Oecologia Australis
24(2):279-300, 2020
https://doi.org/10.4257/oeco.2020.2402.05

INTEGRATING LONG TERM ECOLOGICAL RESEARCH (LTER) AND MARINE PROTECTED AREA MANAGEMENT: CHALLENGES AND SOLUTIONS

Ricardo Jessouroun Miranda[1], Ana Cláudia Mendes Malhado[1], Nidia Noemi Fabré[1], Vandick da Silva Batista[1], Robson Santos[1], João Vitor Campos-Silva[1,2], Ricardo Correia[1], Ana Paula de Oliveira Santos[1], Andrei Cardoso[3], Barbara Ramos Pinheiro[1,4], Bruno Stefanis Santos Pereira de Oliveira[5], Cláudio Luis Santos Sampaio[6], Flávia de Barros Prado Moura[1], Iran Campello Normande[3], Lidia Ramires[7], Lindemberg Medeiros de Araujo[8], Marcio Amorim Efe[1], Marius da Silva Pinto Belluci[3], Melissa Fontes Landell[1], Nicolli Albuquerque de Carvalho[1], Roberto José de Mendonça Cavalcante[1], Taciana Kramer de Oliveira Pinto[6], Tamí Mott[1] & Richard James Ladle[1]*

[1] Universidade Federal de Alagoas, Instituto de Ciências Biológicas e da Saúde, Av. Lourival Melo Mota, s/n, Tabuleiro do Martins, CEP: 57072-900, Maceió, AL, Brazil.

[2] Norwegian University of Life Sciences, Faculty of Environmental Sciences and Natural Resource Management, Ås, 1432, Norway

[3] Instituto Chico Mendes de Conservação da Biodiversidade, Área de Proteção Ambiental Costa dos Corais, Rua Doutor Samuel Hardman, s/n, CEP:55578-000, Tamandaré PE, Brazil.

[4] Universidade Federal da Bahia, Instituto de Geociências, Rua Barão de Geremoabo, s/n, Ondina, CEP:40170-290, Salvador, BA, Brazil.

[5] Instituto Biota de Conservação, Rua Padre Odilon Lôbo, 115, Guaxuma, CEP:57038-770, Maceió, AL Brazil.

[6] Universidade Federal de Alagoas, Unidade Educacional Penedo, Av. Beira Rio, s/n, Centro Histórico, CEP 57000-200, Penedo, AL, Brazil.

[7] Universidade Federal de Alagoas, Instituto de Ciências Humanas, Comunicação e Artes, Av. Lourival Melo Mota, s/n, Tabuleiro do Martins, CEP:57072-900, Maceió, AL, Brazil.

[8] Universidade Federal de Alagoas, Instituto de Geografia, Desenvolvimento e Meio Ambiente, Av. Lourival Melo Mota, s/n, Tabuleiro do Martins, 57072-900, Maceió, AL, Brazil.

E-mails: ricardojdemiranda@gmail.com (*corresponding author); anaclaudiamalhado@gmail.com; nidia.fabre59@gmail.com; vandickbatista@gmail.com; robsongsantos@gmail.com; jvpiedade@gmail.com; rahc85@gmail.com; ana.pesca@yahoo.com.br; andrei.costa@gmail.com; barbara.pinheiro@gmail.com; brunostefanis@gmail.com; claudio.sampaio@penedo.ufal.br; fbpm@mhn.ufal.br; iran.normande@icmbio.gov.br; lidia.ramires@ichca.ufal.br; lindemberg@igdema.ufal.br; marcio_efe@yahoo.com.br; marius.belluci@icmbio.gov.br; melissa.landell@gmail.com; albuquerquenicolli@hotmail.com; rjmc@ic.ufal.br; taciana@penedo.ufal.br; tamimott@hotmail.com; richardjamesladle@gmail.com

---

Abstract: Long Term Ecological Research (LTER) generates unique data sets th at have the potential to identify and quantify trends in ecological processes that may be difficult to detect at lower temporal resolutions. Even though many LTER sites are within protected areas, they do not necessarily produce data that are well aligned with the objectives of the institutions and individuals who manage and govern these sites. There are several potential reasons for this, including: i) insufficient information provided by the LTER on socio-ecological variables of relevance to management; ii) a mismatch between the spatial scale of the data collected by the LTER and the scale of data needed to inform management decisions; iii) a lack of inclusion of policy-makers in crucial steps of LTER project implementation, including experimental design and analysis, and; iv) an absence or insufficiency of formal or informal mechanisms for incorporating LTER data into environmental decision-making and protected area governance. Using examples from recently implemented LTER in the *Costa dos Corais* Environmental Protected Area (known as the PELD-CCAL), we reflect on how some of these challenges can be addressed and provide general recommendations for increasing the conservation management and policy relevance of LTER projects in Brazil.

Keywords: LTSER; coastal reefs; environmental policy; monitoring; governance.

INTRODUCTION

It has long been recognized that there is a fundamental mismatch between the typical time span of an ecological research project (2 to 4 years) and the temporal dynamics of many ecological processes (Callahan 1984). This is particularly problematic at the landscape scale where trends in critical ecological variables such as beta diversity and community composition may require data that spans decades rather than years (Willis & Whittaker 2002). Policy-makers have responded to this challenge in a number of ways, particularly through the creation of long-term ecological research (LTER) sites, where funding is assured for long enough to generate key metrics of ecological change over extended time periods (Callahan 1984). The first dedicated LTER sites were funded by the US government's National Science Foundation (NSF), which began investing in site-based environmental research in 1980 (Willig & Walker 2016). Thus, the oldest dedicated LTER sites in the world have been subject to 40 years of continuous ecological study - although there are several research sites (non-included in LTER network, hereafter indicated as 'non-LTER') with longer records of continuous ecological monitoring (e.g. Wytham Woods in Oxford has been intensively studied since the 1920s - Savill *et al.* 2010). In contrast to North America and Europe, LTER research in Brazil has more recent origins with the national program (known as PELD – *Pesquisas Ecológicas de Longa Duração*) approved in 1998 (Tabarelli *et al.* 2013).

Many LTER sites around the world are located within protected areas (PAs). PAs are ideal for LTER research because they: i) are natural habitats with limited or carefully controlled use of natural resources; ii) often have good historical baselines of ecological information, and; iii) typically have a mature research infrastructure, greatly facilitating the initiation of new projects and reducing costs for ongoing research. PAs can thus contribute enormously to LTER, and may also benefit from the presence of an LTER program within their boundaries. These benefits may be indirect, stemming from the presence of researchers in the PA; this has been shown to deter illegal exploitation activities and significantly contribute to the local economies (Laurance 2013). LTER projects may also directly benefit and contribute to a PA by generating data that directly feeds into management and governance. For example, LTER projects (e.g. North Temperate Lakes LTER site in northern Wisconsin; Luquillo LTER site, Puerto Rico; Konza Prairie LTER site, a tallgrass prairie in northeastern, Kansas) may provide early warning of rapid environmental change, phase shifts in ecological community dynamics and declining trends in populations of endangered or vulnerable species (Callahan 1984, Turner *et al.* 2003). Nevertheless, the objectives of ecological research and PA management are frequently poorly aligned (Gruby *et al.* 2016). Specifically, there are at least four key challenges that need to be overcome for LTER projects to significantly contribute to protected area management: i) generating data on socio-ecological variables of relevance to PA management and governance; ii) solving the mismatch between the spatial scale of data collection and the geographic scale of data needed to inform stakeholders; iii) providing a platform for policy-makers to contribute to the design, implementation and analysis of the LTER project, and; iv) developing formal and/or informal mechanisms for incorporating LTER data into protected area decision-making.

Using examples from the *Costa dos Corais* LTER in Alagoas state, northeast Brazil (hereafter, PELD-CCAL), we reflect on how some of these challenges can be addressed and, based on our experiences, provide some general recommendations for increasing the management and policy relevance of LTER projects in Brazil.

THE APA COSTA DOS CORAIS AND THE PELD-CCAL

The long-term ecological research project at the Costa dos Corais Environmental Protected Area (*APA Costa dos Corais* or APACC in Portuguese) in Alagoas state was approved by the Brazilian government's research funding agency (CNPq) in 2016. The APACC is the largest federal coastal marine protected area in Brazil, with over 400,000 ha including coral reefs, seagrass beds, mangroves, estuaries and about 120 km of beaches accompanied by Atlantic forests. It is located in northeastern Brazil, between the municipalities of Tamandaré in Pernambuco State and Maceió in Alagoas State (Figure 1). The extensive fringing reefs in the APACC are discontinuously oriented near and parallel to the coast at depths of 1 m to 20 m (Leão *et al.* 2019, Figure 1a). Like other near-coast reefs in Brazil, the main threats are from agricultural effluents, urban development, tourism, trade in reef organisms, predatory fishing, and industrial exploitation projects (reviewed in Leão *et al.* 2016). More recently, severe effects of climate change have been observed in APACC and other reefs of Brazil with thermal anomalies reaching up to 31 ºC, intensifying coral bleaching events and their associated effects (Costa *et al.* 2001, Miranda *et al.* 2013, Leão *et al.* 2016), as well as the massive oil spill coming from unknown source offshore ocean affecting coral reefs, sandy beaches, mangroves and local people (Ladle *et al.* 2020, Miranda *et al.* 2020, Magris & Giarrizzo 2020). These reefs and other systems compose a diverse habitat mosaic that includes microorganisms (e.g. fungi and bacteria), corals, octocorals, zoanthids, algae, fish, birds, and vulnerable or endangered species such as coral *Mussismilia harttii,* greenback parrotfish (*Scarus trispinosus*), the hawksbill sea turtle (*Eretmochelys imbricata*), the green sea turtle (*Chelonia mydas*), and the Antillean manatee (*Trichechus manatus manatus*).

Under Brazilian legislation, APAs are designated for sustainable use of natural resources by local communities in addition to the protection of biodiversity (BRASIL 1981). The APACC supports a large population of artisanal fishermen (de Souza *et al.* 2018) with all the associated environmental challenges that this livelihood brings to a region (Batista *et al.* 2014). It also has a very active tourist industry that, in addition to traditional beach tourism, exploits the reefs for snorkeling and scuba diving (de Vasconcellos Pegas *et al.* 2018, Steiner *et al.* 2006). APACC has also developed a highly successful community-based ecotourism enterprise based around the local manatee population (Normande *et al.* 2015).

