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SCUBA tourism and coral reefs: a social-ecological network analysis of governance challenges in Indonesia

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ABSTRACT
In this article, we conduct a social-ecological network analysis of SCUBA tourism human–environmental interactions in the Gili MATra Marine Park in Indonesia. Network methodologies are being increasingly applied, but this study represents – to our knowledge – a first example focusing on the governance of the SCUBA tourism sector. We developed a novel mixed methodology for data collection, data integration and data analyses specific to SCUBA tourism to understand human–nature interactions. This includes interviews with business operators, the use of secondary data on reef compositions and health, and a randomized survey sample of SCUBA tourist perceptions. Our findings indicate a densely interconnected network of social cooperation driven by older and larger businesses with historical leadership roles. High intensity and partially selective patterns of reef use exist, explained by numerous factors including tourist preferences for reef features, site names and business location. However, the analysis of ecological connectivity indicates high dive site similarity, suggesting that alternative sites exist for reducing crowds and increasing safety while still meeting tourist preferences. We discuss methodological innovations and linking results to context with qualitative data. We also propose social-ecological hypotheses (motifs) linked to system outcomes for future SCUBA tourism research.

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Connectivity; centrality; environmental management; coastal governance; cooperation; Southeast Asia; tourist perceptions

1. Introduction

Among marine ecosystems, coral reefs are the hotspots of biodiversity (Hughes et al., 2002, 2017), attracting substantial tourism interest among SCUBA divers and snorkelers (Dimmock & Musa, 2015; Giglio et al., 2015). SCUBA diving allows direct access to coral reef environments and can bring substantial economic opportunity to coastal areas when they are healthy and accessible. Global reef tourism was estimated to be worth about US$35.8 billion dollars, and on-reef tourism value (including SCUBA diving) in Indonesia is estimated to be worth US$1.991 billion dollars per year (Spalding et al., 2017). However, reefs are also threatened by multiple human activities that

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require effective governance locally, regionally (e.g. fishing, diving, anchoring, sewage, sedimentation) (Giglio et al., 2017; Hughes et al., 2017; Lin, 2021) and globally (e.g. climate change warming and bleaching) (Hughes et al., 2018). These impacts not only undermine the role reefs play in supporting and providing for healthy marine ecosystems but also the livelihoods dependent on them.

SCUBA diving tourism needs good governance to ensure the sustainability of reef health and use (Wongthong & Harvey, 2014). Too many SCUBA operators or businesses can lead to overcrowding that can cause reef degradation and water safety issues when coordination and cooperative strategies are absent (Musa & Dimmock, 2012; Wongthong & Harvey, 2014). Degradation can result from high intensity boat traffic noise or anchoring (Ferrari et al., 2018; Giglio et al., 2017; Nedelec et al., 2017). Divers can contact reefs, either purposeful or accidental, leading to damage (Camp & Fraser, 2012; Lin, 2021). Many reefs are accessible to other uses if they are not in marine reserves, where conflicts between other uses such as recreational boating or fishing may lead to water safety issues (Wongthong & Harvey, 2014). Acute pollution or coastal erosion may arise from increasing coastal tourism infrastructure, which can lead to other environmental issues such as waste management and sewage (Wilson & Verlis, 2017). Nonetheless, tourism can importantly help shape more sustainable outcomes. Under conditions of good governance tourism can provide the needed awareness, interest and financial capital to safeguard or restore reefs for their sustainable use. Given the potential for economic benefits, there are growing efforts to build sustainable approaches to reef-related tourism (Spalding et al., 2017) that reduce direct human impacts within and beyond the sector, while supporting conservation initiatives (Lin, 2021; Tynyakov et al., 2017; Wongthong & Harvey, 2014). Self-organized efforts and cooperatives strategies among industry actors, particularly in diving specific locations, can help improve water safety protocols and collective investments into conservations (Dimmock & Musa, 2015; Partelow & Nelson, 2020). However, such initiatives require understanding local human-environment interactions including patterns of reef use, drivers of those patterns and potential governance alternatives, so that governance activities can be tailored effectively and build adaptive capacity within those contexts, related to their specific issues.

There are many context specific factors that can influence the sustainability of SCUBA tourism. Current research has focused on numerous issues including environmental impacts, willingness to pay for marine conservation, governance issues, industry competitiveness, legal protections and rapidly changing technology (Dimmock et al., 2013; Haddock-Fraser & Hampton, 2012; Hillmer-Pegram, 2014; Lucrezi et al., 2017). SCUBA tourism can transform human–nature relationships with coral reefs, but sustainability outcomes are likely to vary based on social-ecological context. These can include providing economic opportunities from non-extractive marine-based incomes, in contrast to fishing, or the ease of physical access to diving locations such as the proximity to international airports. The ability to get certified locally and the degree of difficulty in accessing reefs from shore can play a role in economic growth. Diver preferences for seeing certain types of reefs or species (e.g. sharks, turtles), or specific underwater features (e.g. shipwrecks, arches) can also shape SCUBA business marketing strategies and destination notoriety (Giglio et al., 2015; Lucrezi et al., 2019). Increased destination popularity is likely to raise other sustainable development challenges such as waste and sewage management, property rights for developers and local populations, or fair livelihood opportunities.

While each issue above has its own specific research domain, there remains a lack of locally adaptable system-based methods that can be applied to SCUBA tourism contexts for understanding the patterns of human-environment interactions that shape reef use, business and livelihood outcomes. Drawing on the broader social-ecological systems literature is a useful starting point because it provides substantial empirical and theoretical literature for understanding how environmental outcomes are interdependent with social and economic ones (Bodin, 2017; Bodin & Tengö, 2012; Colding & Barthel, 2019; Folke et al., 2005; Kluger et al., 2020; Ostrom, 2009; Partelow, 2018; Vos et al., 2019). However, few studies have developed methodologies that can contribute to building an empirical basis for social-ecological interactions in SCUBA tourism systems specifically, or have applied existing methodologies or social-ecological theories to examine them.

Network analysis provides an important set of methodological tools for social-ecological systems research due to the need for structured data formats that allow for the hypothesizing and testing of system structures, and their prevalence, with a standardized set of analysis techniques (Barnes et al., 2017; Bodin et al., 2020). Network approaches allow scholars to study relational structures and processes emerging from connected nodes (e.g. actors) with network edges (i.e. linkages) (Borgatti et al., 2009). For example, the centrality of key actors in a network, or the overall density of network connectivity can provide insights into the structural reasons driving system outcomes, when paired with a contextual understanding of the case. Theorizing how system structures (e.g. networks of dive shop cooperation, networks of reef use) might be linked to relevant system outcomes, particularly for governance or sustainability issues (e.g. adaptive capacity, livelihoods, reef health), is an emerging and important part of the field (Enqvist et al., 2020; Pittman & Armitage, 2017; Sayles et al., 2019).

