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A review of ecological impacts from recreational SCUBA diving: Current evidence and future practice

Daminda Sumanapala
College of Arts, Business, Law and Social Sciences, Murdoch University, Murdoch, WA, Australia;
Tourism Research Cluster, Curtin University, Perth, WA, Australia

Kay Dimmock
School of Business and Tourism, Southern Cross University, Lismore, NSW, Australia

Isabelle D Wolf
Australian Centre for Culture, Environment, Society and Space, School of Geography and Sustainable Communities, University of Wollongong, Wollongong, NSW, Australia;
Centre for Ecosystem Science, University of New South Wales, Sydney, NSW, Australia

Abstract

Global demand for SCUBA diving activities in coastal areas continues to grow. Academic research has acknowledged that SCUBA diving can have ecological impacts. To understand the current state of knowledge this study applied the systematic quantitative literature review method (SQLR) to determine what evidence is available on ecological impacts from recreational SCUBA diving. In total 69 research articles about ecological impacts of SCUBA diving were analysed. This paper explored research trends, geographical distribution of research articles, nature of impact and management recommendations for future practice. The research found that SCUBA diving impacted through diver contact with coral reefs caused breakage, fragmentation and led to disease. 10 coral varieties were identified as impacted including some listed as (critically) endangered or vulnerable by the IUCN. Impacts can be minimized using non-regulatory and regulatory management strategies. We present a novel framework that connects diver characteristics with coral reef impacts and discuss how to apply this framework and guide future studies in this area of SCUBA diving research.

Keywords

SCUBA diver impact, tourism management, review, coral reefs, environmental education

Introduction

Marine resources have been used to expand marine tourism activities across the world (Burke et al., 2011; Brauwer De and Burton, 2018; Lavides et al., 2016). In many countries marine tourism has become the main income-generating activity (Balmford et al., 2009; Brauwer De and Burton, 2018; Dimmock and Cummins, 2013). As a result coastal areas have become popular sites for nature-based activities including diving, kite surfing, and snorkelling and SCUBA diving (Ong and Musa, 2012a; Wolf et al., 2019).

Among the natural resources at the centre of SCUBA diving activities are coral reefs. Coral reefs are found in shallow-water ecosystems. They have great ecological importance as they are home to a quarter of all marine coral and are estimated to be associated with more than a million of animal and plant species (Bellwood et al., 2018; Veron et al., 2011). Reefs also provide critical environmental services such as habitat for fisheries, coastal protection and attracting tourists

Corresponding author:
Daminda Sumanapala, College of Arts, Business, Law and Social Sciences, Murdoch University, South St, Murdoch, WA 6150, Australia.
Email: Daminda.Sumanapala@murdoch.edu.au

(Wild et al., 2011). Globally, coral reefs are suffering as already 45% of reefs have been destroyed, and another 20% are at risk from a variety of human activities (Burke et al., 2011; Ku and Chen, 2013; Strona et al., 2021). In order to protect and conserve the world's coral reefs a collective approach is needed to reverse such a decline (Cesar et al., 2003; De'ath et al., 2012; Tun et al., 2004).

Within this context, increasing demand for accessing SCUBA diving sites has potential to cause negative marine environmental impacts (Giglio et al., 2018; Hasler and Ott, 2008; Ward, 1990). Initially, research into SCUBA diving impacts focused on external impacts like large number of boat exceed the limits, with studies eventually moving towards ecological impacts of the actual SCUBA diving activity (Porbjornsson et al., 2002; Rogers, 1990; Roberts et al., 2002), and on coral reefs in particular (Hawkins and Roberts, 1992). Negative impacts included fragmented, abraded or dislodged coral and reduced structural complexity of coral reefs (Hawkins and Roberts, 1992; Zakai and Chadwick-Furman, 2002). Furthermore, physically damaged coral colonies are highly vulnerable to the spread of disease (Guzner et al., 2010; Lamb et al., 2014), which can lead to slow growth rates or coral mortality (Toyoshima and Nadaoka, 2015).

The number of certified SCUBA divers has risen since 1975 to around 30 million, and the number of operators and stakeholders in the diving industry has grown accordingly, placing additional pressures on coral reefs (Davenport and Davenport, 2006). At the same time, this increase in demand has not been met with an adequate increase in research to investigate the ecological impacts of SCUBA diving (Giglio et al., 2020; Hammerton et al., 2012; Holt et al., 2013; Meyer and Holland, 2008). Such an oversight is significant as impacts have been reported in research studies. Researchers noted for instance that divers kicking, trampling, holding, kneeling, or standing on corals cause significant damage (Encarnaçao and Calado, 2018; Hawkins and Roberts, 1992; Rogers, 1990). Impacts have occurred from diver equipment including cameras, fins, and gloves (Dixon et al., 1993; Hawkins and Roberts, 1992; Ong and Musa, 2012b; Riegl and Velimirov, 1991). Ecological impacts on the marine fauna around coral reefs (Hasler and Ott, 2008) in turn affected fish behaviour (Ong and Musa, 2012b), caused habitat degradation (Wong, 1998), and a decline in live coral cover, along with reduced habitat complexity, diminished coral growth, shifts in reef assemblage composition, and increased coral disease (Guzner et al., 2010; Lamb et al., 2014; Lyons et al., 2015; Toyoshima and Nadaoka, 2015; Renfro and Chadwick, 2017).

