For instance, at macro-level, the improvement in LID behavior training as a global standard of international scuba diving certification companies may reduce the rates of diver-reef contacts and consequently the amount of damage to benthic organisms (Hammerton, 2016). Such initiative may be reinforced at micro-level through the use of a pre-dive briefing (Camp and Fraser, 2012; Webler and Jakubowski, 2016; Giglio et al., 2018b) sharing information which stimulates divers to apply LID techniques (compiled in Table S4). Recent initiatives have

Table 2
Challenges and potential solutions/frameworks for improving the management of recreational diving.

Challenge	Solution/Framework
Early diving tourism monitoring and management planning	- Implement early monitoring using BACI design or similar that considers a spatio-temporal baseline of reef condition before visitation begins; - Identify which other human-related activities or natural events (e.g., hurricanes, crown-of-thorns plague) have historically caused potential adverse effects on the reef biota and consider cumulative/synergistic impacts of such activities in management frameworks;
Integration of management and scientific research	- Implement adaptive co-management – real-time feedback mechanisms to improve management with information collected through monitoring of both reef condition, visitation and management framework effectiveness. - Build in-house research and monitoring capacity in management agencies and other stakeholders involved in the management;
Monitoring management frameworks	- Establish a long-term and easily applicable collaborative monitoring of management effectiveness considering not only managers perceptions but the view of different stakeholders;
Include stakeholders in the management process	- Promote stakeholder involvement and collaboration in the management process since monitoring data collection to the learning process through adaptive management; - Establish a regular, long-term two-way communication channel between managers and stakeholders; - Establish a shared (i.e., managers, decision-makers, researchers, diving companies as well as associated service providers) long-term vision of outcomes, management goals and a common sense of purpose, setting clear, short-term achievable goals; - Publicly acknowledge the diving operators or other tourism companies who collaborate with management and monitoring;
Resources for monitoring ecological indicators and management interventions	- Destination of part of the funds from entrance fee to monitoring reef condition and implement and monitoring management frameworks; - Creation of a donation program disclosing the initiative widely on the web, social networks, specialized magazines, etc; - Implementation of long-term monitoring programs using volunteers through citizen science initiatives (e.g., Reef Check).

provided to be successful in stimulating diving operators to improve LID, recognizing sustainable practices (Huddart, 2019). Given the nonlinear and complex processes, and the variety of stakeholders involved in diving tourism management, a conceptual framework synthesizing all management strategies available will provide a roadmap for managers to decide among different policy actions. Choosing the adequate management framework requires understanding the suite of available initiatives, the ability and limitations in implementing them and how they match the type of impacts one wants to mitigate.

The environmental management process consists of three main stages: 1) conceptualization and planning; 2) management implementation and evaluation; and 3) framework evaluation and revision (Schwartz et al., 2018). We reviewed challenges to proper recreational diving management on these three stages that should be addressed in further research and management framework implementation (Table 2). Two important challenges are the lack of baseline data from reef condition previously to the impact inception and lack of long-term reef monitoring. Because of these gaps, we still have a poor understanding of the long-term effects of diving on the reef systems. The baseline data is usually collected through before-after control-impact (BACI) design (Underwood, 1991). Such design is optimal because isolates the effect of the human-induced change from natural variability. Despite the importance of baseline data, only two studies have used BACI designs in reef monitoring to subside recreational diving management (e.g., Garrabou et al., 1998; Rouphael and Inglis, 2002). Most research on diving impacts began after the impacts are happening and became a matter of concern. Early planning of recreational diving is key for effective management.