Social-ecological network analysis (SENA) is growing rapidly (Kluger et al., 2020; Sayles et al., 2019), and has made substantial empirical and theoretical advances using the above techniques in other coastal fields such as small-scale fisheries (Barnes et al., 2019; Bodin et al., 2019). However, applying them to new contexts requires in-depth contextual knowledge as well as multi- and inter-disciplinary competencies due to the need for collecting, integrating and analysing multiple types of both social and ecological data with multiple methodologies. Applying SENA to SCUBA tourism specifically requires conceptualizing the interactions between SCUBA dive businesses, divers and coral reefs as a network of actors with interdependent linkages and feedbacks. More simply, people interact with and influence reefs and those reefs provide value to people and businesses. However, detailed data on each actor is needed as well as the interactions between them, which need to be conceptualized in advance. Further knowledge of how to integrate those data sets in contextually useful ways is needed so that the analysis can provide insights on meaningful governance and sustainability questions. Nonetheless, developing a set of SENA methodologies for SCUBA tourism specifically, ones that can be tailored to across coastal contexts but that can account for the specific nature of diver-reef-business interactions, can help make substantial empirical advances in the field that can aid local management.

A key barrier to SENA progress has been constraints with methodological pluralism, particularly pursuing standardization without losing its contextual meaning (Pokorny et al., 2018; Salpeteur et al., 2017; Sayles et al., 2019). Methodological pluralism is necessary to examine complex system dynamics, but challenging because it requires innovative combinations of existing tools to collect and analyse social and ecological data together. Innovation often takes the form of data transformation, conceptualizing and finding empirical strategies to combine traditionally unconnected data. To do this rigorously, transparency in research design and process are essential to ensure that developed approaches and tools are understandable and can be adopted by tourism scholars and applied to other tourism cases. This has been done in sectors such as fisheries (Alexander et al., 2020; Barnes et al., 2019; González-Mon et al., 2019; Kluger et al., 2019; Yletyinen et al., 2018) and other environmental governance sectors (Fuller et al., 2017; Hamilton et al., 2019; Leventon et al., 2017; Pittman & Armitage, 2017; Widmer et al., 2019), but not yet for coastal nature-based tourism or the SCUBA diving sector specifically.[1] A literature does exist on nature-based tourism using social network analysis (Hwang et al., 2016; Luthe et al., 2012; Pinto & Cruz, 2012), but this has yet to be extended to include ecological nodes and data. As SCUBA diving is embedded within aquatic natural resource systems, we argue it is inherently a SES, and that using social-ecological analysis can enable a more comprehensive understanding of environmental governance problems (Wongthong & Harvey, 2014), and resolving issues of methodological pluralism with new transparent strategies is arguably a step forward for the field.

1.1. Research questions and context focus

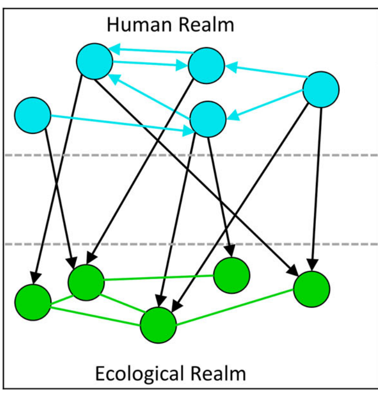
In this study, we address the following research questions, and provide further detail below as to why they are relevant in this context:

(1). What are the identifiable patterns of SCUBA business, diver and coral reef connectivity?
(2). What sets of methodological tools can be used and developed to collected data on social-ecological connectivity in the SCUBA diving sector?
(3). What contextual features on the Gili Islands influence observable patterns of social-ecological connectivity?

SCUBA tourism has unique human–environment interactions. Tourist preferences and business strategies are likely to be drivers, but differ locally (Dimmock & Musa, 2015; Giglio et al., 2015; Lucrezi et al., 2019; Uyarra et al., 2009). The literature has yet to examine how those drivers shape tourism sustainability at the broader system level or at the smaller motif level (e.g. recurring node-to-node structures). Linkages between diver preferences for seeing specific marine life, business cooperation patterns, operating costs and coral reef diversity are not well understood from a systems perspective (Figure 1) (Giglio et al., 2015; Szuster et al., 2011; Uyarra et al., 2009).

The SCUBA industry, in general, is a highly regulated and equipment-intensive activity. Recreational divers must have an internationally recognized certification and the costs for boats, training pools, equipment and safety protocols are higher than other nature-based tourism activities. With relatively high costs of participation, tourist divers may have preferences such as seeing specific marine life or underwater features as well as operator services which may vary based on skill level, comfort or experience (Coghlan, 2012; Giglio et al., 2015; Uyarra et al., 2009). Coral reefs are also highly diverse ecosystems, providing a range of species that may vary based on water depth, currents, available nutrients, human presence or human impacts (Bellwood, 2001; Hughes et al., 2002). Safety risks will also vary with certification level and experience.

In summary, our first and second research questions aim to develop a novel methodological approach for collecting data on these diverse social and ecological features in SCUBA tourism, to be able to identify patterns of social-ecological interaction in our case study (Figure 1). The identifiable patterns aim to be both broad, looking at the whole system, but also at specific, identifiable motifs as recurring micro-level node-node interactions. Social nodes (blue) and ecological nodes



Network components
• Social nodes as Scuba Dive Businesses (SDBs) • Directed social edges (SS) as self-stated collaborations between businesses
• Directed social-ecological edges (SE) as number of divers from each SDB to each coral reef/ scuba diving location
• Ecological nodes as coral reef/ other scuba diving locations • Directed ecological edges (EE) as similarities between coral reefs/scuba diving locations

Figure 1. To the left, conceptual representation of the tourism SCUBA diving tourism as a social-ecological system of Gili as a social-ecological network (SEN), with social (blue nodes) and ecological (green nodes) actors interacting through social-social (SS), social-ecological (SE), and/or ecological-ecological edges (EE) (in blue, black and green, respectively). Network components are described in the table to the right, and conceptual definitions are provided.

(green) are used throughout the graphics representing the social-ecological network below, demonstrated in the conceptualization in Figure 1.