The current study seeks to provide consolidated knowledge of SCUBA diving impacts caused by diving tourists and recreationists and review the corresponding management measures. The findings of our study apply to the full spectrum of dive travel experiences on a continuum ranging from recreational activity to tourism experiences (McKercher, 1996). The specific aims of this review were to: (a) identify trends and the geographical distribution of SCUBA diving research; (b) highlight how SCUBA divers impact on coral reefs; (c) identify the coral affected by SCUBA activities; (d) discuss management recommendations; (e) develop a framework to connect diver characteristics with coral reef impacts and management measures, and discuss how to apply this framework to guide future research in this area of SCUBA diving.

Method

The study used a systematic quantitative literature review (SQLR) to analyse existing academic literature and identify research gaps in the study field (Pickering and Byrne, 2013). This is a widely applied method to produce a quantitative summary of a particular field. This method has been successfully used for reviewing literature in natural and social sciences and is useful for trans-disciplinary research (Kamler, 2008; Pickering and Byrne, 2013; Wolf et al., 2017).

The method involves four screening stages (Barros et al., 2015; Roy et al., 2012; Sumanapala, 2018; Sumanapala and Wolf, 2019, 2020; Scherrer et al., 2020; Wolf et al., 2017) in accordance with the Preferred Reporting Items for Systematic Review Recommendations (PRISMA). In the first (identification) stage English-language publications were identified up until 2018 using electronic databases covering tourism, marine and environmental sciences including Google Scholar, Web of Science, Scopus, Science Direct and Google Scholar Citation. The search terms were: 'SCUBA diving', 'marine impact', 'diving', 'trampling', 'marine ecotourism', 'marine recreational activities' 'marine protected area', 'human impact', 'coral reefs', 'recreational diving', 'coral damage', 'tourism management'. As a result 1234 publications were identified.

In the second (screening) stage only research articles published in peer reviewed academic journals were selected. Book chapters, conference proceedings, theses, non-peer-reviewed articles, reports and other grey literature were excluded due to the difficulty of gathering information on the full set of study variables, and also to avoid potential difficulties with the reproducibility and reliability of the results (Guitart et al., 2012) which narrowed the sample down to 803 publications. The third (eligibility) stage excluded papers which did

not meet the study objectives ($n = 388$) and based on an in-depth reading the remaining 69 publications were included for analysis in this study.

For each article we recorded the following variables (Table 1): general details such as author name, title, journal and year of publication; the location of the study; type of divers' contact with the coral (direct, physical by hand, body, vs equipment) (Daldeniz and Hampton, 2013); taxonomy of corals that were impacted; and management recommendations.

Results

Trends and geographical distribution of published articles

Sixty-nine journal articles were identified that examined the impact of recreational SCUBA diving on the marine environment and resources. Articles were published between 1991 and 2018, with an increased research effort after 2001 (Figure 1). Interestingly, articles were published in only three environmental management journals: *Biological Conservation* published almost one quarter of articles (24%), followed by Journal of Environmental Management (11%) and Ocean and Coastal Management (9%), Journal of Sustainable tourism (6%). The remaining (50%) studies were published in marine, tourism, geography and management journals.

Figure 2 highlights the geographical focus of studies into the impact of SCUBA diving, compared with world coral distribution. The majority of studies (29%) were based in the Atlantic coral region followed by Middle East and South East Asia and Australia and the. Meanwhile, studies in the Pacific (2.9%) and the Indian Ocean (1.4%) were much fewer in number. Only 21% of publications were found which focus on the South-East Asian region (e.g., Thailand, Indonesia, Malaysia, Myanmar and, Philippines) and few of them are reviewing without focusing geographical area. Those are

Table 1. List of variables collected from peer-reviewed journal publications on SCUBA diving impacts included in this review.

Category	Variable	Description	Data type
Publication	Author(s)		Text
	Title		Text
	Journal		Text
	Year		Numeric
Geographic	Continent		Categorical
Effect	Type of contact	Indirect (camera, fin & gloves, diving equipment); direct (knee & hand, walking& touching)	Categorical
	Type of impact	Break, fragmentation, disease	Categorical
Coral taxonomy	Scientific name		Text
	Common name		Text
Management	Recommendation	Regulatory, non-regulatory, research	Categorical

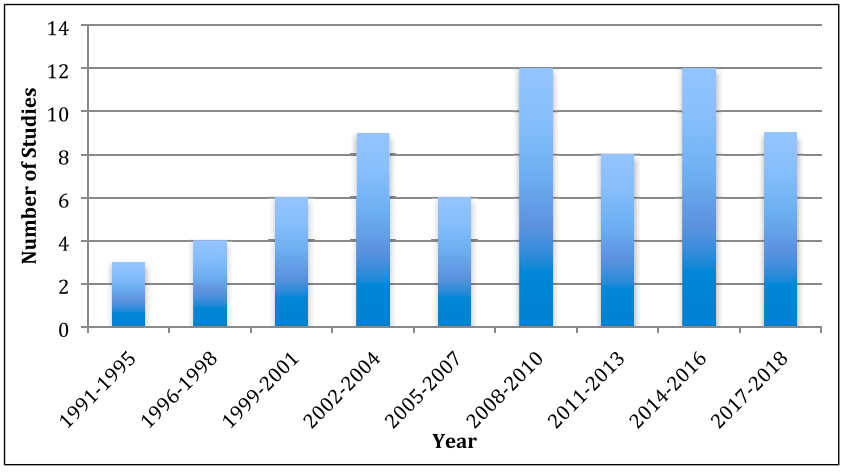

Figure 1. Year of publication of peer-reviewed journal publications on SCUBA diving impacts included in this review.