The emergence of urban development linked to 'second home' tourism (i.e. beach houses exclusively used for holidays and vacations) along 23 km of the APACC in Alagoas State (a tourism destination locally known as *'Rota Ecológica'* or ecological route) may represent a new threat to the local socio-ecological system. The extremely high levels of human use, along with a long history of fisheries research in the area (*e.g.* Ferreira *et al.* 2001), led the LTER researchers of the PELD-CCAL to propose a project that adopted an explicitly socio-ecological perspective; foregrounding integrative, interdisciplinary research and adopting community-based monitoring, as well as a range of new technologies such as the use of remote underwater cameras and drones, the analysis of social media images to evaluate cultural ecosystem services (Retka *et al.* 2019), and the application of molecular tools such next generation sequencing and DNA microarray to monitor anthropogenic activities.

The main long-term aim of the PELD-CCAL is to develop an integrated system of long-term monitoring of the socio-ecological processes that occur within the APACC in Alagoas state (Figure 2, Appendix 1), allowing researchers to address five fundamental and interlinked questions: i) what are the temporal and spatial patterns of biological communities, ecological processes and the perceptions of APACC users?; ii) what are the effects of anthropogenic activities on APACC ecosystems and management zones?; iii) what environmental quality indicators can be used to measure APACC's ecological and cultural resilience?; iv) what are the baselines for biological and social indicators

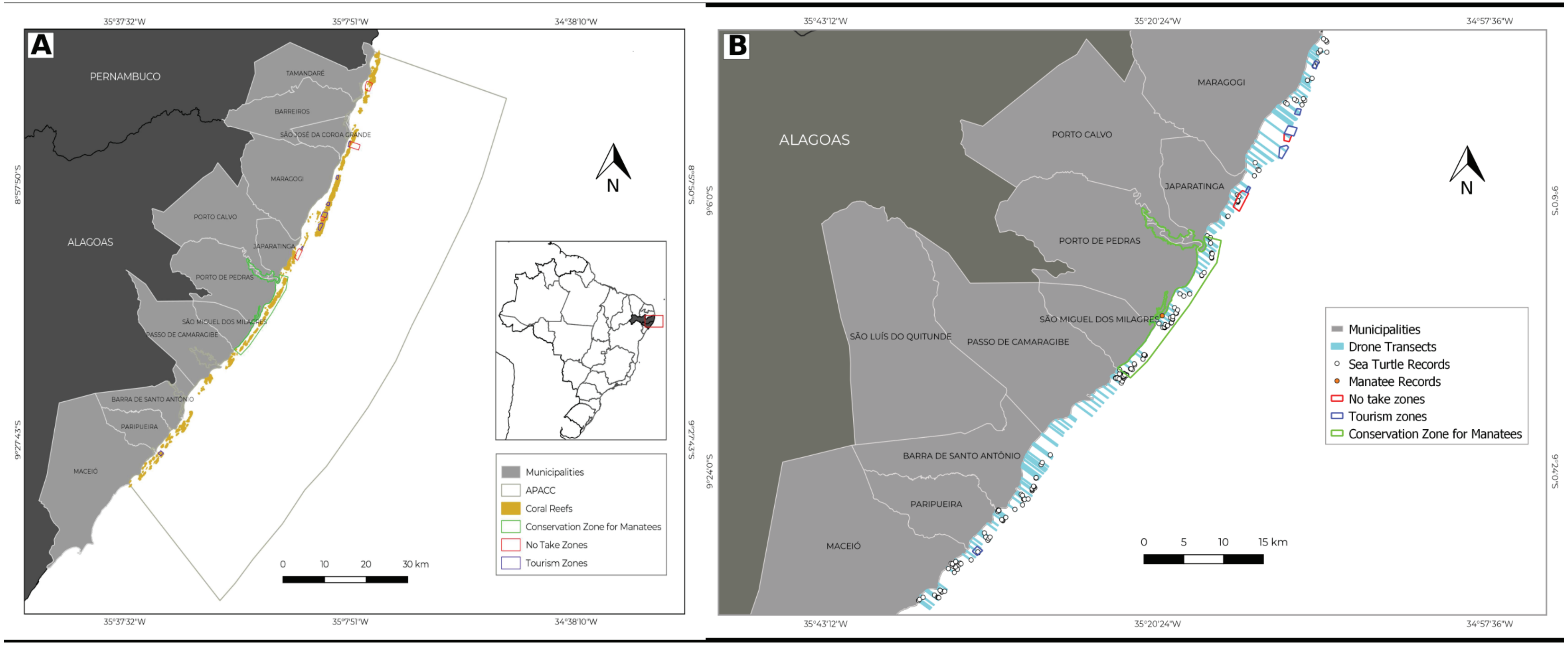

Figure 1. Map of the Environmental Protected Area of Costa dos Corais, Northeast Brazil, A) indicating coral reefs and zoning management areas, and B) sea turtles and manatee records along 147 randomized drone transects from 2018 to 2019.

for ecosystems and management zones within APACC?, and; v) how effective are the management areas of the conservation unit? In parallel and over the medium term, the project aims to generate information on the status of certain target species of conservation concern (*e.g.* the Antillean manatee, sea turtles and scleractinian corals), as well as identify changes in the biophysical and cultural environment that can help identify conservation priorities and test the impact of different management decisions. For example, the APACC has a recently implemented zoning system (including zones for sustainable use, conservation, fishing and tourism - Figure 1a).

The PELD-CCAL was designed in close coordination with key stakeholders (e.g. artisanal fishermen and tourism industry leaders) and the support of the APACC's management team (ICMBIO members - government environmental agencies - who are also full members of the PELD-CCAL's research team). These collaborations are pivotal to achieve the medium and long-term objectives of the PELD. The project team also has developed extensive contacts / partnerships with local NGOs working in the area.

CHALLENGES AND SOLUTIONS

Challenge 1: Generating data on socio-ecological variables of relevance to PA management and governance

The first LTER sites, understandably, adopted a strongly ecological focus in which humans were largely excluded (Hinds 1984). They focused on a wide range of biotic and abiotic indicators, which could allow standardized assessments of the combined effects of multiple drivers at relatively large geographic and temporal scales (Haase *et al.* 2018). However, the last two decades of research have revealed that even environments considered as 'natural' often host social-ecological systems, where anthropogenic activities play (and have historically played) a defining role in driving ecological dynamics (Vitousek *et al.* 1997, Chapin *et al.* 2010). LTER projects, even those established at a time when human influences were routinely down-played, have relevant potential to contribute to a better understanding of the nature of coupled social-ecological systems within which the sites are embedded (Mirtl *et al.* 2013, Dick *et al.* 2018). For example, recent research suggests that effective

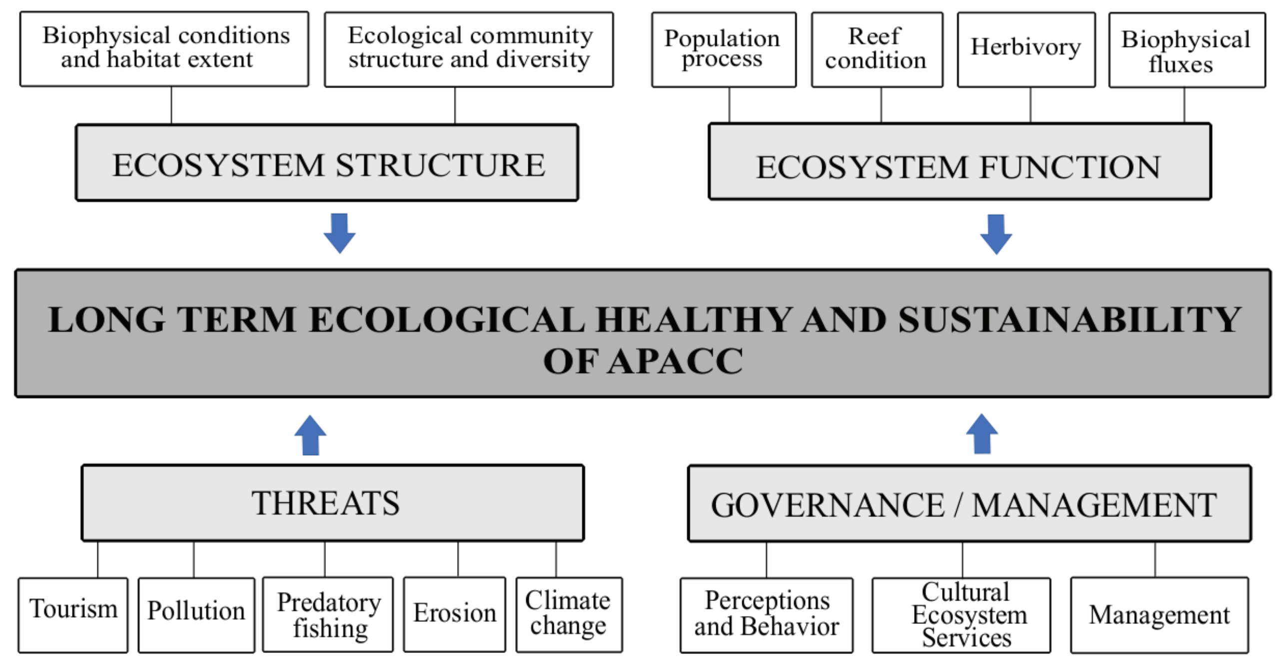

Figure 2. Framework for understanding the long-term ecological health and sustainability of the Environmental Protected Area (APA) Costa dos Corais adopted by the Long Term Ecological Research Costa dos Corais Alagoas (PELD CCAL). Ecological health and sustainability is conceptualized as the result of the interactions between ecosystem structure, ecosystem function, threats and management/governance, aspects monitored during the project. Modified from McField & Kramer (2007).

ecosystem-based conservation requires an in-depth understanding of key cultural characteristics of the stakeholders, including their values and identities, knowledge and practice, governance systems, livelihoods and their interactions with the biophysical environment (Poe et al. 2014).