Although the popularization of the diving industry has been arising from almost three decades, there are no published studies using long-term monitoring data (>10 years). Research usually rely on snapshots or a few years of sampling at most, revealing that long-term reef monitoring is a critical gap to inform recreational diving management. Monitoring changes in the condition of reefs exposed to diving tourism and monitoring of divers' visitation provides a scientific basis for adapting management strategies over space and time such as zoning, carrying capacity and diver-level initiatives. A clear definition of aspects to be monitored is essential to implement and revisit frameworks continuously considering potential changes (Fig. 5). Reef monitoring should focus on reef condition realistic indicators, such as levels of tissue and skeletal damage, changes in distribution and habitat use and disease prevalence. However, monitoring programs may be impracticable because require trained personnel and infrastructure. On the other hand, diving destinations on MPAs usually collect a visitor fee to ensure the sustainability of the activity (Green and Donnelly, 2003). These resources should be used to establish long-term reef monitoring to inform diving tourism management. Besides, there is a growing literature on successful reef monitoring initiatives using voluntaries (Goffredo et al., 2004; Branchini et al., 2015; Lau et al., 2019). Recreational divers are usually willing to contribute financially to conservation through user fees (Casey et al., 2010) and participate in citizen-science based research and conservation initiatives (Hunt et al., 2013). These potential collaborators may represent novel, reliable and cost-effective frameworks for reef monitoring, which can be sustained and embedded within long-term monitoring programs. However, the literature indicates that initiatives using citizen-science or volunteers to collect reef data are poorly explored by researchers and managers from the recreational diving sector (but see Goffredo et al., 2004; Branchini et al., 2015).

One of most important management strategies is the establishment of a limit to diver visitation. Popular diving destinations where visitation was not limited had its reef biota deteriorated in a short time (Riegl and Riegl, 1996; Zakai and Chadwick-Furman, 2002). Estimates of carrying capacity has been the most used approach to establish limits on the number of divers on dive sites (but see the limit of acceptable change [Roman et al., 2007; Leujak and Ormong, 2008] and the percentile approach [Rouphael and Hanafy, 2007]). The ecological carrying capacity (ECC) is expressed as the number of divers per site per year, measured as the number of divers a site could tolerate without becoming degraded (Dixon et al., 1993; Davis and Tisdell, 1995; Hawkins and Roberts, 1997). However, most diving destinations have not established an ECC. Despite there is no current consensus about the criteria and methodology to quantify ECC to recreational diving, an increased number of studies have proposed approaches with different complexities and feasibly of execution (reviewed in Zhang et al., 2016). However, most of tropical dive destinations have used the threshold of 5000 divers per year, established 26 years ago by Dixon et al. (1993), as a 'magic ECC number' (Zhang et al., 2016). Such rough extrapolation is a matter of concern because reef characteristics and the profile of divers are site-specific; thus, ECC needs to be established locally (Lloret et al., 2006). Also, limits to ECC may be dynamic and should be continuously

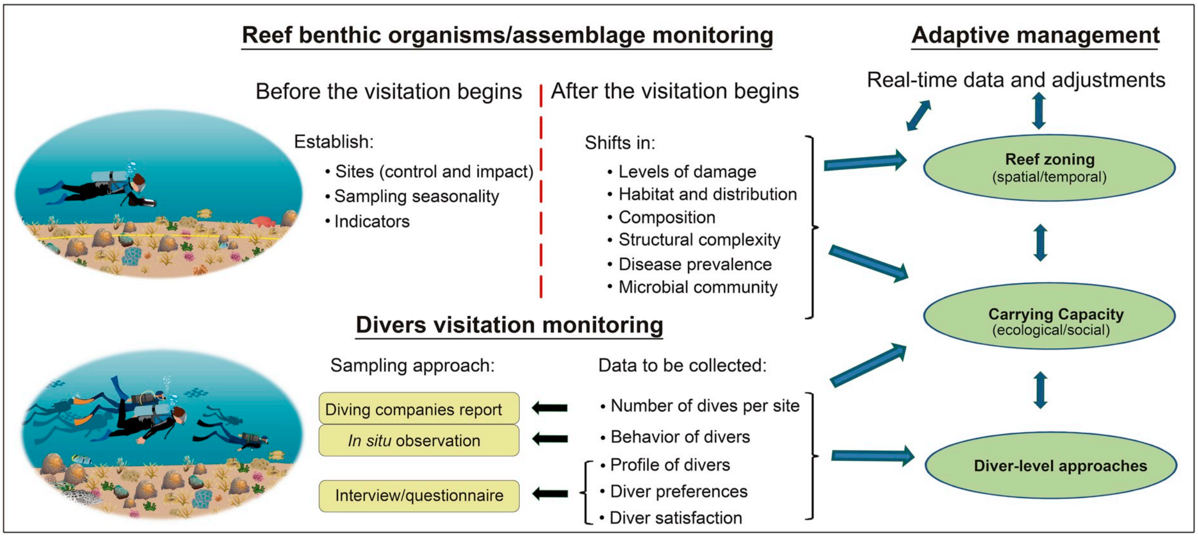

Fig. 5. Framework of key aspects for monitoring of benthic reef organism conditions and divers visitation to inform management innitiatives.

revised, supported by monitoring data. We encourage researchers and managers to establish ECC through a site-level assessment instead of using estimations from other sites.