the countries located within the 'Coral Triangle' which is recognised as hosting over 500 coral species, and not counting Papua New Guinea, Solomon Islands and Timor-Leste. This absence from the research literature is notable considering that South-East Asia encompasses 34% of the world's total coral. Rodriguez-Ramirez et al. (2020) noted that 88% are damaged compared with the least threatened coral reef situated in the Australian region (Burke et al., 2011; Rodriguez-Ramirez et al., 2020; Todd et al., 2010).

Study aim number two was concerned with underwater behaviour of SCUBA divers, especially how their behaviour lead to contact with corals. Figure 3, summarises the number of papers reporting a particular type of contact between the diver and corals in seven categories: cameras, gloves, fins, knees, hands, walking and touching. Contact via cameras (20%), fins (20%) and walking (11%) was most commonly reported. Next, the most commonly reported form of contact occurred via SCUBA diving 'gear' such as cylinders and

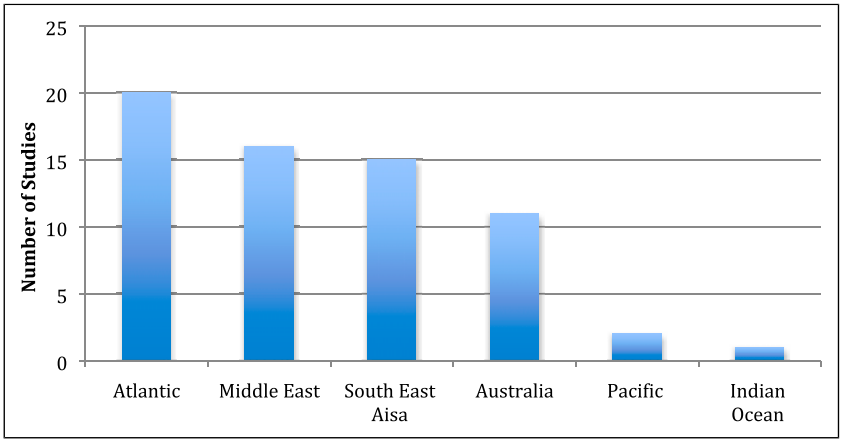

Figure 2. Global distribution of peer-reviewed journal publications on SCUBA diving impacts included in this review. Impacts associated with SCUBA divers' behaviour.

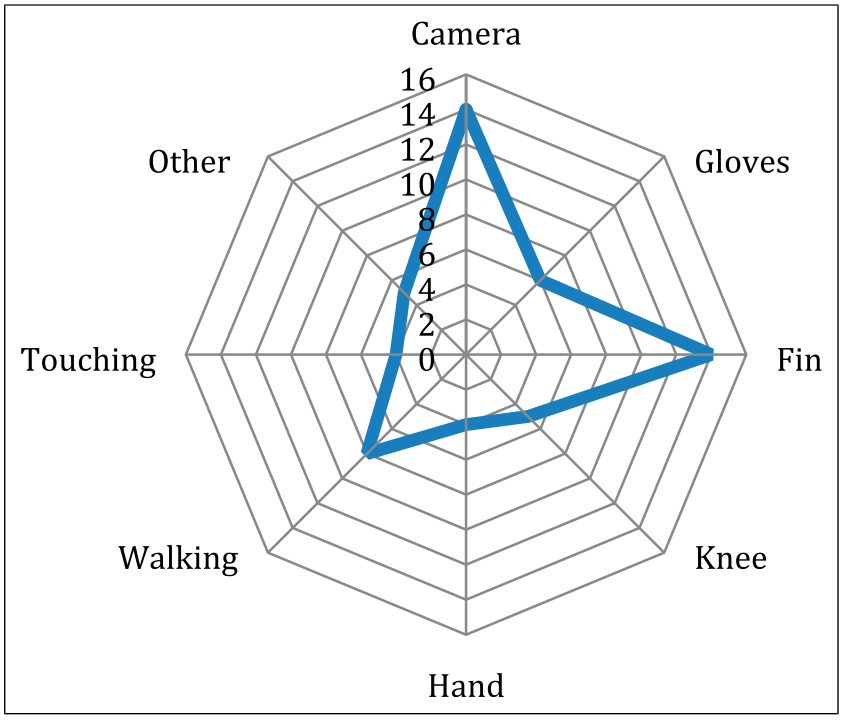

Figure 3. Number of selected peer-reviewed journal publications on SCUBA diving impacts reporting specific types of contact with corals.

gloves. Additionally, studies noted 'other' types of contacts through boats and anchoring (7%).

Types of impacts on corals

The most commonly reported impact on coral was damage (81%) from a type of contact (e.g., fins and camera equipment). Breakage (69%) and coral disease (3%) were less commonly reported (Figure 4). Diving impacts were readily identified as the cause for damage and breakage of corals. The situation was more complicated for coral disease but inferences were substantiated in a handful of studies which related disease to a decline in coral health caused by live coral breakage and reduced branching in coral cover because of contact from SCUBA divers.