Solution 1.1: Creation of Long-Term Social Ecological Research (LTSER) sites or adoption of LTSER methodology and indicators

LTSER sites were specifically developed to monitor changes in social and natural systems at large scales (*e.g.* Haberl *et al.* 2006, Collins *et al.* 2011, Dick *et al.* 2018). Although LTSER can be considered as distinct from LTER, LTSER approaches can be incorporated into more traditional projects. This can be clearly seen in Europe and North America where LTER projects began to shift the way they treated and monitored human activity "from exogenous 'disturbances' to endogenous behavior" (Ohl & Swinton 2010).

The success of such approaches depends, to a large extent, on incorporating social scientists and interdisciplinary researchers into the LTER research team (Gruby *et al.* 2016). The key underlying concept of LTSER research is the understanding that the human dimension, including socioeconomic factors, cultural values, behaviors, attitudes and perceptions, plays a key role in determining socio-ecological dynamics, and should therefore be incorporated into ecological monitoring systems (Collins *et al.* 2011, Poe *et al.* 2014). To date, socio-ecological components have scarcely been addressed in Brazilian LTER projects (cf. Tabarelli *et al.* 2013) and one of the main objectives of the PELD-CCAL was therefore to develop a genuinely integrated monitoring system. This motivation stemmed, in part, from the necessities of working in a sustainable use protected area such as APACC, where maintaining human natural resource exploitation is the main objective of the designation (Silva 2005). In order to integrate socio-ecological assessment into the PELD CCAL, we focused on monitoring four key dimensions of human interactions with the environment: threats, cultural services, livelihoods, and governance and policy. We adopted a multi-method approach (cf. Viera *et al.* 2018). Specifically, we combined data from conventional questionnaire social surveys with data derived from online surveys, key informant interviews, participant observation and content analysis of images retrieved from social media sites.

The potential of big data approaches that use social media sources to generate data on human-nature interactions within the APACC is enormous. Our analysis focuses on cultural ecosystem services (CES), the non-material benefits that arise from human-ecosystem relationships. These play a vital role in generating well-being and health in local communities (Fish *et al.* 2016), though have rarely been monitored in LTER projects. CES may also play an important role in generating positive sentiment towards a protected area. Building on the groundbreaking work of Richards & Friess (2015), we are monitoring CES in APACC using user-contributed georeferenced photographs from Flickr (an image- and video-hosting website). In our initial analysis (documented in Retka *et al.* 2019), we assessed 1,984 photographs taken by 207 users between 2010 and 2016 – by using archived material we were able to extend our analysis to before the initiation of the LTER program. The most represented CES categories were landscape appreciation and social recreation; an unsurprising result given the natural attributes of this tropical beach location. Artistic/cultural expressions and appreciation, and nature appreciation were also highly represented. Engagements with CES had clear spatial and temporal patterns relating to user behavior, reflecting the biophysical and infrastructural characteristics of different sites within the APA. Parallel research in Catimbau national park (Viera *et al.* 2018) suggests that analysis of social media photographs may be biased against some types of CES, and for that reason we are also collecting data from standardized social surveys.

It is important to note that there is no "one size fits all" solution to collecting socio-ecological variables of relevance to PA management, with choice of indicators being strongly dependent on the cultural context of the reserve (Fabre *et al.* 2012). In the case of the PELD-CCAL, the high economic dependence of the local population on artisanal fishing and tourism (mainly national) meant that most of our indicators were chosen to reflect different aspects of these livelihood choices. For example, we are assessing economic and dietary dependence of local communities on seafood and fish, tourist use of beaches and reefs, frequency of reported conflicts between locals and PA managers, and are generating a variety of metrics that quantify artisanal fishing pressure (Appendix 1).

As mentioned previously, issues of spatial and temporal scale are equally relevant to socio-ecological research, and particular care should be taken with the design of social surveys if the aim is to extrapolate trends to larger populations (De Vaus 2013). Consequently, all of our quantitative social surveys are carefully calibrated to ensure that the sample size is sufficient to make robust extrapolations for variables of interest. For example, we are currently quantifying different forms of human interactions (e.g. recreational pastimes, livelihood activities, etc.) with the biophysical features of the APACC with the aim of monitoring long term trends in the number of people engaging in activities that generate different forms of social value (Jepson *et al.* 2017, Gamarra *et al.* 2019). Finally, ecological and social variables will change at different rates, necessitating careful consideration of sampling frequency. For example, changes in attitudes and behaviors often show considerable latency with respect to changes in ecological conditions making annual social surveys redundant.

Scale is a 'fundamental conceptual problem in ecology, if not in all of science' (Levin 1992), though it is rarely rigorously addressed in comparative ecological studies (Whittaker *et al.* 2001). Perhaps the most common challenge of scale is how to robustly generalize the results of point or transect-based sampling to larger areas (upscaling) in a way that is both sufficiently precise and that accurately reflects real-world conditions (Riddle *et al.* 2011). This could be particularly challenging for research focused on providing information for management of conservation units because, while many ecological indicators (*e.g.* measures of alpha diversity) are based on highly localized sampling, management decisions (*e.g.* zoning, fishing restrictions) typically relate to much larger areas. This mismatch may be exacerbated in fragmented or heterogeneous habitats where there may be rapid or discontinuous changes in ecological community structure with distance from a sampling point (cf. Nekola & White 1999, Soininen *et al.* 2007).

Issues of scale are not specific to ecological characteristics and processes, and also present a challenge for interpreting and using the results of, for example, evaluations of stakeholder knowledge, attitudes and behaviors. Such key social variables are typically collected through semi-structured questionnaires or other forms of quantitative social research (De Vaus 2013). In general, these are costly and time-consuming and in protected areas are typically administered at local scales with relatively small samples that may be demographically or culturally biased. Moreover, most such studies do not follow a standard methodology, limiting replicability and comparability between studies conducted at different times and in different locations (Bragagnolo *et al.* 2016).

There are two general solutions for producing LTER data at scales appropriate for informing conservation management: i) adoption of large-scale approaches to data collection. In addition to a range of remote sensing techniques (e.g. sensors mounted on satellites or drones), such approaches include the use of emerging digital technology for both ecological and social monitoring (Arts *et al.* 2015). This category includes the analysis of user generated content on social media sites (Hausmann *et al.* 2018) or dedicated apps (Jepson & Ladle 2015, Muñoz *et al.* 2019); ii) spatial extrapolation of localized data (*e.g.* point or transect data) to larger geographic areas, ideally covering the entire PA.

Solution 1.2: Large-scale data collection

There are a wide variety of approaches to collecting data over larger geographic areas, although all have their limitations. The most extensively used methods involve remote sensing by satellite which, in the context of reefs, can be used for, among other things, structure and habitat composition (*e.g.* benthic cover, rugosity, bathymetry), and also a wide range of variables relating to the physical environment of the reef, such as sea surface temperature, exposure, winds, solar radiation and water quality (reviewed in Mumby *et al.* 2004, Hedley *et al.* 2016, Purkis 2018). While satellite remote sensing cannot provide the detail and precision generated by field surveys, its complete areal coverage makes it indispensable for some aspects of reef management (Hedley *et al.* 2016).

Of course, satellites are not the only sources of remote sensing data. Recent years have seen a considerable increase in the use of unmanned aerial vehicles (UAVs, or drones) in conservation research (reviewed in Wich & Koh 2018). Drones typically collect data at scales intermediate between traditional field sampling and satellite sensing, and are especially suited to collecting data from difficult to access locations and where sampling by other means is expensive or impractical. Using reef monitoring as an example, drones have been used to map reef structures at very high resolution (Casella *et al.* 2017, Chirayath & Earle 2016), identify and map fish nursery grounds (Ventura *et al.* 2016), assess beach erosion (Casella *et al.* 2016), monitor populations of sea turtles (Rees *et al.* 2018) and dugongs (Hogson *et al.* 2013), and have been proposed as an effective way to assess illegal fishing (Arefin 2018). Although this last potential use of drones is of critical importance to many managers of MPAs, its implementation is beset with social dilemmas (Sandbrook 2015, Humle *et al.* 2014, Adams 2017) and any monitoring of the natural resource exploitation activities of local residents needs to be sensitive to cultural context and the potential of exacerbating conflict between resource users and authorities (Keane *et al.* 2008). In the PELD-CCAL, we are using drones to monitor sea turtles and manatees in 147 randomly selected transects that stretch across the length of the protected area (Figure 1b) and, at present, have no plans to use drones to study the temporal and spatial distribution of artisanal fishing crafts.

Even though surveillance of natural resource use activities is potentially problematic, other types of data on human use of the environment are publicly available and can be used for conservation monitoring at large spatial scales. For example, broad datasets of cumulative impact from National Center for Ecological Analyses and Synthesis can be used for conservation purposes and high spatial and temporal resolution data on tourist use of protected areas can be generated from georeferenced photos posted on file sharing web-sites such as Flickr and Instagram (Halpern *et al.* 2008, Ladle *et al.* 2016, Tenkanen *et al.* 2017). Conservation managers in APACC have a strong interest in monitoring trends in tourist use of the PA. This interest is related to concerns about excessive use of certain reefs and beaches by tourists (*e.g.* coral damage and litter). The latter is important because the beaches of the region annually receive several species of migratory birds from the Arctic during the peak of the tourist season M. Efe (personal communication). Disruptions by human recreational use of beaches may reduce the amount of coastal habitat available to migratory birds and this may have individual or population consequences (Gibson *et al.* 2018). In addition to conducting bird surveys, along the length of the protected area, the PELD CCAL has been monitoring tourist use based on the density of social media photographs (Figure 3, data from Retka *et al.* 2019). Our ultimate objective is to combine the data from traditional bird surveys with the analysis of social media photographs to assess the relationship between bird and human abundance in the APA.

Solution 1.3: Extrapolation of data collected at a local scale

Any type of variable can be spatially extrapolated (often referred to as *predictive mapping*) if it has a statistically consistent relationship with another variable or variables whose values are known over a larger area (Wisz *et al.* 2012, Tardin *et al.* 2019). The best-known type of spatial extrapolation in ecology is probably the prediction of species distributions based on the relationship between presence/absence data and as wide range of biophysical variables; known a species distribution modelling (SDM) or ecological niche modelling (ENM) (see Peterson & Soberón 2012 for discussion of underlying concepts). More recently, researchers have developed techniques to simultaneously model multiple species using multi-response algorithms (Nieto-Lugilde *et al.* 2018). However, it is important to note that spatial extrapolation can potentially be used for any variable of interest given sufficiently robust associations with other variables. In the context of inshore coral reefs, predictor variables are typically abiotic variables (such as substrate, seawater temperature, water depth) that can be generated at high spatial resolutions through satellite remote sensing (Hedley *et al.* 2016, Purkis 2018).