Our third research question is to identify contextual features in our case study that may be driving observable patterns of social-ecological interaction. These findings have the potential to be used for informing local governance and business practice. Context is essential for understanding how SCUBA tourism is influencing local livelihoods and economies, but also how it is dependent on the use and conservation of shared reef resources with high competition (Dimmock & Musa, 2015; Partelow & Nelson, 2020; Wongthong & Harvey, 2014). This can lead to substantial governance problems balancing profitability and local economic well-being, and the overuse and crowding of reefs that undermines their sustainability. Increasing conservation actions while finding governance strategies that can make intensive use sustainable can be a constant challenge (Schlüter et al., 2020). Many issues can arise in this dilemma, including conflicts with other businesses and sectors. Secondary effects from intensive tourism can also lead to acute waste management and sewage issues. In answering our third question, we aim to identify these contextual factors driving observable patterns of cooperation and reef use in the Gili MATra Marine Park in Indonesia.

2. Methods

2.1 Case description: SCUBA diving tourism on the Gili Islands, Indonesia

The Gili MATra Marine Park commonly called the ‘Gili Islands’ consist of Gili Trawangan, Gili Meno and Gili Air near Lombok, Indonesia (Figure 2). Although each is less than 6 square kilometres in size, they received heavy tourism due to their accessibility by boat from Bali or Lombok with one of the eleven boat companies (as of January 2019). They host an economically important international tourism economy for the region with more than 750 businesses and up to one million tourists visiting per year (Partelow & Nelson, 2020) before the 2020/2021 COVID-19 travel restrictions.

The three islands have become world-renowned for SCUBA diving, spawning a large supporting economy of hotels, bars and restaurants. The beaches, coral reefs and marine life are the main attractions, receiving increased pressure from tourism expansion (Bowen et al., 2013; Partelow & Nelson, 2020; Schlüter et al., 2019). However, the islands have limited resources and minimal formal government oversight. Businesses are reliant on their self-organizational capacity to ensure that the flow of goods and services, and to create institutions to govern shared coastal access and waste management issues sustainably (Hampton & Jeyacheya, 2015; Partelow, 2020).

Self-organization amongst SCUBA businesses started in the 1990s, leading to the formation of the Gili Eco Trust (GET) and Gili Indah Dive Association (GIDA), which have since established rules, norms, relationships and power structures (i.e. institutions) for local governance (Graci, 2006; Partelow & Nelson, 2020). This has included marine conservation and restoration programs, waste management

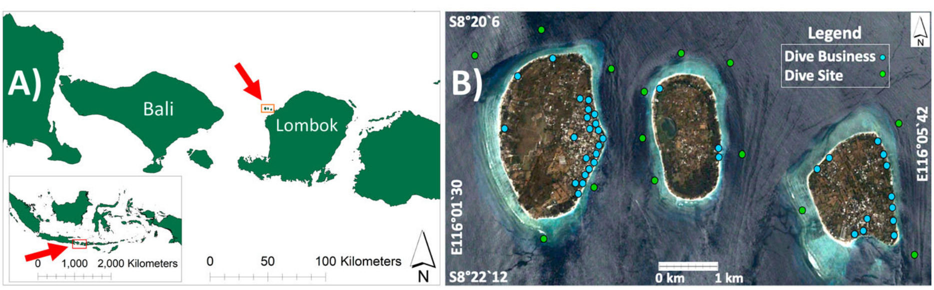


Figure 2. (A) Bottom left: map of Indonesia with the location of Lombok and Bali indicated. Gili Islands circled off the coast of northwest Lombok and east of Bali. Both were created with ArcGIS. (B) Satellite image from the Gili Islands (Google Earth). From left to right: Gili Trawangan, Gili Meno, and Gili Air. Dive businesses (social nodes) are depicted as blue circles ($n = 37$) and dive sites (ecological nodes) as green circles ($n = 14$).

strategies and facilities, formalized SCUBA business cooperation and safety protocols, and cooperation efforts with the hotel industry, local residents, workers and local government. As of January 2019, 39 SCUBA businesses were operating across the three islands, with more planned to open (Figure 2, but note that only 37 participated in the study, as detailed in section 3).

Dive sites are located around all three islands (Figure 2) under a common property regime in the Gili MATra Marine Park with restricted fishing activities and use zoning. Most are accessible in less than 5 minutes by boat. Dive sites named after popular marine megafauna, like Shark Point, Turtle Heaven and Manta Point draw large crowds and substantial boat traffic (Partelow & Nelson, 2020). Thus, the distribution of divers creates concerns for diver-reef impacts, marine noise and dive safety (Partelow & Nelson, 2020).

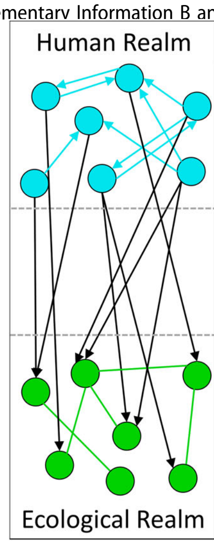
2.2. Conceptualizing diving tourism through a social-ecological network lens

Original data were collected between October 2018 and January 2019. Multiple qualitative and quantitative data collection methods provided input to construct our networks. The definitions and data collection methods in this network study are shown in Table 1. In the following section, social, ecological and SEN data collection are explained separately for clarity. Prior informed consent was obtained verbally from all respondents and interviewees, along with a written description of the project goals with contact information. Participant withdrawal was possible at any time. All data were kept confidential and anonymous.

2.3 Social network data collection

All 39 SCUBA diving businesses were given a self-completion survey (Supplementary Information B). These provided node attribute data on self-stated business size compared to other dive businesses, owner nationality, year founded, and operating features (i.e. bar, restaurant, accommodations). In total, 37 surveys were completed (response rate: 95%). In the survey, examples of collaborations (i.e. SS links) included the exchange or borrowing of gear, sending customers when being overbooked, sharing boats, exchanging employees or staff when needed, or communicating on dive

Table 1. Overview of how components of the social-ecological network were defined and measured in this study. Methods and exact questions/statements used for data collection, and methods for data analysis are stated. All surveys can be found in Supplementary Information B and C.