The coral identified in the studies reviewed were compared with the IUCN Global Marine Coral Assessment level of threat (Table 2). This Table lists coral impacts increasing from 'NC' (least concern) to 'CR' (Critically endangered). In total 10 types of coral were recorded as impacted by SCUBA diving. Six of these corals have not been studied for their impact risk and therefore remain 'NA' (unclassified) in the IUCN classification.

Three of the corals identified in previous research are of low concern of becoming extinct in the near future (LC), two are vulnerable (VU), one is at high risk (EN), and one is at very high risk (CR). Although not a focus of this study, other marine organisms such as sea squirts, sponges and benthic organisms were also frequently reported as impacted by SCUBA divers.

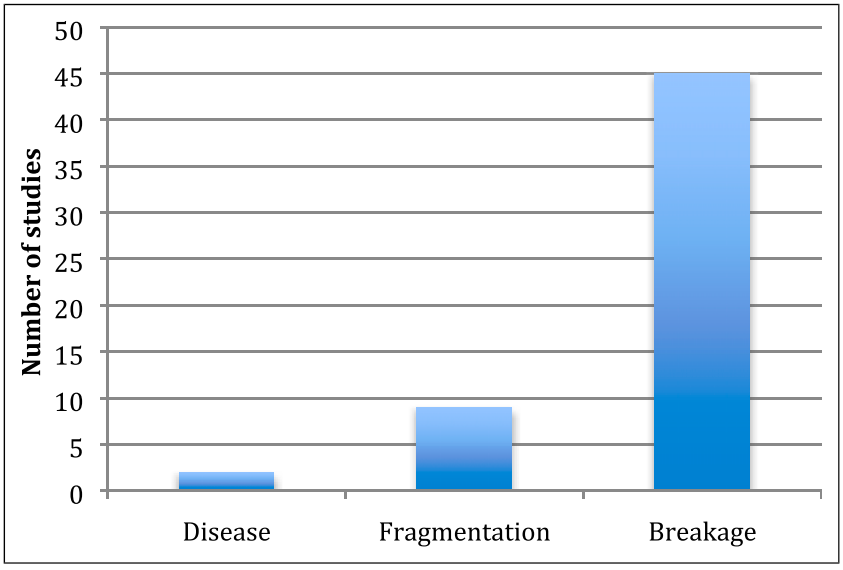

Figure 4. Number of selected peer-reviewed journal publications on SCUBA diving impacts reporting specific impacts on corals at dive sites. Types of coral affected by SCUBA diving activities.

Table 2. Reported threat level to coral/marine species from SCUBA diving.

Common name	Family/Scientific name	IUCN status[a]
Branching table coral	Acropora	CR
Boulder star	Orbicella annularis	EN
Branching table coral	Acropora hemprichii[b]	VU
Graham's sheet coral	Agaricia grahamae	LC
Adeonelle	Adeonella calveti	NE
False coral	Myriapora truncate	NE
Ross coral	Pentapora fascialis	NE
Ciliates	Eliminates	NE
Sea squirts	Ascidiacea	NE
Horn drupe	Drupella cornus	NE

[a]IUCN status: NA: Not Evaluated; LC: Least Concern; VU: Vulnerable; EN: Endangered; CR: Critically endangered.
[b]Due to habitat loss decreasing the population.
Source: IUCN-redlist, 2020

The literature reported on management strategies regarding SCUBA diving and these were grouped into three main approaches: non-regulation, regulation, and research (Figure 5). More than 61% of the studies proposed non-regulatory strategies for minimizing SCUBA diving impacts. Non-regulatory strategies offered were: (a) environmental education, (b) a pre-dive briefing, (d) monitoring activities, and (e) improving diver skills. Regulatory strategies proposed included rule enforcement such as (a) limiting the overall number of diving sites, or (b) limiting access to diving sites depending on the experience level of divers (e.g., excluding novices) or motivation (e.g., excluding photographers). Regulation was further achieved through (c) limiting the use of tools while diving (e.g., spare or inappropriate tools), (d) introducing charges, (e) introducing a permit system, and (f) the establishment of official resting sites for divers. Finally, studies proposed more research be conducted into SCUBA diving impacts to inform future management decisions.

Discussion

Geographical distribution

The research found that the number of studies which focused on environmental impacts from recreational SCUBA diving increased from 2002 onwards mirroring the global growth in the coral diving industry around the world (Dimmock and Musa, 2015).

Early studies were focused on the Mediterranean region, Australia, the Middle Eastern and Atlantic and Caribbean reef areas (Gladstone et al., 2013; Lloret et al., 2016; Luna et al., 2019; Sala et al., 1996).

In contrast, Southeast Asian countries are only marginally represented in articles which researched SCUBA impacts in locations like Indonesia and Malaysia (Brauwer De et al., 2017; Thur, 2010; Vianna et al., 2012). This is surprising, as a large number of coral reefs are located in the Southeast Asia region, in particular the Coral Triangle (70,000 sq. km) (Spalding et al., 2017).

Studies of SCUBA diving impacts and practises around coral reefs located in the Indian Ocean, Pacific Ocean, and Southeast Asia regions warrant attention in the future. Currently SCUBA diving and other nature-based tourism and recreation activities are rapidly developing in these regions (Giglio et al., 2018), with little apparent evidence available to report on environmental impacts in areas of rapid development and demand. For example, coastal zones of Vietnam and China are undergoing dramatic change with rapidly expanding marine tourism and SCUBA diving industries. There appears little evidence of the research into the environmental impacts being experienced in those marine locations from recreational SCUBA diving.