One of the simplest statistical methods for spatial extrapolation is through logistic regressions, whereby the model predicts the probability of the presence/absence of the variable of interest within any given polygon inside the research area. This has been used very successfully to map seagrass beds in North Carolina (United States) based on hydrological characteristics of the study area (Kelly *et al.* 2001). Logistic regressions are particularly appropriate and effective when a simple dependent

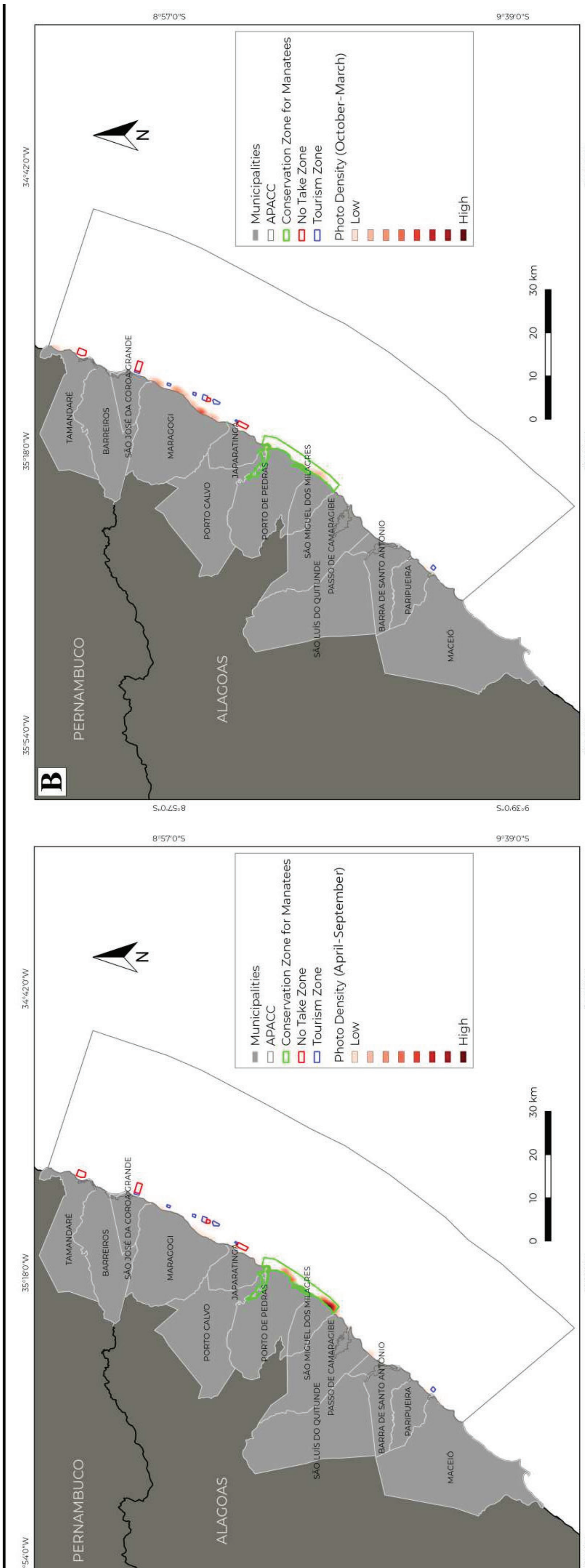

Figure 3. Density of photographs taken inside Environmental Protected Area (APA) Costa dos Corais and uploaded onto Flickr (www.flickr.com) from 2010 to 2016 during: A) tourist low season (April-September); B) tourist high season (October-March). Data from Retka *et al.* (2019).

variable (*e.g.* seagrass presence/absence) is strongly related to small number of biophysical variables.

Many ecological data are not so straightforward to predict, such as the location, density and size of reef fish. Under these circumstances predictive maps are typically generated through more sophisticated statistical techniques such as boosted regression trees (BRTs), generalized linear models (GLMs) and generalized additive model (GAM). These methods are used to model the complex, non-linear relationships between organisms and their environment (Elith *et al.* 2008). BRTs, for example, work by calculating a large number of simple models using random subsets of the database (Schapire & Freund 2013), which are then combined to produce an 'ensemble' model whose output is used for mapping. Working on reefs off the island of St John in the southern Caribbean, Costa *et al.* (2014) successfully used BRTs to model density of large fish (≥ 29 cm) with water depth and standard deviation of depth identified as the most influential variables. Interestingly, the BRTs performed poorly for smaller fish, suggesting that the explanatory variables did not capture the key drivers influencing their density and distribution.

Perhaps the most effective demonstration of the potential of spatial extrapolation concerns the modelling of coral reef fish species richness combined with empirical modelling techniques, remotely sensed data, field observations and GIS using model reefs in the U.S. Caribbean. Pittman *et al.* (2007) evaluated the performance of three different modelling techniques (multiple linear regression, neural networks and regression trees) when applied to two geographically distinct coral reef ecosystems. They found that regression trees outperformed the other two approaches (multiple linear regression and neural networks) and were able to very accurately predict high and low areas of fish species richness. The key abiotic variables determining richness were rugosity and bathymetric variance, with water depth and percentage cover of seagrass/hard cover being of lesser importance. These results are particularly significant because they strongly suggest that, in similar ecosystems, fish species richness could be robustly estimated at broad spatial scales using topographic complexity alone.

Finally, there is an enormous literature on species distribution modelling (marine applications reviewed in Robinson *et al.* 2017) with many associated modelling tools, the most widely used of which is probably MaxEnt (Elith *et al.* 2011). However, the results of SDMs are typically coarse-grained (1 km scale or more) which may be less appropriate or informative for management within more geographically localized protected areas (Farrell *et al.* 2013). This limitation has been partly overcome by using high spatial resolution explanatory variables which, in conjunction with intensive and systematic sampling of the species of interest, can be used to generate SDMs with very fine grain sizes (e.g. 10 m – 100 m). Such models provide insights into the variables influencing local scale species distributions including the location of potential corridors of movement and isolated habitat patches (Nezar *et al.*, 2017). The use of such high-resolution methods is increasing and there have been several notable studies in marine coastal environments. For example, Leong *et al.* (2018) were able to generate high resolution maps of 12 overlapping mangrove species using a digital elevation model as a proxy for small-scale inundation processes.

Solution 1.4: Spatial extrapolation to support management

The PELD-CCAL combines large-scale data collection and spatial extrapolation of key variables to support conservation management and the sustainable exploitation of artisanal fisheries resources. We already had extensive information about large-scale spatial use of the APACC by manatees by way of a long-term satellite monitoring program of reintroduced individuals by members of the PELD-CCAL team (Normande *et al.* 2016). However, there was scant information on green sea turtles (*Chelonia mydas*) – the most abundant of the marine turtles in the APACC and the most likely to come into conflict with artisanal fishermen due to their use of similar parts of the reef ecosystem. Drawing on recent studies that use drones to monitor sea turtles (Bevan *et al.* 2015, Kelaher *et al.* 2019), we instigated long-term monitoring by drone across the APACC (see above). Data from drone transects (Figure 1b) can be used to generate geo-referenced observations of sea turtles which, when statistically associated with biophysical features of importance to them (*e.g.* algal and seagrass beds, reefs, depth), can then be used to generate robust maps of habitat use at the level of the APACC. Our ultimate aim is to compare the relative abundance of turtles and manatees in the APACC with spatially explicit information on habitat use by artisanal fishermen (Appendix 1). Such information is partially available from ethno-knowledge surveys (to date we have surveyed over 1500 fishermen in the APACC) and could also be generated from the drone transects given the full consent of the fishing communities.

In summary, although many LTER projects are situated in protected areas, the data that they generate may not always be at an appropriate scale to inform management decisions within the PA. This challenge can be addressed by: i) incorporating a combination of local scale and landscape scale metrics into the LTER, the latter generated from remote sensing data (*e.g.* via satellite, drones) or by utilizing the growing range of digital metrics that capture different aspects of human-nature interactions (Ladle *et al.* 2016); ii) Extrapolating data collected at local scales through rigorous statistical procedures. The resulting data can be used to support management decisions (*e.g.* change of zoning regulations), monitor landscape scale, socio-ecological trends and evaluate the consequences of new conservation or development initiatives. Clearly, both the types of indicators and their spatio-temporal resolution should be determined in close consultation with the management authorities (*see Challenges III and IV*) and align closely with the objectives outlined in the PA's management plan. Finally, it is important to note that socio-ecological processes in PAs can be significantly influenced by processes within the landscape (or seascape) within which they are embedded. This is a particular challenge for coastal PAs such as the PELD CCAL which are strongly influenced by the many human activities occurring in the land adjacent the shoreline (Alvarez-Romero *et al.* 2011), for example, land management in the catchment areas. Such links may require evaluation and monitoring of socio-ecological processes at a much greater spatial scale than the PA itself, potentially incorporating completely different ecosystems with all the challenges this entails.

Challenge 2: Providing a platform for environmental managers to contribute to the design, implementation and analysis of the LTER project

As might be expected, LTER projects are dominated by full-time academics working from universities and other research centers. However, if the data generated by LTER projects situated in PAs are going to genuinely contribute to environmental decision-making, it is essential that the products generated by the project align with the needs of the PA managers and other stakeholders.

Solution 2.1: Inclusion of PA staff and other key stakeholders in the design, implementation and analysis of the LTER project

In the Brazilian context, federal reserves such as APACC are managed by staff from the Chico Mendes Institute for Biodiversity Conservation (known by the acronym ICMBio), a semi-autonomous institution linked to the Brazilian Ministry of the Environment. The PELD CCAL benefits from particularly strong ties with ICMBio staff with the Director of the APACC and several key staff contributing to the design of the project and fully participating as official research team members. In addition to helping with logistics, this participation extended to data collection and sharing, regular planning meetings and collaboration in the preparation of scientific papers and reports.