Network components	Data collection methods	Question/ statement	Data analysis method
Social nodes as individual Scuba Dive Businesses (n=37)	Survey (n=37) for dive shop managers	How do you rate the size of your dive shop compared to other dive shops on the Gili´s?	Eigenvector centrality, degree and self-stated size are visualized as varied node size
Social-social (SS) edges (n=130) as collaborations between SDBs	Survey (n=37) for dive shop managers	Please list up to 5 dive shops you collaborate with the most on this Island and up to 5 dive shops on the other two islands	Degree, network diameter and average path length were calculated
Directed social-ecological edges (SE) (n=278) as number of divers from each SDB to each coral reef	Diver records (n=20) Estimate survey (n=10)	Two-week sample of diver records, one for both the low and high season. Or, an estimate of the number of divers per site provided by the manager or owner	Average number of divers per week per business to each site was calculated
Ecological nodes (n=12) as coral reefs	Survey (n=390) with people who were diving on the Gili Islands	Please write a "+" next to your 3 most preferred dive site characteristics	Frequencies of preferences were counted, log-transformed and multiplied by site characteristic scores and lastly, grouped into 5 categories
Undirected ecological-ecological (EE) edges (n=13) as similarities between coral reefs	Semi-structured interviews with purposefully selected experts Structured surveys with purposefully selected experts	What are the features that could characterize a dive site? Please indicate low/medium/high for the state of all features at all dive sites	Hierarchical cluster analysis was done to group sites based on similarity of features.

locations and conditions (Supplementary Information B). Examples of collaborations were not differentiated as different social-to-social links. The purpose of giving different examples of collaboration was less about examining specific types of exchange, but rather to prompt the respondent to think about who they cooperate with more intensively and to provide a broader representation of social capital between businesses. The listed collaborations from the surveys were used to create directed, unweighted links between social nodes. They were directed because managers stated their perception of collaborations with other businesses which did not necessarily mean that they were reciprocally perceived. Node attribute data was collected in order to help explain observed network patterns and configurations. In addition, the survey also entailed opinion and preference statements about the diving industry and dive sites to get additional explanatory data for why network patterns were observed (Likert-scale data, Supplementary Information B).

Degree measures were calculated for each social node based on the number of collaborations connected to it – the more stated collaborations with other businesses, the larger the degree (Hanneman & Riddle, 2005; Nieminen, 1974). Total social network connectivity measures were examined to investigate network structure including means of network diameter, average path length and graph density. Network diameter calculates the longest distance present in the network (Janssen et al., 2006; Wasserman & Faust, 1994), and reflects network size. Average path length measures the mean shortest paths of all possible nodes (Janssen et al., 2006; Wasserman & Faust, 1994). Graph density measures how close the network is to complete (i.e. everyone cooperates with everyone), being calculated based on the ratio of realized links to possible links. A complete graph has all possible edges and density equal to one (Wasserman & Faust, 1994). Both average path length and graph density reflect the connectivity of the network.

2.4. Ecological network data collection

Ecological nodes are represented by SCUBA diving locations, i.e. coral reef patches ($n = 12$). Interactions between those (i.e. EE links, $n = 13$) were defined as nodes that cluster together by having similar biophysical characteristics. To generate these data, we first conducted five semi-structured interviews with local SCUBA experts familiar with all dive sites through selective convenience sampling (i.e. we sought out the most experienced instructors at each SCUBA diving business and interviewed those willing to participate). These experts provided a list of all possible features a diving site may have, or that could be assessed as a metric for site preferences. Interviewees gave verbal consent and were aware of the research purpose. Second, we synthesized all features into a table containing the most frequently mentioned traits (i.e. sharks present; coral cover; fish abundance), and distributed it to ten different dive masters and instructors via convenience sampling. Each interviewee had extensive local ecological knowledge of diving locations around the area and gave a score indicating the presence or likelihood of occurrence of each trait at each dive site, either 1 (low), 2 (medium) or 3 (high) (Supplementary Information D, Table S3). Next, the median value for each trait at each site was calculated resulting in a final score per trait per site.

We then conducted a hierarchical cluster analysis to examine the heterogeneity of characteristics between sites, and to see which sites clustered together due to similar characteristics (e.g. divers going to sites clustered together would largely experience the same features) (Supplementary Information D, Figure S1). Lastly, ecological links between dive sites in the SENs were created based on which dive sites grouped together in the hierarchical cluster analysis. Thereby, at each stage distances between clusters were recomputed by the Lance–Williams dissimilarity update formula (Borcard et al., 2011). The mantel statistic and the total within the sum of squares helped to decide which dive sites were similar enough to be allocated in a group (Borcard et al., 2011). All statistical analyses were performed in the R statistical environment (R Core Team, 2018), using the package 'stats' (Murtagh, 2000) for the hierarchical cluster analysis, the package 'factoextra' (Kassambara & Mundt, 2016) for the total within the sum of square test, and the package 'ape' (Paradis et al., 2018) for the mantel statistic.

To examine ecological node (dive site) values, a random sample of tourists who had already been SCUBA diving was designed. From previous studies, we assumed that of about 1,000,000 tourists per year (Partelow & Nelson, 2020), approximately 150,000–200,000 are divers. We calculated the need for a minimum of 384 completed surveys to have a representative result of the divers on the Gili Islands (Rea & Parker, 1997) (Supplementary information E). A non-stratified random sample was applied to make sure that each member of the population had a chance of being selected. To ensure a representative sample of the diver population and to increase the accuracy of the sampling strategy, we went to the harbour of Gili Trawangan, and asked all the eleven operating boat companies about their prices and their departure times, ensuring that our sample of departing tourists accurately represented the population of divers across diversity metrics (e.g. amount spent, origin country).

The survey for tourists (Supplementary information C) provided numerous data inputs. Respondents were asked to mark their three most preferred dive site characteristics from the list of site features based on expert interviews (described above). We used stated tourist preferences to calculate an inductive and place-based preference index for dive tourists for all dive sites existing around the islands based on three steps (Supplementary information D):

(1). For each preference: $x = \log$ c.f.
(2). $x*y = z$
(3). categorization of z

First, frequencies of each preference from the diver survey were counted (c.f. = cumulative frequencies) and log-transformed. The log-transformation was done because only 58% of the diver responses agreed on the following statement: 'Not being able to see my preferred marine wildlife while diving would lower the value of the experience'; otherwise frequencies of preferences would have had too large of an impact on the preference score. Then, the resulting numbers (=x) were multiplied by the final score (low, medium or high) of all the characteristics (=y) (i.e. sharks present; coral cover; fish abundance, etc.) for all sites. Lastly, the results from the multiplication (=z) were categorized from 1 to 5 (1 = low preference score, 5 = high preference score), using these preference indices as ecological node attributes, which were then imported to Gephi.

2.5 Social-ecological network data collection

All operating SCUBA dive businesses were asked if they were willing to share a two-week sample of their dive records for both the low season (September until May) and high season (June until August, plus Eastern and Christmas). Samples were categorized as either low and high season. The dive records included how many people, including customers and staff, were going to each dive site per day. We received direct records from 10 businesses, as the other 20 did not keep record. To fill this data gap, managers of the missing 20 businesses were given an assessment sheet where they estimated the number of divers per week per site. Secondary data and estimations of the dive shops were collated and it was noted that the two data sets roughly matched with their self-stated size when comparing to other similar size businesses that we had actual records for. The remaining nine were not willing to share information about their records because they did not want their diver records to be published (response rate: 77%). From the actual records and the assessment sheets for low and high season, the average number of divers per dive shop per week were calculated, being considered as directed, weighted SE links in the network (c.f. Figure 3).