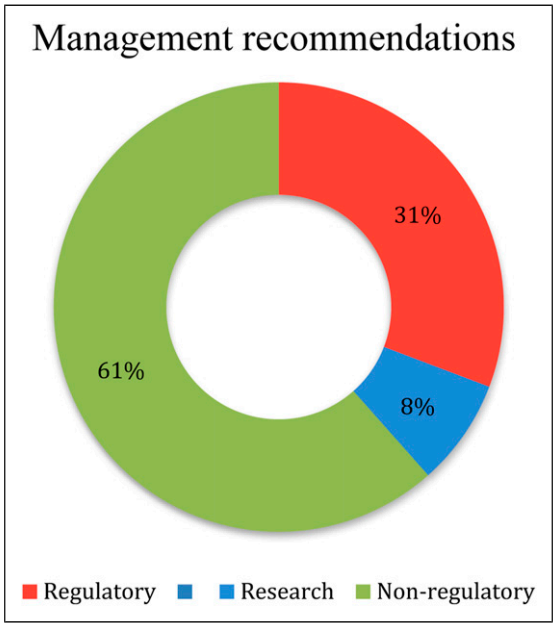

Figure 5. Percentage of selected peer-reviewed journal publications on SCUBA diving impacts proposing specific management recommendations to minimize diving impacts.

Source of SCUBA diving impacts

SCUBA diving is considered a non-motorised nature-based activity so the focus of our study was not on the transportation needed to reach a diving site but the actual activity and associated impacts at the diving site. Since 1987 impacts on marine resources have been reported due to SCUBA diving activities. The significant impacts on marine resources identified in this study occurred mainly through the contact by divers or their equipment with the reef (Dixon et al., 1993; Hawkins and Roberts, 1992; Ong and Musa, 2012b; Riegl and Velimirov, 1991).

Most studies reviewed found that more impacts occurred by untrained divers demonstrating lack of knowledge about impacts from SCUBA diving at sites (Dearden et al., 2007; Giglio et al., 2017, 2018; Harriott et al., 1997; Zakai and Chadwick-Furman, 2002). The impacts resulted from inappropriate diver behaviour and equipment use including cameras, fins, gloves and knee protectors, or the way divers move (including walking on) around corals (Harriott et al., 1997; Hammerton, 2018; Luna et al., 2019; Rouphael and Inglis, 1997; Talge, 1990, 1992).

The greatest reported impact came from divers' camera equipment and the attempt by divers to take underwater photographs (Roche et al., 2016), followed by fin damage and walking on corals. Impacts occur during photography because divers are concentrating more on the photograph than the safety of the coral and marine resources (Brauwer De et al., 2017; Roche et al., 2016). The potential for impact has increased with the availability of new varieties of underwater cameras (Roche et al., 2016). This trend is especially pronounced when using an action camera with an extension pole (muck stick), which can cause substantial impact on small marine fauna like sea horses. As a result some diving sites have banned the use of muck sticks as severe impacts were observed. For example, in locations such as Fernando de Noronha Marine Park, Brazil, and Egypt's Red Sea (Giglio et al., 2018; Roche et al., 2016). Conversely, some studies reported that diving without camera equipment leads to less contact and therefore coral damage (e.g., Barker and Roberts, 2004; Toyoshima and Nadaoka, 2015).

Additionally, diver fins and loose-hanging equipment created considerable impacts on coral reefs (Chung et al., 2013; Roche et al., 2016). Fins damage corals when divers intentionally or unintentionally kick the reef while swimming (Barker and Roberts, 2004; Chung et al., 2013; Camp and Fraser, 2012; Franco Di et al., 2009; Giglio et al., 2018; Harriott et al., 1997; Milazzo et al., 2002; Poonian et al., 2010; Uyarra and Cote, 2007; Worachananant et al., 2008; Zakai and Chadwick-Furman, 2002). This impact is detrimental to hard and soft corals and the tissues of massive corals (Zakai and Chadwick-Furman, 2002).

The damage from walking on corals was recorded in early studies (Hawkins and Roberts, 1992; Kay and Liddle, 1989; Woodland and Hopper, 1977). Impacts from walking on corals reduce the size of coral colonies (height and diameter), increase biological damage and reduce aesthetic appeal of corals (Hawkins and Roberts, 1993). Finally, 'other' impacts occur from boats and anchoring around diving sites (e.g., Giglio et al., 2017).

Type of coral damage

Among the 69 articles reviewed 10 varieties of corals were affected along with other marine resources. From the varieties of corals that have been classified as per the IUCN red list, four of these impacted corals were classified as being at risk of extinction ranging from critically endangered, to endangered and vulnerable. The most frequently reported coral to be impacted by divers is "Acropora" which is a critically endangered coral. It is therefore imperative to develop an in-depth understanding of the type and extent of damage to coral reefs caused by SCUBA divers.