In our experience, the greatest challenge to ensuring the continued contribution of PA staff to the PELD has been dealing with the impacts of the current wave of political instability in the country. There has been a broad and well-publicized restructuring of federal environmental bodies (Pereira *et al.* 2019, Escobar 2019) with ramifications at multiple levels. In the APACC, key ICMBio members of the PELD research team had their management roles changed or were even placed to work in different conservation units. In addition to disrupting data collection and other regular activities, such staff turnover necessitates a repeated phase of network building with uncertain outcomes for future participation and data sharing.

Of course, ICMBio is not the only organization with a stake in environmental management of federal conservation units in Brazil. Local and national NGOs often play a major role in PA governance and management, with many actively engaged in research and data collection. These NGOs often have relevant social capital, which is of important value for communicating the results of LTER to the local communities and, potentially, to mobilize community members to co-produce knowledge. Local NGOs are particularly relevant in this respect, typically being very active on social media. Thus, in addition to staff from government agencies, the inclusion of members of local NGOs in LTER research teams can be extremely valuable – especially in LTSER projects where socio-ecological data are essential to meet project targets. Given the acknowledged importance of co-production of knowledge for effective environmental governance (Wyborn 2015, Nel *et al.* 2016), local NGOs can provide an essential bridge between academics and local communities. Ultimately, this could lead to the creation of community-based monitoring schemes within LTER programs, allowing concerned citizens to track and respond to issues of common community environmental concern and thereby play a more proactive role in the management of natural resources (Conrad & Hilchey 2011, Whitelaw *et al.* 2003).

Solution 2.2: Coproduction of knowledge

As one of the objectives of the PELD-CCAL was to work towards greater community involvement and the coproduction of knowledge with key stakeholders, we considered it essential to include members of the local NGO *Instituto Biota de Conservação* (Biota) as part of the research team. Biota is an environmental NGO that has worked in the region over the last 10 years with a focus on using citizen-based monitoring to identify key areas of sea turtles and marine mammal occurrence in the APACC. To do this they have developed a dedicated app and are also heavily involved in dissemination of conservation information through conventional social media. The data acquired through citizen-based monitoring associated with data from a year of daily monitoring in the entire study area, will help us to understand the accuracy of the citizen-based monitoring regarding the identification of sea turtles and manatees stranding hotspots. Once we understand the relations between data from these two sources, we may be able to monitor the trends of strandings through time using citizen-science - a less costly way of monitor large areas such as APACC. This data can also be cross-referenced to information from our drone surveys and could potentially be used to validate predictive maps of sea turtle occurrence throughout the APA.

In summary, our experience suggests that close working relationships with PA management staff and local NGOs that work in the conservation unit are essential preconditions for the implementation of LTER programs that adopt a broader socio-ecological perspective. Ideally, employees of these organizations should be official members of LTER project teams, and actively participate in the design stage of the project. In addition to the fundamental logistical support and grounded knowledge that such team members bring to the project, their organizations also provide access to considerable social capital that can be mobilized for diverse ends, including community monitoring initiatives and dissemination of results.

Challenge 3: Developing formal and/or informal mechanisms for incorporating LTER data into protected area decision-making

The literature on PA management and decision-making processes is large, diverse (see review in Worboys *et al.* 2001) and a detailed review is beyond the scope of this short perspective. Although there is abundant variation depending on the PA designation and the management authority, most larger PAs have one or more governance entities, the most powerful of which is often termed a ‘management’, ‘consultative’ or ‘steering’ council. Any major changes in management typically entail a revision of the PA’s management plan: one of the key instruments for allocating limited resources, directing conservation actions and ensuring that the broader objectives of the PA’s designation are achieved (Worboys *et al.* 2015). Management plan content should reflect PA objectives, but is also influenced by the perspectives of the contributors, official and unofficial policy guidelines for plan preparation and presentation, the content and structure of previous Management Plans, and third party contracting of Management Plan production (Thomas & Middleton 2003, Gamarra *et al.* 2019).

Several decades ago, PA management council typically reflected the prevailing top-down approach to conservation management with members predominantly drawn from government and academic. This has gradually been changing, spurred on by the Convention on Biological Diversity

Aichi Target 11, which requires the 193 signatory parties to incorporate social equity into protected area (PA) management by 2020. Nevertheless, progress has been frustratingly slow with a recent survey of managers, staff, and community representatives from 225 PAs worldwide indicating shortfalls in ensuring effective participation in decision-making, transparent procedures, access to justice in conflicting situations, and the recognition of the rights and diversity of local people (Zafra-Calvo *et al.* 2019).

Solution 3.1: Ensure that LTER researchers have a presence on management and governance committees

APACC has a diverse and inclusive management council that includes representatives from a variety of government institutions, regional research centers, associations of local fishermen, tourism and agriculture organizations and local NGOs. Current representatives from the Federal University of Alagoas and ICMBio are both important members of the PELD CCAL team and are able to directly draw on and introduce monitoring data into council discussions.

Solution 3.2: Develop strong communication channels with multiple stakeholders, and especially with the official representatives of stakeholder groups and organizations

The PELD CCAL team invests considerable time and resources in communication and awareness-raising initiatives with key stakeholders (*e.g.* fishermen groups, local NGOs), to keep them informed about the objectives and results of the LTER. Such work is detailed and challenging and our experience suggests that it is important to have one or more dedicated communication professionals within an LTER team and a clear communication strategy. From the initiation of the PELD-CCAL, communication and dissemination of results have been coordinated by a professionally qualified journalist from the Federal University of Alagoas' Institute of Social Communication and Arts Sciences. Moreover, we are also working towards an open-access online communication platform that will present the results of the PELD using language and visualizations that can be easily understood by all stakeholders.

CONCLUSIONS

The PELD-CCAL is one of the most recently established LTER sites in Brazil with all of the advantages and disadvantages that this brings. Our greatest disadvantage is, perhaps self-evidently, the lack of long-term socio-ecological data sets on which to build our research framework. This lack was one of the motivating factors (along with the interdisciplinary nature of the core team members) behind our decision to take an intentionally broad perspective of LTER, and to incorporate some innovative technologies such as monitoring by drone and quantitative analysis of photographs posted on social media sites. Nevertheless, in comparison with the vast majority of other LTER sites in Brazil we are only just beginning our research – a fact that may make our PELD particularly vulnerable to any future reductions in funding for Brazilian LTER research.

Among the many advantages of "starting late", was the opportunity to review the evolution of LTER networks in Brazil - the Tabarelli *et al.* (2013) report was invaluable - and other countries and identify research trends. The PELD-CCAL's multidisciplinary team is starting to generate novel data and methods to apply to the challenge of better aligning PA management with societal aspirations. Our adoption of an LTSER approach, integrating key indicators of human-nature interactions into the overall monitoring framework, has been essential in this respect. Brazil's original (and enormously successful) LTER sites were strongly focused on monitoring ecological processes (Tabarelli *et al.* 2013) and we felt that any new initiatives needed to adopt a more human-oriented perspective if they were to align with current international trends. Adopting an explicit socio-ecological research framework also fit with our subsidiary objective of generating data to support and inform management and governance decision-making in the APACC.

The great benefits of adopting such an approach recently became apparent when a large quantity of crude oil began washing up on the beaches, coral reefs, and mangroves of northeast Brazil in late August/early September 2019 (Magris & Giarrizzo 2020). Within four months oil had been recorded along > 3000 km of the Brazilian coastline (> 980 beaches) making it the most extensive disaster ever recorded in a tropical coastal region (Oliviera-Soares *et al.* 2020). Significantly, more than 55 protected areas have been affected by the oil, including the APA Costa de Corais. Fortunately, due to our extensive, robust and up-to-date baseline information on a wide variety of socio-ecological factors we were able to comprehensively assess the consequences of this unprecedented environmental disaster, including the key species as reef-builder corals (Miranda *et al.* 2020), and economic and social consequences for local artisanal fishing communities (Ladle *et al.* 2020). Preliminary analysis indicates that recent events of oil spill strongly impacted local livelihoods, compromising the fish value chain and local food security.

The above is an example of one of the many tangible contributions that LTER sites can make to PA management, though to maximize these certain challenges need to be both recognized and overcome. Most of the solutions to these challenges are simple, but often have profound consequences for what data are generated, how, and by whom. Our view is that as political and developmental threats to PAs increase (cf. Bernard *et al.* 2014), data on complex socio-ecological interplay of human populations, landscapes and species will become increasingly important as an evidence base for conservation advocacy. LTER projects that build the needs of management and governance into their research framework will be best placed to provide this information. Such a close alignment between PA and LTER project objectives not only adds value and urgency to the ecological research, but also opens new space for innovation in monitoring and communication.

ACKNOWLEDGEMENTS

This work is part of the Long-Term Ecological Research – Brazil site PELD-CCAL (Projeto Ecológico de Longa Duração - Costa dos Corais Alagoas) funded by the Brazilian National Council for Scientific and Technological Development – CNPq (#441657/2016-8), the Brazilian Coordination for the Improvement of Higher Education Personnel PELD/CAPES (23038.000452/2017-16) and the Research Support Foundation of the State of Alagoas – FAPEAL (#60030.1564/2016). RJM was funded by FAPEAL (60030000231/2019). ACMM was funded by CNPq grants (#309980/2018-6). JVCS was funded by CAPES-Brazil (PNPD-DIBICT fellowship). APOS was funded by PELD-CNPq.

REFERENCES

Adams, W. M. 2017. Geographies of conservation II: Technology, surveillance and conservation by algorithm. Progress in Human Geography, 43(2), 337–350. DOI: 10.1177/0309132517740220

Alvarez-Romero, J.G., Pressey, R.L., Ban, N.C., Vance-Borland, K., Willer, C., Klein, C.J. & Gaines, S.D. 2011. Integrated land-sea conservation planning: the missing links. Annual Review of Ecology, Evolution, and Systematics, 42, 381–409. DOI: 10.1146/annurev-ecolsys-102209-144702

Arefin, A. M. E. 2018. Proposal of a marine protected area surveillance system against illegal vessels using image sensing and image processing. Acta Ecologica Sinica, 38(2), 111–116. DOI: 10.1016/j.chnaes.2017.06.015

Arts, K., van der Wal, R., & Adams, W. M. 2015. Digital technology and the conservation of nature. Ambio, 44, 661–673. DOI: 10.1007/s13280-015-0705-1

Batista, V. S., Fabré, N. N., Malhado, A. C., & Ladle, R. J. 2014. Tropical artisanal coastal fisheries: challenges and future directions. Reviews in Fisheries Science & Aquaculture, 22(1), 1–15. DOI: 10.1080/10641262.2013.822463

Bernard, E., Penna, L. A., & Araújo, E. 2014. Downgrading, downsizing, degazettement, and reclassification of protected areas in Brazil. Conservation Biology, 28(4), 939–950. DOI: 10.1111/cobi.12298

Bevan, E., Wibbels, T., Najera, B. M., Martinez, M. A., Martinez, L. A., Martinez, F. I., Cuevas, J. M., Anderson, T., Bonka, A., Hernandez, M. H. & Pena, L. J. 2015. Unmanned aerial vehicles (UAVs) for monitoring sea turtles in near-shore waters. Marine Turtle Newsletter, 145, 19–22.