To further study the human-nature interaction, directed and unweighted SE links were used to calculate the in-degrees of ecological nodes (i.e. number of businesses visiting a dive site) and out-degree of social nodes (i.e. number of dive locations visited by dive shop) (Figure 6). In terms of the percentage of divers going to each site, the data from the business records matched the

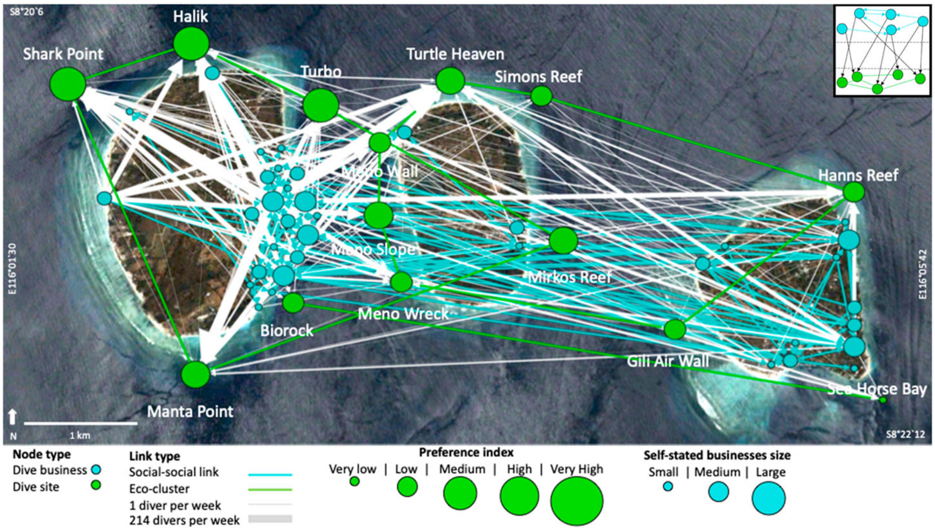


Figure 3. Fully articulated social-ecological network of the SCUBA tourism social-ecological system of Gili Islands. Ecological nodes (dive sites in green) are proportionally scaled to the preference index calculated from diver statements. Social nodes (dive shops in blue) are scaled according to the self-stated size from dive shop owners. Directed and weighted social-ecological edges (in white) represent the diver distribution from shops to sites. Directed and unweighted social-social edges (in blue) illustrate collaborations among dive shops. Unweighted ecological-ecological edges (in green) indicate the cluster groups based on similarities of dive site features.

tourist survey data. To cross-validate and check if SE links were correlated with preference index and social node degree (based on directed social links), correlation analyses were conducted in the R environment (R Core Team, 2018) using the package 'stats' (Murtagh, 2000).

3. Results

3.1 The social-ecological network of the Gili Islands

The fully articulated SEN (Figure 3) was composed of 49 nodes, 12 from the ecological and 37 from the social realm. Within the social realm, 22 nodes were on Gili Trawangan, 12 on Gili Air and 3 on Gili Meno. Among the 421 links of the complete social-ecological network (SEN), 130 were social-social (SS), 13 were ecological-ecological (EE) and 278 were social-ecological, whereby EE links were summarized into 3 clusters (Supplementary information D). In the following subsections, we examine each sub-network of the fully articulated SEN.

3.2 The social network: collaboration among dive shops

Dive shops (social nodes) had on average 7.22 collaborations, as indicated by an average degree (based on SS edges) of 7.22 (min. = 0, max. = 18). Nodes with the highest SS degrees were on Gili Trawangan, with a degree of 18, 17, 16 and 14 (Figure 4). The total number of divers of each shop was positively correlated with social node degree (Spearman correlation coefficient = 0.5590; test statistic = 1444.8; p-value = .002). Social network diameter equalled 6, and the graph density was 0.01. Having many nodes with high degrees, the network showed a local centralization. Furthermore, there were many collaborations (i.e. SS links) between the three islands.

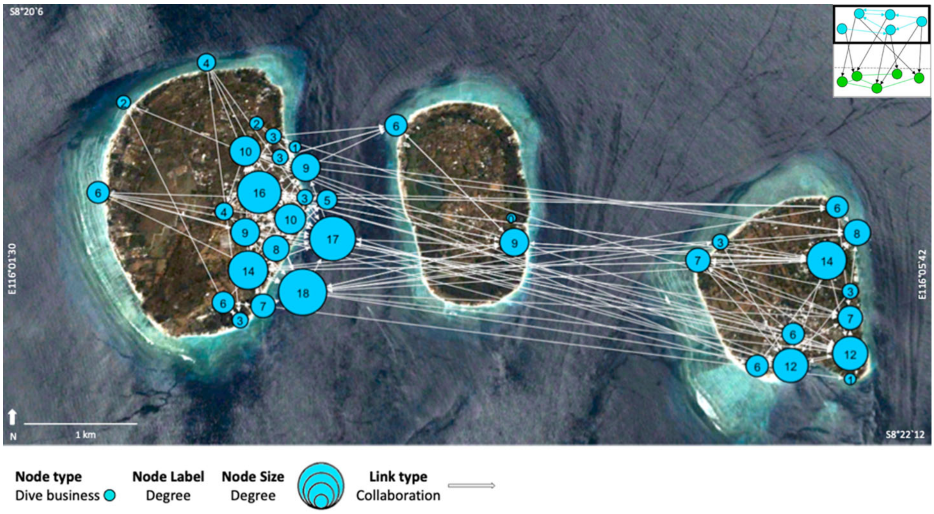


Figure 4. Visualized social network of the SCUBA tourism social-ecological system of the Gili Islands. Nodes are scaled proportionally to node degree, representing the number of directed, unweighted social-social (SS) links. Edges represent directed collaborations among dive shops.

3.3 The ecological realm: dive site connectivity

One ecological cluster that includes Shark Point, Halik, Turbo, Mirkos Reef and Manta Point, had solely 'very high' and 'high' preference indices. These ecological nodes received many divers per week, as indicated by having the highest in-going SE edges with high weights (Figure 5) and high degrees (Figure 6). The only exception of the mentioned cluster was Mirkos Reef, which is furthest from the island with most social nodes, i.e. Gili Trawangan.