This review has identified three main types of ecological impacts from SCUBA diving activities; damage, breakage and spreading of coral disease. Physical damage from coral breakage was most commonly reported (Kalyan De et al., 2020). This affects soft and hard coral and tissues (Zakai and Chadwick-Furman, 2002). In addition, coral growth and reproduction were reduced which can also increase the rate of tissue loss, and expose coral polyps to additional sedimentation loads (Hawkins and Roberts, 1992, 1994; Neil, 1990; Webler and Jakubowski, 2016). This in turn may lead to long-term impacts such as the decline in coral richness, reduction in growth rates of coral skeletons and the reduction in live coral cover and changes in coral zonation (Lamb and Willis, 2011; Winkler et al., 2004). Lamb et al. (2014) revealed that coral diseases like the skeletal eroding band (SEB) and white syndromes (WS) are common in diving sites while black band disease, brown band disease, and/or growth anomaly are common at visitor sites such as on Koh Tao Island at Thailand (Chavanich et al., 2012). As such, the type of disease is indicative of how the impact occurred and whether it originated from SCUBA diving activity.

Lamb et al. (2014) found a 3-fold increase in coral disease at highly used diving sites. As such, coral disease is now recognized as a significant factor in accelerating the degradation of corals in diving sites, including the reduced size of the coral colonies (height and diameter), and increased biological damage (Altizer et al., 2013; Lamb et al., 2014). Therefore, scholars have expressed the requirement for more research into long-term implications and monitoring of SCUBA diving for coral reef impacts (Giglio et al., 2017; Roberts et al., 2002; Smith et al., 2016).

Nonetheless, such recognized impacts on coral are yet to be assessed at diving sites in the Indian Ocean and Southeast Asian countries (e.g., Thailand, Philippines, Indonesia, Maldives, Sri Lanka). Future studies in this geographical region have opportunity to focus on the long-term impacts of breakage and disease on coral reefs. Coral health constitutes an important indicator that should be monitored to assess the status of SCUBA diving impacts at diving sites.

Recommendations to manage SCUBA diving impacts

Our review of management recommendations proposed in past studies highlighted several management strategies to minimize the impacts of SCUBA diving. Collectively, the studies found three types of management strategies: non-regulatory and regulatory types, and research.

Non-regulatory management approaches appear to be more preferable to control and minimize diver behaviour and reduce impacts on marine resources (Dimmock et al., 2013; Giglio et al., 2018; Medio et al., 1997; Rouphael and Inglish, 1995; Rouphael and Hanafy, 2017; Renfro and Chadwick, 2017). Recommendations include guiding of divers by experienced and qualified guides or dive leaders and implementing brief education programmes such as the 'Green Fins' programme to educate divers on "Low-Impact Diving" techniques, and to establish a code of conduct for diving activities (Roche et al., 2016). Training in "Low-Impact Diving" was introduced as global standard and backed up through certification and code of conducts to improve diving skills and has been useful for all skill levels of divers and operators/guides in the industry (Hammerton, 2017). Therefore, the technique has been implemented in professional diving courses as a permanent education component (Hammerton, 2017).

Some studies reported that non-regulatory management measures have failed for reasons like the lack of a monitoring programme, the lack of participation and poor communication with stakeholders in the industry (Harriott et al., 1997; Hawkins et al., 1999; Medio et al., 1997; Schleyer and Tomalin, 2000). As a result, some studies argued that more research is needed to better understand diver impacts as a means to develop more informed management recommendations, or to introduce further management strategies like the implementation of multiple reef-based activities that would reduce the pressure on corals through diving (Lamb et al., 2014), or even introduce artificial coral reefs (Tynyakov et al., 2017).

Based on our review the most effective strategy appears to be environmental education of SCUBA divers. What is particularly effective is the "pre-dive" briefing that should occur directly before the actual diving session. It has been identified as an influential tool for conserving coral reefs at SCUBA destinations around the world (e.g., Apps et al., 2015). The aim is to deliver verbal and non-verbal educational information to increase visitor knowledge about environmental awareness and contemporary issues at a particular site (Hammerton, 2017) including the basic biology and coral reef ecology, conservation efforts and especially simple instructions on how to avoid coral damage while diving. This briefing is focused on improving diving knowledge and skill to reduce coral contact (Neto et al., 2018). Conservation issues raised in a pre-dive briefing can positively reduce the number and intensity of diver impacts (Camp and Fraser, 2012; Toyoshima and Nadaoka, 2015; Webler and Jakubowski, 2016). Rouphael and Inglis (2001) concluded that education helped divers understand the coral environment, including present and potential threats, encouraging responsible behaviour to minimize the impacts at SCUBA diving sites (Hammerton, 2017).

Introducing environmental education by video can be an easy and practical method for the delivery of the briefing (Giglio et al., 2018; Edney, 2012). It was suggested that the video briefing should cover three main areas: (a) positive environmental aspects; contained beauty of the site, site characteristics and species diversity at site (b) descriptive and prescriptive norms of diver behavior; advise and convince about do not collect & do not touch, and (c) reinforce diver accountability and self–efficacy.

Another effective non-regulatory management tool within the SCUBA Diving Tourism System (SDTS) is the establishment of an interconnected SCUBA diving "tourism system" (Dimmock and Musa, 2015; Musa and Dimmock, 2012) to link managers, decision makers and other key stakeholders for a more concerted and orchestrated conservation effort under a shared vision including: protected area managers, policy makers, marine environmental specialists, SCUBA divers, SCUBA diving tourism industry stakeholders and the host community. The advantage of establishing such an SDTS is that SCUBA diving stakeholders can bring together ideas and concerns regarding diving on the reef to protect the marine environment while supporting the local stakeholders in the recreational SCUBA industry (Hammerton and Bucher, 2015).