Bragagnolo, C., Malhado, A. C. M., Jepson, P., Ladle, R. J. 2016. Modelling local attitudes to protected areas in developing countries. Conservation and Society, 14(3), 163–182. DOI: 10.4103/0972-4923.191161

Callahan, J. T. 1984. Long-term ecological research. Bioscience, 34(6), 363–367. DOI: 10.2307/1309727

Casella, E., Rovere, A., Pedroncini, A., Stark, C. P., Casella, M., Ferrari, M., Firpo, M. 2016. Drones as tools for monitoring beach topography changes in the Ligurian Sea (NW Mediterranean). Geo-Marine Letters, 36, 151–163. DOI: 10.1007/s00367-016-0435-9

Casella, E., Collin, A., Harris, D., Ferse, S., Bejarano, S., Parravicini, V., Hench, J. L., & Rovere, A. 2017. Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. Coral Reefs, 36(1), 269–275. DOI: 10.1007/s00338-016-1522-0

Chapin III, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., Olsson, P., Smith, D. M. S., Walker, B., Young, O. R., & Berkes, F. 2010. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. Trends in Ecology & Evolution, 25(4), 241–249. DOI: 10.1016/j.tree.2009.10.008

Chirayath, V., Earle, S. A. 2016. Drones that see through waves–preliminary results from airborne fluid lensing for centimetre-scale aquatic conservation. Aquatic Conservation: Marine and Freshwater Ecosystems, 26(2), 237–250. DOI: 10.1002/aqc.2654

Collins, S. L., Carpenter, S. R., Swinton, S. M., Orenstein, D. E., Childers, D. L., Gragson, T. L., Grimm, N. B., Grove, J. M., Harlan, S. L., Kaye, J. P., & Knapp, A. K. 2011. An integrated conceptual framework for long-term social–ecological research. Frontiers in Ecology and the Environment, 9(6), 351–357. DOI: 10.1890/100068

Conrad, C. C., & Hilchey, K. G. 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. Environmental Monitoring and Assessment, 176, 273–291. DOI: 10.1007/s10661-010-1582-5

Costa, B., Taylor, J. C., Kracker, L., Battista, T., & Pittman, S. 2014. Mapping reef fish and the seascape: using acoustics and spatial modeling to guide coastal management. PLoS One, 9(1), e85555.

Costa, C. F., Amaral, F. D., & Sassi, R. 2001. Branqueamento em *Siderastrea stellata* (Cnidaria, Scleractinia) da praia de Gaibu, Pernambuco, Brasil. Revista Nordestina de Biologia, 15(1), 15–22.

de Souza, C. D., da Silva Batista, V., & Fabre, N.N. 2018. Caracterização da pesca no extremo sul da Área de Proteção Ambiental Costa dos Corais, Alagoas, Brasil. Boletim do Instituto de Pesca, 38(2), 155–169.

de Vasconcellos Pegas, F., Castley, G., Neto, & A. Q. 2018. Tourism development and impacts on reef conservation in Brazil. In: B. Prideaux & A. Pabel (Eds.), Coral Reefs: Tourism, Conservation and Management. pp. 198–211. Abingdon: Routledge.

De Vaus, D. 2013. Surveys in social research. 6th ed. Abingdon: Routledge: p. 383.

Dick, J., Orenstein, D. E., Holzer, J. M., Wohner, C., Achard, A. L., Andrews, C., Avriel-Avni, N., Beja, P., Blond, N., Cabello, J. & Chen, C. 2018. What is socio-ecological research delivering? A literature survey across 25 international LTSER platforms. Science of the Total Environment, 622, 1225–1240. DOI: 10.1016/j.scitotenv.2017.11.324

Elith, J., Leathwick, J. R., & Hastie, T. 2008. A working guide to boosted regression trees. Journal of Animal Ecology, 77(4), 802–813. DOI: 10.1111/j.1365-2656.2008.01390.x

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. 2011. A statistical explanation of MaxEnt for ecologists. Diversity and Distributions, 17, 43–57. DOI: 10.1111/j.1472-4642.2010.00725.x

Escobar, H. 2019. Bolsonaro's first moves have Brazilian scientists worried. Science, 363(6425), 330. DOI: 10.1126/science.363.6425.330

Fabré, N. N., da Silva Batista, V., de Albuquerque Ribeiro, M. O., Ladle, R. J. 2012 A new framework for natural resource management in Amazonia. Ambio, 41(3), 302–308. DOI: 10.1007/s13280-011-0176-y

Farrell, S. L., Collier, B. A., Skow, K. L., Long, A. M., Campomizzi, A. J., Morrison, M. L., Hays, K. B., & Wilkins, R. N. 2013. Using LiDAR-derived vegetation metrics for high-resolution, species distribution models for conservation planning. Ecosphere, 4(3), 1–18. DOI: 10.1890/ES12-000352.1

Ferreira, B. P., Maida, M., & Cava, F. 2001. Características e perspectivas para o manejo da pesca na APA Marinha Costa dos Corais. In: Anais do II Congresso Brasileiro de Unidades de Conservação. pp. 50–58. MS, Brazil.

Fish, R., Church, A., & Winter, M. 2016. Conceptualising cultural ecosystem services:

A novel framework for research and critical engagement. Ecosystem Services, 21, 208–217. DOI: 10.1016/j.ecoser.2016.09.002

Gamarra, N. C., Correia, R. A., Bragagnolo, C., Campos-Silva, J. V., Jepson, P. R., Ladle, R. J., & Malhado, A. C. M. 2019. Are Protected Areas undervalued? An asset-based analysis of Brazilian Protected Area Management Plans. Journal of Environmental Management, 249, 109347. DOI: 10.1016/j.jenvman.2019.109347

Gibson, D., Chaplin, M. K., Hunt, K. L., Friedrich, M. J., Weithman, C. E., Addison, L. M., Cavalieri, V., Coleman, S., Cuthbert, F. J., Fraser, J. D. & Golder, W. 2018. Impacts of anthropogenic disturbance on body condition, survival, and site fidelity of nonbreeding Piping Plovers. The Condor: Ornithological Applications, 120(3), 566–580. DOI: 10.1650/CONDOR-17-148.1

Gruby, R. L., Gray, N. J., Campbell, L. M. & Acton, L. 2016. Toward a social science research agenda for large marine protected areas. Conservation Letters, 9(3), 153–163. DOI: 10.1111/conl.12194

Haase, P., Tonkin, J. D., Stoll, S., Burkhard, B., Frenzel, M., Geijzendorffer, I. R., Häuser, C., Klotz, S., Kühn, I., McDowell, W. H. & Mirtl, M. 2018. The next generation of site-based long-term ecological monitoring: Linking essential biodiversity variables and ecosystem integrity. Science of the Total Environment, 613, 1376–1384. DOI: 10.1016/j.scitotenv.2017.08.111

Haberl, H., Winiwarter, V., Andersson, K., Ayres, R., Boone, C., Castillo, A., Cunfer, G., Fischer-Kowalski, M., Freudenburg, W., Furman, E. & Kaufmann, R. 2006. From LTER to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological research. Ecology and Society, 11(2), 13.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agros, C., Bruno, J., Casey, K. S., Ebert, C. M., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M . P., Perry, M., Selig, E. R., Spalding, M., Steneck, R., Walbridge, S., & Watson, R. 2008. A global map of human impact on marine ecosystems. Science, 319 (5865), 948–952. DOI: 10.1126/science.1149345

Hausmann, A., Toivonen, T., Slotow, R., Tenkanen, H., Moilanen, A., Heikinheimo, V., & Di Minin, E. 2018. Social media data can be used to understand tourists' preferences for nature-based experiences in protected areas. Conservation Letters, 11(1), e12343. DOI: 10.1111/conl.12343

Hedley, J., Roelfsema, C., Chollett, I., Harborne, A., Heron, S., Weeks, S., Skirving, W., Strong, A., Eakin, C., & Christensen, T. 2016. Remote sensing of coral reefs for monitoring and management: a review. Remote Sensing, 8(2), 118. DOI: 10.3390/rs8020118

Hinds, W.T. 1984. Towards monitoring of long-term trends in terrestrial ecosystems. Environmental Conservation, 11(1), 11–18.