We incentive managers to take on approaches based on adaptive management whereby monitoring data are used to continuously assess the state of the system for the purpose of making periodic decisions on changes in management initiatives. Adaptive management will allow managers, scientists, diving staff and operators to discuss, elaborate and test monitoring and management protocols considering the multiple views, enabling real-time adjustments to implemented frameworks (Plummer et al., 2013). Regular, long-term communications between stakeholders, both within and outside of official governance forums, must be established to assure active and collaborative management. Such approach foster that local actors share collective responsibility for resources, learning, and governance outcomes (Sharma-Wallace et al., 2018). Could a diving tourism stakeholder not be interested in retaining the appeal it sells? Is the lack of examples of adaptive co-management of recreational diving a result of lack of interest by the stakeholders or due to poor communication and lack of incentive to be involved? Discussion forums may be organized through MPAs management council meetings or specific forums created to discuss co-management aspects of this segment. Consistent monitoring of both ecological, visitation and management effectiveness are crucial for long-term success of management frameworks engaging stakeholders (Sterling et al., 2017). To be successful, management frameworks need to have a well-organized activity plan, clear policies and guidelines, enforcement, long-term monitoring of the effects and effort to increase the ecological awareness and education (Black et al., 2011; Trave et al., 2017). Management initiatives to dive tourism should not rely uniquely on promoting the responsible use of natural resources, but also must be in accordance with the socio-economic context of stakeholders, be integrated with the community and promote a satisfying diving experience (Wongthong and Harvey, 2014).

Besides the research and effort to implement management actions, we encourage researchers and diving trademarks to develop new technologies aiming to ensure responsible diver behavior. For instance, fins are the main source of damage to benthic organisms. New innovative technologies in fins development may reduce diver-reef contacts, such as a fin with an electronic device that alerts the diver when he gets too close to the reef like a vibration in the fin or a beep on the dive computer. A growing literature has emerged describing new technologies to apply for research and conservation of marine biodiversity (Pimm et al., 2015; Bicknell et al., 2016). We hope that diving tourism follows this trend by developing innovative technologies to mitigate potential impacts on reef biota.

7. Concluding remarks

Our review revealed that relationships between diver-reef interaction and diver experience and gender are idiosyncratic to individual divers' profile and local reef characteristics. The only broader generalization is that divers cause more damage when using a camera and at the beginning of the dive. Cumulative impacts on benthic organisms can alter the physical structure, causing loss of complexity, while could affect the community dynamics of reef systems by increasing the cover of opportunist organisms at disturbed sites. Such negative effects may make benthic organisms less resilient to synergistic effects of climate change, but our knowledge on this topic is in its infancy. There is a gap in the literature regarding reef baseline data and long-term monitoring at diving destinations. Such data are essential to understand recreational diving impacts on reef systems and to inform management.

While acknowledging the growing literature about recreational diving impacts on reef assemblages and management strategies, we verified the gaps, addressed challenges and potential solutions to advance recreational diving management. Results revealed that management effort is concentrated at local level actions, the most feasible strategies in terms of financial and logistical resources. Our review addressed recreational diving management strategies at a broader view, synthesizing a multi-scale framework with actions from micro to macro levels that can be valuable to managers and the entire diving tourism segment. Broadly accepted management frameworks are not always transferable. Each diving destination has specific characteristics and must select or adapt appropriate management strategies for its own need considering the ecological, cultural and socioeconomic aspects (Wongthong and Harvey, 2014). Therefore, future research on recreational diving impacts and management efforts should put more attention to the dynamic context of this segment by implementing adaptive management strategies and integrating the multiple stakeholders that are interested in the financial, social, political and environmental sustainability of the recreational diving.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.109949.

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