Only a handful of the studies reviewed suggested regulatory management strategies as suitable to minimize ecological impacts from recreational SCUBA diving. Regulatory management strategies primarily include limiting the number of divers at sites and controlling overall visitor numbers or those of specific skill levels such as novices to maintain the carrying capacity of diving sites (Davis and Tisdell, 1995; Hawkins and Robert, 1994; Lamb and Willis, 2011; Toyoshima and Nadaoka, 2015; Zakai and Chadwick-Furman, 2002), and stipulating spatial limitations through "no-use zones" (Neto et al., 2018), and a "no-touch regulations" (Dearden et al., 2007). Providing a special training or pre-dive briefing to those diving under specific motivations such as photography is another regulatory tool. Limiting use may be achieved by introducing charges or a permit system. At the same time, certain impactful diver behaviour may be regulated through the limitation of diving tools and the establishment of official resting sites for divers.

Carrying capacity involves identifying the threshold of visitor numbers at a site. In 1995, Dixon and Tisdell sought to study the carrying capacity at a marine park, and noted that fewer visitors should lead to fewer impacts while meeting the threshold. Once above the threshold all those impacts become significant (Davis

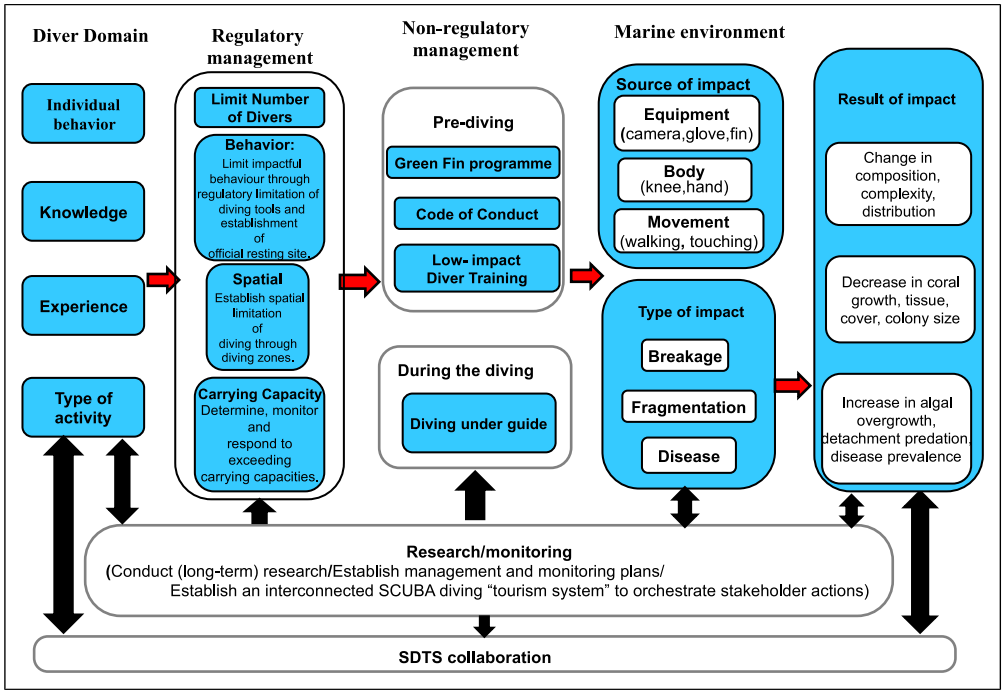

Figure 6. Impact management framework for SCUBA diving tourism and recreation (adapted from Sumanapala & Wolf, 2019). SDTS = SCUBA diving "tourism system" (Dimmock and Musa, 2015) that brings together all stakeholders of the SCUBA diving tourism system.

and Tisdell, 1995) but are still difficult to measure due to the challenge of identifying social or biological thresholds at sites and discerning human effects from natural variability between sites. De et al. (2020) noted that estimating carrying capacity is vital especially in tourism activities in reef areas. Doing so can help minimize and manage diving pressure on coral reefs and benefit reef health and diversity (Jameson, et al., 1999; De et al., 2020). Studies have sought to measure carrying capacity at recreational diving sites (De et al., 2020) and in locations such as Bonaire, Eastern Australia, Eilat-Israel and Sodwana Bay, South Africa (Schleyer and Tomalin, 2000). However, the complexity surrounding the identification of the carrying capacity has hindered ease of calculating threshold limits to visitation. Levels of acceptable change in coral ecosystems have not been given primary concern. As a result some sites have exceeded carrying capacity threshold limits (Guzner et al., 2010; Chung et al., 2013). To maintain a site's carrying capacity one recommendation has been to introduce a permit system based on diver skill level (Abidin and Mohamed, 2014; Poonian et al., 2010) and introduce physical barriers to diving activities (Rouphael and Inglis, 1997). Long-term monitoring systems need to be established to identify when the carrying capacity is exceeded through feedback in real time and management plans developed on how to respond efficiently. Research in more pristine diving sites could enable early research to assess the before and after effects in control versus impact sites (BACI). Future research should assess visitors' perception of diving site management measures which have been applied (Barros et al., 2015). In addition, there is merit in reviewing the performance of individual measures like educational facilities on site and how these influence diver behaviour. Finally, there is a great need for long-term studies that are currently lacking even though the recreational scuba diving industry has emerged several decades ago.