Hodgson, A., Kelly, N. & Peel, D. 2013. Unmanned aerial vehicles (UAVs) for surveying marine fauna: a dugong case study. PloS one, 8(11), e79556. DOI: 10.1371/journal.pone.0079556

Humle, T., Duffy, R., Roberts, D. L., Sandbrook, C., St John, F. V., Smith, R. J. 2014. Biology's drones: Undermined by fear. Science, 344(6190), 1351. DOI: science.344.6190.1351-a

Jepson, P., & Ladle, R. J. 2015. Nature apps: Waiting for the revolution. Ambio, 44, 827–832. DOI: 10.1007/s13280-015-0712-2

Jepson, P. R., Caldecott, B., Schmitt, S. F., Carvalho, S. H., Correia, R. A., Gamarra, N., Bragagnolo, C., Malhado, A. C. M. & Ladle, R. J. 2017. Protected area asset stewardship. Biological Conservation, 212, 183–190. DOI: 10.1016/j.biocon.2017.03.032

Keane, A., Jones, J. P., Edwards-Jones, G., & Milner-Gulland, E. J. 2008. The sleeping policeman: understanding issues of enforcement and compliance in conservation. Animal Conservation, 11(2), 75–82. DOI: 10.1111/j.1469-1795.2008.00170.x

Kelaher, B. P., Colefax, A. P., Tagliafico, A., Bishop, M. J., Giles, A. & Butcher, P. A. 2019. Assessing variation in assemblages of large marine fauna off ocean beaches using drones. Marine and Freshwater Research, 71(1), 68–77. DOI: 10.1071/MF18375

Kelly, N. M., Fonseca, M. & Whitfield, P. 2001. Predictive mapping for management and conservation of seagrass beds in North Carolina. Aquatic Conservation: Marine and Freshwater Ecosystems, 11(6), 437–451. DOI: 10.1002/aqc.494

Ladle, R. J., Correia, R. A., Do, Y., Joo, G. J., Malhado, A. C. M., Proulx, R., Roberge, J. M. & Jepson, P. 2016. Conservation culturomics. Frontiers in Ecology and the Environment 14(5), 269–275. DOI: 10.1002/fee.1260

Ladle, R. J., Malhado, A. C. M., Campos-Silva, J. V. & Pinheiro, B. R. 2020. Brazil's mystery oil spill: an ongoing social disaster. Nature, 578(7793), 37. DOI: 10.1038/d41586-020-00242-x

Laurance, W.F. 2013. Does research help to safeguard protected areas? Trends in Ecology & Evolution, 28(5), 261–266. DOI: 10.1016/j.tree.2013.01.017

Leão, Z. M. A. N., Kikuchi, R. K. P., Ferreira, B. P., Neves, E. G., Sovierzoski, H. H., Oliveira, M. D. M., Maida, M., Correia, M. D., & Johnsson, R. 2016. Brazilian coral reefs in a period of global change: A synthesis. Brazilian Journal of Oceanography, 64, 97–116. DOI: 10.1590/S1679-875920160916064sp2

Leão, Z. M. A. N., Kikuchi, R. K. P., & Oliveira, M. D. M. 2019. The Coral Reef Province of Brazil. In: C. Sheppard (Ed.), World Seas: An Environmental Evaluation. pp. 813–833. Amsterdã: Elsevier.

Leong, R. C., Friess, D. A., Crase, B., Lee, W. K., & Webb, E. L. 2018. High-resolution pattern of mangrove species distribution is controlled by surface elevation. Estuarine, Coastal and Shelf Science, 202, 185–192. DOI: 10.1016/j.ecss.2017.12.015

Levin, S.A. 1992. The problem of pattern and scale in ecology: the Robert H. MacArthur award lecture. Ecology, 73(6), 1943–1967. DOI: 10.2307/1941447

Magris, R. A., & Giarrizzo, T. 2020. Mysterious oil spill in the Atlantic Ocean threatens marine biodiversity and local people in Brazil. Marine Pollution Bulletin, 153, 1–3. DOI: 10.1016/j.marpolbul.2020.110961

McField, M., & Kramer, P. 2007. Healthy reefs for healthy people: A guide to indicators of reef health and social well-being in the Mesoamerican Reef Region. Smithsonian Institute, Washington. p. 208.

Mickwitz, P. 2003. A framework for evaluating environmental policy instruments: context and key concepts. Evaluation, 9(4), 415–436. DOI: 10.1177/1356389003094004

Miranda, R. J., Cruz, I. C. S., & Leão, Z. M. A. N. 2013. Coral bleaching in the Caramuanas reef (Todos os Santos Bay, Brazil) during the 2010 El Niño event. Latin American Journal of Aquatic Research, 41(2), 351–360. DOI: 10.3856/vol41-issue2-fulltext-14

Miranda, R. J., Almeida, E. C. G., Pinto, T. K., Sampaio, C. L. S., Pereira, P. H. C., Nunes, J. A. C. C., & Ladle, R. J. 2020. RE: Oil spill disaster in Brazil: impact assessment neglecting unique coral reefs. Science. 366, 6466. https://science.sciencemag.org/content/366/6466/672/tab-e-letters

Mirtl, M., Orenstein, D. E., Wildenberg, M., Peterseil, J., & Frenzel, M. 2013. Development of LTSER platforms in LTER-Europe: challenges and experiences in implementing place-based long-term socio-ecological research in selected regions. In: S. J. Singh, H. Haberl, M. Chertow, M. Mirtl, M. Schmid (Eds.), Long Term Socio-Ecological Research. pp. 409–442. Springer.

Mumby, P. J., Skirving, W., Strong, A. E., Hardy, J. T., LeDrew, E. F., Hochberg, E. J., Stumpf, R. P. & David, L.T. 2004. Remote sensing of coral reefs and their physical environment. Marine Pollution Bulletin, 48(3), 219–228. DOI: 10.1016/j.marpolbul.2003.10.031

Muñoz, L., Hausner, V. H., & Monz, C. A. 2019. Advantages and Limitations of Using Mobile Apps for Protected Area Monitoring and Management. Society & Natural Resources, 32(4), 473–488. DOI: 10.1080/08941920.2018.1544680

Nekola, J. C., & White, P. S. 1999. The distance decay of similarity in biogeography and ecology. Journal of Biogeography, 26(4), 867–878. DOI: 10.1046/j.1365-2699.1999.00305.x

Nel, J. L., Roux, D. J., Driver, A., Hill, L., Maherry, A. C., Snaddon, K., Petersen, C. R., Smith-Adao, L. B., Van Deventer, H., & Reyers, B. 2016. Knowledge co-production and boundary work to promote implementation of conservation plans. Conservation Biology, 30(1), 176–88. DOI: 10.1111/cobi.12560

Nezer, O., Bar-David, S., Gueta, T., & Carmel, Y. 2017. High-resolution species-distribution model based on systematic sampling and indirect observations. Biodiversity and Conservation, 26, 421–437. DOI: 10.1007/s10531-016-1251-2

Nieto-Lugilde, D., Maguire, K. C., Blois, J. L., Williams, J. W., & Fitzpatrick, M. C. 2018. Multiresponse algorithms for community-level modelling: Review of theory, applications, and comparison to species distribution models. Methods in Ecology and Evolution, 9(4), 834–848. DOI: 10.1111/2041-210X.12936

Normande, I. C., Luna, F. D. O., Malhado, A. C. M., Borges, J. C. G., Viana Junior, P. C., Attademo, F. L. N., & Ladle, R. J. 2015. Eighteen years of Antillean manatee *Trichechus manatus manatus* releases in Brazil: Lessons learnt. Oryx, 49(2), 338–344. DOI: 10.1017/S0030605313000896

Normande, I. C., Malhado, A. C. M., Reid, J., Viana, P. C., Savaget, P. V. S., Correia, R. A., Luna, F. O. & Ladle, R. J. 2016. Post-release monitoring of Antillean manatees: an assessment of the Brazilian rehabilitation and release programme. Animal Conservation, 19(3), 235–246. DOI: 10.1111/acv.12236

Ohl, C., & Swinton, S. M. 2010. Integrating social sciences into long-term ecological research. In: J. Singh, H. Haberl, M. Chertow, M. Mirtl, M. Schmid (Eds.), Long-Term Ecological Research. pp. 399–410. Dordrecht: Springer.

Oliveira Soares, M., Teixeira, C. E. P., Bezerra, L. E. A., Paiva, S. V., Tavares, T. C. L., Garcia, T. M., Araújo, J. T., Campos, C. C., Ferreira, S. M. C., Matthews-Cascon, H., Frota, A., Mont'Alverne, T. C. F., Silva, S. T., Rabelo E. F., Barroso, C. X., Freitas, J. E. P., Júnior, M. M., Campelo, R. P. S., Santana, C. S., Carneiro, P. B. M., Meirellesi, A. J., Santos, B. A., Oliveira, A. H. B., Horta, P. & Cavalcante, R. M. 2020. Oil spill in South Atlantic (Brazil): Environmental and governmental disaster. Marine Policy, 115, 103879. DOI: 10.1016/j.marpol.2020.103879

Pereira, E. J. D. A. L., Ferreira, P. J. S., de Santana Ribeiro, L. C., Carvalho, T. S., & de Barros Pereira, H. B. 2019. Policy in Brazil (2016–2019) threaten conservation of the Amazon rainforest. Environmental Science & Policy, 100, 8–12. DOI: 10.1016/j.envsci.2019.06.001

Peterson, A. T., & Soberón, J. (2012). Species distribution modeling and ecological niche modeling: getting the concepts right. Natureza & Conservação, 10(2), 102–107.

Pittman, S. J., Christensen, J. D., Caldow, C., Menza, C., & Monaco, M. E. (2007). Predictive mapping of fish species richness across shallow-water seascapes in the Caribbean. Ecological Modelling, 204(1), 9–21. DOI: 10.1016/j.ecolmodel.2006.12.017

Poe, M. R., Norman, K. C., & Levin, P. S. 2014. Cultural dimensions of socioecological systems: key connections and guiding principles for conservation in coastal environments. Conservation Letters, 7(3), 166–175. DOI: 10.1111/conl.12068

Purkis, S. J. 2018. Remote sensing tropical coral reefs: The view from above. Annual Review of Marine Science, 10, 149–168. DOI: 10.1146/annurev-marine-121916-063249

Rees, A. F., Avens, L., Ballorain, K., Bevan, E., Broderick, A. C., Carthy, R. R., Christianen, M. J., Duclos, G., Heithaus, M. R., Johnston, D. W., & Mangel, J. C. 2018. The potential of unmanned aerial systems for sea turtle research and conservation: a review and future directions. Endangered Species Research, 35, 81–100. DOI: 10.3354/esr00877

Retka, J., Jepson, P., Ladle, R. J., Malhado, A. C. M., Vieira, F. A. S., Normande, I. C., Souza, C. N., Bragagnolo, C., & Correia, R. A. 2019. Assessing cultural ecosystem services of a large marine protected area through social media photographs. Ocean & Coastal Management, 176, 40–48. DOI: 10.1016/j.ocecoaman.2019.04.018

Richards, D. R., & Friess, D. A. 2015. A rapid indicator of cultural ecosystem service usage at a fine spatial scale: content analysis of social media photographs. Ecological Indicators, 53, 187–195. DOI: 10.1016/j.ecolind.2015.01.034

Riddle, B. R., Ladle, R. J., Lourie, S. A. & Whittaker, R. J. 2011. Basic biogeography: estimating biodiversity and mapping nature. In: R. J. Ladle, & R. J. Whittaker (Eds.), Conservation Biogeography. pp. 45–92. OUP: Oxford.