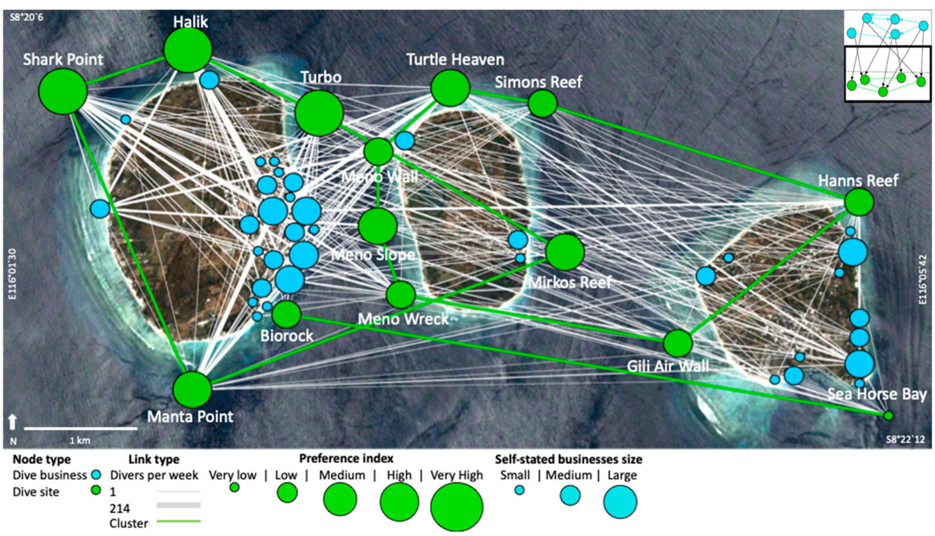


Figure 5. Visualized social-ecological network of the SCUBA tourism social-ecological system of Gili Islands. Ecological nodes (dive sites in green) are scaled proportionally to the preference indices reflecting tourist's inclination towards visiting those sites. Unweighted ecological-ecological edges (in green) reflect the clusters based on similarities of dive site features. Social nodes (dive shops in blue) are scaled proportionally to the self-stated size from the dive shop manager survey. Social-ecological edges (in white) show diver's distribution.

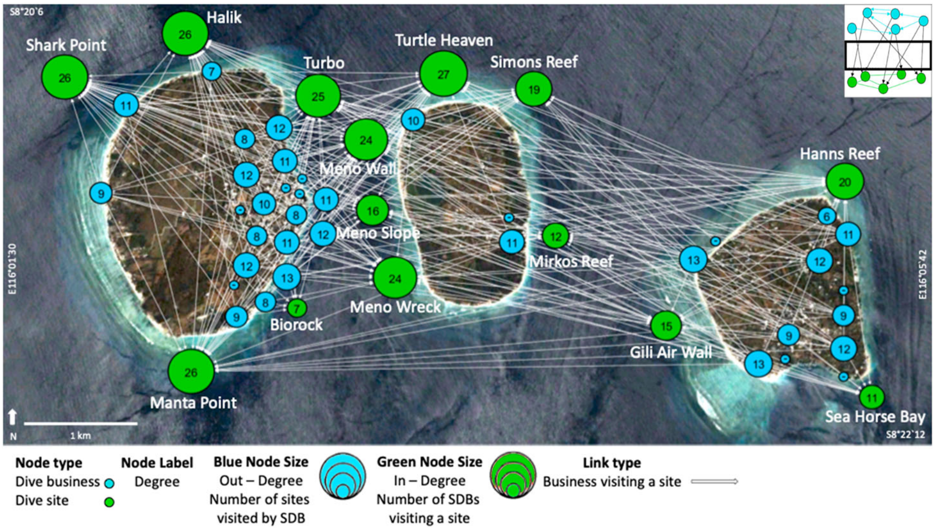


Figure 6. Visualized social-ecological degree network of the SCUBA tourism social-ecological system of Gili Islands, with nodal degrees based on unweighted social-ecological (SE) links. Ecological nodes (dive sites in green) are proportionally scaled to their SE in-degree, i.e. number of dive shops visiting the site, and labelled with the degree value. Social nodes (dive shops in blue) are scaled to their SE out-degree, i.e. number of sites visited by the dive shop, and labelled with the respective degree value. Directed social-ecological edges (in white) represent diver's distribution, i.e. which dive shop went to which dive site, and are based on secondary data and estimation sheets from the dive shops.

Furthermore, the Spearman correlation analysis shows that the number of SCUBA diving businesses visiting a site is positively correlated with the preference index (correlation coefficient = 0.6874; test statistic = 3.279; *p*-value = .006). This is supported by the network visualizations and statistics. Turtle heaven had the highest preference score. Aligned with the social-ecological degree network (Figure 6), the sites mentioned above received most of the diving pressure. The cluster including Biorock and Sea Horse Bay received the least pressure with medium and very low preference scores, and low degrees of 7 and 11 (Figure 6), respectively.

3.4 The human–nature interaction: social-ecological connectivity

The average ecological node in-degree was 19.86 (min = 7 for Biorock, max = 27 for Turtle Heaven), the average social node out-degree was 10.3 (min = 6, max = 13), and the average path length was 1, suggesting a very well interconnected SEN. Ecological nodes with high SE-degree scores (i.e. above average) were mainly distributed around or close by Gili Trawangan. Social nodes with high and low SE-degree scores were distributed throughout all islands.

4. Discussion

4.1 Methodological innovation and application of SENA to SCUBA tourism

Our study demonstrates how SENA can be applied to SCUBA tourism to examine system-level drivers and patterns of human–environment interactions. This type of analysis can aid in understanding how governance challenges emerge or the challenges with current governance strategies. In the case of Gili Islands, we have examined how human-reef interactions are influenced by the self-organization of SCUBA businesses who have a shared interest in governing dive industry safety, coordination and economic organization, as well as pollution and overcrowding. It should be noted that the establishment of governance in our case study is heavily reliant on self-organizational processes, as regional and national governments have taken a minimal role in providing capacity to do so (Graci, 2013; Partelow & Nelson, 2020; Rianto, 2015), and further that patterns of reef use have emerged under a common property regime driven by tourist preferences, ease of access and industry marketing (i.e. site names).

Second, we developed a novel data collection methodology for SCUBA diving tourism to assess dive location characteristics using expert local ecological knowledge via qualitative interviews which were then paired with the development of a preference index to assess diver preferences for those sites. This approach was inductively derived and contextually adapted, which we argue, can be applied in other cases. This approach could be applied easily in other locations and could act as a secondary methodological option for assessing reef characteristics based on local knowledge where sufficient biophysical and ecological data is lacking – independent of whether a (social-ecological) network is to be constructed. Nonetheless, we recognize that ease of application to other SCUBA tourism destinations may be more or less difficult depending on the locations. For example, it was not problematic for us to effectively get a representative sample of tourists due to centralized access points to the island, and business employees and managers were approachable and willing to share information. Collecting such data in other locations may be substantially more challenging.