A novel SCUBA diving impact management framework

Overall, this study reviewed the literature on ecological impacts due to SCUBA diving to identify threats on coral reefs along with recognized management strategies that have been proposed to minimize impacts in previous studies. Ultimately, findings from this research seek to manage and maintain sustainable SCUBA diving in the future.

To achieve the final aim of the study a framework is proposed which incorporates the key elements of the SCUBA diving industry including the characteristics of the diver, the regulatory and non-regulatory

management measures which are moderating the impacts on the marine environment, and finally the research and monitoring underpinning this system and providing an educational, informational and observatory foundation (Figure 6). This framework can for instance be used to guide the focus of future research, which we will discuss in the following section.

The study has identified research gaps which can be explored further to assist the SCUBA diving industry, such as reliable methods for measuring the carrying capacity at diving sites (e.g., Shokri and Mohammadi, 2021). Research and monitoring should underpin and inform all elements of the SCUBA diving tourism system (SDTS) (e.g., Thirumoorthi et al., 2013). As for the diver domain, research is needed to better understand diver behaviour, the culture of diving as a whole and individual perception of diving sites, diving conditions and conservation management measures (e.g., Lucrezi et al., 2013; Lucrezzi et al., 2019). Key questions need to be addressed such as what is the most effective way to influence compliance with low-impact diving behaviour. Studies into persuasive communication that have facilitated compliance in various contexts (e.g., Steckenreuter and Wolf, 2013) and experimental approaches that link SCUBA diving impacts with effects, as recommended elsewhere (Musa et al., 2011, Sumanapala and Wolf, 2019; Wolf et al., 2019), are urgently needed. Here we focussed particularly on coral impacts but impacts are far-reaching and studies on impacted fish communities, etc., should also be considered (e.g., Dearden et al., 2007).

Non-regulatory and regulatory forms of management are currently in place to manage the SDTS. Non-regulatory measures may both be delivered pre-diving or during the diving phase to minimize impacts. Research on the effectiveness of these varied measures especially best-practice design of educational material for the pre-diving phase (e.g., video messaging) should be explored further (Giglio et al., 2018). Research into effective teaching of improving buoyancy skills at diving sites would also be important (Toyoshima and Nadaoka, 2015). Regulatory systems that have yet to be explored in more detail in the context of SCUBA diving are for instance the spatial management and demarcated zoning of sites (e.g., Toyoshima and Nadaoka, 2015).

More generally research needs to be expanded geographically to cover for instance specific developing countries which are currently underrepresented even though diving tourism and recreation is booming there.

Conclusions

This study reviewed research on SCUBA diving and its ecological impacts in particular on coral reefs and management recommendations. Coral reefs around the globe are in decline from human activities and SCUBA diving is one activity that can impact corals including those that are recognised as being endangered by the IUCN. This systematic review assessed the contemporary knowledge of ecological impacts on SCUBA activities across the world. Studies in non-English language journals, social media analysis, and research published outside of peer-reviewed journals may provide additional insights as our focus was on peer-reviewed English-journal publications. Our study revealed that research into SCUBA diving impacts increased mostly since 2002 but does not seem to grow at the same rate as the increasing popularity of SCUBA diving around the world would warrant. Impacts of SCUBA divers and their equipment were substantiated and significant. This review emphasised developing and enhancing educational activities within and across the industry and especially during the pre-dive briefing phase. The study recommends future research in the SCUBA diving tourism industry and has proposed a novel framework to guide study development and question framing. The geographical focus of research needs to be expanded especially into the Southeast Asian region, and long-term monitoring studies need to be conducted.

ORCID iD

Daminda Sumanapala https://orcid.org/0000-0001-9396-2548

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Author Biographies

Daminda Sumanapala's areas of interest are in the field of nature and heritage-based tourism. His current research interests include nature and heritage-based tourism in protected areas. He explored these themes through the lenses of visitors' expectations and experiences of nature and heritage-based tourism in protected areas. He is particularly interested in understanding the challenges of nature and heritage-based tourism practice with human engagement and how it is mitigated and conserved for the future nature and heritage-based tourism industry in South and Southeast Asia. Daminda obtained his Ph.D. degree from the University of Colombo.

Kay Dimmock (PhD) is a Senior Lecturer at Southern Cross University based in the School of Business and Tourism. Her work extends from business to tourism in higher education. Within a marine and coastal context Kay has researched social experiences including perceptions, beliefs and impacts on stakeholders through leisure and tourism. Her research has been individual and collaborative at local and regional levels. She works closely with marine tourism stakeholders including industry, community, researchers and government agencies to understand social dimensions of coastal and marine environments.

Isabelle D. Wolf is an urban nature and protected areas specialist. Isabelle researches various aspects of socio-ecological systems with a particular focus on health and wellbeing outcomes, and tourism and recreation. Isabelle leads research and enhances participatory geospatial methods for people monitoring. Trained as an ecologist, her speciality are the human dimensions of ecosystems, with work on people and animal behaviour and flora and fauna communities among other in tourism and recreation systems. Isabelle has a PhD degree from the University of New South Wales and has published in both social and environmental science journals.