Robinson, N. M., Nelson, W. A., Costello, M. J., Sutherland, J. E., & Lundquist, C. J. 2017. A systematic review of marine-based species distribution models (SDMs) with recommendations for best practice. Frontiers in Marine Science, 4, 1–11. DOI: 10.3389/fmars.2017.00421

Sandbrook C. 2015. The social implications of using drones for biodiversity conservation. Ambio, 44, 636–647. DOI: 10.1111/cobi.12622

Savill, P., Perrins, C., Kirby, K., & Fisher, N. 2010. Wytham Woods: Oxford's ecological laboratory. 1st ed. OUP: Oxford.

Schapire, R. E., & Freund Y. 2013. Boosting: Foundations and algorithms. Kybernetes, 42(1), 164–166. DOI: 10.1108/03684921311295547

Silva, M. 2005. The Brazilian protected areas program. Conservation Biology, 19(3), 608–611. DOI: 10.1111/j.1523-1739.2005.00707.x

Soininen, J., McDonald, R., & Hillebrand, H. 2007. The distance decay of similarity in ecological communities. Ecography, 30(1), 3–12. DOI: 10.1111/j.0906-7590.2007.04817.x

Spilsbury, M. J. & Nasi, R. 2006. The interface of policy research and the policy development process: challenges posed to the forestry community. Forest Policy and Economics, 8(2), 193–205. DOI: 10.1016/j.forpol.2004.09.001

Steiner, A. Q., Eloy, C. C., Amaral, J., Amaral, F. M. D., & Sassi, R. 2006. O turismo em áreas de recifes de coral: considerações acerca da Área de Proteção Ambiental Costa dos Corais (Estados de Pernambuco e Alagoas). OLAM Ciência e Tecnologia, 6(2), 281–296.

Sutherland, W. J., Pullin, A. S., Dolman, P. M. & Knight, T. M. 2004. The need for evidence-based conservation. Trends in Ecology & Evolution, 19, 305–308. DOI: 10.1016/j.tree.2004.03.018

Tabarelli, M., Rocha, C. F. D., da Romanowski, H. P., Rocha, O., & de Lacerda, L. D. 2013. PELD-CNPq dez anos do Programa de Pesquisas Ecológicas de Longa Duração do Brasil: achados, lições e perspectivas. Recife: Editora Universitária UFPE: p. 446.

Tardin, R. H., Chun, Y., Jenkins, C. N., Maciel, I. S., Simão S. M., Alves, & M. A. S. 2019. Environment and anthropogenic activities influence cetacean habitat use in southeastern Brazil. Marine Ecology Progress Series, 616, 197–210. DOI: 10.3354/meps12937

Tenkanen, H., Di Minin, E., Heikinheimo, V., Hausmann, A., Herbst, M., Kajala, L. & Toivonen, T. 2017. Instagram, Flickr, or Twitter: Assessing the usability of social media data for visitor monitoring in protected areas. Scientific Reports, 7, 17615. DOI: 10.1038/s41598-017-18007-4

Thomas, L., & Middleton, J. 2003. Guidelines for management planning of protected areas. IUCN: Gland, Cambridge.

Ventura, D., Bruno, M., Lasinio, G. J., Belluscio, A., & Ardizzone, G. 2016. A low-cost drone based application for identifying and mapping of coastal fish nursery grounds. Estuarine, Coastal and Shelf Science, 171, 85–98. DOI: 10.1016/j.ecss.2016.01.030

Vieira, F. A., Bragagnolo, C., Correia, R. A., Malhado, A. C. M., & Ladle, R. J. 2018. A salience index for integrating multiple user perspectives in cultural ecosystem service assessments. Ecosystem Services, 32, 182–192. DOI: 10.1016/j.ecoser.2018.07.009

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H., & Tilman, D. G. 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecological applications, 7(3), 737–750. DOI: http://doi.org/ftpfnt

Whitelaw, G., Vaughan, H., Craig, B., & Atkinson, D. 2003. Establishing the Canadian Community Monitoring Network. Environmental Monitoring and Assessment, 88, 409–418. DOI: 10.1023/A:1025545813057

Whittaker, R. J., Willis, K. J., & Field, R. 2001. Scale and species richness: towards a general, hierarchical theory of species diversity. Journal of Biogeography, 28, 453–470. DOI: 10.1046/j.1365-2699.2001.00563.x

Wich, S. A., & Koh, L. P. 2018. Conservation drones: Mapping and Monitoring Biodiversity. S. A. Wich, & L. P. Koh (Eds.), Oxford: Oxford University Press: p. 198.

Willig, M. R., Walker, L. R., 2016. Long-Term Ecological Research: Changing the Nature of Scientists. Oxford: Oxford University Press: p. 464.

Willis, K. J., & Whittaker, R.J. 2002. Species diversity-scale matters. Science, 295, 1245–1248. DOI: 10.1126/science.1067335

Wisz, M. S., Pottier, J., Kissling, W. D., Pellissier, L., Lenoir, J., Damgaard, C. F. Dormann, C. F., Forchhammer, M. C., Grytnes, J. A., Guisan, A., Heikkinen, R. K., Høye, T. T., Kühn, I., Luoto, M., Maiorano, L., Nilsson, M. C., Normand, S., Öckinger, E., Schmidt, N. M., Termansen, M., Timmermann, A., Wardle, D. A., Aastrup, P., & Svenning, J. C. 2013. The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. Biological Reviews of the Cambridge Philosophical Society, 88, 15–30. DOI: 10.1111/j.1469-185X.2012.00235.x

Worboys, G., Lockwood, M., & De Lacy, T., 2001. Protected area management: Principles and practice. Melbourne: Oxford University Press: p. 399.

Worboys, G. L., Lockwood, M., Kothari, A., Feary, S., & Pulsford, I. 2015. Protected area governance and management. ANU Press: p. 966.

Wyborn, C. 2015. Connecting knowledge with action through coproductive capacities: adaptive governance and connectivity conservation. Ecology and Society, 20(1), 1–11. DOI: 10.5751/ES-06510-200111

Zafra-Calvo, N., Garmendia, E., Pascual, U., Palomo, I., Gross-Camp, N., Brockington, D., Cortes-Vazquez, J. A., Coolsaet, B. & Burgess, N. D. 2019. Progress toward equitably managed protected areas in Aichi target 11: a global survey. BioScience, 69(3), 191–197. DOI: 10.1093/biosci/biy143

Submitted: 2 September 2019
Accepted: 14 April 2020
Published on line: 15 June 2020
Associate Editors: Camila Barros and Nuria Pistón

Appendix 1

Table A1. Research components, specific aims and metrics for monitoring of the Long Term Ecological Research Costa dos Corais Alagoas.

Research component	Aim	Metric for monitoring
Ecosystem Structure		
1.1	To describe physical-chemical water conditions and extension of coastal/marine ecosystems (estuaries, mangroves, coral reefs and sandy beaches) and management zoning	Physical/chemical variables (e.g. seawater temperature, salinity, pH, turbidity, dissolved oxygen, dissolved organic nitrogen, radon, nitrite, nitrate, phosphate, silicate, calcium carbonate, chlorophyll a). Microbiological variables (total coliforms, *Escherichia coli* and enterococci abundance, and *Bacillus, Staphylococcus* and *Clostridium* presence/absence using phylochip DNA microarray). Area (km^2) of the systems using remote sensing.
1.2	To describe taxonomic diversity and assemblages structure	Abundance, richness, and functional diversity (microorganisms, corals, zoanthids, algae, octocorals, fish, sea turtles, manatees, birds and plants).
Ecosystem function		
2.1	To monitor key populational process of emblematic species (e.g. manatees and sea turtles) important to social and economic issues	Manatees and sea turtles abundance using drones, molecular/genetic identification of *Mugil* spp. a commercially relevant estuarine fish species.
2.2	To assess reef condition inside and outside no take zones specially coral bleaching and mortality	% Bleaching, % mortality, % disease and % healthy in coral community.
2.3	To monitor dynamics of fluxes in river-estuary-reef systems	Invertebrates and fish biomass/abundance in different habitats in the estuarine system.
2.4	To monitor herbivory process, investigating relationships between algae, reef fish, sea turtles and manatees.	Algae, sea grass and herbivores abundances, herbivore fish bite rates, algae biomass in gut contents of sea turtles and manatees.
Threats		
3.1	To identify tourism magnitude.	Tourist number in coral reefs, sandy beaches and manatee conservation zone.
3.2	To monitor marine and estuarine pollution investigating water quality.	Seawater temperature, salinity, pH, turbidity, dissolved oxygen, dissolved organic nitrogen, radon, nitrite, nitrate, phosphate, silicate, calcium carbonate. Total coliforms, *Escherichia coli* and enterococci abundance, and *Bacillus, Staphylococcus* and *Clostridium* presence/absence using phylochip DNA microarray. Hybridization degree of target species for artisanal fishing (*Mugil* spp.).

Table 1. Continues on next page...

Table 1. ...Continued

Research component	Aim	Metric for monitoring
3.3	To investigate socioeconomic fishing activities.	Artisanal fishermen socioeconomic description and fishing activities production.
3.4	To monitor fishing and tourism impacts.	Fish structure stocks for fishing target species. Coral reef communities condition inside and outside Tourism Zones, and tourist number.
3.5	Mapping landscape activities such as agriculture, shrimp farms and urban areas.	A map integrating land, coastal and marine areas of APACC interest.
3.6	To evaluate climate change effects on marine systems.	% Bleaching, % mortality, % disease and % healthy associated to episodes of seawater temperature anomalies. Sedimentation rates and river flows.
Governance/Management		
4.1	To identify attitudes, behaviours and perceptions of the residents, fishermen, teachers about the coastal/marine ecosystem importance for themselves life quality.	Attitudes, behaviours and perceptions of the people.
4.2	To describe the Cultural Ecosystem Services.	Aesthetic values, recreation, spiritual values, inspirations.
4.3	To assess efficiency of no-take areas integrating biological, social and economic metrics aiming establish adaptative/participative police.	Condition, abundance and richness of reef species as corals, urchins, algae, octocorals, fish inside and outside no-take zones. Cultural Ecosystem Services.
4.4	Training local people and students focusing on tropical biodiversity conservation with multidisciplinary approach.	Number of people and students trained.
4.5	To create and share long term socioecological database.	An online database.