Third, we conceptualize and empirically analyse ecological-ecological (EE) edges based on similarities of site characteristics (as do Fuller et al., 2017 for fisheries landing data), not based on classical ecological interactions used in network analysis such as distance (Guerrero et al., 2015), seed/larvae dispersal (Bodin et al., 2016; Bodin & Tengö, 2012), competition (Kéfi et al., 2012, 2015), mutualism (Bascompte & Jordano, 2007; Rohr et al., 2014), movement of organisms (Urban & Keitt, 2001) or trophic linkages (e.g. Allesina & Ulanowicz, 2004; Christensen & Pauly, 1992; Christensen & Walters, 2004; Fath et al., 2007). However, we do this with the assumption that reef similarity acts as an indicator for general local-to-regional reef connectivity because more habitat and species populations are affected if any one reef receives negative impacts. Reefs with high similarity measures are more likely to be ecologically interdependent when located in close proximity, and from a diver impact perspective, when divers have the option to choose between more reefs with similar characteristics, impacts are more likely to be distributed across them, reducing the impact on any single reef. This example highlights the importance of understanding how specific SENA methodologies need to be applied, adapted and interpreted in relation to context in order to extract a tangible meaning from the findings. We encourage further studies to explore this approach. Without further studies, we cannot generalize beyond our case context, and can only encourage further studies to assess if the approach fits their context, and can be validated as useful in multiple contexts.

From a more practical and local governance perspective, our similarity assessment of local reefs is an important methodology for informing spatial management challenges in SCUBA tourism such as diver distribution across different reefs and times during the day to avoid overcrowding and safety issues associated with businesses who attempt to access popular reefs at the same time. Furthermore, SENA has helped us identify key social and ecological nodes such as businesses that play a central role in cooperation efforts and reefs that provide important value to the island's tourism economy and tourist experience. Older businesses tend to better understand the history of shared reef use on the island, and the need to cooperate for ensuring sustainability over time (Partelow & Nelson, 2020). These businesses also have more social capital in the community, with informal friendships and knowledge of the business practices of others, their motivations and history (Partelow, 2020). Perhaps any necessary shift in reef use behaviour would best be targeted at engaging the older businesses who have informal influence and formal leadership roles to motivate collective action. However, while we have now focused on descriptive network analysis, a clear next step is to examine how the structural patterns in the network more explicitly link to locally relevant outcomes such as reef health, industry safety, economic stability and tourist satisfaction.

For example, findings indicate that dive sites with high preference indices were visited with a higher frequency, which is supported by the spearman correlation results. Sites closer to Gili Trawangan, the largest island with the most dive businesses, were visited with higher frequency suggesting business location is an important factor in determining reef use. Although we identified three clusters of dive site similarity, a sub-group of sites receives the most pressure. Dive shops seemingly select the reefs they visit based on the preference of their customers and cost, meaning that individual nodes causally influence the overall network structure. At the same time, why customers request visiting specific sites seems to be linked in part to their names such as Shark Point, Turtle Heaven, and Manta Point, which are more popular than sites such as Halik, Meno Wall and Biorock, which have similar features.

Fourth and last, we address what Sayles and colleagues (2019) have termed 'fully articulated SEN' and show different partially articulated SENs. At the same time, we believe that the differentiated analysis of different parts of the fully articulated SEN provides substantial insight into particular processes, supporting the argument of Kluger and colleagues (2020) that a complete SEN approach is not necessarily needed to contribute to solving a governance challenge. Rather, the choice of complexity of a given network should be driven by the respective research question and problem to be solved in a specific context.

Overall, our multiple networks allow a closer and differentiated look into the human-environment relationships in SCUBA tourism and the potential drivers shaping outcomes such as diver preferences, reef characteristics, reef name, business location, business size and extent of cooperation. We would like to stress that, in our local context, it is important to zoom into the different network parts to better understand multiple social, environmental, and coupled processes, as well as drivers and interactions, and if they can be sustainable based on local contextual knowledge. Coastal ecosystems and coral reefs play an essential role in directly supporting thousands of local livelihoods on the Gili Islands, and support a massive regional tourism economy that draws millions of tourists a year to the Lombok/Bali region. This trend is playing out across the global tropics, and the SCUBA industry is often one of the first sectors establishing a presence in many locations as a seed for broader coastal tourism growth.

4.2. Linking network features and observed structural patterns to outcomes

Our network metrics indicate a highly interconnected and dense social-ecological network, meaning that most of the dive shops of all three islands are cooperators and are going to almost all dive sites. However, an important practical question needs to be asked: what does this suggest about the ability of the network to address governance and sustainability challenges? Similarly, from a theoretical perspective, a core goal of the literature is to ask: what is the link between different types of observed social-ecological network structures and system outcomes? We discuss the practical question first, then continue with the theoretical question in the next section.

Competition for the use of reef space is high and has been increasing over time with new SCUBA businesses opening each year, with the Gili Islands being no exception. Also, Gili Island reefs are increasingly impacted by more users, local pollution (e.g. waste water, trash and noise from boats) and broader pressures such as coral bleaching and regional ocean pollution. However, the COVID-19 pandemic shutdowns have almost entirely stopped international tourism for more than a year, leading to many business closures and likely reorganization of the islands political economy post-pandemic. This will likely be catalysed by a core set of well-established actors, who have a 20-year history of self-organizational capacity (Graci, 2013; Partelow & Nelson, 2020; Rianto, 2015). Established organizations that set rules and norms for waste management, dive safety and marine conservation have allowed tourism expansion while buffering pollution and overuse impacts, and will likely help drive tourism development once international travel re-opens. During peak seasons prior to 2020, it was evident that popular reefs and the capacity of the islands to meet their own needs for waste management and the number of divers may be nearing the limits of the islands (Partelow & Nelson, 2020). These issues will still need to be addressed when tourism re-starts.

We believe the dense and integrated networks emerging from our work represents the history of cooperation among SCUBA businesses and industries local social capital. This has allowed widespread open access to its reefs to proceed relatively smoothly due to established institutional capacity for diver safety (i.e. GIDA), price competition (i.e. a majority of shops collect a ~$3.50 USD fee from each diver to support the local Gili Eco Trust) and conservation efforts (i.e. SCUBA businesses established the Gili Eco Trust to do marine conservation and waste management). However, we can also see that new SCUBA businesses are less connected into the cooperation network and a certain percentage do not support the suggested conservation donation or take part in the established institutions for diver safety, although they also access the same reefs sites and contribute to the same sustainability issues. We also observe that, while divers prefer to experience certain features (e.g. seeing a turtle; high coral cover), there are different reef options around the island, making the reef system likely more resilient than currently recognized by operators – allowing them the potential option to distribute the impact of divers across sites with similar features. Our preference index and ecological clusters provide input for spatial diver distribution management in this regard, showing similar but alternative (i.e. less crowded) dive sites that still have high preference index ratings and/ or site characteristics (e.g. Meno Slope and Mirkos Reef respectively).

Nevertheless, it is also clear that dive shop decision-making includes many factors that need to be considered, to place their interpretation into local context. Shop location matters because it is coupled with operating costs (e.g. fuel and turnover efficiency as some shops do up to five trips a day), as do customer wishes, competition and standing-out among other dive shops (39 shops on three small islands) (Partelow & Nelson, 2020). A very large portion of divers are first-time divers, and many beginners want to see megafauna such as sharks, rays and turtles. Sites with those names receive increased pressure even though the desired features and species can be observed in other sites as well. Biophysical features are also important for dive site choice, reef water depth and currents are important for diver safety linked to experience levels.

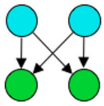
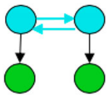
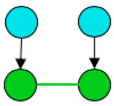
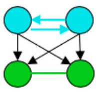
4.3 Moving forward: understanding human–nature tourism interactions from a network point of view

Due to the nature of networks as reductionistic representations (Bodin et al., 2019; Sayles et al., 2019), their interpretations should be placed in context and in tangent with other data sources. Nonetheless, reducing complex interactions into simpler network structures (motifs) has the benefit of enabling scholars to hypothesize relationships between repeating structural configurations and system outcomes (Barnes et al., 2017; Bodin et al., 2016). Further empirical findings across diverse cases will be needed to help support these hypotheses, but they nonetheless provide useful exercises for the design and interpretation of future research.

Edges and nodes in our study, as for any network approach, were scaled down to singular measurable indicators. We argue that while doing this, it is important to develop or adapt the definitions and data collection methodologies in a way that makes those indicators contextually meaningful and at the same time representative of broader governance phenomena for that system. We also believe that, while context is important, observed motif patterns can help advance more generalizable theoretical goals.

We propose some general hypotheses linked to observed structural patterns (i.e. motifs). Table 2 provides four hypothesis motifs that have emerged from our findings and discussions. Without cross validation in other cases, these remain hypotheses to inspire future research, but also help provide an explanation of how we view our descriptive data in our case. The fourth motif, although not

Table 2. Network structures or motifs between ecological (green) and human (blue) nodes, and their hypothesized effects on outcomes.

Network motif or structure	Hypothesis on social-ecological outcomes	Observation on Gili Islands, Indonesia
	Likelihood of dive businesses cooperation is low, suggesting governance issues may be difficult to resolve. Reefs are not connected or may be isolated, with lower likelihood of being resilient to impacts.	Not present. Although low coordination takes place on diver distribution, businesses are highly cooperative on other issues.
	Likelihood of social cooperation for governance, but reefs may not be as resilient due to lack of connectivity if governance is not sufficient to mitigate impacts.	Partially observed. Dive shops are cooperating well. However, most reefs are shared by most shops. Some reefs are connected in clusters, according to similarity.
	Low likelihood of actors cooperating to resolve governance issues. Incentive may be lower to cooperate because impacts on reefs aren't feeding back due to their resilience. Ecological disturbance may also spread in some cases due to ecological connectivity such as diseases, requiring social collaboration to solve across sites.	Partially observed. Only some dive shops are non-cooperators. Reefs are shared by most shops. Some reefs are connected in clusters, according to similarity.
	Likelihood of both social cooperation for governance and ecological resilience of reefs. Balance between two becomes central goal of governance.	Most common observation. The network is dense. Dive shops cooperate well for governance, and similarity assessment suggests alternative options for divers makes reefs more resilient to impacts.

Note: Explanation of each in the relation to our case study on the Gili Islands is provided.

formally tested for frequency in our analysis, we believe, is the most present in our case. This represents a dense interconnected network of high cooperation and reef similarity. It should be noted that motifs would rarely be singular or exclusive in a network, but it is instead likely that many different types of simple motifs interact with each other to form the broader system dynamics that produce outcomes. For example, all motifs can be identified in our analysis, but the frequency and combination of them is where the value of the broader systems analysis helps place their influence. We also argue that outcomes are normative and place-dependent. Meaning that while there are objective ways to measure social and ecological outcomes, the desired outcomes themselves are value oriented depending on who decides what they should be, and in our case should be based on the local stakeholder preferences. As both the combinations of motifs interact and dependent outcomes vary, how we think about developing our hypotheses should follow accordingly.

5. Conclusion

In this study, network analysis has been applied to SCUBA diving tourism on the Gili Islands, Indonesia, with the aim to understand a social-ecological tourism system as a social-ecological network. Our study provides numerous methodological insights for SCUBA diving tourism research and practical management. SCUBA dive businesses were conceptualized as social nodes and dive sites as ecological nodes, with the number of divers being taken from dive shops to dive sites representing social-ecological edges, collaboration among dive shops describing social edges, and dive site similarities capturing ecological edges. We also demonstrate how to assess dive location characteristics using expert local ecological knowledge and how to cluster reef sites similarity based on a tourist preference index and site characteristic diversity.

Overall, our multiple networks allow a closer and differentiated look into the many relationships in a SCUBA tourism SES and the potential drivers shaping outcomes such as diver preferences, reef characteristics, reef name, business location, business size and extent of cooperation. Results suggest that SCUBA tourism on the Gili Islands is a dense and centralized social-ecological and social network, meaning that most dive shops take tourists to most available dive sites and are cooperating. Yet, there are dive sites in close vicinity to Gili Trawangan that are highly overcrowded causing diver water safety and reef damage issues. The network findings suggest that SCUBA tourism businesses have been historically cooperative, and that cooperation is driven by older larger businesses. As new businesses continue to open – increasing crowding – the cooperative structure of the network still suggests a high likelihood of collective action for continued self-organized governance to address on-going problems. We have further suggested four simple motifs that hypothesize the link between structural patterns in SCUBA networks and their influence on outcomes. We encourage applications of our methodology to examine its usefulness beyond this case study, how it could be validated, adapted or improved to assist researchers in identifying sustainability and governance issues in SCUBA tourism locations using local contextual knowledge.

Note

1. This is supported by a literature search in the database Web of Science – Core Collection examining the number of manuscripts applying social-ecological network analysis in the context of tourism (n = 1 hit for search string "tourism" AND "social-ecological network") (Supplementary Information A).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethics

All interviewees provided prior informed consent to participate in the interviews and surveys in this research. The research design and implementation followed all required procedures by the Leibniz Centre for Tropical Marine Research (ZMT) and partner institutes.

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